H. P. Garg

Advances in Solar Energy Technology

Volume 3

Heating Agricultural and Photovoltaic Applications of Solar Energy

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A MEMBER OF THE KLUWER ACADEMIC PUBLISHERS GROUP

DORDRECHT / BOSTON / LANCASTER / TOKYO

Library of Congress Cataloging in Publication Data

CIP

Garg, H. P.
Advances in solar energy technology.

Includes bibliographies and indexes.
Contents: v. 1. Collection and storage systems— v.2. Industrial applications of solar energy— v. 3. Heating, agricultural and photovoltaic applications of solar energy.
1. Solar energy. I. Title.
TJ809.2.G37 1987 621.47 86–31441
ISBN-13:978-94-010-8189-4 e-ISBN-13:978-94-009-3797-0
DOI: 10.1007/978-94-009-3797-0

Published by D. Reidel Publishing Company,
P.O. Box 17, 3300 AA Dordrecht, Holland.

Sold and distributed in the U.S.A. and Canada
by Kluwer Academic Publishers,
101 Philip Drive, Assinippi Park, Norwell, MA 02061, U.S.A.

In all other countries, sold and distributed
by Kluwer Academic Publishers Group,
P.O. Box 322, 3300 AH Dordrecht, Holland.

Dedicated to my parents who
believed in Honesty, Sincerety
and Hardworking.
To my wife, Kusum, and my children,
Meenu, Neelu, Naina and Darpan, for
their support and perseverance.

CONTENTS

PREFACE

This volume is the third in the series of the book entitled, 'Advances in Solar Energy Technology'. The purpose of writting this multiple volume book is to provide all the relevant latest information in the field of Solar Energy (Applied as well as theoretical) to serve as the best source material at one place. Attempts are made to discuss topics in depth to assist both the students (undergraduate, post - graduate, Research Scholars) and the professionals (consulting, design, contracting firms). The third volume discusses the heating, agricultural and photovoltaic applications of Solar Energy.

Chapter 1 deals with solar cookers, one of the important application area for developing countries. After discussing the history of solar cookers, eight types of direct solar cookers, two types of box solar cookers and two types of advanced solar cookers are discussed in detail. The performance studies carried out on direct type and on box type solar cookers are also presented. A test procedure for rating a box type solar cooker is also introduced. The limitations and advantages of various cookers are discussed briefly in the chapter.

Desalinated water for drinking purposes, for industrial and agricultural applications is required. The topic of Solar Distillation is discussed in detail in chapter two. Solar Distillation has a long history and in this chapter various kind of solar stills like conventional solar still, tilted tray solar still, wick type solar still, multiple effect diffusion solar still, multistage flash distillation, etc. have been discussed in depth. The single effect basin type solar still (the so called conventional solar still) has been discussed in somewhat greater detail including its design, basics, prediction model and experiments conducted on the same.

There is a considerable post-harvest food losses amounting to 25 percent of the total production mainly in developing countries. This post-harvest food losses can be reduced by using solar drying techniques which is a topic of chapter three. This chapter starts with the basics of solar drying and then discusses different types of convective solar dryers, indirect type solar dryers and forced circulation type solar dryers. The design of various dryers falling in these three categories are discussed in detail. To understand the drying mechanism and the dryer behaviour various analytical simulation models are developed from time to time. In this chapter mathematical models both for single layer drying and deep bed drying are discussed briefly.

For increasing the crop production water is an essential ingradient and the pumping of water is therefore an important topic. There is a long history of solar operated water pumps which is a topic of chapter four. After discussing various components of solar energy operated pumps, typical solar pump systems, which are of different capacity, using different kind of solar energy collectors, storage systems, heat engines, working fluids and installed in different climatic conditions are discussed in detail. In all eight solar pump installations are discussed in this chapter.

The topic of solar greenhouse which is a common feature in many European countries and is becoming popular in other countries also is discussed in chapter 5. The basics of plant growth like light intensity, temperature, humidity, air movement, carbon dioxide, nutrients, watering, etc. are discussed in this chapter briefly. The main components required for greenhouse design and the heat transfer mechanism taking place in respect of both glass and plastic greenhouses are also discussed. Both the heating techniques required in cold countries and cooling techniques required in hot countries are discussed briefly. Various energy conservation methods to make fullest use of solar energy are presented in this chapter. Eight typical greenhouse designs which are installed in different climatic zones are also discussed in this chapter in detail. A performance prediction model for predicting the crop production and thermal environment in greenhouse is also presented in this chapter.

The last chapter (chapter 6) of this volume and of the series is on solar cells which is a exploding field all over the world and scientists have great hope to convert solar energy into electricity through solar cells at a price comparable to that produced by the convectional methods. Perhaps maximum number of papers are published on this topic alone, and therefore it has a long history. The chapter on solar cells starts with the historical background and then goes in depth with the fundamentals of photovoltaic conversion where the semiconductor materials, p-n junction, photon absorption, solar cell materials, etc. are discussed. The factors responsible for the low efficiency of solar cells are also discussed in detail with a view so that reader would know the possible limitations and improvement possibilities for higher conversion efficiency. Basic models in respect of p-n junction, heterojunction, metal semiconductor junction are also presented. Silicon solar cells are produced commercially and used both in the space and on the ground for many applications and therefore silicon solar cells are discussed in this chapter in great detail. The purification of silicon, methods of growing crystal and techniques of making single crystal silicon solar cells, polycrystalline silicon cells, amorphous silicon cells and high efficiency silicon cells are briefly discussed. For high conversion efficiency under high temperature operation, gallium arsenide solar cells are recommended. The advantages and disadvantages of these cells are also discussed. The CdS/Cu_2S solar cells and cadmium telluride solar cells which can cheaply be produced on large areas and have great hope in the near future are also discussed briefly. The photovoltaic concentrators which increases the intensity on solar cells are also discussed in this chapter.

Finally a few appendices are added at the end of these chapters in which conversion units, properties of materials and other useful data are included.

The book is written with the intention for its use as a text book for students of higher learning and as a reference book for consulting engineers, designers, technologists, and scientists who have interest or engaged in the field of solar energy utilization.

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ACKNOWLEDGEMENTS

The author is grateful to several international research institutes and organizations who responded to his requests of supplying published and unpublished literature required for writing this volume. Many research papers, reports, and articles published by many publishers have been referred in this book. I am particularly grateful to Dr. Peter E. Glaser, Editor-in-chief, Solar Energy; and Pergamon Press, Inc., London for providing literature and giving permission to use the material published in solar Energy Journal. The author is also grateful to many other publishers like John Wiley & Sons Ltd., Inc. England; Mc-Graw Hill Book Co., Inc., New York; Academic Press, Inc., New York; Applied Science Publishers, England; Addison Wesley Pub. Co., California; International Solar Energy Society, Inc; U.S. Department of Energy, Washington, D.C. USA; Marcel Dekker, Inc., New York; Butterworths, Inc., London; etc. who have permitted to use literature published by them.

The encouragement and support of Shri Maheshwar Dayal, Secretary, Department of Non-Conventional Energy Sources (Govt. of India), New Delhi; Prof. M.S.Sodha, Indian Institute of Technology, New Delhi; Dr.C.L.Gupta, Tata Energy Research Institute (Field Research Unit), Pondicherry; and Dr.R.K.Pachauri, Director, Tata Energy Research Institute, New Delhi is gratefully acknowledged. The author is thankful to the Head, Centre of Energy Studies andDirector, Indian Institute of Technology, New Delhi for the encouragement and for providing part financial support for completing the manuscript of this volume.

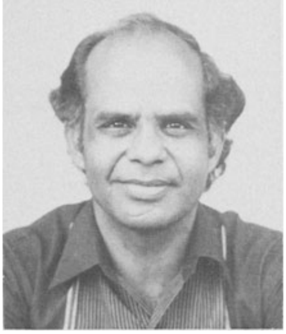
The author had the opportunity to travel extensively to different countries like USA, USSR, Australia, Italy, Canada, England, Thailand, Singapore, Iraq, Iran, Bangladesh,Indonesia, Spain, Austria, West Germany, etc. and had discussions with scientists from many other countries also. I am particularly grateful to Dr.P.E.Glaser, USA; Dr.E.D.Howe, USA; Dr.W.A.Beckman, USA; Dr.J.A.Duffie, USA; Dr.W.W.S.Charters, Austrialia; Dr.D.K.Edwards, USA; Dr.J.D.Walton, USA; Dr.R.N.Morse, Australia; Dr.R.V.Dunkle, Australia; Dr.U.A.Arifov, USSR; Dr.B.J.Brinkworth, England; Dr.A.Sayigh, Kuwait; Dr.G.Furlan, Italy; Dr.N.Al-Hamdani, Iraq; Prof.E.Hahne, West Germany; Prof. G.Lehnar, West Germany; prof.A.Boettcher, West Germany; prof.W.H.Bloss, West Germany; Prof.K.W.Boer, USA; Prof.D.Tinaut, Spain; etc.

who have helped me directly or indirectly in the preparation of this book.

The author is also thankful to some of his friends like Dr.N.K.Bansal, Dr.Ashok Bhargava, Dr.Jai Prakash, Dr.V.K.Sharma, Dr.(Mrs.) Usha Rani. Dr.(Mrs.) Gouri Datta, Mr.S.N.Garg, and many others who have helped him at several stages while preparing the manuscript. I am also thankful to Mr.Ramesh for draft typing, Mr.Navdeep Singh for final manuscript typing and Mr.Kirpal Singh for drawing making.

The author's thank are due to the staff of Centre of Energy Studies, Indian Institute of Technology, New Delhi, India, who have been, at all times, kind and helpful. My special appreciation is to my wife Kusum Garg, daughters, Meenu, Neelu, Naina and son Darpan for all moral support and patience during the preparation of the manuscript.

New Delhi, India H.P.Garg



ABOUT THE AUTHOR

H.P.Garg is professor and coordinator of solar energy at Indian Institute of Technology, New Delhi, India. He is internationally recognised as one of the world's leading authorities in the field of solar thermal applications. Dr.Garg is involved in research and teaching of Solar Energy for the last 21 years and is the author of more than 250 research papers. He has arranged several national and international training programmes and conferences in the field of solar energy utilization and visited several countries of the world. He has made significant contribution to the field of Solar Energy Collectors and Solar Heating Systems. His designs on solar systems are quite popular both nationally and internationally and he has three Indian patents to his credit. Prof.Garg is the author of 'Treatise on Solar Energy' published by John Wiley & Sons (1982), England; co-author of 'Solar Thermal Energy Storage' published by D.Reidel Publishing Co. (1985), Holland; and edited a book, 'Solar Water Heating Systems' published by D.Reidel Publishing Co.(1985), Holland. His main fields of interest are Solar Energy Technology and Utilization, Energy conservation, Bio-gas systems, Wind power utilization, and Energy planning.

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CHAPTER - I

SOLAR COOKERS

1.1 INTRODUCTION

Food, cloth, and shelter are the three main necessaties of human beings. Availability of cheap and abundant supply of energy is an index of the prosperity of a country. Firewood is the fourth most important source of energy after coal, oil, and natural gas, considering the World as a whole. The fuel wood used in developing countries and developed countries are 80 percent and 10 percent respectively [1]. For the world as a whole about 50 percent of the fuel wood is used for cooking of food, and 50 percent for the other household purpose like heating, process applications and in industries[2]. The per capita of forest in Asia is very low, and in many Asian and African Countries, the commercial fuels like coal, oil and electricity is not available and therefore they have to depend on the fuel wood for cooking of food. In these countries the forests are fast depleting and therefore the fuel wood price has increased three fold during the last five years. The forest area per capita(hactare) and the fuel wood consumption per capita (Kg of coal equivalent) for some of the developing countries is shown[1] in fig.1.1. It is seen from this figure that in many countries there is a shortage of fuel wood and therefore afforestation programmes and forest management procedures are to be adopted. The scracity of fire wood imposes economic and social burden on the poor.

Both commercial energy sources like coal, oil, and electricity and non-commercial energy sources like firewood, cow dung, and agricultural wastes are used for cooking of food. But in rural areas where transportation and money is a problem, non-commercial energy sources are used for cooking of food. It has been estimated[3] that in Rural India more than 95 percent of the energy consumed goes for cooking only and most of which is derived from firewood(33 percent), agricultural wastes(24 percent) and Cow dung cakes (33 percent). The large scale cutting of trees (deforestation) is a growing worldwide concern over the ecological problems and human sufferings. It has been estimated[3] that more than 15 million hectares of forest cover is lost every year in developing countries mainly its use as fuel wood. This causes soil erosion, land degradation, loss of

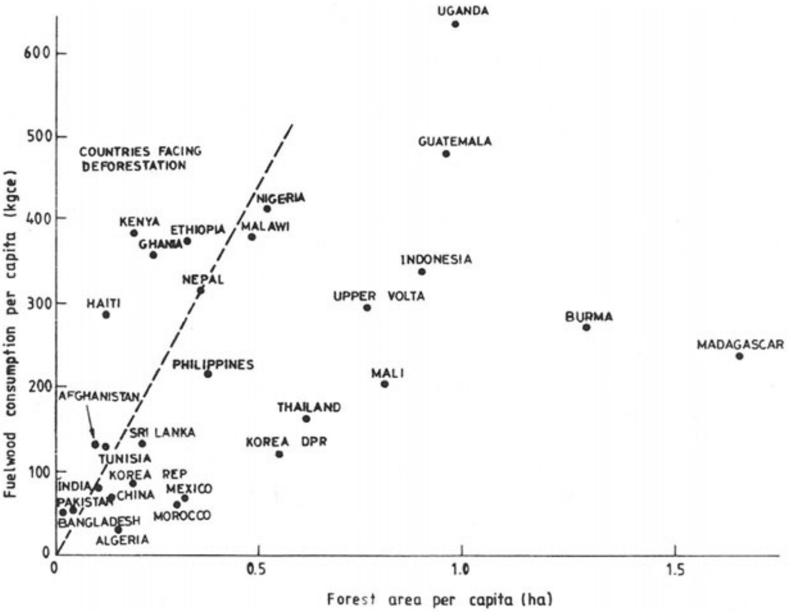


FIG 1.1 FIREWOOD CONSUMPTION PER CAPITA AND FOREST AREA FOR SOME OF THE DEVELOPING COUNTRIES (From Parikh[1])

watershed and deep water table resulting in widespread desertification.

The use of dried cow dung as cooking fuel is extremely unfortunate since it is a very good fertilizer than a fuel. About 400 million tons of wet dung which becomes 80 million tons when dried-are annually burned for fuel in India alone, robbing farmland of badly needed nutrients and organic matter. The agricultural wastes which is mainly derived from crop residues is also used as a fuel for cooking and its use is increasing which otherwise can also be used as a fertilizer.

Since food is to be cooked, and in the absence of any alternate cooking fuel, it is impossible to stop the rural people of using fuel wood, agricultural waste, and dried cow dung. The solar cooker if available and suits to their requirements can offer a partial solution to the multitude of problems faced by the poor and the people living in the sunny belt of the developing countries. Solar cooker if it is properly developed, engineered, and studied; introduced; and proper education and training is provided; can be used on a mass scale and will therefore releive hundreds of millions of people of the world from sufferings and hardships.

1.2 HISTORY OF SOLAR COOKERS

One of the simplest, earliest and most required application of solar energy is its use for cooking of food. Solar energy has been used by men for drying of food products and for cooking of food since the begining of recorded history. Attempts were made about 200 years ago to develop different types of solar cookers even when fuel was cheap and abundantly available. De Saussure[4] in 1776 in Switzerland developed the first hot box type solar cooker consisting of an insulated, airtight wooden box blackened from inside and covered with two colourless window panes seperated by an air space. The sunlight entered the box through the glass and was absorbed by the black surface. A temperature of about 90°C was achieved in this simple hot box cooker. John Herschell[5] in 1837 in England developed a solar oven which was a black box and insulated it by burrying in sand leaving only the top exposed with two glass covers through which solar energy entered the box. The vegetables and meat was cooked in this box and has shown a temperature of 116°C. Lavoisier was able to melt several metals and fuse platinum(1773°C) by using a hollow lens, 1.3 m in diameter, filled with alcohol. Mouchot[6] in 1869 in France developed a solar cooker consisting of a parabolic reflector reflecting solar radiation on to a cooking pot and the same was commissioned by the French emperor, Napoleon III for the French colonial troops in Africa. He demonstrated its use at the world Exhibition in Paris in 1878 cooking a pound of beef in about 20 minutes. W.Adams [7], an Englishman working in India, during the year 1876 developed a solar cooker using flat-mirrors arranged in an eight-sided pyramidical structure, 70 cm in diameter at the larger end. Sunlight falling on the mirrors was focussed on a pot of food placed at the focus. This cooker was able to cook vegetables and even meat but was expensive for the average person to buy. Samual Pierpont Langlay[8] in 1884 built a hot box type of solar cooker and demonstrated its use atop Mount Whitney in California. Inspite of the snow and frozen ground the cooker was able to cook food at high altitudes. In the United States C.G.Abbot[9,10] in 1916 built several solar cookers using cylindrical parabolic reflector focussing sunlight onto a blackened pipe filled with motor oil and the tube enclosed by a transparent glass tube to prevent heat loss. The blackened pipe carried hot oil to a reservoir in an insulated box where the cooking utensil is located, and the return pipe form the reservoir carried cooler oil to the inlet of the pipe completing the circuit. In this cooker the cylindrical reflector was turned automatically by a clockwork during the day. The cooker designed by Abbot was exhibited at the Smithsonian Institution Museum in Washington and had attained a temperature of about 180 °C. The cost of cooker was too high for practical use but the oil reservoir was able to held heat for a long time and therefore the food was cooked even after many hours of sunset. During the early 1930's, Mourain[11] conducted some experiments on Solar Cookers primarily for the French colonies but could not show any worthwhile results During the year 1952, the National Physical Laboratory of Great Britain, identified the area of Solar Cooker as one of the main research area in the field of Solar Energy utilization.

The pioneer work on Solar cooker was conducted at the National Physical Laboratory of India by a group of scientists[13,14,15] who made the first practical solar cooker. This cooker used a aluminium parabolic reflector on a stand that enabled the angle to be adjusted, with a cooking pot held at its focus. These cookers were tested under different climatic conditions and were manufactured commercially for a limited time by Devidayal Industries in Bombay. A UNESCO conference on Wind Power and Solar Energy[16] was held in New Delhi during October 1954 in which several solar energy devices including Solar Cookers were exhibited. In these cookers several manually adjustable mirrors were mounted in a frame, reflecting sunlight on to a cooking pot. Each mirror was to be manually adjusted more frequently to keep the focussed light on to the pot making the system unattractive and combursome from utility point of view. Lectures on Solar Cookers were given by Duffie[17], Telkes [18], and Ghai[19] at the first World Symposium on Solar Energy At Tucson and Phoenix in 1955 and several Solar Cookers were exhibited during the conference period. Several papers[20-27] dealing with the designs and performances of solar cookers were presented at the united Nations conference on Solar Energy, Wind Power, and Geothermal energy in Rome during August 1961. A Plastic Solar Cooker[28,17] was developed at the university of Wisconsin consisting of a plastic shell lined with aluminized mylar suspended in a U-frame helping in tilting the reflector easily and reflecting the sunlight on to a cooking pot held at its focus. Lof[22] described a lightweight portable solar cooker using an umbrella frame with aluminized mylar laminated to the inside of the cloth and grill for holding the kettle or frying pan. Several types of Solar Cookers are described by F.Daniels in his book on 'Direct use of the Sun's energy' with the simplest one consisting of a fixed, spheroidal reflector made by forming a spheroidal depression in the ground. This depression is lined first with a mixture of soil and cement to stablize the shape and then with aluminized mylar.

Extensive studies on a simple hot box type Solar Cooker [29,30] was conducted by M.K.Ghosh(1932) in India. This solar cooker was consisted of 2 wooden boxes, one placed within the other and the top was covered with the glass sheets fitted in a wooden frame. A plane mirror of the size of the window was hinged on to one side of the cooker to enhance the solar radiation input into the box. Temperatures as high as 120°C was reported in the hot box. Dr.Maria Telkes[18,23,31] under the auspices of the united Nations developed a Solar oven which consists of an insulated box with double glazed window and four plane slanting reflectors of bright aluminium at the sides of the window reflecting sunlight down through the window into the window. The insulated box may be filled with some suitable heat-storage salts, making the cooker suitable even for late evening use. Temperatures as high as 210 °C are reported in this oven. The performance of this oven can be improved by using more plane reflectors in series known as compound wedge reflector instead of using one large plane reflector as is done by Telkes[31]. The analysis of this type of concentrator is done by Mannan[32] and has shown that by compounding the reflector, the surface area of the reflector can be reduced and higher effective concentration can be attained. Cobble [33] has analysed the conical reflector system with a circular cylindrical target or a conical target and has shown that a conical mirror with either target is capable, theoretically, of higher concentration than the parabolic cylinder mirror with either a flat-plate target or a circular cylinder target.

A solar steam cooker using a shallow cylindro-parabolic reflector and a double walled insulated hot box was developed by Whillier[34] in Canada in 1965. The reflector consists of a shallow parabolic cylindrical section made of thin hardboard laminated with aluminium foil on the inner side. Reflected radiation generates the steam by heating the water in the blackened pipe which goes into the insulated box heating the cooking vessel.

A.Whillier[35] in Canada in 1965 developed a solar steam cooker consisting of a tube in plate type of flat plate collector and an insulated hot box containing the cooking vessels. Water in the flat-plate collector($0.75m^2$) gets boiled when the collector is exposed to solar radiation and this low pressure low temperature steam goes in the hot box giving its heat to the cooking vessels thereby cooking the food. Several cooking trials are conducted and concluded that this can be used for boiling the food.

Hazzard et al[36,37] in 1966 in USA as a VITA effort developed a solar cooker using Fresnel mirror type-parabolic -reflector made up of concentric rings of reflective material on a rigid backing. These reflective rings are mounted on a wooden frame in such a way that these concentrate sun light at a focal length of 75 cm. The diameter of the outer ring is 1.15 m^2. This reflector is mounted on a tripod with two fixed legs on the front side and one pivoting wooden leg to keep the cooker at the desired angle. In order to find their durability and usefulness, 90 such cookers were supplied to the villagers of Morocco in the year 1966. All variety of food was practically cooked with this cooker.

In an effort to reduce wind load due to a large size single reflector, Tabor[38] in Israel in 1966 developed a solar cooker which uses 12 identical, 0.29 m diameter concave glass mirrors mounted in an iron frame in a 2-axis azimuthal mounting, permitting reflection of radiation on the bottom of the cooking pot. When the incoming solar radiation was 890 W/m^2, the cooker was equivalent to 500 watts. A similar multifacet solar cooker was developed and tested in USSR by Umarov et al[39].

A concentrating type solar cooker using a cylindrical concentrator(0.75 x 1.2 m) mounted on a polar axis with automatic suntracking mechanism and a heat pipe at its focus with 'Daytherm A' heat transfer fluid in it and an indoor hot plate was developed by Swet[40,41,42] in USA in 1972. The working fluid in the heat pipe boils gives its heat to the specially designed hot plate, gets condensed and returns by gravity and is distributed by wicking action over the entire inner surface of the heat pipe. When no cooking is required a heat storage material is proposed to store the heat for later use.

Garg[43] in 1976 in India also designed a Fresnel reflector type of solar cooker with a reflector of diameter 1.2 m and focal length 0.6 m. Seven anodized aluminium strips each of 7.5 cm wide are used and fixed on a wooden frame in grooves whose angles are different and calculated in such a way that the reflected radiation meets at one point. Trials conducted on this cooker have given encouraging results bringing 1.0 litre of water to boiling point within 30 minutes.

Garg[44] in India in 1976 developed a single reflector type hot box solar cooker with double glazed window inclined at an optimum tilt to collect more solar radiation. The cooking chamber was large enough to accomodate even more than four cooking vessels. Several cooking trials are conducted and temperatures as high as 178°C was recorded on a very sunny day in summer months.

Garg[45] in India in 1976 developed a solar oven similar to the one developed by Telkes except that the hot box was of cylindrical shape which was well insulated and the double glazed window surrounded by eight looking glass reflectors out of which four of square shape and four of triangular shape. This oven under arid zone conditions has given a temperature as high as 300°C and was able to cook all variety of food.

In 1976 in Upper Volta[46], studies on shallow spherical dish reflector(1.5 m^2) of focal length 0.5 m made of aluminium were conducted and 250 solar cookers were distributed to families in various urban and rural areas of upper volta. The reflector is suspended above ground in a welded and bolted steel frame. The support frame contains a cross bar from which the cooking pot is suspended upto the focal point. Several tests are conducted and 2 litres of water could be brought to the boiling point from 30°C just in 18 minutes.

M.Parikh[47] of Agriculture Tools Research Centre, Bardoli, India in 1976 developed a portable hot box type solar cooker consisting of inner and outer metal boxes and space between them filled with dried rice paddy husk. The box is covered with openable double glass window. Several cooking trials are conducted in this cooker.

In 1977 Garg and Thanvi[48] studied the performance of a solar steam cooker using a flat-plate collector(0.9 m^2) and an insulated box containing a tiffin of three compartments. The steam cooker was fixed at the top of the flat-plate collector.

Brace Research Institute, Quebec, Canada, in 1977 developed and tested a simple hot box type solar cooker made of brick structure with three sides having double glazing and an insulated north wall and base. The cooker does not have provision of a reflector.

Von Oppen,[49] an economist in India in 1977 developed a solar cooker called 'sun basket' consisting of a deep parabolic bowl (1.2 m diameter) made of jute reinforced papier mache backed by a woven bamboo frame with aluminium reflecting foil. The reflector can have automatic or manual tracking arrangement. The bamboo frame is fitted with a curved stand to allow for easy adjustment for the basket for sun-tracking. One litre of water was brought to boiling point with this cooker in 5 minutes time.

An openable focussing type solar cooker using two highly polished parabolic metal mirrors which can rotate about a horizontal axis to focus solar radiation onto a glass enclosed oven was developed in 1977 in the Federal Republic of Germany[50] and in 1979 in Kenya[51]. The two mirrors form two arms of a parabola with the oven permanently fixed at the focus.

Morris[52] in Canada during the year 1978 studied the performance of a solar assisted-hay box solar cooker consisting of wood, stone, brick or clay box insulated heavily with dry hay or straw and a solar air heater. Air gets heated in passing through the air heater, heating the gravel in the bottom of the hay box thus providing additional heat to the large stone(previously heated seperately in a fire).

This system provided rapid and late evening cooking.

The volunteers for International Technical Assistance (VITA) for the United States Department of Commerce, office of the Technical Services in 1977 compared the performance of twelve solar cookers available to them to determine their potential usefulness in countries served by the International Cooperation Administration. Some of the points considered for evaluation are: Cooking performance and efficiency, durability, cost, shiping weight, portability, ease of operation, ease of local manufacture, and adaptiability to local techniques and people. The cookers compared are: Wisconsin design, Boeing reflector, Thew cooker, Burmese design, Fresnel reflector type, umbroiler, Solnar, inflatable, and oven type such as Telkes solar oven, Ghosh Hot box. Garg et al[54] at Jodhpur have compared the performance of five different type of solar cookers such as NPL type parabolic solar cooker, Fresnel reflector solar cooker, Flat-plate steam cooker, Hot box solar cooker, and solar oven. Walton et al[55] in Georgia Institute of Technology, Atlanta, USA prepared a survey report on solar cookers, solar pump and cook stoves in which 10 different types of solar cookers have been described. Bowman and Blatt[56] described several type of solar cooker in an effort to select/develop a suitable solar cooker for introduction in Haiti. The German Appropriate Technology Exchange (GATE) has published a report[57] in 1978 describing 17 solar cookers together with a evaluation of their usefulness in the view of the consumer. Looking to the renewed interest in Solar Cookers and Indian Government's strong desire of its introduction a National Workshop on Solar Cookers was arranged by Garg[58] at New Delhi India in April 1983. Recently a Comprehensive solar cooker manual describing various type of solar cookers developed upto now is prepared by Alward[59] from Canada.

1.3 SOLAR COOKING

As discussed earlier solar cookers are required since firewood used for cooking causes deforestation, commercial fuels are not available, dried cow dung and agricultural wastes used for cooking is a good fertilizer, and human resources used for collecting fuel can be diverted and used for some other useful purpose. Although a variety of solar cookers have been developed, but these are not in use as expected. Some of the reasons for their non-acceptance are: (1) Too expensive for individual family ownership, (2) Incompatible with traditional cooking practices, (3) too complicated to handle, (4) cooking can be done only in the direct sun, (5) can not cook at night, (6) can not cook in cloudy weather, (7) can not cook indoors, (8) danger of getting burned or eye damage, (9) are not locally available, etc.

However, it is pointed out by Walton[55] that the above reasons are not the only reasons for non-acceptance of solar cookers. The above reasons are generally given by solar technologists but the field results suggest that these cookers will be accepted only through a serious and continuous programme of introduction, education and training, and involvement of Women folk who can make it successful. Moreover, solar cooker itself should be able to meet some of the technical and economic requirements before it is selected for introduction.

A couple of attempts have been made in the past to introduce and popularise the solar cookers. The most extensive attempt was perhaps made with the help of solar scientists and anthropologists to introduce some 200 solar cookers in Mexico in the states of sonora, Coahuila and Oaxaca. The cooker selected for the study was the one developed at the university of Wisconsin[21]. In the beginning the cookers selected use a rigid plastic reflectors with reflective films bonded to the front surfaces. In the beginning these cookers were not successful due to some mechanical failures of the cookers. Later based on the findings the cooker was redesigned, modified and the focal length was made within the easy reach from the ground and the final resulting cooker(model 3) was found to be most successful and reported that for early periods of its introduction these were used for 100 percent of the times but later the villagers turned to their original traditional way of cooking. In the states of Oaxaca (Mexico), with the support from Rockfeller Foundation, the cooker was further modified which used polyester shells, reinforced with muslin cloth, and burlap, and with a myriad of small glass reflectors glued to the front surface. These cookers were used for many years and finally these were also dropped. Some of the reasons given for the non acceptance of solar cookers in the villages of Mexico are:

(1) A part of the reflector either plastic film or glass mirror pieces were to be replaced periodically.
(2) The cooker needed frequent adjustment towards the sun and exposure of the cooking pot to the blowing dust and sand effected the food taste.
(3) The easy availability of alternative cooking fuels like wood and fuel wood.
(4) There was no provision of storing the heat therefore cooking of food was not possible where there were clouds or sun was not strong.

Another attempt to introduce solar cookers in India during the years 1950-1960 where a commercial firm had started manufacturing solar cookers has failed. This cooker which was a direct-focussing type using parabolic reflector made of aluminium, polished and anodized was able to cook a variety of food items and the reflectivity remained unchanged for many years of its use outdoors. This cooker was also not accepted due to its high cost, easy availability of alternative cooking fuels, no provision of storing the heat, and requirement of frequent adjustment towards the sun. Currently an effort was made under the help from Danish AID Organisation Danchurchaid to introduce 250 solar cookers in Rural areas of upper volta (West Africa). The cooker was of direct reflector type where the frames of the parabolic dish was made locally and the reflector surface uses a aluminized plastic film pasted to the parabolic dish. It is reported that during the first year of its introduction, almost all the cookers worked well and there had been no problem in getting the local women to understand the system and to see its advantages. The cooker was able to cook all of the local native dishes. It is also reported that in due course of time the local women had made few technical innovations in their design and use.

From the above, it can be concluded that the ultimate success of the introduction of solar cooker will not only depend on the method of introduction, education and training but the solar cooker itself should meet some of the technical and economic requirements.

The principle ways of cooking food are boiling, frying, roasting, and baking. When boiling is the principle way of cooking food such as rice, lentils, etc. the temperature of food being cooked is about 100 °C. For other methods of cooking, higher temperatures are required. For frying and boiling of food,heat is supplied from all the sides and heat is transferred to the food by radiation and convection. In most of the foods, water is present and when cooking by boiling is done some water is always added to the food such as in the boiling of rice. Because of the large amount of water, the specific heat of food may be assumed to be close to water i.e. 4 KJ/Kg °C. In such cases, once the boiling temperature i.e. 100 °C is reached, not much heat is required except the heating rate should be equal to the rate of thermal loss from the vessel. Thus the difference of time in cooking by two cookers of equal quantities of food can be due to their difference in lengths of heating up periods. The thermal losses from the cooking vessel are: evaporation loss from the food; and radiation and convection loss from the surface of the cooking vessel. The largest heat loss from the food is due to evaporation of water from the food which is about 2.5 MJ/Kg. Convection heat loss from walls of vessel and oven is also quite large and can be reduced by the use of covers on the utensils and by insulating the oven walls. If the area of the food container is about 0.1 m^2 per Kg of container contents, the energy input for 1 hr of food boiling and one fourth of water present is to be vaporised and hourly convection heat loss at boiling temperature of about 6.8 MJ/per square meter of utencil, then the percentage heat loss at boiling temperature of about 6.8 MJ per square meter of utencil, the percentage heat loss would be:

Vaporization of water	35 percent
Heating food to boiling temperature	20 percent
Convection losses from vessel	45 percent

Considerable heat losses can be reduced by insulating the sides of the vessel and keeping the vessel covered with a lid. The temperature required for cooking of many foods is about 100 °C, but to have high heat transfer rates, the temperature of the heat source should be high. In conventional cookings, the temperature of the fire is quite high, resulting in high heat transfer. Generally, where electricityor gas is used for cooking, the burner is rated at 1.0 KW which brings about 2 litres of water to boiling point in about 10 minutes. Therefore a solar cooker should be designed such that it provides about 1.0 KW which brings about 2 litres of water to boiling point in about 10 minutes. Therefore a solar cooker should be designed such that it provides about 1.0 KW of energy which can be obtained with 2.0 m^2 of flat-plate collector with efficiency of 50 percent.

1.4 TYPES OF SOLAR COOKER

Several basic types of solar cookers have been developed todate. These cookers are broadly divided into three types: (1) Direct of focussing type, (2) Indirect or box type, (3) Advanced or separate collector and cooking chamber type. The difference between each of them is as follows:

(1) Direct or focussing type: In these cookers some kind of solar energy concentrator is used which when directed towards the sun focus the solar radiation on a focal point or area on which a cooking pot or frying pan is placed. In these cookers the convection heat loss from cooking vessel is large and the cooker utilizes only the direct solar radiation. A few focussing solar cookers are shown in fig.1.2.

(2) Indirect or box type: In these cookers an insulated hot box(square, rectangular, cylindrical) painted black from inside with double glazing is used. To enhance the solar radiation plane sheet reflectors (single or multiple) are used. Here the adjustment of cooker toward the sun is not so frequently required as in case of direct type solar cooker. This is a slow cooker

and takes longtime for cooking and many of the dishes can not be prepared with this cooker. Some of the box or oven type cookers are shown in fig.1.3.

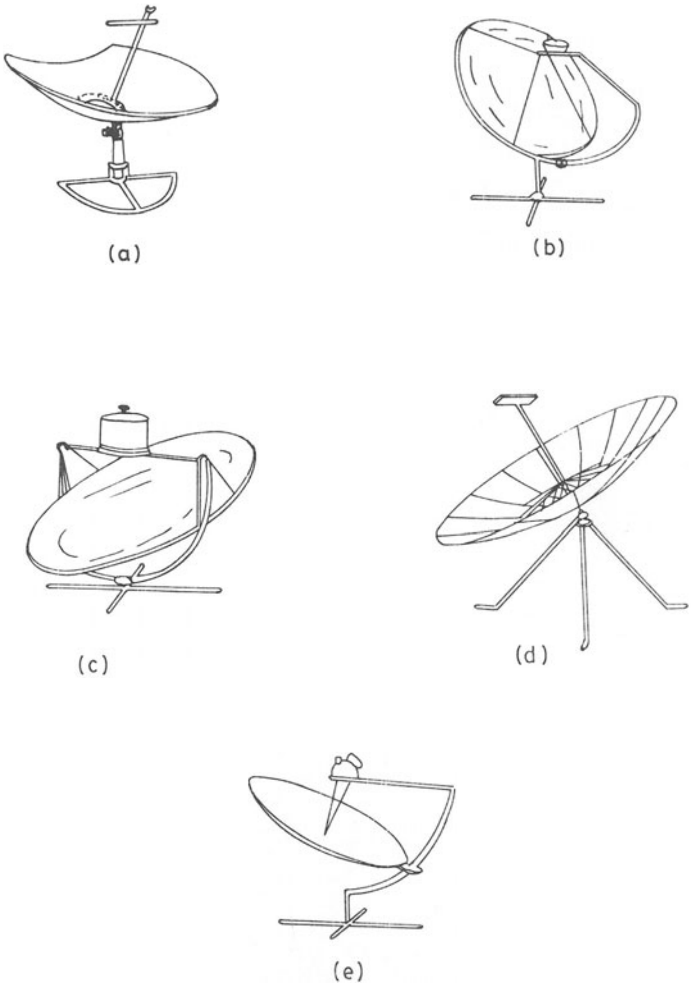


FIG.1.2. DIRECT (FOCUSING) COOKERS

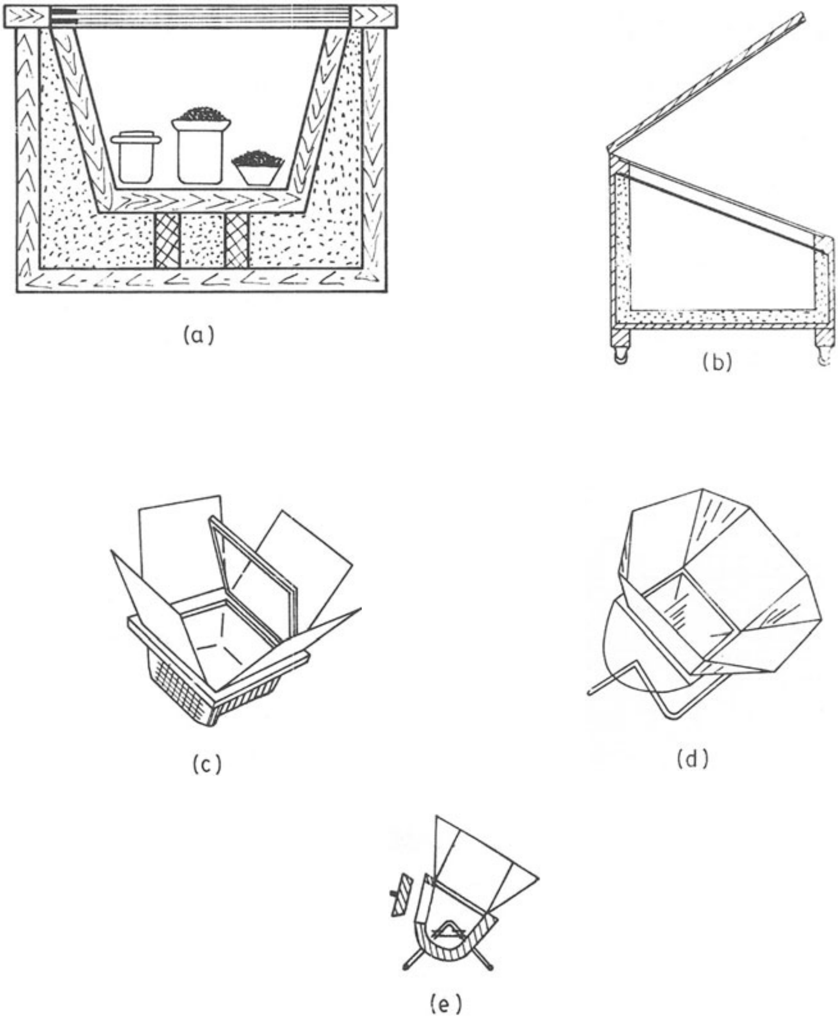


FIG.1.3. SOLAR BOX COOKERS

(3) Advanced type: In these cookers, the problem of cooking outdoors is avoided to some extent. The cooking in some cases can either be done with stored heat or the solar heat is directly

transferred to the cooking vessel in the kitchen. The cookers use either a flat-plate or focussing collector which collect the solar heat and transfers this to the cooking vessel. A few typical advanced cookers are shown in fig.1.4.

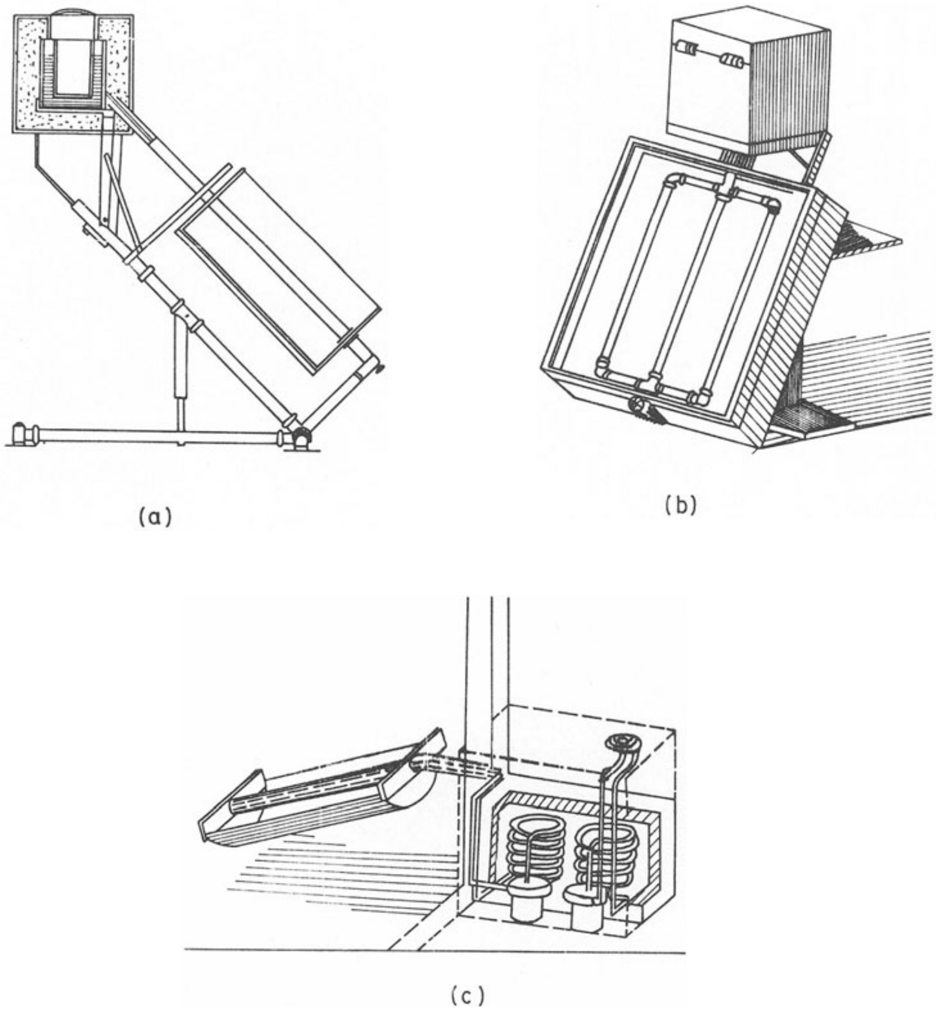
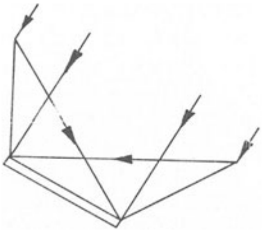
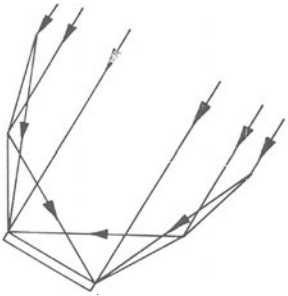


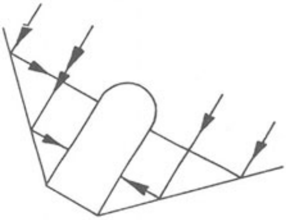
FIG.1.4. A FEW ADVANCED TYPE SOALR COOKER



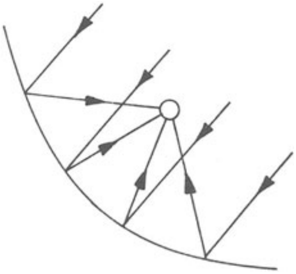
(A) Flat-plate collector with plane side reflector



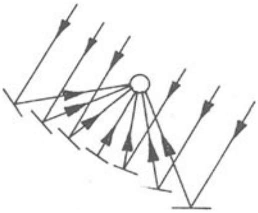
(B) Flat-plate collector with compound side reflector



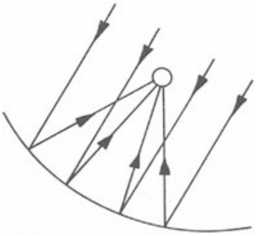
(C) Conical reflector



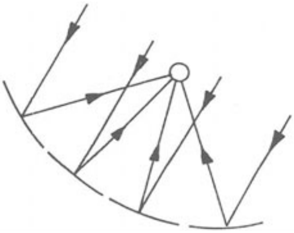
(D) Paraboloidal reflector



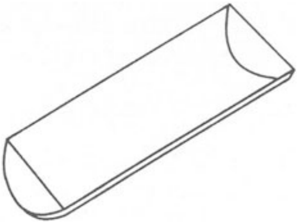
(E) Step reflector or fresnel reflector



(F) Spherical reflector



(G) Multifacet spherical reflector



(H) Cylindro-parabolic reflector

FIG.1.5. SOME POSSIBLE FOCUSSING REFLECTOR CONFIGURAIONS USED IN SOLAR COOKERS.

There are a large number of focussing collectors which may be used in solar cookers. The cross section of some of the focussing collectors are shown in fig.1.5. All these systems can use cylindrical reflectors or refractors, circular reflectors or refractors giving a line focuss or a point focus of radiation respectively. The most important is the concentration ratio which is defined as the ratio of area of the concentrator aperture to the energy absorbing area of the receiver. The concentration ratios for surface of revolution reflectors can be much higher than their cylindrical counterparts. A simple flat-receiver with plane side reflectors is shown in fig.1.5(a). In this case the direct as well as diffuse radiation are directly received and absorbed by the flat receiver which is further augmented by the reflected radiations. The concentration factor in such types are generally not more than three. This can be further improved by using more plane reflectors known as compound wedge reflector shown in fig.1.5(b). Parabolic reflector as shown in fig.1.5(d) focusses the parallel rays of the sun on a small area and gives a very high concentration ratio and thus high temperatures can be obtained. Here the reflecting surface can be of silvered glass, polished metal, or aluminized plastic film. If a very sharp focus is not required then a spherical reflector as shown in fig.1.5(f) can be used instead of a parabolic reflector. This reflector can be made easily. A fresnel reflector (fig.1.5 E) or fresnel refrector can also be used for concentrating the solar radiations. The individual plane or curved segments or strips are so arranged that the reflected or refracted light meets at one point(focal point). This type of reflector can be easily made. To get high temperature at the focus, large number of concave mirrors can be used as shown in fig. 1.5(G) where all or individual mirrors can be adjusted to get sharp focus at one point. Cylindro-parabolic reflector as shown in fig.1.5(H) can be used which provides line focus to heat water or oil which can be further used for cooking of food. A few typical solar cookers are discussed below:

1.5. DIRECT OR FOCUSSING TYPE SOLAR COOKER

Direct or focussing type of solar cookers appear to have high potential since these provide higher temperatures so that all the dishes can be produced with them. Although these cookers require frequent adjustment towards the sun, there are considerable high convection heat loss from cooking vessel, and the cooking vessel is exposed to outside dust and dirt and wind. Moreover, at those places where the diffuse radiation percentage is high, these cookers will not work so effectively. In these cookers there is always a possibility of skin or eye burning with focussed sunlight and their stability against wind storm is not so good. Inspite of all these problems, several focussing type of solar cookers have been developed and tested in the past. A few of these cookers are discussed here:

1.5.1 WISCONSIN SOLAR COOKER(Spherical Parabolic Type)

Perhaps the best known direct cooker and which can be used for comparison purposes is the molded plastic reflector developed at the solar laboratory of the University of Wisconsin, Wisconsin[17,21]. The plastic reflector uses a drape-formed, high impact polystrene shell of 120 cm diameter with a focal length of 45 cm and 0.15 cm thickness, stiffened at the rim with a ring of 1.25 cm diameter thin walled aluminium tubing (Fig.1.6). A reflective lining of aluminized mylar polyster film is applied to the shells with an adhesive, so that the clear film forms a protective covering over the specular surface. The specular reflectivity in new condition of the material is in the range of 75 to 80 percent which reduces with time and requires replacement after two years of constant use. The azimuth adjustment and vertical stability in this cooker are provided by two spun discs at the base which fit one within the other and turn with respect to one another; this results a more

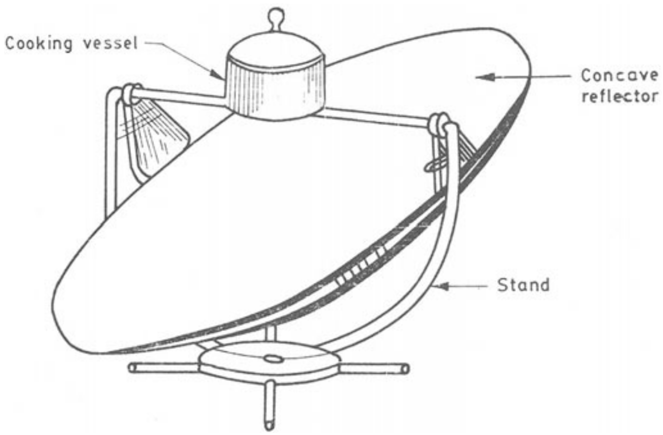


FIG.1.6. WINCONSIN SOLAR COOKER.

stable cooker. Adjustment in altitude is provided by a locking device on a sector attached to the reflector, and the grid is supported from each side for additional stability. The frame members of this cooker are of thin-wall steel tubing and 19-gauge sheet metal formed by stamping or (for the base discs) spinning. The cooker which has an effective area of about 1.1 sq.m. delivers about 40 to 55 percent of incident beam radiation to a cooking vessel 18 cm in diameter i.g., maximum delivery rate of 400-500 watts at an incident beam total energy of 1.0 kilowatt on the unshanded reflector. It is reported that a cooker with a reflector several years old and used intermittently in the laboratory, with average direct radiation of 940 w/m^2 heated 0.90 litres of water from 32 °C to boiling point in 13 minutes, 1.81 litres from 32°C to boiling in 28 minutes and 3.63 litres of water from 32°C to boiling in 62 minutes.

These cookers were found to be very useful for cooking a wide variety of food, including beans, staws, soups, meats, tortillas, and eggs. These can also be used for heating water.

1.5.2 Umbrella Type Solar Cooker

This folding umbrella type solar cooker was first made by Lof and Fester[22] in USA. The reflector is composed of a frame work, similar to an umbrella frame, covered with a metallized plastic film laminated to cloth. The reflector looks like a umbrella, when it is opened, with a highly reflective lining. It is made with a light aluminium frame, has 16 ribs, and is covered with aluminized mylar rayon laminated cloth. It is 115 cm in diameter and has focal length of about 60 cm. The reflecting material between adjacent forms a wedge like segment which has a base length of 23 cm between rib tips. Hence any pot that is less than 23 cm across will not receive all the light that is reflected back. For a 15 cm pot, about 1/3 of the light gathered near the periphery is lost, increased efficiency would result from introducing more ribs. It was observed that the focal point remains diffuse due to the folds in the cloth and partly due to the fluttering of the cloth in stiff wind.

The reflector is supported by a tripod frame which incorporates an adjustable sqivel joint for proper alignment of the cooker with respect to the sun(fig.1.7). Adjustment of the altitude angle requires removing the cooking vessel. The designer and manufacturer of this cooker, G.O.G. Lof., has suggested a number of modifications to make this design more rugged and suitable for continuous use. These includes heavier fabric, larger tube diameter for the umbrella shaft, heavier grill and more rugged support joint for the entire unit.

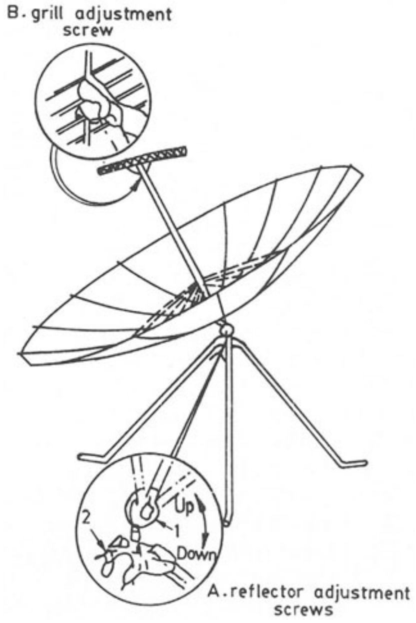


FIG.1.7 SKETCH OF UMBRELLA TYPE SOLAR COOKER

Maximum concentration ratio of the cooker was found to be 12. It was also found that 45 percent of the specularly reflected radiation was intercepted by the 23 cm square focal zone and 31 percent fell inside a 18 cm diameter circle centred on the theoretical focal point. Net efficiency of this cooker(solar to water) was observed as about 23 percent. This cooker is equivalent to about 400 watts and a variety of foods can be cooked with this cooker.

1.5.3 Paraboloidal type solar cooker

This cooker was first developed in India by M.L.Ghai et al[13,14,15] and consists of a paraboloid reflector of equation $Y^2 = 180\ x$, with a focal length of 45 cms. This reflector is spun from aluminium sheet to the desired shape and then anodized to protect from weather and to maintain reflectivity. In elevation, the paraboloid has a diameter of 110 cm but with 24 cm cut off horizontally across the top for a vertical height of 85 cm. The face area normal to the incident solar rays is 0.76 sq.m. which is reduced to a net or an effective area of 0.67 sq.m. by the necessary attachments. The reflector is mounted on a stand that provides for manual adjustment to accomodate the daily and seasonal movement of the sun. The support for the cooking utencil is a wire netting fixed to a steel ring that can be adjusted manually to provide a horizontal position for the vessel.

The cooking utencil is a cylindrical brass vessel 18 cm in diameter and 8 cm high with a flanged ring at the top. The reflectivity of the surface of reflector is about 75 percent. One edge of the reflector is truncated in order to cut down side heating and facilitate easy handlikng of food while cooking. Also because of the shadow caused at the centre of the reflector by the cooking utencil, this portion does not contribute towards concentrating solar radiation and thus reduces the effective area. A small circular portion from its centre is therefore, cut out without loss of efficiency. This opening also guides in the proper adjustment of the cooker for solar radiation to fall normally to the reflecting surface by observing whether the utencil shadow on the ground is uncentric with the circular sunlight patch. These improvements effect a saving in the reflector material and to reduce its overall cost and weight. The various components of this cooker are shown in fig.1.8.

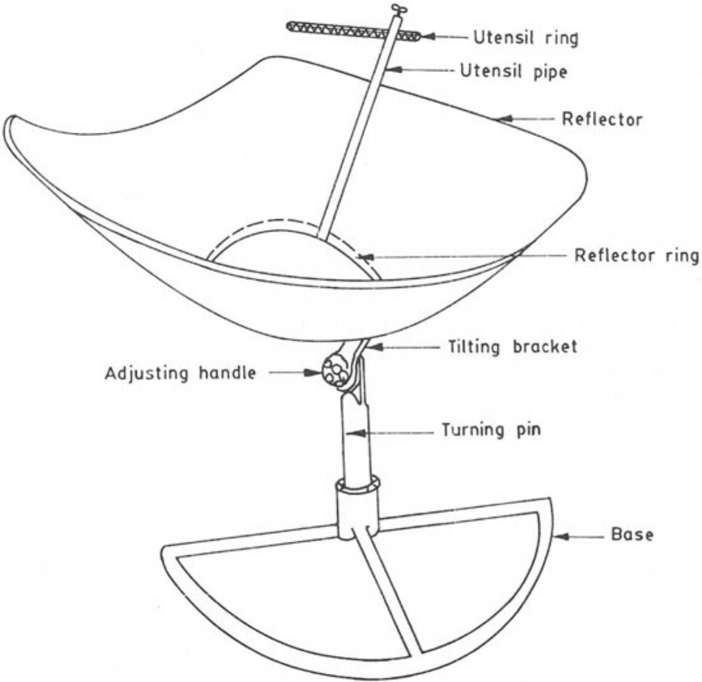


FIG.1.8 PARABOLOIDAL TYPE SOLAR COOKER

The overall efficiency and cost structure of this NPL reflector type solar cooker is comparable to those produced anywhere else in the world. About 50 experiments were conducted in the laboratory on this cooker to study its performance under different atmospheric conditions. It was observed that under clear calm days, one litre of water comes to boiling point within 25 minutes. Variety of foods can be cooked with this cooker and its output is equivalent to about 400 watts of electric hot plate.

1.5.4 Fresnel Reflector type Cooker

A simple reflector type solar cooker which can be made in a domestic workshop with the help of wooden battens and anodized aluminium strips has been designed by Garg[43] in India. This step reflector or the Fresnel reflector used in the cooker has a diameter of 120 cm with a focal length of 60 cm. Seven aluminium strips each of 7.5 cm width, which are finally anodized are used. The angle of the strip, α_n, to get concentration, can be calculated with the help of the following formula:

$$\alpha_n = \frac{1}{2} \tan^{-1} \left(\frac{R_N}{F} \right)$$

Where R_N is the distance of the strip from the centre of the reflector and F is the focal length. This step reflector is mounted on a stand for its manual adjustment towards the sun. The cooking pot can be placed on a wire netting fixed to a steel ring. It was observed that 1.0 litre of water comes to boiling point within 30 minutes under clear and calm sky conditions. The actual cooking trails are also conducted and it was found that all types of dishes can be prepared under very clear sky conditions.

A similar type of cooker was also made by VITA[53] in which the reflector used only simple, curved surfaces and is constructed of 3 mm masonite to which aluminized myler has been cemented. The reflector is 115 cm in diameter and has a focal length of 75 cm. On a clear day, it delivers in excess of 500 watts to a focal spot of about 15 cm in diameter. This reflector is supported at two places on the ground, and a single, pivoting wooden leg supports the cooker at the desired angle. This stand is simple and easy to adjust. The pot holder consists of a rod to which a grill is attached which holds the pot at the proper focal distance, and which permits the pot to be held horizontally, independent of the reflector position. This cooker is shown in fig.1.9.

Several trials on this cooker are conducted and it was observed that under clear sky conditions, 4 cups of rice can be cooked in 30 minutes and a small chicken can also be cooked in about 30 minutes.

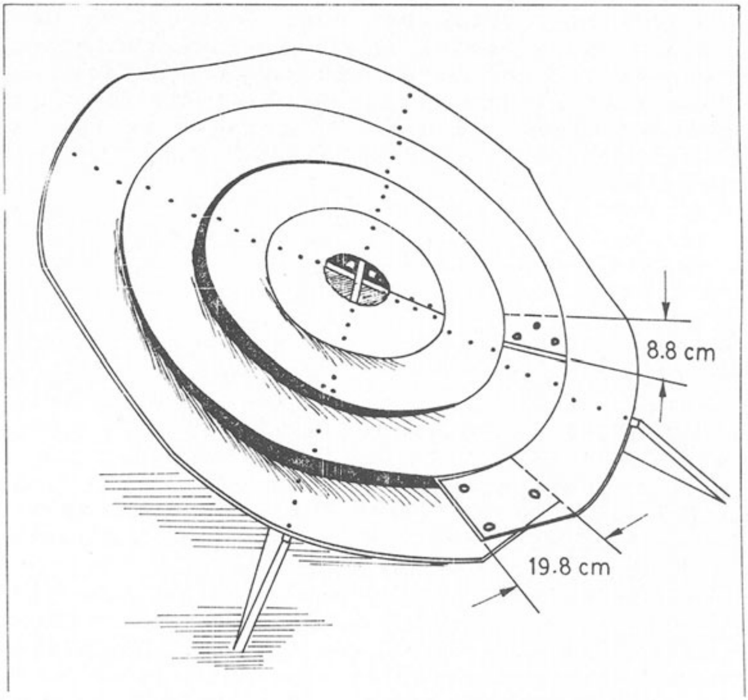


FIG.1.9. FRESNEL REFLECTOR TYPE SOLAR COOKER

1.5.5 Fixed Soil-Cement Spheriodal Reflector Solar Cooker

In this type of solar cooker[17] a spheriodal depression in the ground is lined first with a mixture of soil and cement to stabilize the shape and then with aluminized plastic. The symmetrical depression is formed by swinging a pendulum, or blade, fastened to a wire which is secured at a fixed point above the ground on a tripod. After the rough shape is made, a shallow layer of soil and cement mixture is placed in the depression, smoothed with the blade and wetted. When this has set, and after some further work on the surface, a reflective lining of aluminized myler pressure-sensitive tape is applied. The cooking pot support is built so that the pot follows the shift in the focal spot due to the daily motion of the sun.

The advantages of this cooker are its simplicity and ease of construction in the field and the large sizes possible. No reflector mounting is necessary and the cooking pot support is simple to fabricate. The orientation can be fixed during construction so as to make the reflector usable during the desired time of day.

The disadvantages of this cooker are its lack of mobility, which might result in physical damage due to weather conditions, and the limited period of time during which it can be used(estimated at 4 hours a day).

Stam[27] suggests a variation of this design in which he proposes integrating a large reflector, capable of delivering 2000 watts or more, into the design of a desert home. Such a device constitutes the nucleus of a desert home. Stam has worked out a whole system of cooking and utilizing the solar energy in such a design. The reflector would be made out of adobe or some such material and lined with a reflective material such as aluminium foil. Only a scale model has been constructed to date.

1.5.6 Light weight molded aggregate reflector type solar cooker

Reflector shells have been made of light weight concerete aggregate of sawdust and vermiculite which are formed over molds and lined with aluminized plastic and plastic tape. The most successful of this type of cooker is designed by Duffie[17]. It consists of a reflector 105 cm in diameter with a focal length of 45 cm, made of vermiculite aggregate and reinforced with wire and rim of thin-wall tubing. This reflector is mounted on a wooden post in the ground arranged to pivot about its axis. Holes are drilled through it to hold a rod from which hangs a pan support basket. The top edge of the reflector leans against the post and its lower edge is supported at variable distances from the post on an arm secured to the post.

The advantages of this type of cooker are the simplicity of the mounting device and its component parts and the possibility of using locally available materials and labour for its construction. Major disadvantages are the weight of the reflector, which makes it cumbersome to handle and the fact that reflective lining is difficult to apply.

Another inexpensive method of fabricating this type of reflector has been suggested by Jennes[60]. A convex, wire reinforced, plaster paraboloid die is first cast from a centrifugally formed concave paraboloid mould. The surface of the die is coated with wax, then a layer of wood pulp. Papier mache or laminated newspaper is spread over it. After a few layers are built up, they are pressed to squeeze out excess liquid. The process is repeated untill the compressed laminate is 3 mm or 6 mm thick. Woven basket is suggested as a reinforcement. After removal from the die, strips of aluminium foil are pasted on the surface.

Another simple cooker is suggested by Von Oppen[49] and he named it as Sun basket. The sunbasket is basically a paraboloic mirror made from paper mache, reinforced by a layer of jute fabric and held in place by a bamboo frame. The reflector lining is aluminium foil which is glued on the inner side of the basket.

For fabricating the sun basket a mound of cement concrete of paraboloidical shape is made on the ground which is done with the help of a plywood frame of parabolic shape, previously fabricated which is revolved on the masonry work while still soft. A bamboo basket is woven in such a way that it fits exactly over the shape of paraboloid mound. At the same time, papier mache is prepared from 5 Kg.of shredded waste paper, 2 Kg of wheat flour, 1 Kg. of methi flour and sufficient quantity of water to make a thick pulp. The ingradients are mixed well and heated to nearly boiling temperature. The mould is then covered with one layer of water-soaked newspapers so that the papier mache would not stick to the mould. The papier mache is then pasted in a

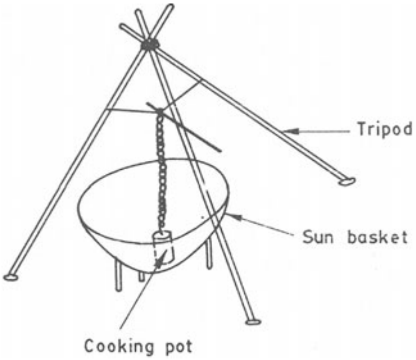


FIG.1.10 SUN BASKET.

layer of about 1.2 cm., well-pressed upon the paper-covered mould. On top of this, the bamboo basket is then placed and pressed well onto the wet surface. The papier mache is then taken out. The inside of the papier mache is then pasted with silver foil for reflecting solar rays. Nine sheets of (40 x 60 cm) silver paper are necessary for a basket. For cooking purposes, the sun basket is focussed towards the sun and the cooking pot is suspend from a tripod stand as shown in figure 1.10 at the focus.

It is claimed that the sun basket under clear sky conditions can cook rice in 10 minutes and dal in 20 minutes. One litre of water can be brought to the boiling point in 5 minutes. The sunbasket is estimated to be equivalent to 700 Watts.

1.5.7 Multi-mirror or multi-facet type solar cooker

A multimirror solar cooker which is more durable was designed by Tabor[38] specifically with a view to fabrication in centralized workshops in developing countries. In this cooker twelve concave glass mirrors each having an area of 675 sq. cm. are used. These mirrors are arranged in three rows of five, four and three and are held in position by 12 circular rings made of iron rod and welded at their points of contact. These iron rings are suitably welded to get the correct overall shape. The mirrors are attached to the rings either by three clips at the edges or by having three holes near the periphery and binding with thread. This attachment can be carried out by the user as no technical skill is required. The mounting is made entirely of iron. The vertical axis comprises two concentric water pipes, one of which is inserted about 40 cm into the ground to improve stability. It has two angel-iron feet at right angles welded on and resting on the ground. The horizontal axis passes through the tubes of the rotating frame. The rotating frame is also made of iron tubes(water pipe at the bottom, thin walled conduit pipe for the sides) with a building iron ring-similar to those used for the mirrors to act as pot holder. The clamp of the tilt adjustment comprises a flat-iron strip having a large number of holes along its length. It is hinged at the bottom(on the verticle axis tube) and the upper end passes close to the trailing edge of the mirror frame on which an iron pin is welded. This pin engages with any one of the holes in the strip. The mirror tilt is set by slightly lifting the bar, which disengages from the pin, adjusting the tilt to the desired position and allowing the bar to drop back reengaging to the pin. Disengagement can not be caused by the wind. The cooker is shown in fig. 1.11.

The area of each mirror is 675 sq.cm. which would yield 67.5 watts for a solar intensity of 1 KW/m^2 for 100 percent reflectivity. The mirror reflectivity is about 82 percent giving 55 watts per mirror. Actual observations on this cooker have shown that it gives about 550 watts. About 1.84 litres of water comes to boiling point within 22 minutes. The results are better than those reported for the 120 cm diameter aluminized plastic cookers even though the area of this cooker is only 70 percent. The explation is in the high reflectivity of the glass mirror and the better absorption by the pot due to smaller angles of incidence.

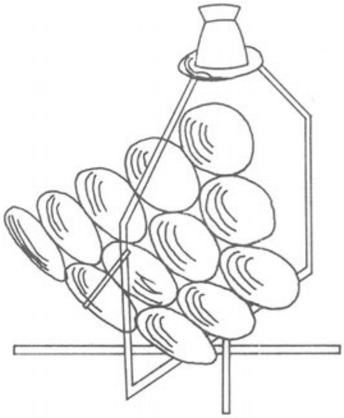


FIG.1.11 MULTIFACET REFLECTOR SOLAR COOKER

Similar collapsible protable seven-facet concentrator with electropolished facets cooker has been developed in USSR[39] and is now mass produced in that country for its possible use in the republics of central and South Asia, Kazkhastan etc. Here the reflecting elements, the facets are made in parabolidal form of electropolished aluminium. This portable collaposible solar stove, consisting of seven facets is designed to prepare liquid and certain second-course dishes, to boil water, milk, coffee, and to produce distilled water. The diameter of each facet is 0.56 m and the total reflecting area is 1.85 sq.m. The focal distance of the cooker is 0.65 m and the focal diameter is 0.08 m.

It was experimentally observed that under normal calm sky conditions when the solar radiation is 784 watt/m^2 about 6 litres of water comes to boiling point within one hour. The total weight of the cooker is 20 kgm. The cooking pot in this case is a aluminium container, fast-boiling with heat insulating case and fixed in a ring at the focal point.

The body of the concentrator is assembled from six hexahetral planes of the same kind. Seven metal rings are attached to each frame to hold the facets. The concentrator body and the frames are assembled and the rings installed on an appropriate paraboloidal matrix, thus elementating the need for facet alignment. For easy operation the design provides for an equatorial rotation system. Rotation takes place about an axis parallel to the celeastial axis. A screw mechanism adjusts the concentrator position, depending on the annual declination of the sun; the adjustment is made periodically every 2 or 3 days. The concentrator is suspended near the centre of gravity of the concentrator-receiver system, which makes it easy to control.

1.5.8 Cylindro-parabolic solar cooker

This solar cooker as designed by Prata[25] takes advantage of the direct type of solar cooker and also of heat box type of solar cooker. This cooker consists of two parts, the cylindro parabolic reflector and oven. It consists of two cylindro-parabolic mirror with a focal length of about 1.05 m and each mirror having an area of 0.4 sq.m. made of nickel-plated brass sheet and attached to a wooden structure traversed by a supporting shaft about which it may be rotated. This shaft permits the reflector to be focussed. It may be fixed in any desired position by means of slip rings. The oven is double walled insulated cylinder made of aluminium sheet with openable end covers. This oven is kept on wooden stand as shown in schematic fig.1.12. In its lower part the cylinder(oven) has an elongated window along one generatix to allow the concentrated solar radiation. The area of the window is about 0.06 sq.m. To reduce the convection and radiation losses from indoors, a glass sheet is used on the inner side and a mylar plastic sheet is used on the outer side of the window. The reflectors are eccentrically placed relative to the window, so that the position of the apparatus need not be frequently adjusted to the changing azimuth of the sun.

It was observed that 1.0 litre of water comes to boiling point within 30 minutes with this cooker and it operates at an efficiency of about 30 percent. All types of cooking like boiling, baking, frying and roasting can be done in this solar cooker. On a day when the direct solar radiation was 840 W/m^2, about 1.5 kgm of potatoes with 1.0 litres of water were cooked within 150 minutes.

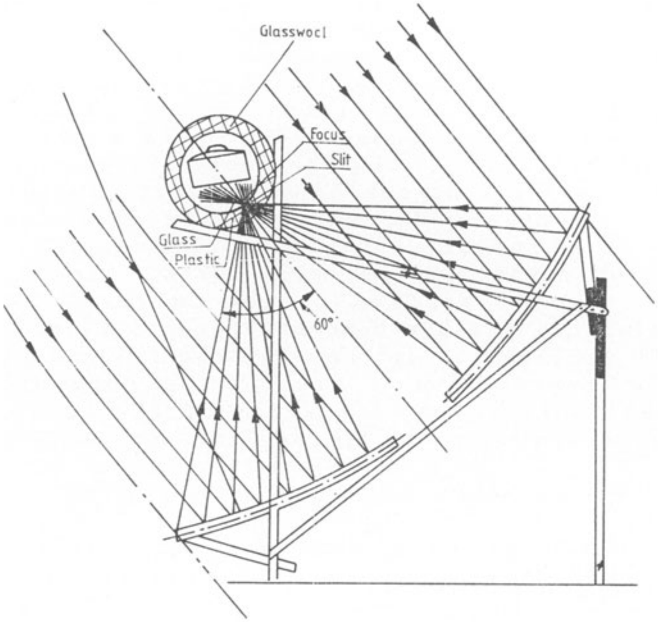


FIG.1.12 SCHEMATIC DIAGRAM OF A CYLINDRO PARABOLIC SOLAR OVEN

1.6 INDIRECT OR BOX TYPE SOLAR COOKER

Hot box type solar cooker typically use some concentration of solar radiation, generally with plane reflectors, in an insulated chamber with a transparent cover (glass) for trapping the heat (green house effect). A typical hot box is shown in fig.1.3(a). De Saussure[5] appears to have been the first to use the hot box. His hot box consisted of an insulated, air tight, wooden box, balckened on the inside and covered with two layers of plane glass seperated by an air space. Langley built a similar hot box and carried it on an expedition to Mount Whitney. The most common types of cookers are described below:

1.6.1 Solar hot box cooker

This hot box cooker as designed by Ghosh[29,30] consists of two double walled boxes made of teak wood with an air space in between. The inner box is tappered and the walls are inclined at an angle of 45 degrees. The inner box lined with blackened aluminium sheet rests on springs and contains the cooking utencils with the food material. The dimensions of the inner box are 25 x 25 cm at the base, 50 x 50 cm at the top and 14 cm high. Two clear window glass sheets with the outer glass having double the area of the inner glass are fixed in frame and are hinged to the box and served as the box door.

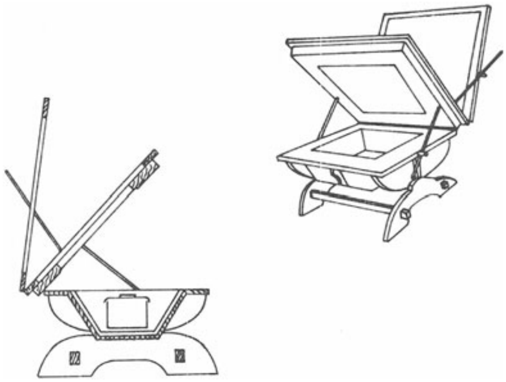


FIG.1.13. BOX-TYPE COOKER AS DEVELOPED BY GHOSH (INDIA)

The reflector was one looking glass (70 x 70 cm) fixed on a plain wooden plank and hinged to one side of the box. The angle of the reflector can be changed with the help of rod and tube arrangement. The maximum temperature recorded in this cooker was about 160 °C. Cooking of food by boiling can also be done with this cooker. The cooker is shown in fig.1.13. In this cooker as expected the cooking is slow but the timings as is observed for cooking rice and chopped meat varies between 2 and 3 hours depending on the sun's intensity.

Similar type of hot box solar cooker was designed and studied by Garg[44] and the same is shown in fig.1.14. It consists of double walled(base area is 45 x 45 cms) with the outer wall made of teak wood, 1.25 cm thick, and inner wall made of blackened thin galvainzed iron sheet with 3.75 cm fibreglass insulation in between and an openable double glazing at the top with an inclination of 26 degrees from horizontal at Jodhpur(India). The reflector is adjustable and is a plain looking glass (60 x 55 cms) which is fitted on the inner side of a wooden cover. The cooker and the reflector can be adjusted towards the sun with the help of castor wheels and slotted kamani provided in the cooker. The solar radiation directly and after reflection enters through the double glass window and heats the plate and the air inside the box.

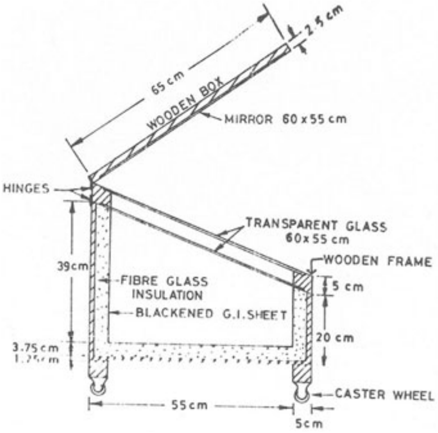


FIG.1.14. SCHEMATIC DIAGRAM OF HOT BOX TYPE SOLAR COOKER. AS DEVELOPED BY GARG(INDIA)

It was observed that maximum temperature in the cooker reaches to 178 °C in summer season and 148 °C in winter season on clear days at Jodhpur. The cooker requires adjustment after every 30 minutes towards the sun.

A variety of foods like rice, potatoes, vegetables and arhar dal are satisfactorily cooked with this cooker and 1.0 kgm of each of these items took about 1.5, 2.5, 3.0 hours respectively. Moreover two dishes can be cooked simultaneously in the cooker which may take slightly longer time as compared to single dish. Thus both lunch and dinner within the period of sun up hours can be prepared. The food remains warm even at the time of dinner. The performance is not effected by the wind and dust.

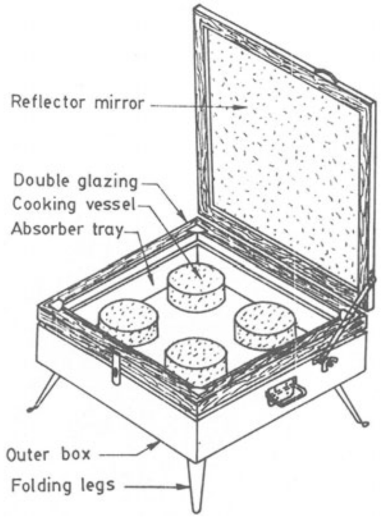


FIG.1.15 BOX TYPE SOLAR COOKER.

Mohan Parikh and Rahul Parikh of Bardoli[61], India have also designed a similar cooker with both the inner and outer boxes made of metal and the inner box with vertical wall. The cooker is schematically shown in fig.1.15.The dimensions of the inner box (absorbing tray) are 45 x 45 x 8 cm. This space is enough to accomodate 4 cooking utensils of 20 cm. All varieties of food like cereals, pulses, vegetables, roots(like potato), eggs, soups, porridges, etc. are cooked in this cooker.

Another box type solar cooker with a three-step reflector, consisting of plane mirrors, is designed and tested by Mannan[62,63] in India. The cooker is schematically shown in fig.1.16. The folding three step asymmetric reflector box cooker retains the essential festures of a box cooker and fitted with a three-step asymmetric reflector. As the reflector is adjusted relative to the box window, the distance of the mirror from the box window changes. Therefore this design will not give optimum performance in different seasons of the year. Optimum performance can be obtained if the mirrors also are hinged together so that their relative angles can also be changed. This arrangement is done in a two-step reflector box cooker by Mannan and Cheema[63]. In this design the two reflecting mirrors are hinged with each other and the width of each

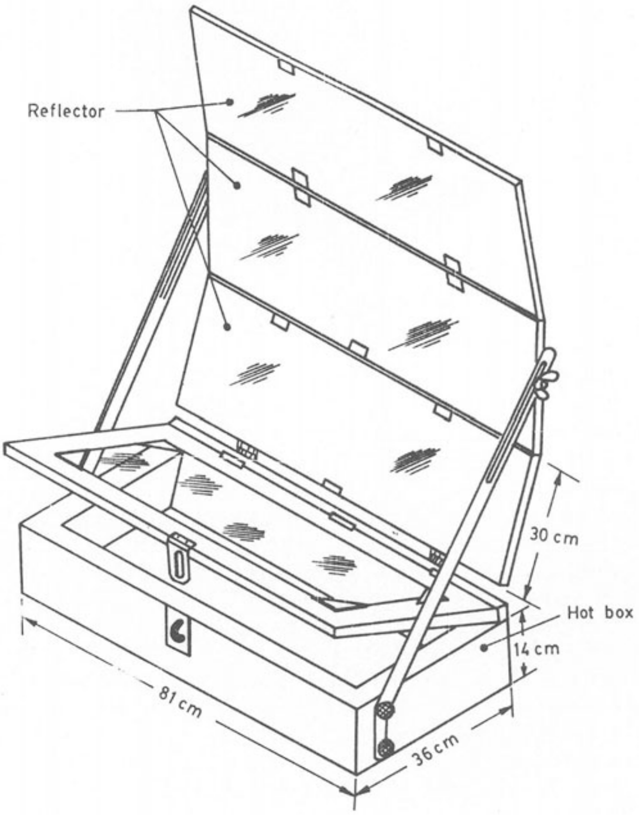


FIG.1.16 A THREE STEP REFLECTOR TYPE BOX COOKER

mirror is about 1.25 times the width of transparent window. This folding two-step asymmetric system is designed to give a concentration ratio of 1.89 in summer and 2.0 in winter. Mannan and Cheema[63] have compared the performance of two-steps reflector box cooker with the single reflector box type solar cooker and observed that the two-step reflector box cooker gives 190 °C temperature in summer and 170 °C in winter which is 30 °C and 45 °C higher compared to single reflector type cooker in summer and winter respectively.

1.6.2 Solar Oven

A solar oven is similar to a hot box cooker using an insulated box and multiple reflectors. The area of the box is kept as small as possible while the reflector area is large. The major difference is in the machanism of directing solar radiation to the cooking area. In the hot box cooker direct solar radiation penetrates directly through the glass window while in a solar oven additional radiation after reflection also penetrates through the glass window. Due to enhanced solar radiation penetration and decreased cooker area for heat losses, the temperatures inside solar ovens can attain quite high temperatures sufficient for cooking all varieties of foods. The mirrors are generally fixed at certain angles relative to the glass cover and the whole oven is oriented and tilted in the direction of the sun.

The solar oven was first designed by Telkes in [18,23,31] USA. The three models, the triangular oven, the pot stove and cylindrical oven as described by Telkes are schematically shown in figs.1.17,1.18,1.19 respectively. The Telkes triangular oven is designed especially for equatorial latitudes with the window tilted at 30 deg from the horizontal. Reflectors are made either of highly polished aluminium sheet, or reflector foil, or plane glass mirrors. The inner box is made of sheet metal and blackened and having double or triple glazed window. Four reflectors are mounted at 30 deg from the normal to the window. The outer box is made of thin sheet metal or other suitable material like plywood or thin wood etc. The spacing between the two boxes which is about 7 to 10 cm is filled with some suitable insulating material which can withstand a temperature of about 300°C. On the back wall of the oven a plug-type door through which cooking pots can be placed inside or taken outside is provided. It is reported that the cooking time taken by this oven is about the same as with conventional cooking fires. Temperatures as high as 210°C are commonly experienced with this oven.

The pot stove as shown in fig.1.18 is designed to permit cooking from the top which is said to be the preferred way. The cooking pot which is blackened from outside is pivoted inside the oven so that it can swing over a rather wide range of about 60 degree angle. The interior of the oven is made of reflecting material and the shape is so designed such that it can reflect maximum radiation on the cooking pot. The outer box can be made with any material such as thin sheet metal, plywood, thin wood etc. The space between the two boxes is filled with insulation. Four square and four triangular reflectors made of highly polished aluminium, or aluminized mylar or looking glass reflectors are used. Double glazing is used as window of the inner box. A plug type door above the cooking pot which is fitting

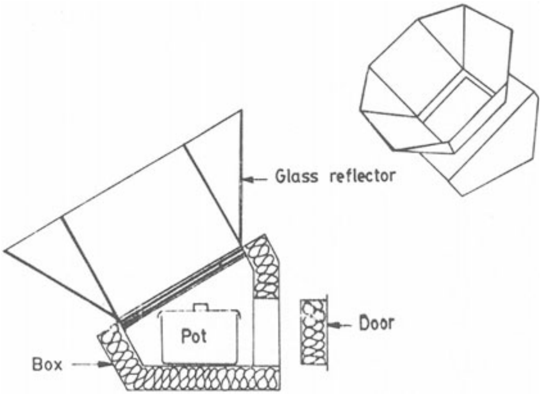


FIG.1.17 TRIANGULAR SOLAR OVEN.

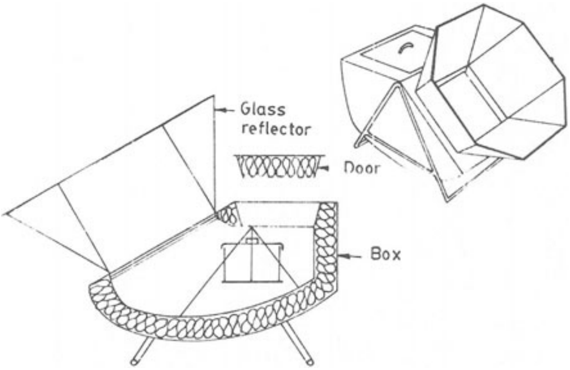


FIG.1.18. TELKES POT STOVE.

in the opening is used to operate the oven. This pot stove is mounted on a tripod type of stand with the help of which the pot stove can be tilted towards the sun. The appropriate tilt is maintained by a peg attached to one of the stove legs. This pot stove can also cook all varities of food and temperatures of about 210 °C can easily be obtained.

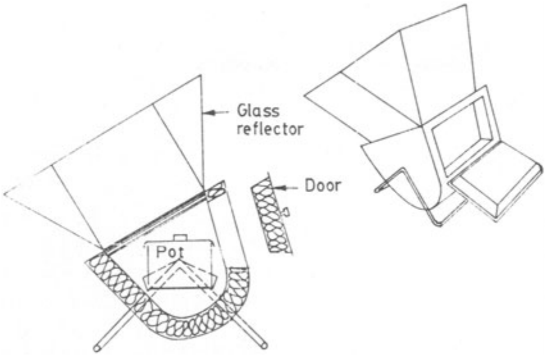


FIG.1.19. CYLINDRICAL SOLAR OVEN.

The cylindrical oven as shown in fig.1.19 can be titled in any position from 0 to 90 deg from horizontal to follow the sun. The inner surface of the cylindrical box is lined with reflector lining reflecting solar radiation on to a blackened cooking vessel kept on a cradle like cooking platform which remains horizontal irrespective of the tilt of the cylindrical oven. The outer side of the cylindrical box can be made of thin sheet metal, wood, plywood, or weatherproof cardboard. The space between two shells is filled with good insulation. The window is double glazed and the four square mirrors and four triangular mirrors are mounted at 30 deg to the normal to the window. An insulated plug type door for the operation of the cooking vessel is provided on the back wall of the oven. The whole oven can be inclined and oriented with the help of the pipe stand as shown in the figure. The length of the oven in the axial direction can be increased if several cooking vessels are to be used simultaneously. Several cooking trials and performance studies are carried out on this oven and it is concluded that all type of cooking like boiling, roasting, backing, etc. can be done within 45 to 100 minutes. Temperatures as high as 220 °C on clear days can easily be observed.

This oven was further modified and extensive trials were conducted by Telkes and Andrassy[23]. The body of the modified solar oven consists of a well-insulated semi-cylindrical form, made of sheet aluminium, sheet steel, galvanised iron. Two shells are made and the space between them is filled with insulating materials. The interior shell is painted black, using heat resistant paint. Aluminium sheet is not painted since this will help in concentrating solar radiation on to the pot. An openable door(window) of the same material is made to keep and remove the food. The area of the window is 0.19 sq.m. In some ovens this window is hinged with the oven and is used as a door to introduce food. The reflectors are made of anodized sheet aluminium of the type known as [3]Alzak'. The size of one reflector is 43 x 43 cm and the total effective solar collection area is 0.56 sq.m. The angle of these reflectors are so fixed relative to the window that the effective solar intensification is about 3. The stand and the orienting device is made of tubular metal with pivoting axle for rotating the semi-cylindrical oven part. The position of the oven is fixed by using a pin which engages into openings on the side of the oven-body. The cooking platform is made of hollow sheet metal shell, filled with heat storage material and is blackened to absorb solar radiation.

This oven intercept solar radiation directly through window and by reflection from mirrors. Temperature as high as 240 °C has been recorded inside this oven near New York city on a clear day. It was also observed that 1.0 litres of water comes to boiling point from a temperature of 20 °C within 30 minutes. Calculations show that this oven is equivalent to 150 watts of electric hot plate. All types of cooking, baking, roasting and boiling can be performed in this oven.

This solar oven is considerably improved by Pandya[64] and Garg[45] and extensive trials are conducted on the same both at Ahemedabad and Jodhpur. The solar oven developed by them is described. This solar oven consists of a well insulated semicylindrical box made of sheet aluminium and wood. Two shells are made and the space between them, 7.5cm, is filled with fibre glass insulation. The interior shell is painted black. A door of the same insulating material is also made for keeping and taking out of food. The Window (40 cm x 40 cm) of the oven consists of two

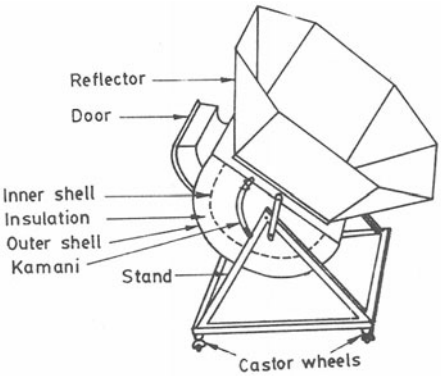


FIG.1.20 CYLINDRICAL SOLAR OVEN AS DEVELOPED BY GARG(INDIA)

transparent glass sheets (3 mm thick) with a spacing of 2.0 cm. Eight reflectors, made of silvered glass mirrors, four of square shape and four of traingular shape have been used. The oven can be manually tilted and oriented towards the sun. A cradle like cooking platform is made in the oven which helps in keeping the vessel containing food horizontal irrespective of the sun. This solar oven is shown in fig.1.20.

Few such solar ovens have been installed in villages near Jodhpur (India) for demonstration-cum-test purposes and performance has been found satisfactory. On very clear days, maximum plate temperature in the oven reaches to 350 °C in summer season and 250 °C in winter season. Practically all types of food preparations like cooking, roasting, baking and boiling can be done within 25 to 75 minutes under clear sky conditions. It is reported by a villager using the solar oven that the Bati, a local preparation prepared(baked) in this oven was more tasteful than made with conventional fuel(cow dung cake).

Recently Nahar[65] has compared the performance of a solar oven (cylindrical type as developed by Garg[45]) with the solar hot box cooker(with single plane reflector as developed by Parikh & Parikh[61]), at Jodhpur both in winter and summer. The parameters considered for comparison are : (i) stagnation plate temperature, (ii) time required for bringing a known amount of water to boiling point, (iii) time taken for cooking of various dishes, and (iv) diurnal variation of plate temperature. Some of the conclusions are : (i) In winter season the maximum stagnation temperature on a typical day for solar oven and hot box were 175 °C and 125°C respectively, (ii) In winter season, on a typical day, two Kg of water kept in four vessels reached to boiling point in 90 minutes and 150 minutes in solar oven and solar hot box respectively, (iii) On a typical winter day, two Kg of water reached to 97.5°C in one hours time in solar oven whiletwo Kg of water in solar hot box reached to 89.5 °C in one hours time, (iv) one Kg of dry food product (500 gm rice and 500 Kg moong Dal) was cooked in 2-hour in solar oven while it took 3-hour in solar hot box cooker on a typical winter day (v) hard foods like Rajmah, Chhole, etc. in winter season can only be cooked in solar oven and not in solar hot box cooker, and (vi) two meals can be cooked in a day in solar oven while only one meal can be cooked in solar hot box cooker in winter season.

1.7. ADVANCED SOLAR COOKERS

The main problem with the conventional solar cooker i.e. direct type or box type is that cooking is to be done outdoors and there is no provision of heat storage device so that cooking can not be done in the evenings or on cloudy days. A few solar cookers are either tried or proposed to overcome these two problems. Some typical solar cookers of this type are discussed below:

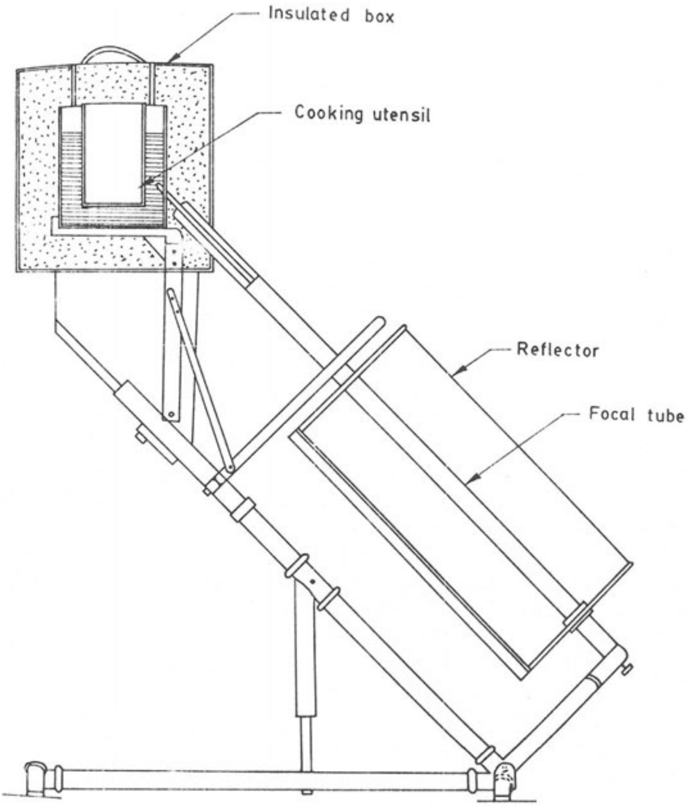


FIG.1.21. HEAT TRANSFER TYPE SOLAR COOKER AS DESIGNED BY ABBOT

1.7.1 Heat transfer system type solar cooker

Several solar cookers are made where some kind of heat transfer fluid is used transfering the heat from solar energy collector(cylindro-parabolic or flat plate collector) to the cooking vessel. The first cooker of heat transfer type was made by Abbot[9,10] in USA. The cooker is schematically shown in fig.1.21. It consists of two parts, a cylindro parabolic reflector and a hot box. The cylindro parabolic reflector measures approximately 3m x 2m x 0.5 deep and hot box 0.4m x 0.4m x 1.2 m. The polished aluminium cylindro parabolic reflector focuses solar radiation onto a 4 cm diameter blackened brass pipe enclosed in a circular glass tube. The tube contains oil which when heated rises due to natural convection to the insulated hot box. The oil reservoir is surrounded from outside with insulation and is designed to incorporate one or two chambers one above the other in case of two chambers. Hot oil from the pipe enters the reservoir at the top and the cooker oil sinks at the bottom which returns to the reflector through the return pipe. The reservoir is kept always at a higher position relative to the reflector to help in the natural circulation of oil. The reflector had an equatorial mounting alowing adjustment for seasonal variation of sun (north-south) and diurnal variation of sun (East-West).For automatic tracking, a simple clock mechanism can also be used. The temperature at the top of the reservoir reaches to 150 °C and at night rarely falls below 100 °C on sunny days. All types of cooking except frying can be done with this cooker.

In some other cookers, flat-plate collectors have been used to heat water to produce steam which in turn heats a remote hot plate. Unfortunately, the maximum temperature obtainable with a flat-plate collector is of the order of 130°C and at this temperature the efficiency becomes very low. One such cooker using flat-plate collector has been developed at the Solar Energy laboratory of the University of Khartoun, Sudan. The collector consists of a number of parallel pipes welded on two headers at the top and bottom. Water is filed upto about three quarters of the length of tubes. The system is allowed to reach thermal equilibrium which is about 130 °C at 3.5 atmosphers absolute pressure. By opening a valve the steam goes to the hot plate, gets condensed on the hot plate and thus release the heat of vaporization to the plate. This cooker operates at a very low efficiency and is suitable only for light stewing or water heating and because it works under pressure it may lead to potential safety hazards in the village environment.

A similar solar steam cooker is developed at Brace Research Institute, Canada[35,66]. In this case the heat from the steam passes directly into a steam box or oven. A perspective view of this cooker is shown in fig.1.22. This steam cooker consists of two parts that are rigidly and permanently joined to each other. The first is a flat-plate solar collector (tube in plate type) with single or multiple risers heated by the sun causing water to boil and producing steam. The second is the insulated steam cooker, in which the food containing saucepan(pot) is placed. The Solar collector is at a fixed tilt angle of 45 degrees, and is supported on a single pivot pipe that can be fixed into the ground, or mounted on a cross stand. The entire cooker is pointed towards the point of sunrise all morning and the point of sunset all afternoon. More frequent adjustement of the collector position can be done, but is not essential, except in poor weather. The solar collector always contains some water, about one cup of water being added each evening to replace the water that has boiled away. Steam is produced within an hour of sunrise and will continue to be

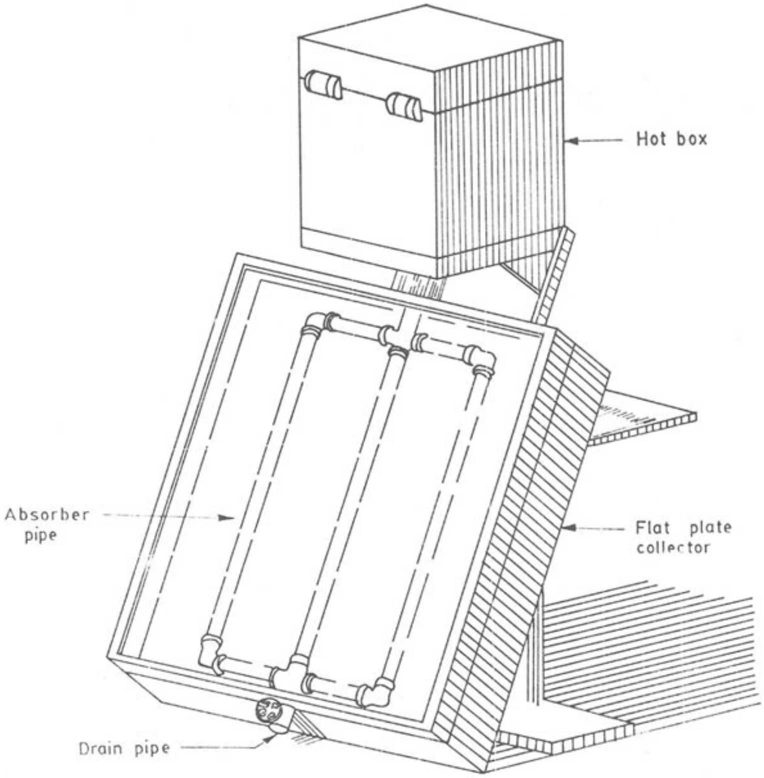


FIG.1.22. FLAT-PLATE COLLECTOR TYPE SOLAR STEAM COOKER.

produced for the rest of the day as until sunset. Thus it is possible to cook both the midday meal and the evening meal. Food left in the cooker will remain hot for several hours after sunset. This solar cooker is a slow cooking device, and is best suited for foods that require long slow boiling, such as stews, cereals and vegetables.

A similar solar steam cooker with an optimized flat-plate collector has been designed by Garg and Thanvi[48] and tested extensively at Jodhpur. This solar cooker, which is relatively simple in construction, absorbs direct and diffuse solar radiation and does not require adjustments towards the sun, consists of two parts; an optimized tube-in-plate type of flat-plate collector and an insulated steam cooker. The collector plate having an absorbing area of 0.9 sq.m. (120 x 75 cm) consists of a wire would steel fin of 28 gauge thick with steel pipe of 19 mm diameter spaced at 25 cm centres. Two glazings are used over the flat-plate collector.

The steam cooker fixed at the top consists of a double walled insulated cylinderical box made out of 24 gauge galvanized iron sheet. The diameter and height of inner box with an openable lid is 15 cm and 26 cm respectively and of outer box with openable lid 26 cm and 36 cm respectively. A steel pipe of 19 mm diameter and 15cm long is welded at the bottom of the inner tank which acts as an inlet of water to the absorber and outlet of steam. A metal ring of diameter 12 cm and height 4 cm is also placed in the inner box over which the tiffin containing food is placed. The tiffin of diameter 13 cm and height 22 cm is made of aluminium with three compartments. The food requiring cooking is placed in the compartments of the tiffin.

The entire cooker is fixed at an inclination of 41 degrees from horizontal at Jodhpur with the help of stand made of wooden batten and is pointed towards the point of sunrise all morning and the point of sunset all afternoon. More frequent adjustment is not required. The solar collector always contains water, about one cup of water can be added each morning to replace the water that has boiled away. Steam is produced within an hour of sunrise and will continue to be produced for the rest of the day as along as the sun shines on the collector. Because the cooking pot is located above the collector, the same condensate returns by gravity flow and boils up again. The entire cooker can be cleaned by flushing the water through the cooker by opening the gate valve provided at the bottom of the collector.

This solar cooker can be used for cooking or boiling of cereals, rice, potatoes, dal, vegetables, etc. This cooker can be installed in the open lawn or right on the chajja of the house and then connected with a pipe of the steam cooker placed inside the kitchen. Even in multistorey buildings this solar steam cooker can be used with suitable location of the kitchen.

An improved heat transfer fluid type solar cooker is proposed by Swet[40] in which a heat pipe is used to transfer heat from the focus of the cylindro parabolic concentrator to the hot plate. A cylindro parabolic concentrator is mounted on a solar axis and by using an inexpensive bimetalic helix tracks the sun movement and focuses the solar radiation on a stationary heat pipe. The heat pipe uses a ^{3}daytherm-A' as heat transfer fluid and

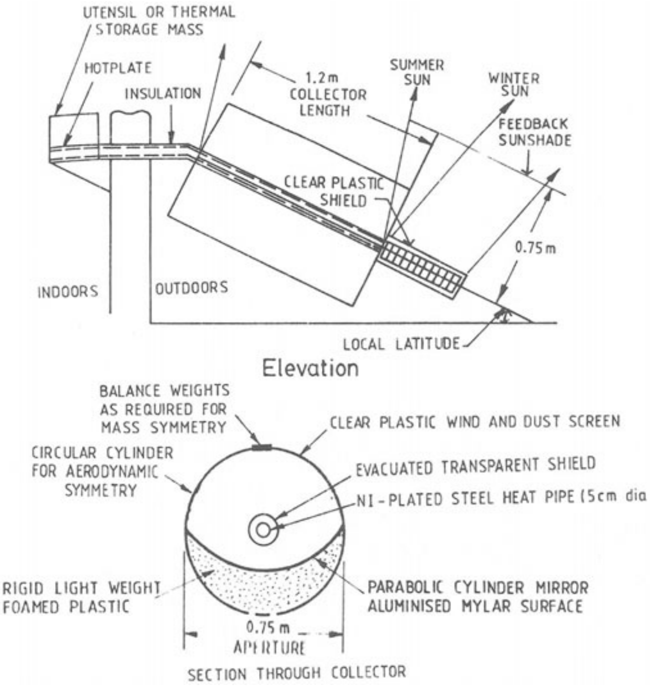


FIG.1.23. HEAT PIPE TYPE SOLAR COOKER.

both the concentrator and heat pipe are enclosed in a transparent polycarbonate cylinder reducing heat losses. The working fluid in the heat pipe quickly gets evaporated upon irradiation and gets condenses upon giving heat to a specially designed indoor hot plate. The working fluid condensate returns by gravity gets quickly distributed by wicking action in the heat pipe and again reevaporated and gives heat to the hot plate. When cooking is not required a heat storage mass can be placed on the hot plate, absorbing the solar heat for later use. Only one such cooker was made and tested in USA in 1974. The cooker is shown in fig.1.23.

Another solar cooker using a line focus concentrator, heat transfer oil, an automatic sun tracking arrangement, and a specially designed hot-plate with phase change storage material is proposed by Stam[27]. Here the sun tracking is done by a weighted pulley arrangement in which the downward movement of a driving weight is caused to coincide with the speed of flowing sand in a hour-glass. This rotation is from east to west and is at a speed of 15 degrees per hour.

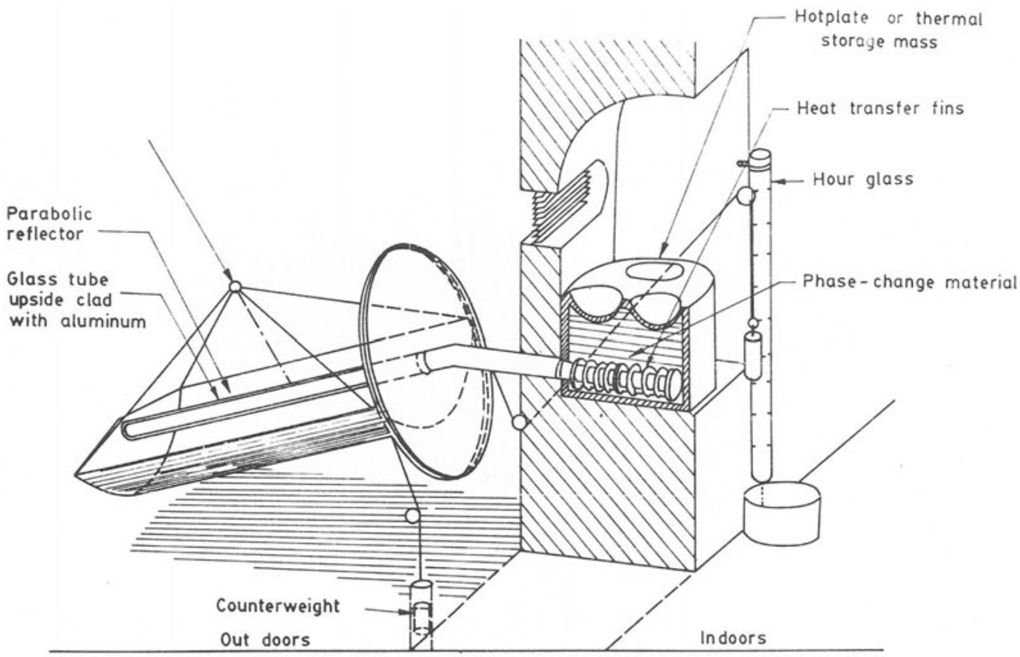


FIG.1.24. ARTIST CONCEPT OF A HEAT TRANSFER SOLAR COOKING SYSTEM PROPOSED BY STAM.

The cooker is shown in fig.1.24.

Another conceptual design of a indoor solar cooker is given by Farber et al[67] and the same is schematically shown in fig.1.25. In this cooker two heat transfer loops are employed, one loop receives energy from the focussing concentrator and transfers it to a thermal storage medium (phase change material) and the second loop receives heat from the storage medium and transfers it to the hot plate for cooking of food.

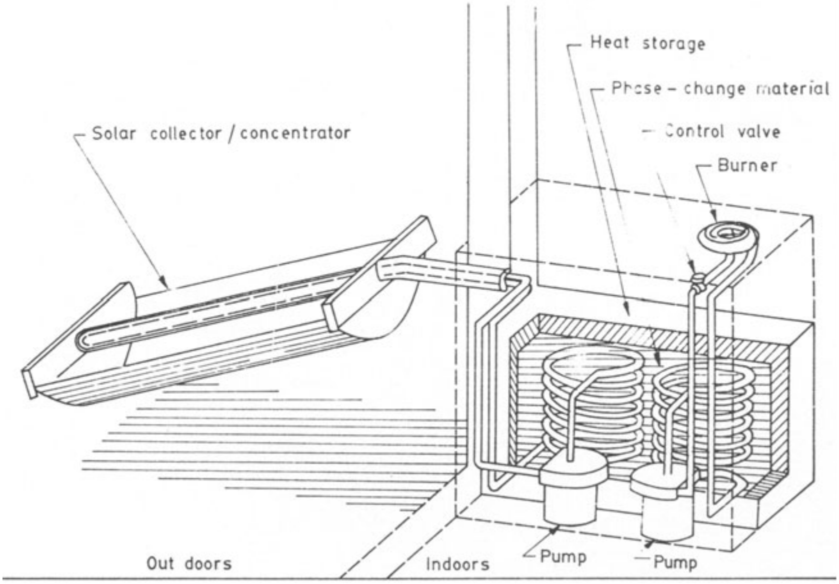


FIG.1.25. ARTIST CONCEPT OF THE SOLAR COOKING HEAT TRANSFER STORAGE SYSTEM PROPOSED BY FARBER.

1.7.2 Energy Storage type Solar Cookers

If suitable heat storage device is coupled with a solar cooker, then it can be used indoors and even in the evenings when the sun is not shining. Solar thermal energy can be stored either in the form of sensible heat, latent heat, or chemical energy. All these systems of thermal energy storage is described in detail in a recent book by Garg et al[68].

Water is the best sensible heat storage material because of its highest heat capacity (4.0 KJ/Kg K). Water has a boiling point of 100 °C and therefore as such it can not be used for storing heat for cooking purpose unless it is pressurised which is difficult and requires costly container etc. Dual storage media i.e. crushed rock alongwith some oil in a sealed container which can store heat in the temperature range of 150 to 200 °C can be safely employed with solar cooker. Rock has a heat capacity of 0.84 KJ /Kg K and oil about 3.35 KJ/Kg K and if a system is having 70 percent by volume of rocks and 30 percent oil then the combined system will have heat capacity of about 1.17 KJ/Kg K. In this system properly sized rock bed provides large surface area and oil acts as a heat transfer fluid. A simple calculation will show that for storting heat sufficient for cooking food only for storing heat for a family of six persons, we require about 140 litres of storage volume assuming about 50 percent combined storage-cooking efficiency. The space, cost, insulation etc. of such a large size storage device is out of reach of the typical village family.

There are many latent heat storage materials which melts between 150 to 250 °C and are stable. These materials store many a times (more than 100 times) of heat compared to sensible heat storage materials and therefore preferred. Some candidate materials suitable for storing heat in the cooking range are listed[55] in table 1.1.

Table 1.1 Candidate latent heat for storing thermal energy in cooking range.

Material	Composition (mole)	Melting Point (°C)	Heat of fusion (cal/gm)
$NaNO_2$-$NaOH$	27-73	240	58.33
$NaNO_3$-$NaOH$	70-30	248	37.76
$NaBr$-$NaOH$	22.3 -77.7	261	38.67
$Ba(NO_3)_2$-$LiNO_3$	2.6 -97.4	253	87.43
$Ca(NO_3)_2$ -$LiCl$	40.85-59.15	270	40.07
$NaNO_3KNO_3$	54-46	222	23.60
Na_2CO_3-Na_2O-$NaOH$	6.5-7.4-86.1	288	56.40
$NaCl$-$NaNO_3$-Na_2SO_4	8.4-86.3-5.3	287	42.44
Al_2Cl_6	-	194	114.80
$LiNO_3$	-	254	90.87

The phase change storage system will require a tank filled with phase change storage material in which series of pipes or coil are immersed. Heat transfer fluid circulates through these pipes or coil, heats the salt(phase change material) melts it at its melting point and further heat it sensibly if temperature goes higher. When heat delivery is required, some heat transfer oil at low temperature through a seperate loop circulates through the salt tank and hot plate(cooker). Initially sensible heat and later latent heat of fusion is supplied through the pipe to the heat transfer fluid. Because of the low thermal conductivity of most of the phase change storage materials, it is very difficult to recover 100 percent of the heat.

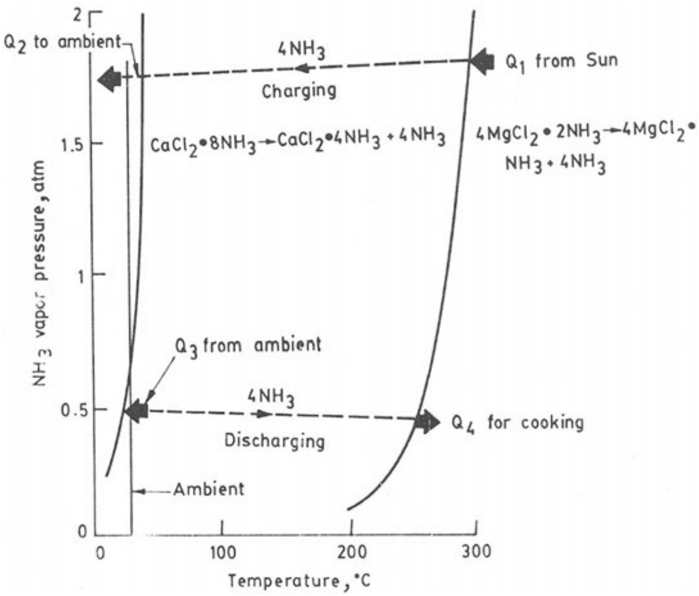


FIG.1.26 CHARGE-DISCHARGE CYCLE OF CHEMICAL HEAT PUMP PROCESS

There are several reversible chemical reactions where reactions takes place when heated (using solar heat) and heat can be recovered when the reaction is reversed. The main advantage of chemical energy shorage is that heat is stored at ambient temperature for longer durations. Several systems including sulphuric acid-Water is proposed to store thermal energy. Hall et al[69] have proposed a chemical heat pump storage concept in which ammoniated salts of calcium chloride and magnesium chloride is used to store solar energy for cooking purpose. The system has two basic elements: a solar concentrating collector may be a fresnel lens, and a heat storage unit. In the heat storage unit there are ammoniated salts of $MgCl_2$ and $CaCl_2$. In the charging mode solar heat is supplied to the high temperature salt bed ($MgCl_2$) side from where the NH_3 is driven to the low temperature salt bed ($CaCl_2$) side. Following reaction takes place in the charging mode:

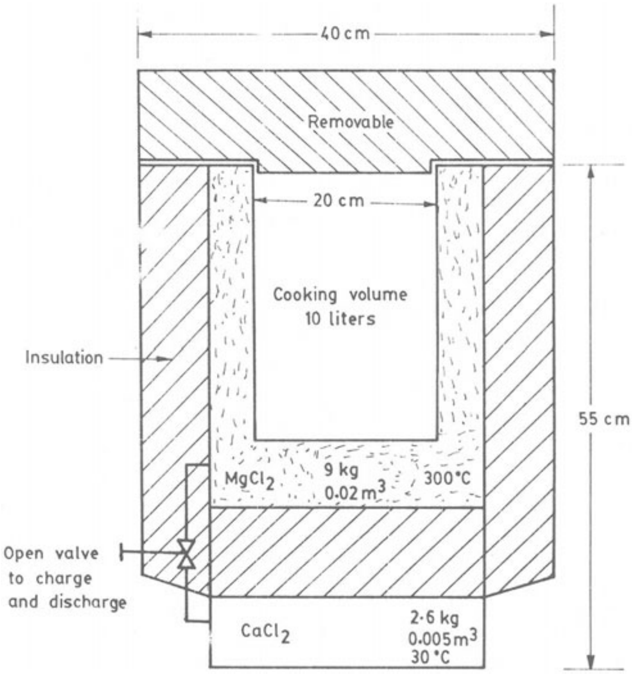


FIG.1.27 STORAGE/COOKING UNIT AS PROPOSED BY HALL et al

Heat can now be stored for infinite time at room temperature. On slightly heating the low temperature salt bed ($CaCl_2$), NH_3 will dissociate and return to the high temperature bed, reacting with $MgCl_2$ exothermally freeing heat for use in cooking. In the discharging mode following reaction will take place:

$$CaCl_2.8NH_3 + Q_3 \longrightarrow CaCl_2.4NH_3 + 4NH_3$$

$$4NH_3 + 4MgCl_2.NH_3 \longrightarrow 4MgCl_2.2NH_3 + Q_4$$

The charge-discharge cycle for these salts is shown in fig.1.26.

The storage/cooking unit as proposed is shown in fig. 1.27. Here the concentrated solar energy is allowed to fall at the top of the unit. While the system is being charged, the low temperature salt bed is cooled by surrounding air. The thermal capacity of the storage unit is 2 KWh and the discharge rate is 1 KW. The total weight is about 20 Kg. Several such charged unit can be used for cooking purpose where cooking requirement is large.

1.8 PERFORMANCE OF SOLAR COOKERS

There are many parameters which effects the performance of a solar cooker. The parameters effecting the performance in case of direct type solar cookers are different than those in case of a box type solar cookers. Hence the performances in both the types will be discussed seperately.

1.8.1 Direct type solar cooker

Most of the direct or focussing type solar cooker makes use of direct or beam solar radiation. The performance of focussing cookers can be studied from the studies of heat balance. The useful heat Q_u derived from a solar cooker is

$$Q_u = Q_A - Q_L \qquad (1.1)$$

where Q is the net heat absorbed by the cooking vessel and is given as

$$Q_A = A_r \gamma \alpha I_d \qquad (1.2)$$

where A is the net aperture area of the reflector intercepting solar radiation, r is the specular reflectance of the reflector, γ is the intercept factor representing the fraction of specularly reflected radiation that is intercepted by vessel, α is the absorptivity of the vessel, and I_d is the beam radiation normal to the aperture. Q_L is the heat loss from vessel which includes heat loss by radiation, convection, and evaporation. If evaporation heat loss is considered as a part of cooking then for simplicity the heat loss term Q_L can be written as

$$Q_L = A_rU\ (T-Ta) \qquad (1.3)$$

Where A_r is the heat loss area of the vessel, U is the combined heat loss coefficient due to convection and radiation, T is the cooking vessel temperature, and Ta is the ambient temperature. The expression for the rate of useful energy collection, Qu, is now given as :

$$Q_u = Ar\ \gamma\alpha\ I_d - A_rU(T-Ta) \qquad (1.4)$$

or rate of useful energy collection per unit of aperture area A is given as

$$q_u = r\gamma\alpha I_d - \frac{U}{C}(T - Ta) \qquad (1.5)$$

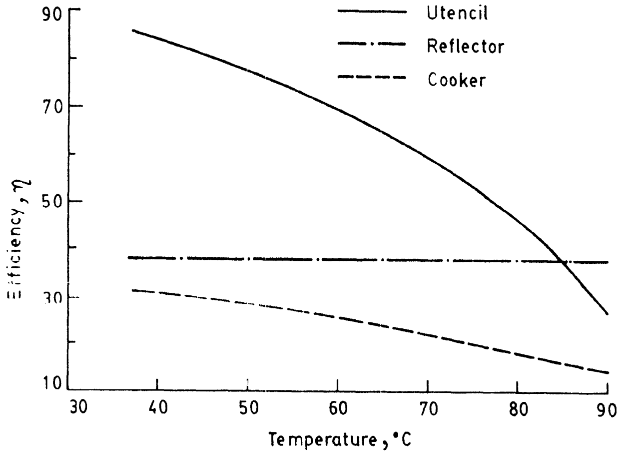


FIG.1.28 VARIATION OF EFFICIENCY OF UTENCIL, REFLECTOR, AND THE COOKER WITH TEMPERATURE OF WATER.

Where C is the concentration ratio. From this expression it is seen that as the concentration ratio 'C' increases, the rate of useful energy collected increases due to reduced heat losses from the cooking vessel at temperature T.

Fig.1.28 shows[70] the general performance equation of a solar cooker. From this figure it is seen that the performance efficiency of a solar cooker decreases with the increase in its operating temperature, while the efficiency of reflector remains unchanged with temperature of cooking vessel and mainly depends on specular reflectance r and intercepting factorγ. It is therefore essential to have the reflecting surface of highly specular. The specular reflectance of a surface depends on its nature and smoothness. The values of specular reflectance for various surfaces are given by Garg[71]. Generally keeping cost and availability into consideration, polished and aluminized aluminium, aluminized polyster film, back silvered mirror, etc., are used as reflecting surfaces in solar cookers. The intercept factor depends on many parameters including accuracy of reflector profile, alignment of the reflector and vessel, etc.

For efficient cooking it is required that the cooking vessel is heated from the bottom i.e. all the reflected rays should strike the bottom of the cooking vessel and the vessel should remain horizontal. In winter season or when the altitude angle of the sun is low i.e. in the early mornings or late afternoons, some of the reflected rays may strike the side of the vessel. Ghai et al[14] have derived an expression for maximum angle through which a reflector of focal length F and aperture deameter D can be tilted so that no reflected ray may miss the bottom of the vessel.

$$\tan \psi = \frac{16\ R^2 - 1}{8\ R} \qquad (1.6)$$

where $R = f/D$

This relationship between maximum tilt angle and the ratio of focal length to aperture diameter(f/D) is shown in fig.1.29. The effect[70] of blackening the bottom of the cooking vessel on the temperature is compared with a vessel without blackening the bottom in fig.1.30. The advantage of blackening the bottom is appreciable and hence blackening of bottom of the cooking vessel is essential. One of the main limitation of the focussing type cooker is that if the wind speed is high, the cooker will not be able to cook the food because of high forced convection losses. The effect of wind speed for two days one on calm day i.e. wind-speed is 0.4 m/s and other on windy day i.e. wind-speed is 2.3 m/s on the performance of the solar cooker is shown in fig.1.31. The performance of direct type solar cooker also gets effected on hazy and dusty days.

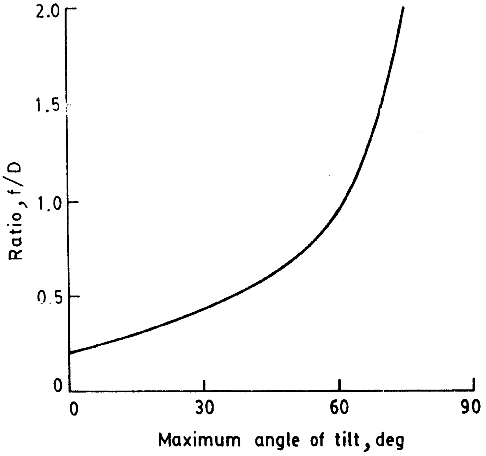


FIG.1.29. EFFECT OF REFLECTOR PARAMETER ON THE MAXIMUM ANGLE OF TILT

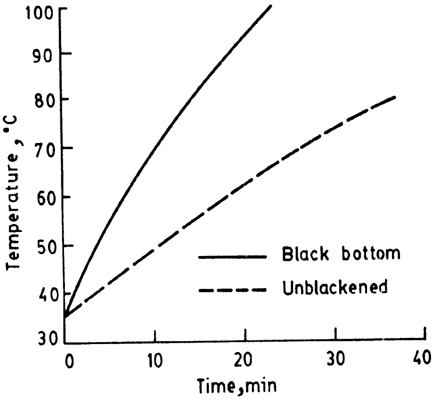


FIG.1.30 EFFECT OF BLACK BOTTOM OF VESSEL ON THE TEMPERATURE.

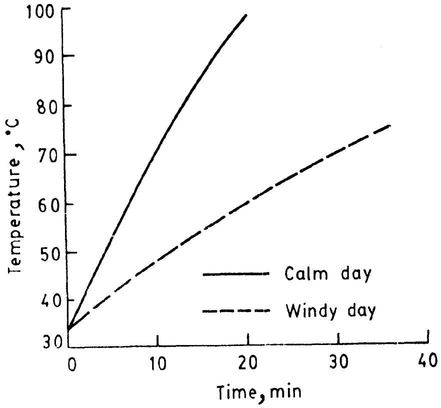


FIG.1.31 EFFECT OF WIND SPEED ON THE TEMPERATURE.

1.8.2 Box type solar cooker

The performance of a simple box type solar cooker with single plane reflector which is convenient to use depends on many parameters such as climatic parameters like solar insolation, ambient temperature, wind speed etc., design parameters like properties of black paint used in tray, type of cooker, number of glazing, insulation properties, effectiveness of reflector-booster system, etc; and on operational parameters like amount and type of food kept for cooking, numbers of cooking vesells used, etc. Generally as a matter of routine, three parameters are experimentally measured: (1) time-temperature history of solar cooker when it is empty, (ii) Cooking times of different food products, and (iii) the time required to heat sensibly a known amount of water upto the boiling point. A little design variation in solar cooker will effect the above three parameters. The cooker tested here consists of a rectantular hot box with inner box made of sheet metal (60 cm x 60 cm) and outer box made of sheet metal (70 cm x 70 cm) and the space between them filled with loose glass wool. The window is 60 cm x 60 cm with double glazing. The reflector of size 60 cm x 60 cm made of looking glass is hinged on one side of box and its angle can be adjusted relative to the window plane. The cooker alongwith the reflector can be adjusted towards the sun.

The above cooker was tested extensively at IIT, New Delhi on different winter and summer days. The cooker and its reflector was adjusted every half on hour towards the sun. The variation of cooker plate temperature with time of the day when it is empty for a typical winter day is shown in fig.1.32. It is seen that cooker plate temperature

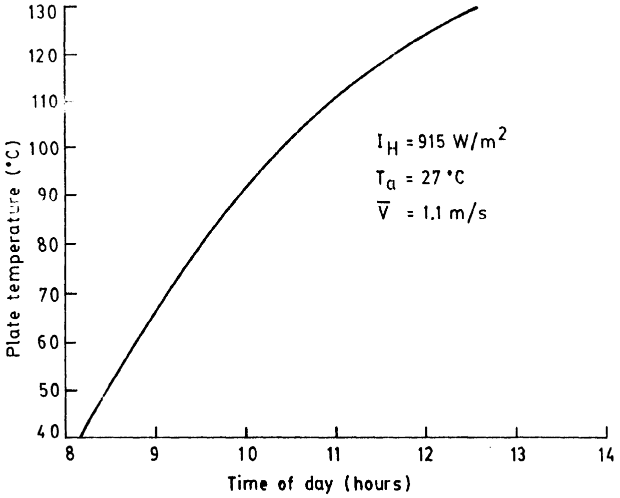


FIG.1.32 DIURNAL VARIATION OF COOKER PLATE TEMPERATURE WITHOUT LOAD ON A TYPICAL WINTER DAY

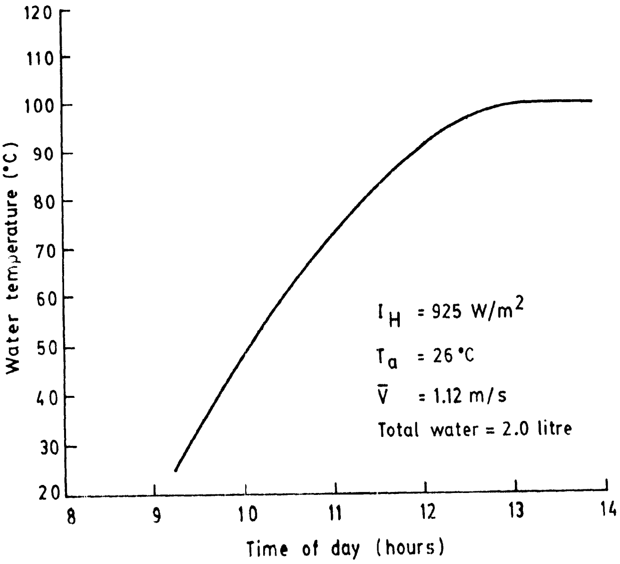


FIG.1.33. DIURNAL VARIATION OF WATER TEMPERATURE WITH 2.0 LITRES OF WATER IN FOUR VESSELS

increases with the time of the day and maximum temperature (stagnation temperature) reaches at about 12.30 hours when the solar incolation is 915 W/m^2. When the cooker is loaded with water i.e. 2.0 litres of water was kept in four blackened cooking vessels, then the plate temperature drops down considerably. The variation in water temperature with time of the day when 2.0 litres of water was kept in four vessels in the cooker on a typical winter day is shown in fig.1.33. It is seen from this figure that 2.0 litres of water reaches to boiling water at about 13.0 hours. If the water amount is reduced then the time required to reach at the boiling point will also be reduced. In summer season when solar insolation, ambient temperature, and initial water temperature is high the boiling point for the same amount of water will reach much faster compared to that in winter seasons. The performance of the box type solar cooker with or without load can also be calculated using the mathematical model developed by Garg et al[72].

1.9 TESTING OF SOLAR COOKER

Although solar cookers have been the topic of research for the last 100 years, there is no standard test procedure for thermal rating of solar cookers. There are many test procedures for thermal rating of flat-plate collectors in different countries but the most widely accepted and used procedure is ASHRAE standard 93-77[73]. Generally cookers are thermally rated according to (i) stagnation plate temperature, (ii) time required for cooking different food products and (iii) time required to bring a known amount of water to the boiling point. The above procedures are not acceptable since the testing will depend on the climatic parameters. Recently an attempt has been made by Saxena et al[74,75] for evaluating the hot box type solar cooker which is independent of the climatic parameters. In this procedure two figure of merits, F_1 and $F_2$are determined by conducting the stagnation temperature test (without load), and by sensibly heating of known amount of water. The first figure of merit, F_1, which is defined as the ratio of optical efficiency to heat loss factor is determined as follows.

The expression for heat loss factor (U_{LS}) at stagnation temperature (T_{PS}) as from fig.1.32 is given as

$$\eta_o I_S = U_{LS}(T_{PS}-T_a) \qquad (1.7)$$

Where η_o is the optical efficiency, I_S is solar insolation on horizontal surface at the time of stagnation, and Ta is ambient temperature. Since Cookers operate near the stagnation temperature, the first figure of merit F_1 is given as

$$F_1 = \frac{\eta_o}{U_{LS}} = \frac{T_{PS} - T_a}{I_S} \qquad (1.8)$$

This figure of merit is convenient to measure and its comparison for different cookers will show the relative merit for their thermal performances. A lower limit of F_1 is proposed ($F_1 \geqslant 0.12$) to ensure that the cooker will show reasonably high stagnation temperature. The cooker under consideration (Fig.1.32) has given a figure of merit F_1 as 0.11 which is slightly lower than the prescribed limit and may therefore is likely to be rejected since the cooker will not be able to cook the food.

The determination of second figure of merit, F_2, involves the measurement of water temperature of known amount of water during the course of the day. It is desired that the water temperature should reach the boiling point as quickly as possible to reduce the cooking time. The time interval dT required for a known thermal capacity of water $(MC)_w$ to increase its temperature by dT_w is given as

$$dT = \frac{(MC)_w \, dT_w}{Q_u} \qquad (1.9)$$

Where Q_u is the rate of useful heat gain by water and is given as :

$$Q_u = AF' [\eta_o H - U_L(T_w - T_a)] \qquad (1.10)$$

where A is the aperture area, F' is the heat exchange efficiency factor, and H is the solar insolation on horizontal surface. Integrating equation (1.9) for the time internal T during which water temperature rises from T_{w1} to T_{w2}, and rearranging the terms we get

$$F'U_L = -\frac{(MC)_w}{AT} \ln \left[\frac{1 - \dfrac{U_L}{\eta_o} \left(\dfrac{T_{w2} - T_a}{\bar{H}} \right)}{1 - \dfrac{U_L}{\eta_o} \left(\dfrac{T_{w1} - T_a}{\bar{H}} \right)} \right] \qquad (1.11)$$

It is seen from equation (1.11) that both the parameters F' and U_L are almost independent of the climatic parameters. However the time internal T required to increase the known amount of water temperature from T_{w1} to T_{w2} will depend on climatic parameters. For a cooker F' should be large and heat loss U_L should be small and hence the produce $F'U_L$ will give misleading results. Therefore the second figure of merit F_2 is given as

$$F_2 = F_1 \, (F'U_L) = \frac{\eta_0}{U_{LS}} \, (F'U_L) \qquad (1.12)$$

$$\simeq F'\eta_0$$

Where it has been assumed that heat loss U_L is approximately the same as the heat loss at stagnation temperature. Now the second figure of merit F_2 which should be as large as possible can be given as :

$$F_2 = F_1 \, \frac{(MC)_w}{AT} \, \ln \left[\frac{1 - \dfrac{1}{F_1} \left(\dfrac{T_{w2} - T_a}{\bar{H}} \right)}{1 - \dfrac{1}{F_1} \left(\dfrac{T_{w1} - T_a}{\bar{H}} \right)} \right] \qquad (1.13)$$

From the above expression, the second figure of merit F_2 can be calculated and compared for different cookers.

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CHAPTER - 2

SOLAR DESALINATION

2.1 INTRODUCTION

Adequate quality and reliability of drinking water supply is a fundamental need of all people. Without potable or fresh water (less than about 550 parts per million (ppm) of salt) there is no human life. Industries and Agriculture also need fresh water without which they can not function or thrive. Water is therefore the key to man's prosperity; it is intimately associated with the evolution, civilization and destiny; hence it is aptly said that water is everybody's business. Fresh water which was obtained from rivers, lakes, and ponds is becoming scarce because of industrilization and population explosion. Moreover these potable water sources are being polluted constantly by industrial wastes and large amounts of sewage. It is said that presently more than 2000 million people are not getting potable water which leads to many deseases and stops the development. Looking to the scaracity and large demand of fresh water, the United Nations on November 10, 1980 declared the years 1981-1990 the decade of water supply and sanitation. Many U.N. organisations like UNDP, WHO, and the Worldbank are now actively involved throughout the world in promoting projects concerning to supply of fresh water for drinking purposes.

In the past also, the shortages of fresh water existed but it was confined to arid and semi-arid regions and regions where only brackish water is available. But now due to industrialization and population rise, the shortage has come into prominence. In older days when the population was small and people lived near the water resources, the average consumption of water used to be 15 to 25 litres per person per day which increased to 50 to 75 litres per person per day in the nineteenth century. Because of large demands of fresh water, big industries and agriculture (increased irrigation land for growing more food) the per capita consumption has been increasing by enormous leaps. Sixty years ago united states of America was using about 40 billion gallons of water and now uses about 240 billion gallons and which will be 600 billion gallons after 20 years. Similar trend is observed in all countries. The demand of fresh water per person varies throughout the world, from 200 k gallons per year in a developing country to 600 k gallons per year in an industrialized country like United States.

There are many methods of converting brackish water into potable water. Some of the processes which are now commercially employed are :

1. Desalination: In this method, the brackish or saline water is evaporated using thermal energy, and the resulting steam is collected and condensed as final product.
2. Vapor Compression: In this process of distillation water vapour from boiling water is compressed adiabatically and vapour gets superheated. The superheated vapour is first cooled to saturation temperature and then condensed at constant pressure. This process is derived by mechanical energy.
3. Reverse Osmosis: In this process saline water is pushed at high pressure through special membrances allowing water molecules selectively and not the dissolved salts.
4. Electrodialysis: In this method a pair of special membrances, perpandicular to which there is an electric field are used and water is passed through them. Water does not pass through the membrances while dissolved salts pass selectively.

There are many parts of the wrold like arid and semi-arid areas and coastal areas where plenty of underground water is available but this is highly saline (2000 ppm to 3500 ppm) and therefore unfit for human consumption. The ocean covers some 70.8 percent of the earth's surface containing about 1350 million cubic kilometers of saline water containing about 35000 ppm impurites out of which about 28000 of this is common salt, sodium chloride which is an essential part of our body. The minimum level of acceptance of fresh water for human consumption is only 550 ppm. However, there are communities in the world which are taking water upto 1500 ppm without any ill effect. For agricultural purposes a salt content of 1000 ppm is generally thought to be upper limit but there are many corps which can grow even in higher salinity water. The requirement of impurities (salinity) in water for industrial purposes varies to great extent. For example saline water as such can be used for many cooling operations except frequent cleaning of exchangers is required. In some industries like in modern steam power generation, very pure water with a dissolved salt of only 10 ppm is required.

Distillation process is considered to be one of the simplest and widely adopted technique for converting seawater into fresh water. More than 90 percent of the worldwide installed seawater desalination capacity is due to distillation process. One of the main advantage of a distillation process is that it required heat only upto 120°C which can be supplied from solar energy or other cheap fuels, while in reverse osmosis, vapour compression, and electrodyalysis processes some mechanical or electrical energy is used. Distillation divides into four main types of sub-processes: (a) (i) single effect distillation, (ii) multiple effect distillation; (b) Vapour compression distillation; (c) (i) single stage (ii) multiple stage, and (iii) multiple effect multiple stage flash distillation; and (d) Solar distillation.

Solar energy is an abundance, never lasting, available on site, and pollusion free, however the cost of its collection and utilization becomes expensive because solar energy is diffuse, low intensity, and intermittent and therefore required some kind of thermal energy storage. But for applications like distillation of bracking water using solar energy, the intermittent nature of solar energy will not limit its use and distilled water will be produced as and when solar energy is available. Because of the simplicity of apparatus design, requirement of fresh water, and free thermal energy, work in the field of solar distillation is in progress for the last 110 years.

2.2 HISTORY

In the hydrologic cycle, the nature is utilising solar energy for converting brackish water into fresh water where due to solar heating of water from oceans, lakes, rivers, and other large bodies of water, vapours are being continuously generated and transported by wind to distance places which get condensed and precipitated in the form of rain at cooler regions. This god made distillation process can be repeated on a much smaller scale on earth and brackish water can be repeated on a much smaller scale on earth and brackish water can be converted into fresh water. Since the distribution and amount of rain water is very erretic, it is not easy and economical to collect all the rain water. This results in large percolation of water in the ground which can be in some cases recovered by drilling holes at suitable sites, large amount gets evaporated again into the atmosphere, and the rest flows into the rivers and finally into the Ocean. Distillation of sea water by men is not a new idea. Even in sixteenth century fresh potable water was used to be distilled from sea water on ships. It was considered to be more economical to produce distilled water on ship than to carry it from long distances.

The first recorded use of solar energy for distilling sea water is that of the Arab alchemists in 1551 and described by Mouchot[1] later in his paper. He used some kind of glass vessel to distill the water. Della porta in 1589 conducted an experiment in which two earthen pots, one filled with bracking water and exposed to strong sun is used and distilled water is collected in the second pot. Their work is reported later by Nebbia and Menozzi[2]. A French Chemist Lavoisier in 1862 produced distilled water using solar energy by using two large glass lenses and focussing the sunlight on the pot containing brackish water. In 1869 Mouchot[1] used plane looking glass reflectors for concentrating solar energy for distillation purposes. An excellent historical review of the growth of solar distillation is given by Talbert et al[4]. Carlos Wilson, a Swedish Engineer was the first who in 1872 designed and built a solar distillation plant which is presently known as 'Solar Still' near Las Salinas in Northern Chile. This 4700 sq.m surface area solar still as described by Harding[5] consists of a wooden bay of 1.14 m wide and 61 m long which was covered with ordinary glass. The inside wood was painted with logwood dye and alum to absorb solar radiation. In the bays, brackish water was put daily, which on evaporation due to solar radiation absorption and condensation on underside of glass cover was giving the distilled water. This still worked for more than 50 years and was giving about 4.9 litres/m^2 day which is till comparable to todays still. This solar still was later abandoned due to salt deposition in the bay and cheaper methods became available for converting bracking water into fresh water. After the first world war, interest in solar distillation was revived and solar stills of roof type, tilted wick, V-covered, inclined tray, plastic cover, tubular and air inflated stills, and suspended envelope type, etc. were studied. Several scientists like Mouchot[1], Kausch[6], Pasteur[7], and others used metal reflectors to concentrate solar radiation onto a copper boiler and fresh water was obtained by cooling the steam in the condenser. But its efficiency was less than 50 percent. Abbot[8] developed a solar distiller by using a clock driven cylindrical parabolic reflector with aluminium foil surface concentrating solar rays on to a vacuum jacketed tube containing water. This focussing type distiller showed efficiency of the order of 80 percent but boiling of water in tube caused some difficulties. In 1926 the French Government announced a prize for the design of a portable solar still (9,10). Maurian et al[11,12] described and tested solar still of 0.9 sq.m area with inclined glass plate facing south. These stills had given an efficiency of 15 percent only. Richard[13] also conducted experiments on flat-solar still of 1.4 sq.m area with inclined glass plate at Monaco and obtained an efficiency of 25 percent. Later attempts were made to improve the performance of these stills by using porous black wicks of cotton cloth to increase the evaporating surface[12] or by cooling the glass plate by water[13]. The simple basin type solar still which is studied and used most is schematically shown in fig.2.1 where there is shallow blackened basin of saline water covered with a sloping transparent roof. Solar radiation that passes through the glass roof heats the water and the blackened basin, therefore allowing the water to evaporate which gets condensed on the underside of the glass and gets collected in tray as distillate attached to the glass.

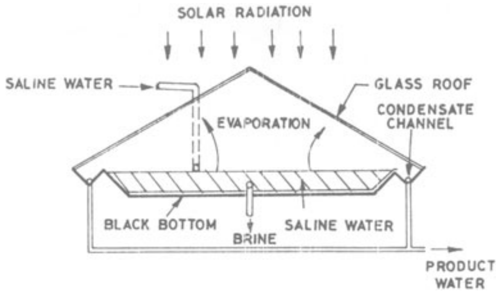

FIG.2.1. SCHEMATIC OF SHALLOW BASIN TYPE SOLAR STILL

The interest on solar distillation was reborn during world war II when a project was sponsored by Godfrey L. Cabot Solar Energy at the Massachusetts Institute of Technology, USA to investigate the principles of solar distillation and to develop a portable solar distiller suitable for life rafts for use by US Navy and Airforce. These units consisted of a black felt pad of 0.2 sq.m area saturated in sea water placed inside a transparent inflatable plastic envelope and a distillate collector bottom connected to the bottom of the plastic envelope (fig.2.2). While in use, the whole assembly floated in the sea alongwith the raft after inflation, and the solar radiation striking the black felt pad makes the water evaporate which would condense on the inside of plastic envelope and finally dripping into the bottle at the bottom of the assembly. It is reported that more than 200000 such units were produced during the world war II and each device was able to supply about 1 litre of fresh water on a clear day.

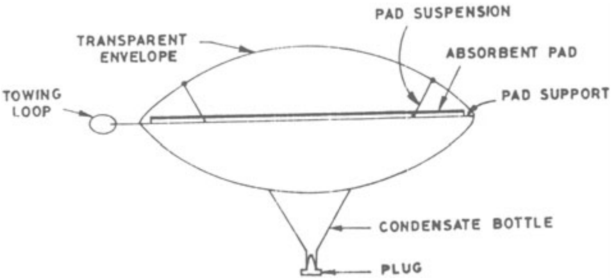

FIG.2.2. LIFE RAFT TYPE SOLAR DISTILLER

Immediately after world war II for a decade, in many parts of the world serious shortage of fresh water was experienced due to prolonged drought conditions. Several desalination techniques were proposed and one of them was solar distillation. In united states, the state of California, National Congress, and Department of interior, sponsored research programmes on solar distillers. In Europe, the European Economic Corporation also became active and funded few projects on solar distillers. In Algeria some small size solar stills were put to use on some Caribbean islands and mediterranean islands. The work on solar distillation was at the peak during 1950 to 1960 but after 1960 the work on solar distillation proceeded at a diminishing rate. A long term project was commenced at the Sea Water Conversion Laboratory, University of California in January 1952 with the ultimate aim to provide fresh water at a cheaper rates than that produced by using other fuels. By now it was realised that the solar stills can supply drinking water to isolated residences and small communities due to high cost of solar distilled water and therefore the main effort later was to improve the operating efficiencies of different type of solar stills. Research work on solar distillation was therefore continued in many countries including USA[16-23], USSR[24,25], Australia[26-28], India[29-31], Pakistan[32,34], Japan[35], Italy,[36,37] Chile[38-39], Cyprus[40], Kenya, France[41,42], Senegal, Iran[43], Egypt [44], Greece[45,46], Ethiopia, Tunicia, South Africa[47], Algeria[48,49], Spain[50,51], Morocco, Iraq[52], U.A.R.[53], Sudan[54], and Saudi Arabia[55,56]. Several large basin type solar stills are made in many countries of the world and a brief summary of them is given in table 2.1.

The ordinary basin type solar still is known as ^{3}single effect' since it uses the supplied solar energy only once and most of the heat gets lost to the atmosphere and therefore these stills operate at low efficiency. Such stills are studied experimentally by many workers like Howe and Tleimat[19], Gomkale and Datta[57], Garg and Mann[31], Telbert et al[4], Cooper and Read[58]. Computer simulation studies for performance evaluation of single effect basin type solar still were conducted by Cooper[59,60]. Based on thermic circuits and Sankey diagrams assuming sine wave heat flow, Frick[61] also developed a mathematical model of solar still. The effect of heat capacity in a solar still was studied by Hirschmann and Roefler[62] considering solar insolation as periodic in nature. Baum et al[63], Sodha et al[64], and Nayak et al[65] have done the periodic and transient analysis of a single effect solar still. Looking to the low efficiency of these single effect stills work on other type of stills are also conducted. Studies on inclined tray and stepped stills are conducted by Howe[20] Akhtamov et al[66], and also in Tunisia[67]. Studies on tilted wick type solar still which is also a single effect solar still but gives higher output are conducted by Frick and Somerfeld [68], Moustafa[69], Tanaka et al[70,71], Sodha et al[72] Cooper et al[73]. A new generation of solar stills called the ^{3}multiple effect solar stills' where the distillate output increases considerably is studied by many workers like Dunkle[74], Selcuk[75], Telkes[76], Hodges et al[77], Eibling et al[78], Tleimat[79], Oltra[80], Bartoli[81], etc. Solar powered distillation units where the steam generated in solar boiler is the main source of energy and electrical energy is used to drive the system has also been studied in combination with multieffect or multistage-flask distillation by Howe and Tleimat[19], Eibling et al[78], Baum[24], Lessley et al[82], Brice[83], Tleimat et al[84,85], Weihe[86], and Tabor[87]. To increase the distillate output, the heat transfer coefficient ranging from static devices such as deformed tubes, horizontal sprayed tubes, vertical foamy upflow[88], to mechanical enhanced devices such as by Tleimat[89], Landa[90], Webb et al[91], etc are tried. A high performance solar film covered still and wiped film rotating-disk evaporator is studied by Tleimat [89], Narov et al[92], Menguy et al[93]. Solar still greenhouse combination is now a common practice in Europe and in many places of North America where the transpired and evaporated water from plants field is used again and again and is therefore suitable for water-deficient countries. Some of the problem related to solar still greenhouse combination are studied by Selcuk[94,95]. The production of distillate of a single effect solar still can be enhanced by increasing the temperature of the feed saline water using either waste

Table 2.1 MAJOR BASIN TYPE SOLAR STILLS OF THE WORLD

Country	Location	Productivity (m^3/day)	Year	m^2	Feed	Cover	Remarks
Australia	Muresk I	0.83	1963	372	Brackish	Glass	Rebuilt
	Muresk II	0.83	1966	372	Brackish	Glass	Operating
	Coober pedy	6.35	1966	3160	Brackish	Glass	Operating
	Caiguna	0.78	1966	372	Brackish	Glass	Operating
	Hamelin Pool	1.21	1966	557	Brackish	Glass	Operating
	Griffith	0.91	1967	413	Brackish	Glass	Operating
Cape Verde islands	Santa Maria	2.12	1965	743	Seawater	Plas.	Abandoned
Chile	Las Salinas	14.76	1872	4460	Brackish	Glass	Abandoned
	Quillagua	0.40	1968	100	Seawater	Glass	Operating
	Quillagua	0.40	1969	103	Seawater	Glass	Operating
Greece	Symi I	7.56	1964	2686	Seawater	Plast.	Rebuilt
	Symi II	-	1968	2600	Seawater	Str.P.	Dismantled
	Aegina I	4.24	1965	1490	Seawater	Plast.	Rebuilt
	Aegina II	-	1968	1486	Seawater	Str.P.	Abandoned
	Salamis	1.10	1965	388	Seawater	Plast.	Abandoned
	Patmos	26.11	1967	8600	Seawater	Glass	Operating
	Kimolos	7.57	1968	2508	Seawater	Glass	Operating
	Nisyros	6.06	1969	2005	Seawater	Glass	Operating
	Fiskardo	-	1971	2200	Seawater	Glass	Operating
	Kionion	-	1971	2400	Seawater	Glass	Operating
	Megisti	-	1973	2528	Seawater	Glass	Operating
India	Bhavnagar	0.83	1965	377	Seawater	Glass	Operating
	Awania	-	1978	-	Brackish	Glass	Operating

Table 2.1 contd...

Mexico	Natividad Island	0.38	1969	95	Seawater	Glass	Operating
	Puerta Chale	1.0	1974	300	-	-	-
	Punta Chucca	1.5	1974	470	-	-	-
Pakistan	Gwadar I	-	1969	306	Seawater	Glass	Operating
	Gwadar II	27.0	1972	9072	Seawater	Glass	Operating
Spain	Las Marinas	2.57	1966	868	Seawater	Glass	Operating
Tunisia	Chakmou	0.53	1967	440	Brackish	Glass	Operating
	Mahdia	4.16	1968	1300	Brackish	Glass	Operating
U.S.A.	Daytona Beach	0.53	1959	228	Seawater	Glass	Rebuilt
	Daytona Beach	0.57	1961	246	Seawater	Glass	Dismantled
	Daytona Beach	0.38	1961	216	Seawater	Plas.	Dismantled
	Daytona Beach	0.61	1963	148	Seawater	Plas.	Dismantled
USSR	Balcharden Turkmena	1.62	1969	600	Brackish	Glass	Operating
West Indies	Petit St.	4.92	1967	1710	Seawater	Plast.	Operating
	Vincent Haiti	0.76	1969	223	Seawater	Glass	Operating
India	Bitra	0.2	1980	-	Brackish	Glass	Operating
	Kulmis	0.3	1980	-	Brackish	Glass	Operating
China	Wuzhi	-	1976	385	Seawater	Glass	Operating
	Zhungjian	-	1979	50	Seawater	Glass	Operating

heat if available or from solar energy collectors. Studies on such indirectly heated solar stills are conducted by Proctor [96,97], Soliman[98], Garg and Mann[31] and Sodha et al[99]. Solar stills can also be used for the combined production of fresh water, chlorine and magnesium from sea water. Studies on such solar stills are reported from India[100] and Kettani[101,102] from Saudi Arabia.

The subject of solar distillation is quite vast and several review articles are recently written discussing the design principles, mathematical modelling, performance characterists, and economics of various solar stills, but the most comprehensive work discussing the uptodate advances in the field of solar stills are presented by Malik et al[103].

2.3 SINGLE EFFECT BASIN TYPE SOLAR STILL

As a result of large interest in solar distillation several types of solar stills are evolved. Out of the several stills like single effect basin stills, multiple effect stills, single or multiple wick stills, inclined tray or stepped stills, the multistage-flash distillation stills, solar film covered stills, and solar concentrator stills, only the basin stills using single effect distillation have been used for the supply of large quantities of water for isolated communities or for small supplies of water such as for battery charging, analytical purposes, etc. The conventional basin type solar still as shown in fig.2.1 consists of an insulated (sometimes uninsulated) shallow basin lined or painted with a waterproof black material holding shallow depth (5 to 20 cm) of saline or brackish water to be distilled and covered with a sloped (single or double sloped) glass/plastic sheet supported by an appropriate frame and sealed tightly to reduce vapour leakage. A condensate channel runs along the lower edge of the glass/plastic pane which collects the distillate and carry the same outside the still. In fig.2.1, a pipe is shown which is used to fill the basin with saline water and another pipe is used to control the level of the saline water and is also used to flush the brine. The still can be fed with saline water either continuously or intermittently but the supply is generally kept as twice the amount of fresh water produced by the still but it all depends on the initial salinity of the saline water. The ratio of saline water supply and amount of water to be flushed depends on the salinity of basin water and is found to be proportional to the amount of fresh water produced. The still is erected at an exposed area with long axis of the still facing East-West direction.

In operation solar radiation after transmission through the transparent pane (cover) is absorbed in the water and basin and therefore water temperature becomes high compared to the cover. The water now loses heat by evaporation, convection, and radiation to the cover and by conduction through the base and edges of the still. The evaporated water from the basin increases the moisture content in the enclosure and finally condenses on the underside of the cover(glass/plastic), slips down into the condensate channels and through them out of the still for use. The main important things in this still are that only durable materials should be used in its construction, the basin should be waterproof, and the whole enclosure should be airtight.

2.3.1 Types of single effect basin still

There are several small-small variations in the geometric configuration of single basin still. some of the geometric[104,105] configurations of the solar stills are shown in fig. 2.3. The solar still shown in fig.2.3(a) is a double sloped symmetrical still with continuous basin of 2.8 m wide and 31 m long which is made water tight by using heavy asphalt sheets. Glazings are supported on precast concrete pillars placed on lining. Distillate is collected in stainless steel channel embeded in the concerete pillar on the lower side of the glass pane. The average water depth in the basin was about 10.0 cm. Asphaltic mastic caulking material was used as sealing material for all glass joints. This still was used at Las Marinas, Spain and is a modified version of deep basin still tried at Daytona Beach, Florida Laboratory.

The solar still shown in fig.2.3(b) is a double sloped symmetrical design with divided (separate) basins. This design popularly known as CSIRO Australia Mark VI design consists of a basin insulated with 25 mm polystyrene foam and internally lined with 0.76 mm butyl rubber. Concerete side members contain grooves in which lower edges of glass cover rests and distillate collected. At the top, the two glasses are sealed using silicone sealant and thus eliminating the need of a ridge support which is possible only in small width solar stills. These stills are designed for the continuous supply of saline water and therefore a slope in the basin is required. Shallow depth of water(2 to 3 cm) in the basin is maintained by placing dams across the still after every 1 to 1.5 m. The still shown in fig. 2.3(c) is a single sloped glass solar still used by Brace Research Institute of Mc-Gill University, Canada at La Gonave, Haiti. The still was installed on a gentle sloped hill with each bay arranged like steps of a stair case. The concrete pillar supports the glass and contains two cast troughs, one for collecting distillate and second the rain water. The basin liner used is butyl rubber which is glued and has given problems. The design of solar still shown in fig.2.3(d) is used in Greek Islands. In this design the glass supports and distillate troughs are made of aluminium

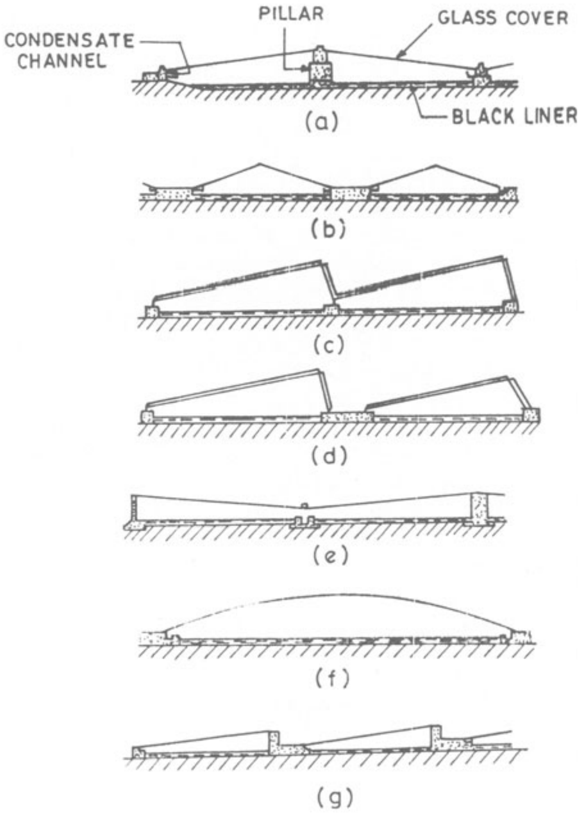

FIG.2.3. CROSS SECTION OF SOME TYPICAL BASIN TYPE SOLAR STILL (a) SOLAR STILL WITH DOUBLE SLOPED SYMMETRICAL WITH CONTINOUS BASIN, (b) SOLAR STILL WITH DOUBLE SLOPED SYMMETRICAL WITH BAISN DIVIDED INTO TWO BAYS, (c) SOLAR STILL WITH SINGLE SLOPE AND CONTINOUS BASIN, (d) SOLAR STILL WITH UNSYMETRICAL DOUBLE SLOPED AND DIVIDED BASIN, (e) V -TROUGH TYPE SOLAR STILL, (f) SOLAR STILL WITH PLASTIC INFLATED COVER, (g) SOLAR STILL WITH STRECHED PLASTIC FILM WITH DIVIDED BASIN.

extrusions. Butyl rubber is used as basin liner and side walls and curbs are made of concrete. The 1.5 m wide bays are arranged in pairs so that passage is made between each pair.

The V-trough or sawtooth type solar still shown in fig-2.3(e) is developed at the university of California for use on the south Pacific Islands and is yet to be constructed. Due to reduced length of distillate trough in this design, it will minimize the re-evaporation of distillate from trough. The plastic inflated solar still as shown in fig.2.3(f) uses tedlar plastic film 0.1 mm thick and chemically and mechanically treated to make it wettable, is used by Mc-Gill University at Petit St. Vincert Island in the Caribbean. The edges of butyl rubber linning and the edges of tedlar cover film are clamped against the concrete curbs making an airtight enclosure. The cover is inflated by maintaining an air pressure of about 6 mm of water in the enclosure. The plain streched plastic film type solar still shown in fig. 2.3(g) is the same as in fig. 2.3.(f) but here the plastic cover is not inflated but streched. concrete curbs with casted distillate troughs and butyl rubber as basin liner is used in this design.

2.3.2 Basics of solar still

We would like that the solar still should provide as much of distillate as possible per unit of area per day. The distillate output from a solar still depends on many parameters[31] like climatic parameters such as solar insolation, ambient air temperature, wind speed, atmospheric humidity, sky conditions, etc; and design parameters such as thermophysical properties of the material used in its construction, orientation of still, tilt angle of cover, spacing between cover and water surface, insulation of the base, vapour tightness, absorption-transmittance properties of still etc; and operating parameters such as water depth in the basin, initial water temperature, water salinity etc. The ultimate aim is to increase the distillate output and the important parameter effecting the output is solar insolation on horizontal surface(H_T) measured in w/m^2. If Q_e is amount of heat (w/m^2) utilized by solar still for evaporating M Kg of water per m^2 per day, then the efficiency of solar still is given as:

$$\eta = \frac{Q_e}{H_T} \qquad (2.1)$$

The daily distillate output Me (Kg/m^2 day) of still is given as:

$$Me = \frac{Q_e}{L} \tag{2.2}$$

where L is the latent heat of evaporation of water (2.43×10^6 J/Kg). The efficiency of the still should be as close to unity as possible which can be done by reducing the conduction, convection, and radiation heat losses.

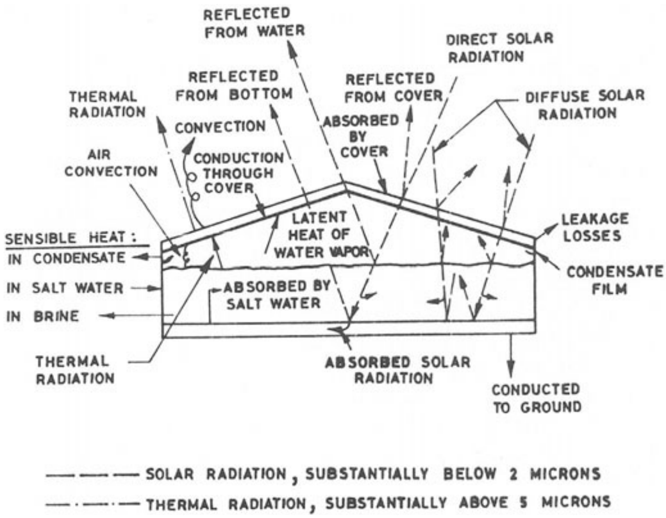

FIG.2.4. ENERGY TRANSFER IN A SINGLE EFFECT BASIN SOLAR STILL.

The energy transfer mechanism in the single effect basin solar still is shown[106] in fig.2.4. A part of the solar radiation incident on the glass cover gets reflected, part gets absorbed within its thickness, and the rest is transmitted to the still enclosure. A part of the transmitted energy is reflected from the water surface, from the side walls of the still, and from the bottom of the basin liner while the rest is absorbed within the water. A part of the heat from the heated water is lost in evaporating the water, by convection to the enclosed air, by radiation to the glass cover, and by conduction through the bottom and sides of the solar still. Some heat is also lost by vapour leakages through the still. The glass cover receives heat as latent heat from the condensing vapours, from heated air by convection, by radiation exchange from heated water, and by the direct absorption of solar radiation. This heat from glass cover is finally lost to the atmosphere by convection and radiation processes. Energy exchange also takes place in the brine in the still, distillate leaving the still and saline water entering the still. Thus the incoming energy is the direct, diffuse and atmosphere radiations while the outgoing energy is convection, radiation and reflection to the atmosphere; conduction through base and edges; brine leakage and vapour leakage from the enclosure; and sensible heat of distillate.

Longterm systematic experimental data on double sloped solar still was collected at Bhavnagar, India[57] to find out energy balance around solar still having water depth of 2 cm and cover slope 20 deg. from horizontal and the typical results are given in table 2.2.

Table 2.2 Cumulative heat balance on a solar still

Energy Transfer	Percent of solar radiation
Heat energy for evaporation	38.4
Heat loss by convection in still	3.7
Heat loss by radiation in still	12.2
Heat loss by reflection from glass cover	10.0
Heat absorbed by cover	10.0
Heat loss by conduction through bottom	16.0
Unaccounted heat loss such as vapour leakage and side losses	9.7

From the above it is seen that the heat losses from the ground are quite high, this may be due to the fact that these stills were small uninsulated ones. If large stills on ground are made then possibly these ground losses can be reduced considerably. The heat loss by radiation from hot saline water in still to the glass cover is also very important and can be reduced by using a good quality glass cover. In small stills the vapour losses may be small, but in large stills it has been observed that vapour leakage constitute the largest heat loss from the still. Hence the above table gives only an idea of energy balance on a small solar still.

Apart from the design of solar still, the materials used in its construction should be carefully selected. The choice for transparent cover can be either glass pane or plastic film. Glass cover is preferred in solar stills because it has high transmittance for solar radiation, opaque to thermal radiation, resistance to abrasion and high stability over extended period of time, high wettability for water, and universal availability. Problems with the glass are its vulnerability to mechanical damage, high weight, and require special skill to fix over the still. Plastics used in solar stills are transparent to solar as well as to thermal radiation, degrades to different amounts due to ultravoilet radiations, requires special treatment to make it wettable with water, less vulnerable to mechanical damage, light-weight, and easy to apply over the solar still. Another important material in a solar still is the liner. Generally asphalt matt, black butyl rubber, or black polyethylene liners are employed. The material selected should absorb more solar radiation, should be durable, should be water tight, easily cleanable, and should be able to withstand temperatures around 100°C. Asphalt matt is a good choice as basin liner for deep basin stills but is too stiff for use in the shallow basin stills. Therefore in shallow basin stills black butyl rubber and black polythelene film are preferred. Butyl rubber has an added advantage that it can withstand high temperatures which may happen in case the still run dry.

One of the most important material in a solar still is the sealant material. Some of the sealant materials used are putty, tars, tapes, silicone sealant, etc. The sealent selected should remain resilient at very low and very high temperatures. It is observed that various kind of puttys, tars, and tapes used, deterioriate with time and become brittle and therefore cracks through which after sometimes the vapour starts leaking. The sealant used and found most effective is silicone rubber sealant which remains resilient (elastic) for very longtime. Some of the structural materials used in a solar still are wood, galvenized iron, aluminium, asbestos cement, masonary bricks, and concrete. It has been observed that the use of galvanized iron as a tray or distillate channel is not a good choice since it corrodes badlly in contact with saline water or ground. Aluminium can be used as a distillate channel but it also corrodes at high temperatures. Wood can be used in small stills but with time it also gets damaged and its use in large stills is completely ruled out. Asbestos cement is a good material since it can be given any shape and is not effected with the salinity of water. Masonary bricks or concrete are probably the best materials as structural supports or basin since they are most durable and long lasting. Its main problem is weight particularly when it is to be transported to remote areas.

Insulation of still in the base increases the distillate output. Any insulating material which has low thermal conductivity, withstand high temperature (when the still gets dry), and sufficient strength can be used as base insulation. Insulation materials like fibreglass, rock wool, polyurethane, polystyrene, straw etc. with some care can be used. Insulation should remain dry and even a pin hole leak in the basin liner will spoil the properties of the insulation. Pipes for the supply of saline water and transport of distillate are used. The pipes recommended are asbestos cement pipe, PVC pipe, or ABS pipe.

2.3.3 Performance prediction of basin-type still

The performance of solar still can be predicted by writing energy balance equations on various components of the still. A steady state model of solar still was first described by Dunkle[74] which was modified by Morse and Read[28] and later by Cooper[59,60] and Howe[104] and the same will be described here. Referring to fig. 2.5, the instantaneous heat balance equation on basin water can be written as

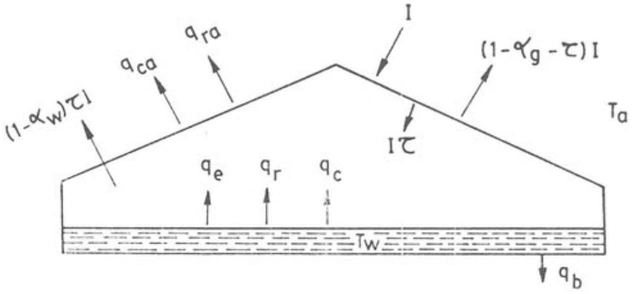

FIG.2.5. MAJOR HEAT FLUXES FOR A SOLAR STILL.

$$I\alpha_w\tau = q_e + q_r + q_c + q_b + C_w\frac{dT_w}{dt} \qquad (2.3)$$

where I is solar radiation on horizontal surface; α_w is absorptivity of water and basin liner; τ is transmittance of glass cover; q_e, q_r and q_c are the evaporative, radiative and convective heat loss from water to the transparent cover respectively; q_b is the conductive heat loss from water basin; C_w is heat capacity of water and basin; T_w is water temperature; and t is the time. Similarly the instantaneous heat balance equation on glass cover will be:

$$q_{ga} + C_g \frac{dT_g}{dt} = I\alpha_g + q_e + q_r + q_c \qquad (2.4)$$

where $q_{ga}(= q_{ca} + q_{ra})$ is the heat loss from cover to atmosphere, C_g is heat capacity of glass cover, T_g is glass temperature, α_g is the absorptivity of glass cover, q_{ca} is the heat loss by convection from cover to atmosphere, and q_{ra} is heat loss by radiation from cover to atmosphere.

Now the heat balance equation on the still is:

$$I\,\alpha_w\tau + I\alpha_g = q_{ca} + q_{ra} + q_b + C_g \frac{dT_g}{dt} + C_w \frac{dT_w}{dt} \qquad (2.5)$$

The parameters like $(1-\alpha_g-\tau)I$ and $(1-\alpha_w)\tau I$ are not included in equations since these do not add into evaporation or condensation of water.

The heat transfer by radiation q_r from water surface to glass cover can be calculated from the equation:

$$q_r = F\sigma\,(T_w^4 - T_g^4) \qquad (2.6)$$

Where F is the shape factor which depends on the geometry and the emissivities of water and glass cover, and σ is the stefan Boltzmann constant. For the basin type solar still and for low tilt angles of glass cover, the basin and glass cover can be assumed as two parallel infinite plates. Then the shape factor can be assumed equal to the emissivity of the water surface which is 0.9. Hence equation(2.6) will be

$$q_r = 0.9\sigma\,(T_w^4 - T_g^4) \qquad (2.7)$$

The convective heat loss from hot water surface in the still to the glass cover can be calculated from the following expression:

$$q_c = h_c\,(T_w - T_g) \qquad (2.8)$$

where h_c is the convective heat transfer coefficient the value of which depends on many parameters like temperature of water and glass; density, conductivity, specific heat, viscosity, expension coefficient of fluid, and spacing between water surface and glass cover. Dunkle[74] has suggested a empirical relation for the convective heat transfer coefficient, which when converted in SI units is given as

$$h_c = 0.884 \left[T_w - T_g + \frac{(P_w - P_g)}{268.9 \times 10^3 - P_w} T_w \right]^{1/3} \qquad (2.9)$$

Where P_w and P_g are the saturation partial pressure of water vapor (N/m^2) at water temperature and glass temperature respectively.

The evaporative heat loss q_e from water to the glass cover can be calculated by knowing the mass transfer coefficient and which can be calculated from convective heat transfer coefficient. The expression for q_e as given by Dunkle[74] and converted into SI units is given as

$$q_e = 16.28\, h_c\, (P_w - P_g) \qquad (2.10)$$

Heat loss through the ground and periphery q_b is difficult to compute since the soil temperature is unknown. Moreover, the heat conducted in the soil during daytime comes back in the basin during night time. However, it can be computed from the following simple relation:

$$q_b = U_b\, (T_w - T_a) \qquad (2.11)$$

where U_b is the overall heat transfer coefficient.

The convective heat loss q_{ca} from glass cover to ambient air can be calculated from the following expression:

$$q_{ca} = h_{ca}\, (T_g - T_a) \qquad (2.12)$$

Where h_{ca} is the forced convection heat transfer coefficient and is given as

$$h_{ca} = 2.8 + 3.8\, V \qquad (2.13)$$

Where V is the wind speed in m/s

The radiative heat loss q_{ra} from glass to sky can be determined provided the radiant sky temperature T_s is known which very much depends on atmospheric conditions such as the presence of clouds etc. Generally for practical purposes when the still is operating, the average sky temperature T_s can be assumed as about 12 K below ambient temperature i.e. $T_s = T_a - 12$. Thus radiative heat loss q_{ra} from glass cover to the atmosphere is given as:

$$q_{ra} = \varepsilon_g \sigma (T_g^4 - T_s^4) \qquad (2.14)$$

where ε_g is the emmissivity of glass cover.

The exact solution of the above simulataneous equations is not possible and hence iterative techniques are employed to find the solutions. The digital simulation techniques

[59,60] for solving the above equations for a particular set of conditions can also be adopted. Even charts are given by Morse and Read[28], and Howe[107] which can be used for performance prediction of solar stills for a particular set of conditions.

As is seen from equations (2.7),(2.8), and (2.10) the amount of heat flow by radiation, convection, and evaporation depends on the temperature difference between water and transparent cover, (T_W-T_g). The maagnitude of heat flow by radiation, convection, and evaporation expressed as percent of total flow for various values of (T_W-T_g) and water temperature can be seen[60] from fig.2.6. From this figure it is concluded that for a particular set of (T_W-T_g) if the water temperature T_W increases the evaporation heat flow increases which means that the efficiency increases. The chart as given by Morse and read[28] for the performance prediction of solar sill for a given set of conditions is shown in fig.2.7. For finding out the hourly distillate rate using chart shown in fig.2.7 use of equations 2.4 and 2.5 are made. Hourly rise in basin water temperature T_W from sunrise to sunset is determined using equation (2.5) after knowing various quantities in equation (2.4) for an assumed value of T_g from chart fig.2.7. Interative procedure is adopted till the equation (2.4) is satisfied.

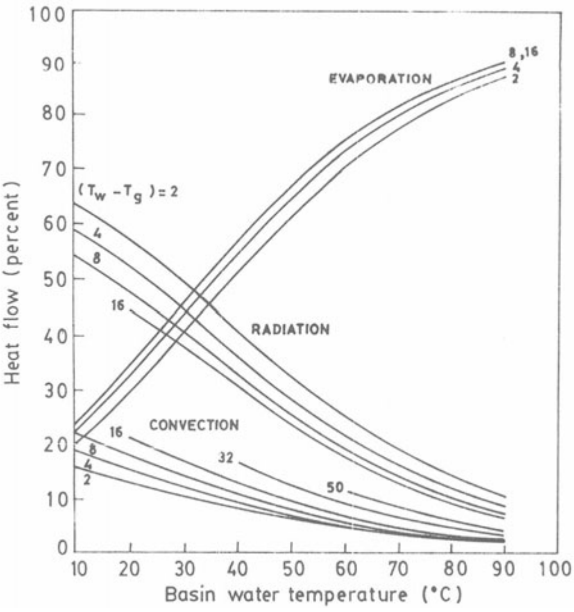

FIG.2.6. EFFECT OF BASIN WATER TEMPERATURE ON THE EVAPORATIVE CONVECTIVE RADIATIVE HEAT FLOW IN A STILL

The values of overall heat loss coefficient U_b through the bottom has been assumed by Morse and Read[28] as 5.68 w/m^2 which appears to be quite high. Later Lof[108,109]suggested a value for bottom loss and edge loss coefficient as 0.49 w/m^2. Cooper[110] conducted careful experiments and determined a value of U_b varying from 2.8 w/m^2 to 1.7 w/m^2. The value 2.8 w/m^2 is for narrow and seperated basin type solar stills and 1.7 w/m^2 is for large size basin solar stills. The mathematical model presented above can be used to study the effect of solar radiation, ambient temperature, wind speed, basin water depth, transparent cover tilt, orientation of still, insulation properties, transparent cover properties etc. on the distillate output. Some of the conclusions as drawn by Cooper[111] are as follows:

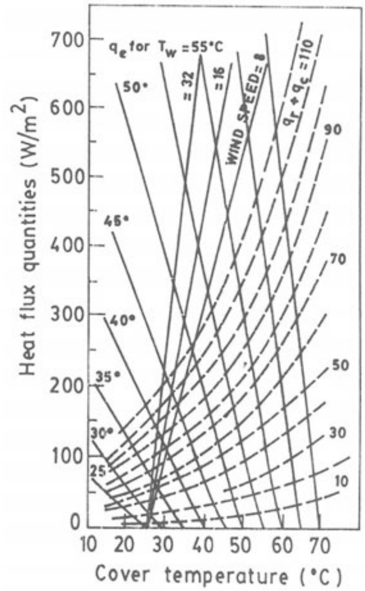

FIG.2.7 CHART FOR ESTIMATING PRODUCTION RATE OF A SOLAR STILL

(1) The solar still output(distillate) is a strong function of solar radiation on a horizontal surface. The distillate output increases linearly with the solar insolation for a given ambient temperature. If the ambient temperature increases

or the wind velocity decreases, the heat loss from solar still decreases resulting in higher distillation rate. It is observed for each 10 C rise in ambient temperature the output increases by 10 percent.

(2) The depth of water in the basin also effects the performance considerably. At lower basin depths, the thermal capacity will be lower and hence the increase in water temperature will be large resulting in higher output. However, it all depennds on the insulation in bottom of the still. If there is no insulation, increase in water temperature will also increase the bottom heat loss. It has been observed that if the water depth increases from 1.2 cm to 30 cm the output of still decreases by 30 percent.

(3) Number of transparent covers in a solar still do not increase the output since it increases the temperature of the inner cover resulting in lower condensation of water vapour.

(4) Lower cover slope increases the output but from practical considerations a minimum cover slope of 10 deg. is suggested.

(5) The maximum possible efficiency of a single basin solar still is about 60 percent.

(6) For higher receipt of solar radiation and therefore the higher yield the long axis of the solar still should be placed in the East-West direction[31] if the still is installed at a high latitude station. At low latitude stations the orientation has no effect on solar radiation receipt.

2.3.4 Experiments on Solar stills.

Experimental studies on small, medium capacity, and large capacity solar stills are conducted in many countries. But longterm and reliable experimental data on solar stills are available only from few countries like USA[112], Australia[58], and India[57,31]. The experimental work as conducted by Garg et al[31,113,115] will be discussed here in brief.

The effect of climatic parameters on the still output was determined by using two small, single sloped solar stills, each having a basin area equal to 0.58 m^2. These two solar stills have identical design features except one with sawdust insulation(2.5 cm) in the bottom and second without any insulation. Hourly values of distilled water output, solar radiation on horizontal surface, ambient air temperature, mean wind speed were determined for one complete year on these two solar stills at Jodhpur(26.3^{o}N), India. From hourly values, daily distilled water output (1/m^2 day), total solar radiation(MJ/m^2), daytime ambient

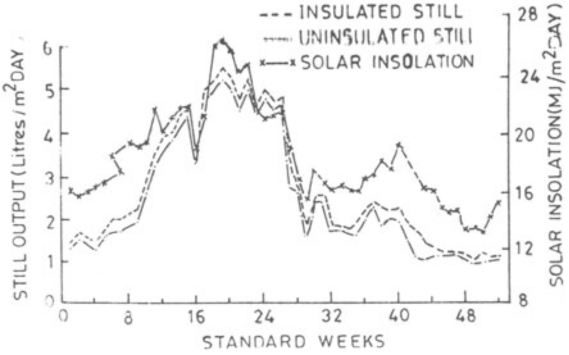

FIG.2.8. VARIATION OF SOLAR STILL OUTPUT AND SOLAR INSOLATION FOR DIFFERENT WEEKS OF THE YEAR.

temperature(^{o}C), and daytime windspeed (km/hr) were determined and means for 52 standard weeks for a year were computed. Fig.2.8 shows the variation of still output for insulated and uninsulated solar stills. From this figure it is seen that insulated solar still gives higher output (8 percent) compared to uninsulated solar still. The maximum output observed was 5.271 1/m^2 day in summer in 19th week and minimum output was 0.89 1/m^2 day in winter in 49th week. A linear relation between solar radiation on borizontal surface and still output was observed as shown in fig.2.9. The still output increased from 1.76 1/m^2 day at the radiation intensity of 16.74 MJ/m^2 day to 5.11 1/m^2 day at the radiation intensity of 27.08 MJ/m^2 day. An increase in still output was also observed with the increase in ambient temperature. The increase in output is about 0.87 1/m^2 day for each 5^{o}C rise in ambient temperature.

The effect of some of the design variables was studied on four double sloped permanent type of solar stills made of cement concrete each with dimensions of 245 x 125 x 15 cm i.e with a basin area of 3.0 m^2 . Still No.1 does not contain any bottom insulation while still nos.2,3 and 4 each contained 2.5 cm thick saw dust insulation. The glass angles for stills 1,2,3 and 4 are 20^{o},20^{o},30^{o} and 10^{o} from horizontal respectively. Thus the difference in output between stills 1 and 2 will show the effect of base insulation while the difference in output between stills 2,

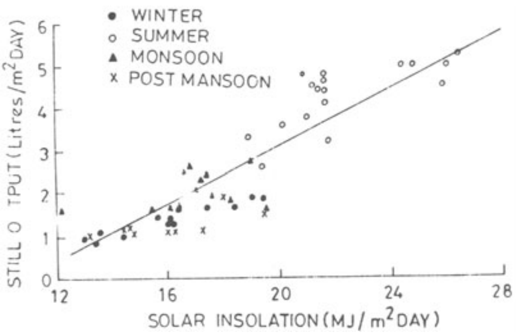

FIG.2.9. RELATIONSHIP BETWEEN STILL OUTPUT AND DAILY SOLAR INSOLATION

3 and 4 will show the effect of glass slope. Each of the four stills was filled daily with about 5 cm of water daily in the morning and hourly values of distillate were collected and measured. From the hourly means of distillate, the daily distillate and the mean monthly distillate (ml/m^2 day) were determined for the twelve months of 1974 for both the channels, i.e. glass facing south and facing north. The results are summarised in table 2.3.

It can be seen from this table that still 2, with base insulation, gives a higher output. The average increase is 7 percent. By comparing the distillate output of stills 2-4, it can be seen that the still with the lowest glass angle gives the highest output. This may be because of low air capacity and lower diffusion space. Still 4, with glass angle of 10 deg. and base insulation, gives the highest output, i.e. 2447 ml/m^2day. By comparing the distillate output of stills land 3, it can also be observed that still 1, with 20 deg glass inclination and without base insulation, performs better than still 3, with 30 deg glass inclination and with base insulation. After comparing the distillate output of each of the two channels for each of the solar stills, it was observed that all channels collect almost equal amounts. Therefore, the usual assumption made for double-sloped solar stills, that one of the glass side

Table 2.3 Mean monthly distillate output(ml/m^2day) for four experimental cement concrete type Solar stills for the year 1974

Month	STILL I			STILL II			STILL III			STILL IV		
	SOUTH	NORTH	TOTAL	SOUTH	NORTH	TOTAL	SOUTH	NORTH	TOTAL	SOUTH	NORTH	TOTAL
JANUARY	423	167	590	407	341	748	242	192	434	288	250	538
FEBRUARY	402	278	680	449	386	835	290	322	612	406	226	632
MARCH	751	685	1436	693	678	1371	639	664	1303	791	766	1557
APRIL	1242	1178	2420	1255	1241	2496	1136	1124	2260	1354	1393	2747
MAY	1592	1493	3085	1687	1675	3362	1485	1499	2484	1171	1909	3680
JUNE	1533	1428	2961	1598	1537	3155	1415	1404	2819	1653	1796	3449
JULY	1399	1288	2687	1484	1346	2830	1277	1251	2528	1421	1646	3067
AUGUST	1487	1412	2899	1594	1489	3083	1382	1365	2747	1507	1729	3236
SEPTEMBER	1472	1379	2851	1581	1457	3038	1343	1313	2656	1502	1727	3229
OCTOBER	1252	1185	2437	1399	1312	2711	1179	1155	2334	1375	1529	2904
NOVEMBER	1182	1096	2278	1253	1154	2407	1046	1013	2059	1188	1349	2537
DECEMBER	831	749	1580	914	794	1708	705	625	1330	783	1007	1790
AVERAGE	1131	1026	2157	1193	1117	2310	1011	994	2005	1170	1277	2447

remains at a lower temperature and thus collects more distillate, may not be correct.

To study the effect of some of the operational parameters, five small single sloped solar stills each with a basin area of 0.58 m^2 were made. All the five solar stills are of identical design except that still 5 had 5 cm thick sawdust insulation in its base.

In order to study the effect of water depth, each of the five stills was filled with water of varying depths, viz. 2.0,4.0,6.0,8.0 cm for the uninsulated stills and 4.0 cm for the insulated still. All the stills were tested for a number of days, and the results are shown in Table 2.4. Variation in productivity for the same water depth on different days is due to different solar intensities, ambient air temperatures and wind speeds. But for each day the productivity increases with a decrease in water depth. The insulated still shows even greater productivity than the uninsulated solar still with a low water depth. Actually, in the case of lower water depth, the thermal inertia of the system becomes low and, hence, the minimum temperature difference between water and glass required for condensation of vapours on the glass is reached more readily.

Table 2.4 Effect of water depth (cm) on the distilled water output (1/m^2 day) of single sloped solar still.

Test No.	UNINSULATED STILL				INSULATED STILL
	2.0 cm	4.0 cm	6.0 cm	8.0 cm	4.0 cm
1.	2.93	2.95	2.82	2.67	-
2.	4.11	4.06	3.87	3.43	-
3.	3.77	3.72	3.65	3.31	-
4.	3.87	3.50	3.59	3.54	-
5.	3.55	3.21	3.28	2.98	-
6.	3.59	3.30	3.18	3.08	-
7.	3.47	3.24	3.16	3.10	4.21
8.	3.11	3.00	2.84	2.63	4.09
9.	3.54	3.29	3.22	3.19	4.67
10.	2.98	2.70	2.76	2.73	3.86
11.	3.02	2.72	2.61	2.27	3.61
12.	2.20	1.98	2.00	1.99	3.28
13.	3.03	2.78	2.59	2.55	3.81
Average	3.32	3.11	3.04	2.86	3.93

It appears that the effect of colouring the water i.e. the effect of dye on still productivity, has not been tried. Cooper[116] reports that about 2-6 percent of solar radiation is directly reflected back by the clear water surface in the basin, 30 percent of the radiation is absorbed by the water, and the rest is transmitted through the water which is further reflected and absorbed by the basin liner. From this it is clear that the productivity of the still can be increased by increasing the absorptivity of water for solar radiation. For this purpose, blue and red dyes were tried by Garg[31] for a number of days and the results obtained are shown in Table 2.5. It is interesting to note that by colouring the water i.e by increasing the absorptivity of water, productivity can be increased.

Table 2.5 Effect of dye on the distilled water output (1/m^2 day) for single sloped solar still.

Test No.	No colour in water	Blue colour in water	Red colour in water
1.	1.97	2.33	2.53
2.	1.79	2.14	2.33
3.	2.05	2.27	2.53
4.	2.29	2.52	2.75
Mean	2.02	2.31	2.53

The effect of dye has recently been studied by Rajvansi and Hsieh[117] also by considering the base black and water column to be thermally stratified system.

The productivity of the solar still increases as the temperature difference between the water and glass increases. The importance of the use of waste heat in a solar still has been described by Proctor[96], and it has been shown that the productivity of the still can be considerably increased by using preheated water(as from a solar water heater) or rejected heat(as from various industrial processes or from internal combustion engines in remote areas). Keeping this in mind, a small study was conducted[31] by using the left-over heated water in the solar water collected in the early morning. For this purpose, two identical solar stills were selected. One was filled with water at a temperature of 30 °C and the other with water at 45°C. This experiment was conducted for a number of days and the amount of distilled water obtained daily for both cases is shown in Table 2.6. From this table it is seen that the productivity of the solar still can be increased by using preheated water. The productivity can be further improved by using a suitable heat exchanger fixed in the basin of the solar still, but this will add further cost.

Some of the additional conclusions drawn from experimental studies carried out in Australia[58,111] are as follows:

The saline water in the still can be supplied either continuously or in batches. In Australia continuous supply of saline water in the solar still is preferred at a rate of about 1.70 l/m^{2}hr which is twice the maximum distillate rate. This helps in reducing the salt deposition from the salt solution. From thermal efficiency point of view batch filling i.e. filling of saline water when the basin water is coolest(early morning) is the best but it involves greater labour costs and special plumbing arrangements.

Table 2.6 Effect of preheated water on the distilled water output(l/m^2 day) of single sloped solar still.

Test No.	Water temperature in the still in the morning at 8.30 A.M.	
	45°C	30°C
1.	3.84	3.68
2.	3.32	3.15
3.	3.18	2.92
4.	3.29	3.07
Mean	3.41	3.20

Algae growth within the solar still also effects the performance to a little extent but its growth must be checked since its growth is unsightly and may finally block the basin and contaminate the distillation troughs. The algae growth can be checked by adding copper sulphate and chlorine compounds in the saline water in the still. The main problem in a solar still is the salt deposition of calcium carbonate and calcium sulphate on the basin liner which are white and insoluble and reflect solar radiation from basin water and basin liner and thereby lowering the still output. It is difficult to stop the salt deposition. The physical methods suggested to prevent the salt deposition are frequent flushing of the stills with complete drainage and refilling or continuous agitation of the still water by circulating it with a small pump. Once the salt gets deposited then the only way is completely draining the still and then scrubbing the sides and basin liner and then refilling the still. Another serious observation made in Australia is the crystalline salt growth which takes place on the sides of the basin and into the distillate trough effecting the purity of distilled water. Some success in preventing the crystalline salt growth is achieved in Australia by pre-treating the feed water with a complex phosphate compound which reduces the rate of nucleation of salt crystals.

2.4 TILTED TRAY SOLAR STILL

Some of the limitations of a single effect horizontal basin solar still are:(1) the water surface is horozontal and hence it receives less radiation in winter particularly at those places away from the equator,(2) very shallow water depths are not possible, and (3) large space between the basin water surface and the condensing surface. In a tilted tray type solar still, which will be discussed here, both the water tray and glass cover are at an optimum tilt angle receiving more radiation, less water depth increases water temperature resulting higher output and both tray and glass cover are parallel and closer and thus reduces reflection losses and less thermal intertia.

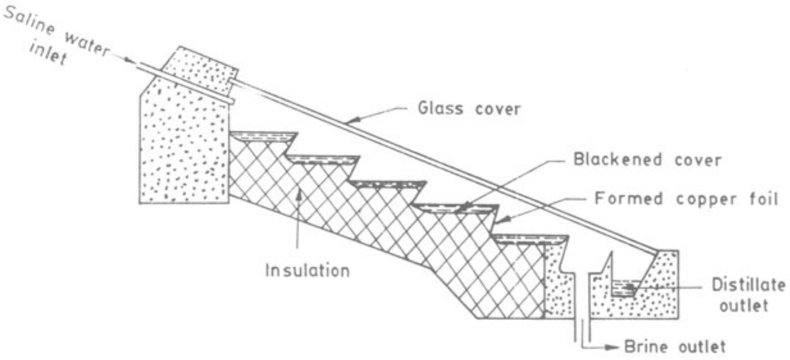

FIG.2.10. CROSS SECTION OF TILTED TRAY SOLAR STILL

The tilted tray solar still as shown in fig.2.10 is studied in great detail by Howe[20] at the university of California, USA. The still is sloped at an angle so that direct radiation is received at near normal incidence which is not possible in a horizontal still. The still consists of a series of steps with narrow widths and shallow depths of water(1.27 cm) with insulation on the rear side and glass cover on the exposed side parallel to the tilted tray. The saline water is supplied at the top step which flows down the steps and finally drained at the bottom. The water distillate is collected in a trough attached to the glass at its lower end. This tilted tray solar still has given very good results. The distillate output of the inclined tray solar still is compared[118] with the deep basin(30 cm water depth) solar still in fig. 2.11. From this figure, it is seen that during sunshine hours, the output of tilted tray solar still is considerably higher compared to the deep basin solar still. The reason is that during daytime, the tilted solar still operates at an average water temperature of about 60°C while the water temperature in the deep basin solar still is only 40°C. But during night time reversal takes place. The water in the deep basin solar still remains warm during night time and therefore it produces distilled water while the water in the tilted tray solar still gets cooled in the evenings due to low capacity. Achilov et al[119] also conducted experiments on portable inclined tray(step) solar still with a total evaporation area of 1.6 m^2 using foamed plastic and polyethylene. The idea of conducting detailed calculation and experimentation was to determine optimum distance between evaporation and condensing surface, number of steps and optimum value of step height. Maximum output was recorded in a still when the distance between evaporating and condensing surface is

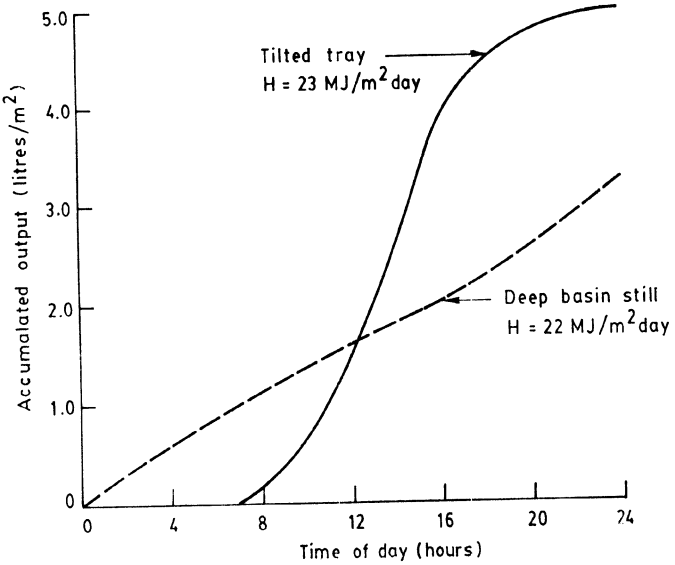

FIG.2.11. COMAPARISON OF PRODUCTIVITY OF TILTED TRAY STILL WITH DEEP BASIN

9-10 cm, number of steps is 10-12 steps per meter width with a maximum step height of 4 cm. This optimized solar still has given an output of 5-6 litres/m^2 day in summer and 1.5 to 2.3 litres/m^2 day in winter at the Bukhara State Education Institute, Bukhara, USSR.

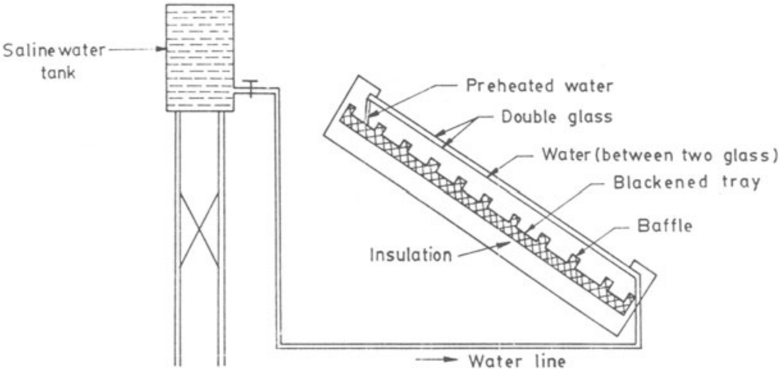

FIG.2.12 REGENERATION INCLINED STEP SOLAR STILL

In the solar stills discussed upto now, the latent heat of condensation given to the transparent cover by the condensing water is lost by the transparent cover to the atmosphere. A part of this latent heat can be utilized by allowing the cold water to flow over the condensing surface and use this heated water in the still. This type of rogenerative solar still was studied by Akhtamov et al[66] who gave a name 'regenerative inclined step solar still(RSS)' to this type of still. The solar still as shown in fig. 2.12 consists of a blackened tray with baffles placed in a box with insulation on the rear side and double glass cover at the top. Saline water from an overhead tank flows between two glass covers, gets heated during its passage along the length of glass and from the other end of the glass enters at the top of the blackened trays, flows through baffles plates, part gets evaporated during its passage(top to bottom) and at the bottom leaves the box. The condensade from the underside of the inner glass is collected and goes out of the still. The angle of the still is kept at 30 deg. from horizontal to collect more solar radiation. This still was tested for few months at Bukhara State Pedalogical Institute, Bukhara, USSR. This still has given about 1.5 times more distilled water compared to single slope inclined stepped solar still.

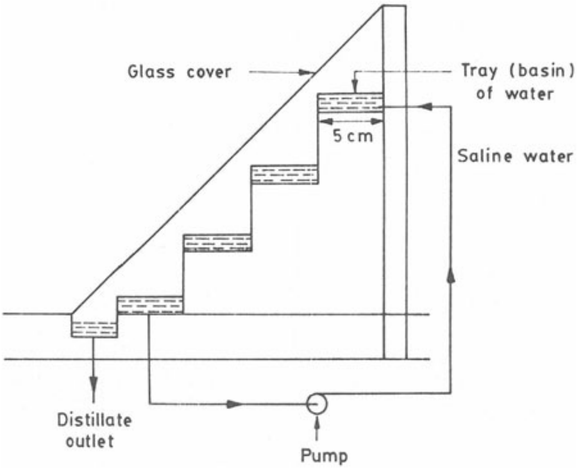

FIG.2.13 MULTIBASIN STEPPED SOLAR STILL

Another type of solar still in which small basins are put in steps like a stair case and named as multibasin system is designed and tested by Moustafa et al[69]. One of the still is shown in fig.2.13. This still consists of saline water trays in an airtight box with glass cover, charging pump, and distillate collecting tray. The projected basin area of the still is 0.836 m^2 and the glass cover is inclined at an angle of 45 deg. The depth of water in the tray was kept as 5.0 cm. In this still higher output was not recorded due to high heat losses.

2.5 WICK TYPE SOLAR STILL

The inclined wicktype solar still is of academic interest only since no commercial or large plant has been installed. The only advantage of the inclined wick type solar still is that due to its very low thermal capacity and exactly parallel and very near to transparent cover absorb more solar radiation and therefore produced high distilled water. The main problems are in the chocking of pores of wick with salt in due course of time, deterioration of the wick cloth, decolouring of wick cloth, and maintaining uniform flow of water. Telkes[76] in 1956 suggested the use of black porous fabric dipped in water placed over an insulation in an airtight box with glass cover at the top as an efficient solar still. The cross-section of such a still is shown in fig.2.14. Saline water is supplied from the top side of the still to the entire width of the wick with the help of a distributor at a very slow flow rate such that the entire area of the black cloth wick remains wet all the time. A water proof liner is placed between the insulation and the wick. Solar energy is absorbed by the water in the wick and gets evaporated and condensed on the underside of the glass and finally collected in the condensate channel fixed on the lower side of the glass. Twenty such solar stills each of 1 m wide and 2.32 m long with a total wick area of 46.4 m^2 were installed at Daytona Beach, Florida, USA. In 12 units, glass cover was used. In 4 units weatherable mylar film was used. In 4 units Tedlar film was used. Initially soacked wick of black terrycloth was used which was later replaced by sailcloth and glass fibers pressed into black plastic. The stills were tilted 30 deg. towards south and have given an output of 4.48 litre/m^2 day at 22.72 MJ/m^2 day.

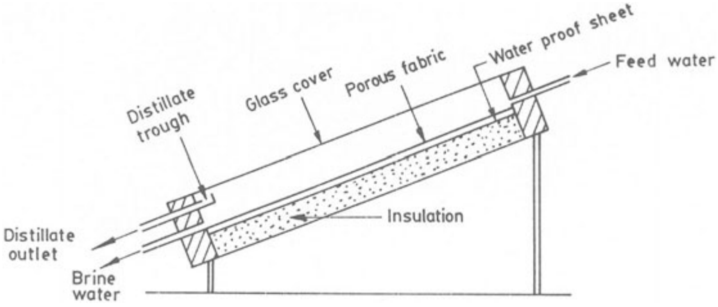

FIG.2.14 CROSS-SECTION OF TILTED WICK TYPE SOLAR STILL.

A similar inclined wick type solar still was also tested by Moustafa[69] et al in which a black synthetic wettable mat of 2.5 cm thick and area 0.182 m^2 was placed over a plastic sheet. The flow of water in the wick was controlled using a flow regulator and shut-off valve operated with a photocell. Another novel idea in a wicktype solar still was given by Frick and Sommerfeld[68] who suggested the use of Jute cloth along the width of the still dipped in saline water trays. The Jute cloth remains wet due to capillary action and therefore avoiding the use of water distribution system. Efficiencies as high as 40 to 50 percent are reported with this type of still.

A series of experimental and theoretical studies on inclined wick type solar stills are conducted by Mimaki et al[120], and Tanaka et al[121,122] in Japan. The wick used is of black cotton towel with an effective area of 2.79 m^2. The still is insulated with 5.0 cm thick cellular glass insulation. The still was supplied water from the top using a distributor and a pump system. The still was tested extensively under the solar insolation at Yokohama(35^o 33'N), Japan. The still output recorded was 5.0 l/m^2 day at solar intensity of 23 MJ/m^2 day.

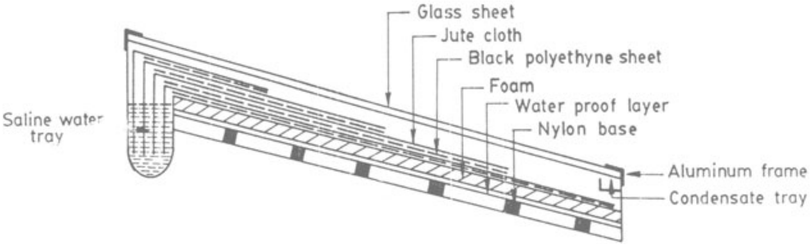

FIG.2.15 CROSS SECTION OF TILTED MULTIPLE WICK TYPE SOLAR STILL

Detailed theoretical and experimental studies on tilted multiple-wick type solar still are carried out in India by Sodha et al[72] who instead of using a thin layer of flowing water or a single piece of wick, used black Jute cloth pieces of uneven length placed one upon another and separated by black polythylene film. The cross section of the still is shown in fig. 2.15. The still consists of blackened jute cloth pieces of increasing length separated from each other with black polyethylene film, with their top edges immersed in the water tank which is along with width of the still. The entire wick remains wet due to capillary action. The width of each jute cloth is 0.86m and the total length of the wick (multiple pieces) is about 1.0 m. The entire wick is placed over a waterproof thin sheet(plastic) and then on a thin sheet of foam which acts as an insulation layer on the rear side. Over the wick, a glass sheet of 3.0 mm thick is placed. The entire system is kept in position with the help of aluminium angle frame on all the four sides and nylon ribbon netting on the bottom side. The distillate is collected in a galvanised iron channel fixed on the lower side of the glass. Experiments are conducted with the still inclined at an angle of 15 deg facing south at New Delhi, India.

Analysis of the wick type solar still is carried out similarly as was carried out in case of basin type solar still(section 2.3.3) and it has been assumed that the wick surface behaves as a very thin layer of water and the capacity of water in the wick and that of glass is very small. The energy balance on the glass cover is written as:

$$I\alpha_g + q_e + q_r + q_c = q_{ra} + q_{ca} + q_g \qquad (2.15)$$

and energy balance on the wick surface is written as

$$I\alpha_{w}\tau = q_e + q_r + q_c + q_b + q_w + q_f \qquad (2.16)$$

where q_g, q_w, q_f are the heat stored in glass, water and still, and heat going out with the distillate. All other terms are defined earlier. For the whole still the energy balance equations are given as:

$$I(\alpha_w\tau + \alpha_g) = q_{ca} + q_{ra} + q_b + q_g + q_w + q_f \qquad (2.17)$$

Under steady state conditons, the terms q_g ,q_w and q_f can be neglected. Using Dunkle's[74] relation for q_e ,q_c and q_r, the amount of water distillate m_e(l/m^2hr), can be calculated from the following expession:

$$m_e = \frac{q_e}{L} = 16.273 \times 10^{-3} \frac{q_c(Pw-Pg)}{L(Tw-Tg)} \qquad (2.18)$$

The values of Tw andTg for a particular place and still can be calculated by solving equations(2.15) and (2.16) using numerical methods. Values of some of the important parameters for a wick type solar still (effective area 2.79 m^2 and spacing between glass and wick 6 mm) are calculated using above equations by Tanaka et al[122] and the same are given in Table 2.7.

Table 2.7 Typical computed results for a wick type solar still.

Parameter	Value
I (KW/m^2)	0.80
Tw(°C)	61
Tgi(°C)	56
Tgo(°C)	54
$I\alpha_w\tau$ (KW/m^2)	0.63
q_c (KW/m^2)	0.03
q_e (KW/m^2)	0.44
q_r (KW/m^2)	0.04
q_b (KW/m^2)	0.06
q_f (KW/m^2)	0.06
q_{ca} (KW/m^2)	0.30
q_{ra} (KW/m^2)	0.26
m_e $(1/m^2hr)$	0.68

2.6 MULTIPLE EFFECT DIFFUSION SOLAR STILL

The single effect basin solar still has advantage such as simple, reliable, and does not require additional power to operate, but require large area to obtain per unit of water distilled because of its low efficiency. This low efficiency is due to the fact that the heat loss by convection and radiation from the water in the basin are high and the latent heat given by the condensing water to the glass are completely lost to the atmosphere. In a multiple effect solar still, the latent heat given to the condensing surface is further used in heating the saline water at a lower temperature. Thus it becomes a multistage system, where everytime, the latent heat of condensation heat the saline water and lesser quantities of distilled water is produced in successive stages. These multiple effect solar still definitely gives much higher distilled water output compared to the single effect basin still but these are comparatively sophisticated in design and are expensive. The multiple effect stills are studies by Telkes[76], Dunkle[74], Selkuk [75], Hodges et al[77], Eibling et al[78], Tleimat[79], Oltra[80], Bartoli[81], etc.

The multiple effect solar still as described by Dunkle [74] consists of two parts, a distillation unit and a solar heater unit. A solar heater unit consists of flatplate collectors used for heating water and the hot water is stored in the storage tank as shown in fig. 2.16. The distillation unit consists of an airtight chamber with five vertical plates (Fig 2.16), the first plate being heated by solar heated water circulated through tubes attached to the left side of the first plate. On the right side of this plate(first) water is allowed to fall in a very thin layer and the heat will cause evaporation of saline water. This vapour will condense on the left side of the second plate and gives its heat of condensation to the plate which is used in evaporating the saline water flowing on the right side (back side) of the second plate. This operation will continue upto the last plate where the heat of condensation is used in preheating the incoming saline water. The condensate on the front sides of each plates drips down and finally collected in each trays and channeled out. The brine is collected from the bottom of the chamber. The performance of this multiple effect solar still can be predicted by the simple analogy as is suggested by Dunkle[74].

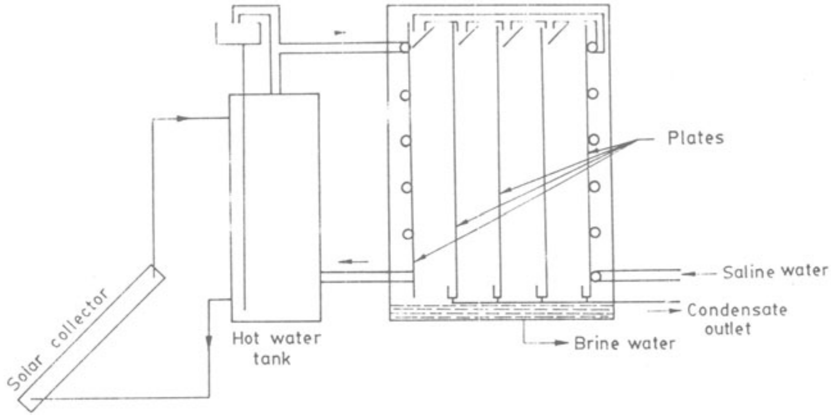

FIG.2.16 MULTIPLE EFFECT DIFFUSION SOLAR STILL

The heat transfer between the plates takes place by convection, radiation, conduction, and diffusion of vapor. The convection heat loss can be eliminated if the spacing between the plates are kept such that the Grashof's number, Gr, becomes less than 2000. Thus

$$Gr = \frac{x^3 \rho^2 g \beta \Delta T}{\mu^2} \leqslant 2000 \qquad (2.19)$$

where x is the plate spacing in metres, ρ is density of air (kg/m^3), g is acceleration due to gravity (m/s), β is coefficient of volumetric expansion of air (per °C), ΔT is temperature difference between plates, and μ is coefficient of viscosity Kg/ms. From equation (2.19) it is seen that for humid air at a temperature of 65 °C and temperature difference of 11.1 °C between the plates, the free convection will be suppressed if the spacisng between the two plates is kept at 1.33 cm.

The rate of diffusion Ww in Kg/m^3 hr is given as:

$$Ww = - \frac{DMw}{RT} \quad \frac{P_T}{((P_T - P_W)} \quad \frac{dPw}{dx} \qquad (2.20)$$

where D is the diffusion coefficient and is given as:

$$D = \frac{0.0043\ T^{3/2}}{P_T (V_W^{1/2} + V_B^{1/3})^2} \left(\frac{1}{M_W} + \frac{1}{M_B} \right)^{1/2} \qquad (2.21)$$

Where M is the molecular weight and V is the molecular volume. Now substituting D from equation (2.21) in equation (2.20), we get

$$Ww = - \frac{0.0043\ T^{1/2}\ M_W}{R(V_W^{1/3} + V_B^{1/3})^2} \left(\frac{1}{M_W} + \frac{1}{M_B} \right) \left(\frac{1}{P_T - P_W} \right) \frac{dPw}{dx} \qquad (2.22)$$

From this equation it is seen that for lower values of molecular volume V_b and molecular weight M_b of a gas, the rate of diffusion will be higher. Therefore a lighter gas such as hydrogen in the chamber will be preferred since it will provide higher values of diffusion rate. By increasing the pressure gradient dP_W/dx, the diffusion rate can be increased which can be done by decreasing the spacing dx between the plates. If the total pressure P_T in the chamber is also decreased then the diffusion rate can also be increased. Maintaining low pressure in the chamber will be difficult from practical considerations.

The expressikon of rate of diffusion of water vapor Ww(equation 2.22) can further be written as follows if diffusion is in air:

$$Ww = \Phi_a \frac{\Delta Pw}{\Delta x} \left(\frac{Ps - Pwm}{P_T - P_{wm}} \right) \qquad (2.23)$$

where Φ_a is diffusion constant for water air system at one atmosphere, ΔPw is partial pressure difference across space for water vapor, Ps is atmospheric pressure and Pwm is the mean partial pressure of water vapor in the space. The diffusion constant Φ_a is a function of temperature for water-air mixture and at a temperature of 60°C, $\Phi_a = 0.0033$.

Simulation studies on five effect diffusion still was conducted by Dunkle[74]. He observed an still output of 14.0 litres/m^2 day for a temperatur range of 48.9°C to 37.8°C.

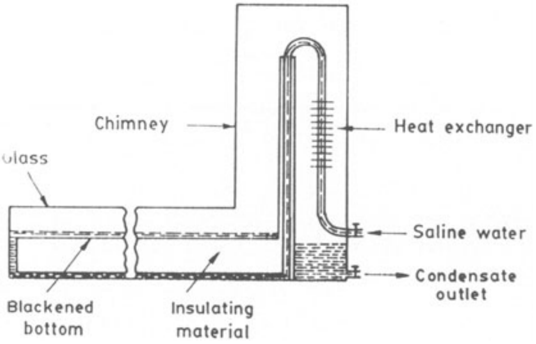

FIG.2.17 THE CHIMNEY-TYPE SOLAR STILL

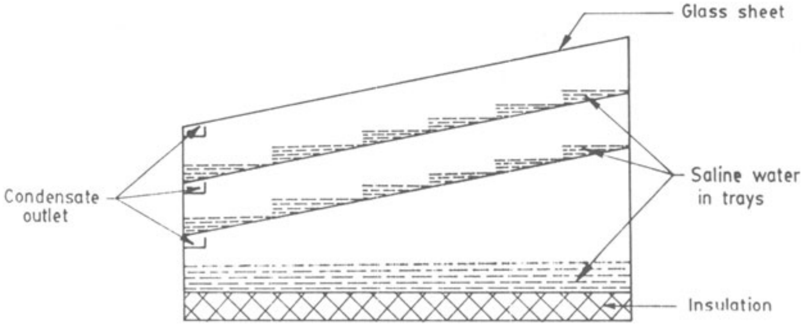

FIG 2.18 MULTI-TRAY MULTIPLE EFFECT SOLAR STILL

Bartali et al[81] have developed a multiple effect solar still known as chimney-type solar still as shown in fig. 2.17. As is seen from the figure there is a still with blackened sheet over insulation and a glass cover at the top. At one of its ends, a chimney containing a heat exchanger is used. The saline water drawn through the heat exchanger flows over the blackened plate in the still where it gets heated and evaporated. The vapour goes in the chimney chamber and gets condensed over the heat exchanger giving its latent heat to the incoming saline water and therefore preheating it. The distilled water is collected from the bottom of the still. Bartali et al[81] from theoretical studies observed that it would be better to distribute preheating and vaporization and to seperate heat collection from evaporation.

Lobo et al[123] studied a simple multibasin-multieffect solar still as shown in fig.2.18. Here several transparent basins full of water are formed on glass sheets using glass vertical retaining walls. The still consists of a shallow water basin kept on an insulation and a clear window glass at the top inclined at 10 deg. to the horizontal. On two other glass sheets water basins are formed by making 9 vertical retaining walls seperating 10 channels which contains saline water required to be distilled. Condensation of water vapor takes place on the underside of the three plates.

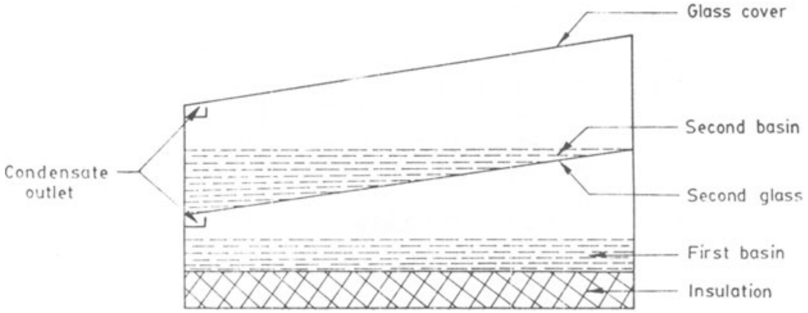

FIG.2.19 DOUBLE BASIN SOLAR STILL

A detailed theoretical and experimental studies on a double basin-multiple effect solar still are conducted by Malik et al[124] and Sodha et al[125]. The double basin solar still is shown in fig. 2.19. Here two glass covers are used. Over the second glass cover i.e. the inner glass cover a thin layer of saline water is filled. The second basin is as usual in case of conventional single basin still. The water vapor evaporated from the lower basin will condensate on the lower glass sheet of the second upper basin giving its latent heat to the saline water. The condensate is collected in a channel. The latent heat which is used in heating the water in the second basin and the heat which is directly absorbed by the second basin from the sun is used in evaporating the water from the second basin which gets condensed on the lower side of the top glass cover and collected in a condensate channel. The heat collected by this upper glass is finally lost to the atmosphere. The upper basin reduces the solar radiation reaching the lower basin. A periodic theory is used in analysing the performance of this solar still by Sodha et al[125]. The experiments conducted on this still have given encouraging results. an efficiency of 36 percent higher compared to single basin solar still is determined.

Unfortunately the additional distillate output obtained in a multiple effect solar still compared to single basin still has not compensated for additional cost, sophistication, and maintenance. The cost of distilled water from a simple single basin solar still is always lower then the cost of multiple effect solat still. Moreover, no commercial solar operated multi-effect solar still is in operation.

2.7 MULTISTAGE FLASH DISTILLATION

In the multistage flash distillation process the latent heat of condensation is used in heating the feed water while in the multiple effect distillation process the latent heat of condensation is used to evaporate the feed water. Most of the large modern distillation plants are of the multistage flash distillation type mainly because these are commercially successful and the cost of fresh water produced by these plants is low compared to that from multi-effect distillation plants.

The first solar operated multiple-stage flash distillation plant better known as humidification-dehumidication process of 18.9 m^3 /day capacity was installed at Puerto-Penasco in Mexico on the shore of Gulf of California which is based on the work at the university of Arizona[77]. Work on humidification-dehumidication technique is also conducted in India [126,127] and a plant of 4500 litres/day was designed and operated. The humidification-dehumidification plant as described by Hodges et al[77] is shown in fig.2.20. As is seen from this figure, the plant consists of three main parts: the solar collector system, the hot water storage system, and evaporated condenser system. Five bays of simple cheap plastic collectors each with 2 m wide and 10 m long with total collecting area of about 966 m^2 are used. Saline water heated in these collectors is stored in one underground storage tank, from where it is pumped and sprayed in the packed tower(evaporator) from its top. This water drips down in the packed tower to its bottom and comes in direct

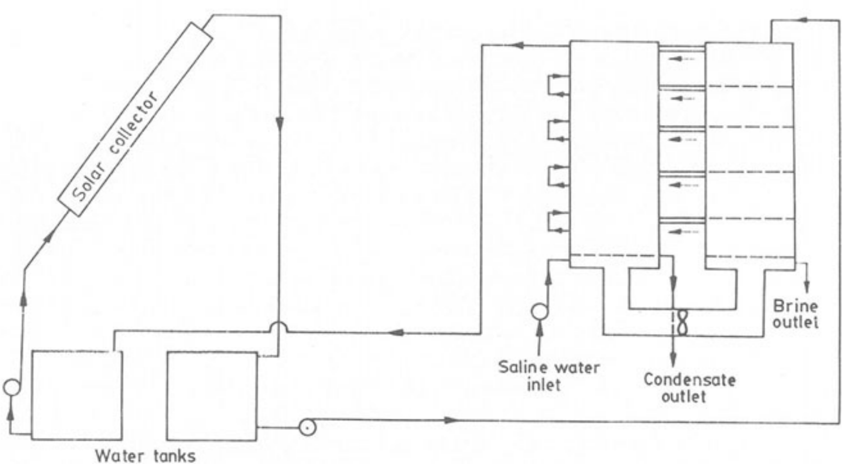

FIG.2.20. PRINCIPLE OF HUMIDIFICATION-DEHUMIDIFICATION DISTILLER

contact with the upcoming air forced from the bottom of the evaporator tower. This dry air comes in touch with hot saline water and humidified at higher temperature. This hot and humidified air is then passed through condenser tower which is parallel to the evaporator tower and connected through horizontal cross connections. This hot humid air in the condenser tower moves from top to bottom and comes in touch with the finned tube condenser coils through which cold sea water is flowing in the upward direction. A part of the humidity of the air gets condensed on the coil and heats the incoming sea water in the coil. The condensate is dripped off the finned tubes and collected in the bottom of the condenser tower from where it is piped out. The dehumidified air from the condenser tower is also taken out and recirculated by a blower again to the evaporator tower. The incoming seawater which is preheated after receiving latent heat of condensation from the condensing vapour of the air is taken out and is also stored in an underground storage tank as is shown in fig. 2.20.

It is seen that the humidification-dehumidification distiller described above is similar in operation to that of a steam operated multiple-stage flash distiller. The hot saline water passes from one stage to the second with each time flashing off vapor and going to lower pressure/lower temperature stage. The incoming sea water also gets heated in stages, each time receiving heat from condensing vapor and getting preheated. The only difference appears to be in the procedure used in reducing the pressure in stages. In the conventional steam operated multiple stage flash distiller, the pressure in successive stages is reduced using orifices between stages while in the humidification-dehumidification distiller, pressure reduction occurs due to lowered temperature in each stage of the plant. Theoretically the plant appears to be quite promising. But the power requirement for running the pumps for circulating the saline water and brine and the blowers used for the circulation of air in the Puerto Penasco installation three water pumps rated at 12 KW and an air blower rated at 30 KW are used. For meeting the power requirement a 50 KW diesel electric generating set was used and its waste heat was used to heat the saline water after the solar collectors while a vapor-compression distillation plant of the same distilled water output uses only 15 KW. So from energy utilization point of view, the humidification-dehumidification distiller is not attractive.

Since the electrical energy consumption in the above distiller was large hence the use of solar energy as heat source was proposed in several conventional distillers. These distillers use electrical energy for pumping and vacuum production and solar energy is used as heat source hence these distillers are termed as solar assisted distillers. Several scientists like Howe and Tleimat[19], Eibling et al[78], Baum[24], Lessley et al[82], Brice[83], Tleimat et al[84,85] Weihe[86] and Tabor[87] suggested the use of solar energy to produce hot water or steam and drive the conventional vacuum type distillation plant. Baum[24] suggested the use of paraboloidal reflector to produce the steam while Eibling et al[78] and Weihe[86] suggested the use of line focus cylindro parabolic reflector to produce steam at a pressure slightly above atmospheric pressure. Howe and Tleimat[19] suggested the use of flat-plate collectors to heat the saline water upto 70°C for supply to the distillers.

A solar assisted mulistage (3-stage) flash distillation unit is shown in fig.2.21. As is seen from the figure, the saline water passes through tubes in the upper portion of the flash chambers, where it gets heated by the condensing vapours and is further heated in a solar collector, from here it is released to the first flashing chamber maintained at low pressure which causes the flashing of the sea water and reduces the boiling temperature to saturation value. These generated vapours condense on the tubes and the brine goes at a low pressure to the second flash chamber where it further flashes and the brine temperature gets further reduced, the vapours again condenses on the tube in the upper half of the chamber. This process is repeated in the third and subsequent stages. The condensate from all the chambers is collected and taken out.

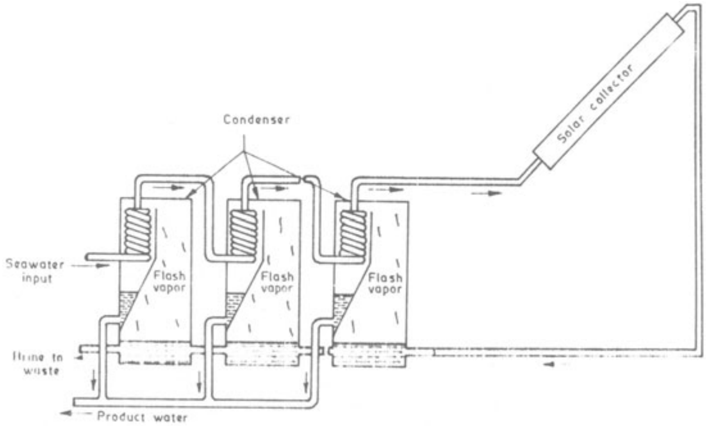

FIG.2.21. MULTISTAGE FLESH DISTILLER USING SOLAR COLLECTOR

The efficiency of the plant is generally given as the radio of weight of distillate produced to the steam used and is termed as Gained output Ratio(GOR). The GOR of a multiple effect distiller depends on the number of stages as well as on the temperature of steam used. For higher GOR, the number of effects should increase which results in decrease in temperature difference for heat transfer surface in all effects. This large heat transfer area will result in higher capital cost. But higher GOR of the distiller will consume less steam resulting in smaller solar collector area. Therefore the decrease in solar collector area should be balanced with the increase in number of effects. Recently efficient heat transfer evaporators, a vertical Tube Evaporator(VTE) developed by Sephton[88] and the rotating wiped film type developed by Tleimat[89] have become available. The rotating wiped film evaporator is shown in fig.2.22. It consists of flat copper disks clamlped onto rings to form cavities within which the vapours condense. The sea water is fed along the length of the stationary wipers on the outside surfaces of the copper disks. The condensate from the inside of the cavities is thrown out by centrifugal force and collected and conveyed to the outside of the rotating cavity by stationary radial scoops.

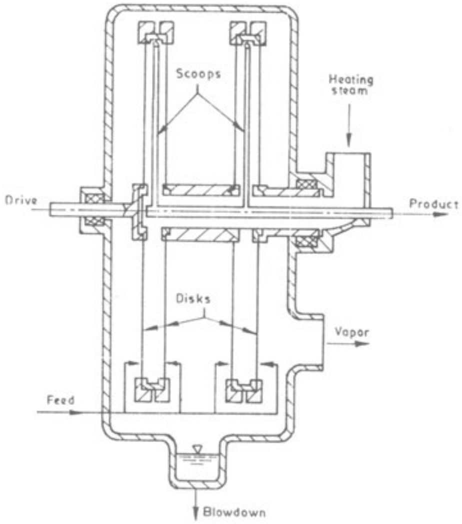

FIG.2.22. SCHEMATIC OF ROTATING-DISK WIPED-FILM EVAPORATOR

Using the above rotating disk film evaporator (15 Nos. in series) a 40 m^3/day plant was made by Tleimat and Howe[84]. The system basically consists of two parts (fig.2.23), a steam production unit, and a multiple effect desalination unit. In the steam production unit, solar flat plate collectors are used to heat the water in storage tanks 1 and 2. Hot water from either of the storage tanks is introduced into the degasser where the pressure corresponds to a saturation temperature slightly below the water temperature so that all the noncondesible gases are removed by vacuum pump. Now hot water enters the flash chamber where part of it is flashed into vapour and the rest is cooled and sent back. The vapour from the flash chamber is now introduced into the cavity of the first effect of the multiple distiller and is condensed and returned to the solar collector. The vapour produced in the first effect is used as the heating steam in the second effect and is condensed and

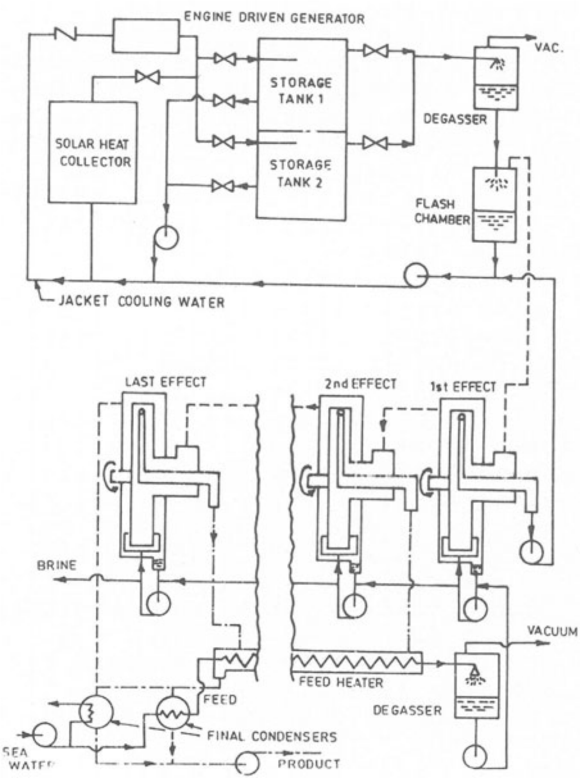

FIG.2.23 SOLAR-ASSISTED WIPED-FILM MULTISTAGE FLASH DISTILLATION UNIT

removed as product. The vapour produced in the second effect is used as the heating steam in the third effect and so on until the last effect where the vapour is finally condensed. The condensate from effect 2 to 15 is collected as product.

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CHAPTER - 3

SOLAR FOOD DRYING

3.1 INTRODUCTION

It has been estimated that the world population will increase from the present value of 4 billion to 7 billion by the year 2000. It is also estimated that about 600 to 900 million people do not have enough food to eat now and this number is likely to increase with the increase in population. There are obviously two direct ways solving the problem: (1) increase the food production by bringing more area under cultivation and irrigation, using newer mechanised methods of agriculture, and using hybrid seeds and better management and agricultural practices, (2) reduce the food demand by reducing the population growth. The third alternative which is equally important but not given adequate attention is reducing the loss of food during and after harvest. The actual estimate of food loss during post harvest due to spillage; contamination; attack by brids, rodents, and insects; and during storage is difficult to know due to technical and practical reasons[1] but it is so enormous that most conservative estimates were enough in 1975 to result in a resolution by the Seventh Special Session of the United Nations General Assembly to seek 50 percent reduction of post-harvest food losses within a decade.

A very conservative estimate indicate that a minimum of 107 million tonnes of food were lost in 1976 out of 750 million tonnes produced including durables and perishables. In countries (Developing Countries) where cold storage fascilities are not adequately available, post harvest losses between 30-50 percent in perishables are reported[2]. These food loss can be reduced in developing countries if these countries establish and maintain adequate harvesting, storing, and handling practices, particularly in rural areas and create efficient policy and administrative infrastructure. The post harvest losses vary considerably and depends on crop variety, climate, the system of harvesting, processing, storage handling, marketing, and the social and cultural setting. The developing countries produce about 15 percent of the world crop. Many commercial crops like tea, coffee, cocoa, tobacco, nuts, etc., are grown only in developing countries. Crops like wheat, paddy, potatoes, barley etc. contribute about 40 percent of the world harvest.

About 36 percent of the vegetables and 50 percent of the food of the world are produced in Developing Countries. Fish is another food product whose estimate is not available but is produced in large quantities in developing countries. If even the 50 percent of the post harvest food losses are reduced then in many developing countries the food is not to be imported.

There are several ways of preserving the food for later use. Drying is a traditional method for preserving the food. It also helps in easy transport since the dried food becomes lighter because of moisture evaporation. Drying of seeds prevents germination and growth of fungi and bacteria. The traditional age old practice of drying food crops in developing countries is spreading food products in open sun in thin layer which may be termed as open sun drying or natural sun drying. In this technique the product is spread in thin layers on a hard platform and the product is turned once or twice a day. This natural sun drying is simple and economical but suffers from many drawbacks such as :
(i) there is no control over the crop drying, the crop may be overdried resulting in discolouration, loss of germination power, nutritional changes, and sometimes complete damage. (ii) there is no uniform drying, (iii) in case of slow drying there can be deterioration of food due to fungi and bacteria, (iv) the rain and duststrom may damage the crop since in open drying there is no protection, (v) there will be considerable damage due to birds, insects, rodents, etc. in the open sun. The moisture content and the temperature at which the food product is to be dried is always fixed and which is possible only in controlled drying. There are several advantages of controlled drying of grains such as : product quality, storage capability, and hygiene improves; reduce wastage, time, and space; provide better quality and better return; and improve transportability. There are three basic methods of drying (i) In-storage layer drying, (ii) Batch drying, and (iii) continuous flow drying. The fuel used in control drying of food is electricity, oil, natural gas or coal. The energy consumed in United States by food processing industries during the year 1975 was 1.13 x 10^{-5} TJ which constitutes o.2 percent of the total energy consumption. This energy demand is fast increasing and it is unlikely that this increasing demand will be met by natural gas and electricity. If a little technology and money is applied then solar energy can be a possible solution for the dehydration of food. Experiments conducted in many countries have clearly shown that solar dryers can be effectively used for drying food. It is a question of adapting it and designing a right type of solar dryer for a particular product. Solar energy is all the more effective for food drying because of following reasons :
(a) Solar energy is diffuse in nature and provides low

grade heat. This characteristic of solar energy is good for the drying at low temperature, high flow rates with low temperature rise.

(b) The intermittent nature of solar radiation will not effect the drying performance at low temperature. Even the energy stored in the product itself will help in removing excess moisture during this period.

(c) Solar energy is available at the site of use and saves transportion cost.

(d) The high capital cost of solar dryiers can be compensated if the dryer is used for drying other products also or atleast is put to other multiple uses such as space heating, etc.

3.2 HISTORY OF SOLAR DRYING

Although natural drying of food in open sun is practised since time immemorial, but the concept of collecting solar heat and using it for food/crop drying has received increasing attention in recent years. The dryers developed so far vary from simple small cabinet dryer to forced convection dryer where solar energy is used to heat air and the heated air is used in more or less in conventional dryers. A good history of solar dryers is given by Sodha et al[3] and the present one is from their work. Cabinet or box type of solar dryers appear to be the simplest dryer where the heating of air and moisture removal takes place in the same unit. Such simple cabinet dryers were first made by Lawand [4,5] and field tested them[6] for many years. These cabinet dryers are made in many countries by locally available materials with small modifications in the original designs and dried fruits and vegetables. Some such studies are conducted by Garg and Krisnan[7] in India, Harahap et al[8] in Indonesia and Pablo [9] in Philippine. The drying rate can be increased by combining the air heater and the box dryer and is known as shelf type dryer. Such shelf type of dryers are used for drying grapes in Australia by Szulmayer[10], for drying cocoa in Brazil by Ghosh[11], for drying orchard in USA[12], for fruit drying in Turkey by Akyurt and Uzdaglar[13], and for drying Cassava stick in Columbia[6]. Akyurt and Selcuk[14] developed a shelf type dryer supplemented with auxiliary energy for its continuous operation. A solar wind ventilator dryer was developed by Nahlawi[15] at the Brace Research Institute, Canada where a air heater is used to preheat the air and the wind driven fan is used to circulate the air through the shelf type dryer.

Studies on drying of timber(kiln) using solar energy employing a glass house and simple flat-plate collectors are conducted by Rehman and Chawla[16], Johnson[16], Maldanado and Peck[17], Tao and Hsiao[18], Chundoff et al[19], Troxell and Mueller[20], Sharma et al[21] and Tschernitz and Simpson [22]. Supplemental heat source is also sometimes employed in a solar kiln as is done by Terrazawa[23]. Solar kiln as large as 60-120 m^3 drying capacity are in operation in united States[24]. Several large size solar kilns are also planned in USA.

The early work on solar drying using solar heated air was conducted by Beulow[25,26] and Becker and Boyd[27] in USA. Peterson[28], and Lipper and Davis[29] developed a system for drying grain using solar energy. Studies conducted in Kankas [30], Iowa[31] and Ohio[32] in USA on solar drying of shelled corn and soybeans clearly indicated that apart from saving in time significant saving in conventional fuel can be achieved. Studies on solar rice drying in Texas[33] has also clearly revealed that 20 to 60 percent drying time can be reduced by using solar energy. Studies on large scale solar drying using solar air heaters and tunnel type dryers are conducted by Kaminakas[34], Luke[35], and Carnegie and Pohl[36] and in some system even rockpile heat storage system is employed. Evacuated tube collectors are used[37] to supply heat to an industrial drying plant at Gilroy, California for the dehydration of Onion.

Solar energy can be used for drying grains in two ways: using high temperature, high speed systems where collectors of sophisticated designs are used and solar energy can only supplement the auxiliary energy, the second is low-temperature, in-storage drying systems where low levels of heat input over extended periods are used and therefore simple low cost plastic collectors are employed. Considerable work on low temperature-bin drying either by using seperate plastic collectors or collectors integrated with the bin wall is conducted in USA for the drying of grains[38-42].

Solar drying is a heat and mass transfer process and without its full appreciation it may not be possible to effectively design a solar drying system. Basics of solar drying principles are discussed in books[43,44] and other publications[45,46].

3.3 BASICS OF SOLAR DRYING

Drying or dehydration of material means removal of moisture from the interior of the material to the surface and then to remove this moisture from the surface of the drying material. In natural sun drying where the product is directly exposed to the sun in the open air, the necessary heat required for moisture removal is supplied from the sun and a little from the ambient air and the wind and the natural convection disperse water vapour. While in the convection type of dryers, a stream of preheated air from solar energy supplemented by auxiliary energy is allowed to pass over the product which supplies the necessary heat for moisture removal from inside to outside and also carries the moisture. Sometimes both the direct heating and preheated air system are combined. The drying of product is a complex heat and mass transfer process[46] which depends on external variables such as temperature, humidity and velocity of the air stream and internal variables which is a function of drying material and depends on parameters like surface characteristics (rough or smooth surface), chemical composition (sugars, starches, etc.) physical structure (porosity, density, etc.), and size and shape of the product. The rate of moisture movement from the product inside to the air outside differs from one product to another and very much depends weather the material is hygroscopic or non-hygroscopic. Non-hygroscopic materials can be dried to zero moisture level while the hygroscopic materials like most of the food products will always have a residual moisture content. This moisture in hygroscopic material may be a bound moisture (remained in the material due to closed capillaries or due to surface forces) and unbound moisture which remained in the material due to surface tension of water(fig.3.1). When the hygroscopic material is exposed to air, it will either absorb moisture or desorb moisture depending on the relative humidity of air. The equilibrium moisture content (EMC) will soon reach when the vapour pressure of water in the material becomes equal to the partial pressure of water in the surrounding air. The equilibrium moisture content in

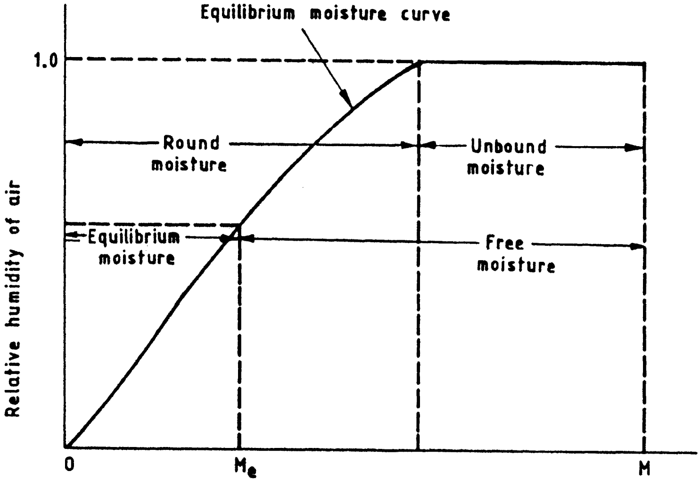


FIG.3.1. MOISTURE IN THE DRYING MATERIAL

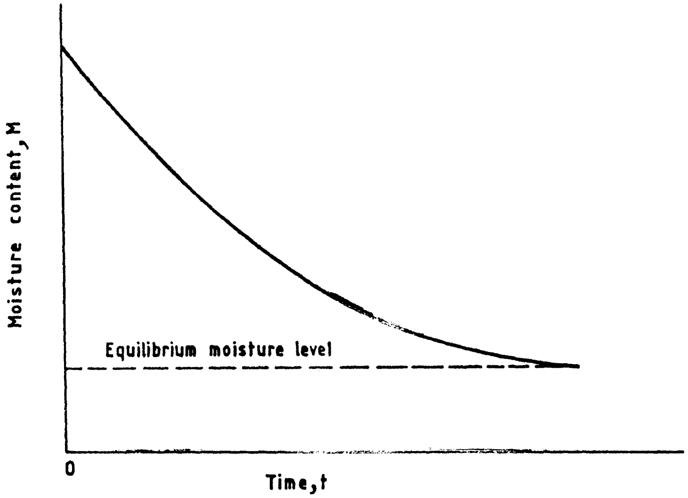


FIG.3.2. RATE OF MOISTURE LOSS

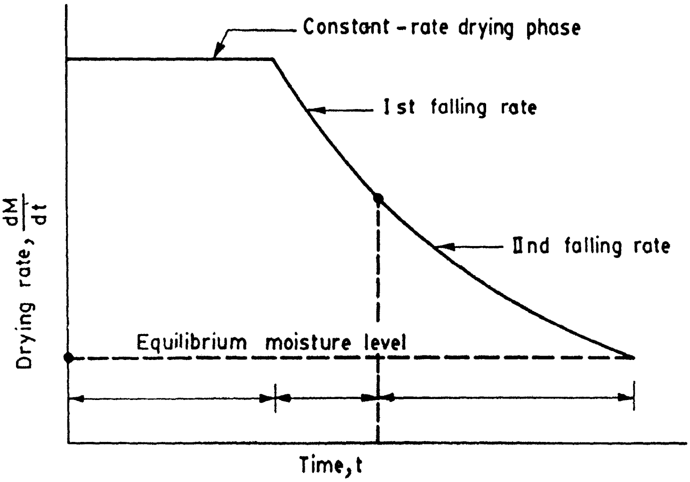


FIG.3.3. DRYING RATE WITH TIME CURVE.

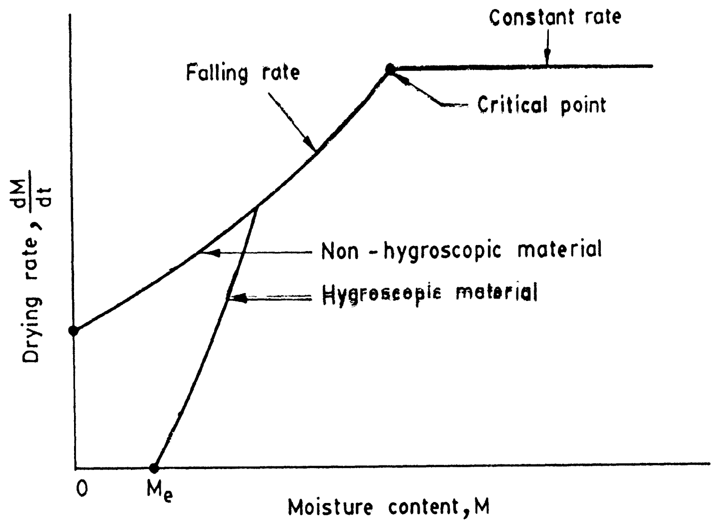


FIG.3.4. TYPICAL DRYING RATE CURVE

the drying is therefore important since this is the minimum moisture to which the material can be dried under a given set of drying conditions.

A series of drying characteristic curves can be plotted. The best is if the average moisture content M of the material is plotted versus time as shown in fig.3.2. Another curve can be plotted between drying rate i.e. dM/dt versus time t as shown in fig.3.3. But more information can be obtained if a curve is ploted between drying rate dM/dt versus moisture content M as shown in fig3.4. As is seen from fig.3.4 for both non-hygrocopic and hygroscopic materials, there is a constant drying rate terminating at the critical moisture content followed by falling drying rate. The constant drying rate for both non-hygroscopic and hygroscopic materials is the same while the period of falling rate is little different. For non-hygroscopic materials in the period of falling rate, the drying rate goes on decreasing till the moisture content becomes zero. While in the hygroscopic materials, the period of falling rate is similar until the unbound moisture is completely removed, then further decreases and some bound moisture is removed and continues when the vapour pressure of material becomes equal to the vapour pressure of drying air. When this equilibrium reaches then the drying rate becomes zero. The constant drying rate referred as adiabatic drying since the total heat content of the air remains constant and depends on external factors such as air flow rate, thermodynamic state and transport properties of air, and state of aggregation of material. Under dynamic equilibrium conditions, rate of water evaporated is equal to the rate of heat transfer to the surface:

$$\frac{dM}{dt} = \frac{Ah_D}{R_v\ T_{abs}} \left(P_{vwb} - P_{v\alpha} \right) \qquad (3.1)$$

and
$$\frac{dM}{dt} = \frac{Ah_c}{L} \left(T_\alpha - T_{wb} \right) \qquad (3.2)$$

Where A is the surface area of drying material, h_D is mass transfer coefficient, h_c is convective heat transfer coefficient, L is latent heat of vaporisation, P_{vwb} is the vapour pressure of water in air at temperature T_α , $P_{v\alpha}$ is the vapour pressure of water at the surface of material, and T_{wb} is the wet bulb temperature.

In the constant-rate period, the drying time, tc is given as:

$$tc = \int_{M_e}^{M_o} \frac{R_v\ T_{abs}\ dm}{AH_D(P_{vwb} - P_{v\alpha})} = \int_{M_e}^{M_o} \frac{LdM}{Ah_c(T_\alpha - T_{wb})} \qquad (3.3)$$

In the constant drying conditions, the driving forces $(T_\alpha - T_{wb})$ and $(P_{vwb} - P_{v\alpha})$ are constant and therefore equation (3.3) will yield

$$t_c = \frac{(Mo - Me)\ Rv\ T_{abs}}{Ah_D(P_{vwb} - P_{v\alpha})} = \frac{L\ (Mo - Me)}{Ah_c(T_\alpha - T_{wb})} \qquad (3.4)$$

From equations(3.1) and (3.2), it is seen that the drying rate in the constant-rate period can be increased by increasing the initial air temperature, increasing the surface area of the material, increasing the heat transfer and mass transfer coefficients, increasing the drying air temperature with respect to the wet bulb temperature, and also by increasing the vapour pressure differential between the drying air and the drying material. Atleast the heat and mass transfer coefficient is a complex function of many variables such as air flow conditions, geometry of air-material interface, temperatures, etc.

In the falling-rate period, the effect of external factors starts diminishing and the transport properties of the material becomes important. In this stage the temperature of the material starts increasing and the satisfactory drying can be done by properly controlling the temperature and humidity of the air. It is therefore not easy to obtain a general expression of drying rate for predicting the drying time in the falling-rate period. Several mechanisms to explain the movement of moisture in the material such as liquid movement due to capillary forces, vapour or liquid diffusion due to concentration gradients, etc., are given but no theory can clearly explain the drying phenomena. Therefore empirical equations are used in this region. Since the constant rate period and falling rate period are quite different, therefore the design criterian for the dryer design will be different in each case.

The period of constant drying for most of the organic materials like fruits, vegetables, timber, etc. is short and it is the falling rate period in which we are more interested and which depends on the rate at which the moisture is removed. In the falling rate regime moisture is migrated by diffusion and in products with high moisture content, the diffusion of moisture is comparatively slower due to turgid cells and filled interstices. In most agricultural products, there is sugar and minerals of water in the liquid phase which also migrates to the surfaces, increases the viscosity hence reduces the surface vapour pressure and hence reduces the moisture evaporation. Drying is done either in thin layer drying or deep layer drying. In thin layer drying which is done in case of most of the fruits and vegetables, the product is spread in thin layers with entire surface exposed to air moving through the product and the Newton's Law of cooling is applicable in the falling rate regine. Most of the grains are dried in deep layer which can be considered as series of thin layers and the temperature and humidity varies from layer to layer.

With the help of sorption isotherms which is a relation between moisture content, M, and equilibrium relative humidity, ERH, at constant temperature for different products, it is possible to know the relative forces holding the water in the product. The equilibrium relative humidity, ERH, of a product is the relative humidity of air when the product neither gain water nor lose water. The sorption isotherm for few agricultural products are shown in fig.3.5

There are eight moist air thermodynamic properties which are generally used in drying such as vapour pressure, relative humidity, humidity ratio, dry bulb temperature, dew point temperature, wet bulb temperature, enthalpy, and specific volume. Each of these parameters can be calculated by empirical relations[47]. However, it is tedious job and therefore special charts which show the thermodynamic properties of the moist air are prepared and the same are known as psyschrometric chart. An example of a psychrometric chart is shown in fig.3.6. If one of the parameter changes,

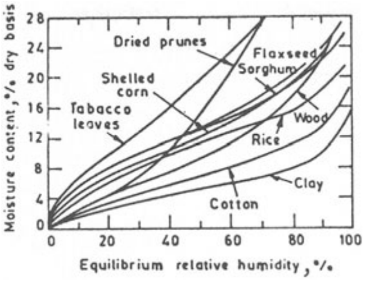


FIG.3.5. SORPTION ISOTHERM FOR SOME AGRICULTURE PRODUCTS AT 25°C

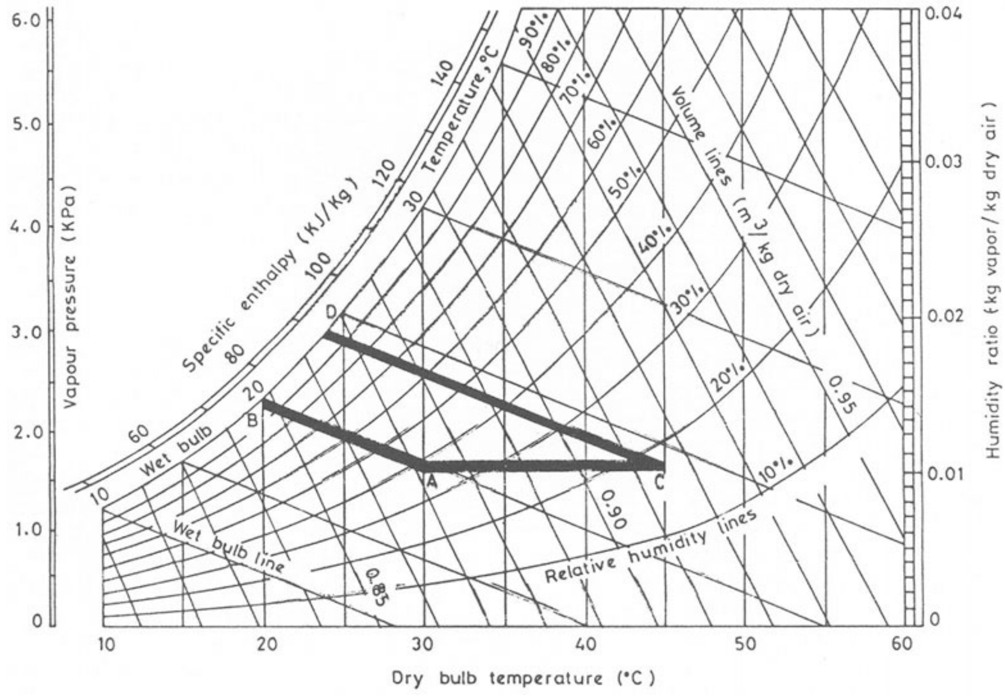


FIG.3.6. PSYCHROMETRICCHART FOR PRESSURE 101.35 KPa WITH DRYING PROCESS INDICATED

its effect on the other parameters can be seen from psychrometric chart(fig.3.6). The most important parameter is the saturation vapour pressure which is the maximum pressure of water vapour which depends on the temperature. Values of saturation vapour pressure at different temperatures are given in table 3.1. The drying process can be explained with the help of the psychrometric[45] chart of fig.3.6. If the air is not saturated (say dry bulb temperature is 30°C and wet bulb temperature is 20°C) and is allowed to pass over the material and if no external heat is applied, then the sensible heat of air and material is exchanged for latent heat of vaporization of water and the path travelled on psychrometric chart(fig.3.6) will be 20°C wet bulb line shown by line AB. Looking to the chart during this process the humidity ratio has changed from 0.0114 to 0.0140 i.e. about 0.0036 Kg of vapour per Kg of dry air is absorbed during this process. Now if using solar energy, the air is heated to 45 C with a relative humidity of 17 percent and is passed over the drying material. During the drying process, this air is cooled adiabatically along the 24°C wet bulb line, then the final humidity ratio will be 0.0189. Thus the moisture evaporated with the heated air will be 0.0075 Kg of vapour per Kg of dry air which is almost double the water evaporated compared to when air was not heated.

Table 3.1 Saturation vapour pressure Ps(KPa) of water, humidity ratio w of saturated air at 100 kpa, and latent heat L (MJ/Kg), for various temperatures.

Temperature (C)	Vapour pressure (KPa)	Humidity ratio	Latent Heat(MJ/Kg)
10	1.23	0.0077	2.491
15	1.71	0.0108	2.467
20	2.34	0.0149	2.455
25	3.17	0.0204	2.442
30	4.25	0.0276	2.431
35	5.63	0.0371	2.419
40	7.38	0.0496	2.407
45	9.59	0.0660	2.395
50	12.30	0.0872	2.383
55	15.80	0.1167	2.371
60	19.90	0.1545	2.359

As noted above the moisture content of the product at the time of harvest is very important from drying point of view and the equilibrium moisture content from the safe storage point of view are important parameters. The initial moisture contents for some of the crops at the time of harvent are given in table 3.2.

Table 3.2 Initial moisture content (percent) of some crops at the time of harvest.

Crop	Moisture content (Percent)	crop	Moisture Content (Percent)
Apple	82	Oats	20
Barley	20	Onion	80
Chillie	80	Paddy raw	22-24
Cassava	65	Paddy paraboiled	30-35
Coffee	60-70	Peach	89
Coffee beans	55	Potatoes	75-80
Cocoa beans	50	Rice	18-24
Corn	20-30	Sorghum	18-30
Fish	75		
Grape	80	Wheat	18-25
Green peas	80	Wood	60
Ground nut	40		
Hay	40		
Maize	35		
Millet	21		

The value of equilibrium moisture content for some crops are given in table 3.3.

Table 3.3 Equilibrium moisture content of some crops, percent wet basis.

Product	Temperature (°C)	Relative humidity of air(Percent)				
		10	30	50	70	90
1	2	3	4	5	6	7
Barley	25	4.4	8.5	10.8	13.5	19.5
Cabbage	25	1.3	4.7	9.1	16.0	-
Carrot	25	2.1	4.4	9.5	18.2	-
Lumber	25	2.8	5.7	8.4	12.2	18.0
Milk Powder	10	2.7	3.4	7.0	7.6	-
Oats	25	-	-	-	13.1	18.5
Onion	20	-	8.3	12.0	15.2	-
Peaches (dried)	24	0.7	2.6	7.3	16.8	-

TABLE 3.3 Contd...

1	2	3	4	5	6	7
Peanut	20	-	4.5	6.0	8.7	-
Peas	25	6.6	9.0	11.2	14.1	-
Potatoes	10	4.9	7.3	10.7	14.3	-
Prunes (dried)	24	2.1	6.6	12.7	20.7	-
Raisins	24	2.9	8.2	14.5	23.1	-
Rice	25	5.9	9.5	12.2	14.1	19.1
Shelled Corn	25	5.1	8.4	11.2	14.0	19.6
Sorghum	25	4.4	8.6	11.0	13.8	18.8
Tomato	20	-	7.8	10.6	13.5	-
Wheat	25	5.8	9.1	11.6	14.5	20.6

For safe storage, the material is to be dried upto a particular moisture content. The safe storage moisture contents for some of the materials are given in table 3.4.

Table 3.4 Safe storage moisture content for some of the Agricultural products.

Product	Maximum moisture for safe storage (Percent)	Product	Maximum moisture for safe storage (Percent)
Annas	15-18	Maize	15
Apple	24	Mushroom	5
Apricot	15-20	Musturd	11
Banana	3- 6	Oats	14
Barley	14.8	Onion	4
Canary seed	12	Peabeans	17
Carrot	5	Peach	15-20
Cauliflower	6	Peas	5
Cherry	15	Potato	8-12
Cocoa	8-9	Rapeseed	8.5
Coffee	11-12	Rice	13
Copra	5	Rye	14
Corn	13	Sorghum	13
Fix	24	Soyabean	13
Flax	10.5	Sunflower	9
Grape	15-20	Wheat	14.5
Hay	20-25	Wood	20

Drying temperature is also critical since higher temperature will surely increase the rate of drying but the product may be damaged. Grain drying is particularly sensitive to temperatures. When the gain is dry or nearly dry then high temperature drying may cause more damage. Initially when the grain is damp, the grain remains cool due to evaporative cooling when moisture is evaporating. As the grain becomes drier, the temperature of grain increases since moisture evaporation decreases. When the grain gets dried then the grain temperature becomes almost equal to the temperature of the drying air. Therefore to avoid the grain from damage, it is to be heated upto a certain maximum temperature only. The maximum allowable drying temperatures for some grains are given in Table 3.5. These maximum storage temperatures are for drying products upto the safe storage moisture contents shown in table 3.4.

Table 3.5 Maximum drying temperature (°C) for grain.

Grain	Seed (°C)	Commercial use (°C)	Feed (°C)
Barley	45	55	80-100
Buckwheat	45	45	-
Corn	45	60	90-100
Flax	45	80	80-100
Mustard	45	45	-
Oats	50	60	80-100
Peas	45	70	80-100
Rapeseed	45	65	-
Rye	45	60	80-100
Sunflower	45	50	-
Wheat	60	65	80-100

Product drying can be done either at low temperature known as low temperature drying or at high temperature known as high temperature drying. Low temperature drying is adopted generally for drying corn in storage bins which is a slow drying with natural air or air heated to few degrees above ambient and therefore is economical, energy efficient and results in high quality product. Low temperature drying depends on airflow, weather, initial moisture content, and amount of heat used. Approximate number of days required for drying corn to 15 percent moisture level with air at 4.4 °C and at 70 percent relative humidity are given in table 3.6.

Table 3.6 Approximate number of days for drying at low temperatures.

Initial Moisture Content (percent)	AIR FLOW RATE (m^3/m^3 storage)				
	0.013	0.02	0.03	0.04	0.07
	DAYS FOR DRYING				
20	44	36	21	14	9
24	41	35	28	19	12
26	60	45	34	24	15
28	70	55	40	27	21

High temperature drying (>50°C) is practiced for drying food products like fruits and vegetables containing high moisture content. In case of deep bed brying, high temperature drying may cause overheating and overdrying at the inlet side or in lower layers and underdrying at the outlet or at upper layers. The overdrying of lower layers should be avoided to preserve nutritious value of the product, since by this, the product may be spoiled and may become unfit for even animal feed. The efficiency of drying, no doubt, increases with the increase in the temperature of drying air but also on the flow rate of air. In high temperature drying, the outlet air containing high humidity may also be at high temperature and hence it can be recirculated to improve the drying efficiency.

3.4 TYPES OF SOLAR DRYERS

The traditional way of drying agricultural products in developing countries is to spread the material in thin layer on a platform in open sun. The natural drying does not involve money except some labour, but results in poor quality of product due to no control over drying rate, unhygienic conditions, and spoilage. Solar energy can be more effectively employed for control drying resulting in good quality product. Actually control drying means controlling the drying parameters like drying air temperature, humidity, drying rate, moisture content, and air flow rate. Therefore, a solar dryer is to be designed carefully keeping all the above drying parameters in mind and the appropriateness of the dryer. Since there are many options in the design of the solar dryers, hence there is a large variety of solar dryers. These solar dryers has been classified in many ways. The scientists of Brace Research Institute[12] have classified the solar dryers as passive dryers or active dryers or in a more general way in five types : direct type dryers, natural dryers, indirect type dryers, mixed mode type dryers, and timber dryers. Szulmayer[46] has classified the dryers into three types : direct radiation type dryer, indirect dryer, and mixed mode type of dryer. Based on operational mode, recently Malik[48] et al has classified the dryers into six types: direct mode dryers, indirect mode dryers, mixed mode dryers, timber dryers, structural integrated dryers, and other noval dryers. But considering the operational modes and practicability of dryers, these can be classified basically into two types: the direct type or natural convection type dryers, indirect type dryers and forced circulation type dryers.

3.4.1 Natural convection or Direct type solar dryers

These dryers appear to be more attractive for use in developing countries since these do not use any fan or blower to be operated by electrical energy. Moreover, they are low in cost and easy to operate. However, the problems with these dryers are: slow drying, not much control on temperature and humidity, small quantities can be dried, and some products due to direct exposure to sun changes colour and flavour. In its simple form, they consists of some kind of enclosure and a transparent cover. The food product gets heated due to direct absorption of heat or due to high temperature in the enclosure and therefore moisture from the product evaporates and goes out by the natural circulation of air. There are several designs of direct type dryers and either these are developed keeping in mind the availability of local materials required for its fabrication or for drying a particular product. Several dryers are fabricated, tested, and analysed in several countries.

3.4.1.1 Rack type solar dryer

Perhaps the simplest and effective dryer is the rack type dryer which is extensively used in Australia[49] for drying grapes and in Columbia for drying of Cassava particles. The dryer consists of racks of certain width, length, and some spacing made of wire mesh over which the drying material is placed and covered at the top by a metal or wooden roof to protect the material from rain and excessive sun. The drying unit used for drying sultanas (Grape Variety) in Australia consists of wire racks consisting of 8 or 10 tiers spaced vertically each of 45 m long and 1.2 m wide oriented N-S direction. The spacings etc. are such that the sultanas are exposed to direct solar radiation during morning and afternoon hours and not during the middle of the day when the sultanas are shaded by the roof or the racks above them. About 15-20 Kg of grapes are put on racks in an area of 1 m^2 and these get dried upto 13 percent moisture content within 9 to 15 days. It is concluded that better quality product can be obtained in this way of sun-drying than by artificial dehydration methods. It has been suggested that the sultanas should be covered with some cheap plastic sheet to avoid it from rewetting during the night period.

3.4.1.2 Solar Cabinet or box dryer.

Another dryer which has attracted the attention of many scientists is the Cabinet dryer which is also a natural convection type and was first developed by Lof[50] and which was later modified/studied by many workers including Lawand [5], Kapoor and Agarwal[51], Garg and Krishnan[7], Ismailova[52], Khan[53], etc. The solar cabinet dryer in its simple form consists of a wooden or of any material box of certain width and length (length is generally kept as three times its width), insulated at its base and also preferably at the sides and covered with a transparent roof. The details of the cabinet dryer are given in fig.3.7. The inside surfaces of the box are painted with black paint and the product to be dried are kept on the trays made of wire mesh bottom. These loaded trays are kept through an openable door provided on the rearside of the drier. Ventilation holes are made in the bottom through which fresh outside air is sucked automatically and also holes are provided on the upper sides of the drier through which moist warm air escapes. When the food product is placed on the trays and exposed to solar radiation, the temperature of the product rises resulting in evaporation of moisture. This warm moist air passes through upper ventilation holes by natural convection, creating a partial vacuum and drawing fresh air up through the holes provided in the base of the dryer. Temperatures as high as 90°C have been recorded[54] in this dryer when it is empty. Observations made on this dryer in many countries are quite encouraging and concluded that this dryer can reduce the drying time from one half to one third compared to open sun drying.

3.4.1.3 Green house type solar dryer

This dryer appears to look like a small greenhouse (fig.3.8) where there are two parallel long drying platforms made of wire mesh and are covered with slanted long glass roof with long axis along the N-S direction. There is a mettalic cap at the top of the glass roof leaving some space in between through which moist warm air can go out creating partial vacuum inside and therefore fresh outside air is sucked through holes provided on the side walls facing east

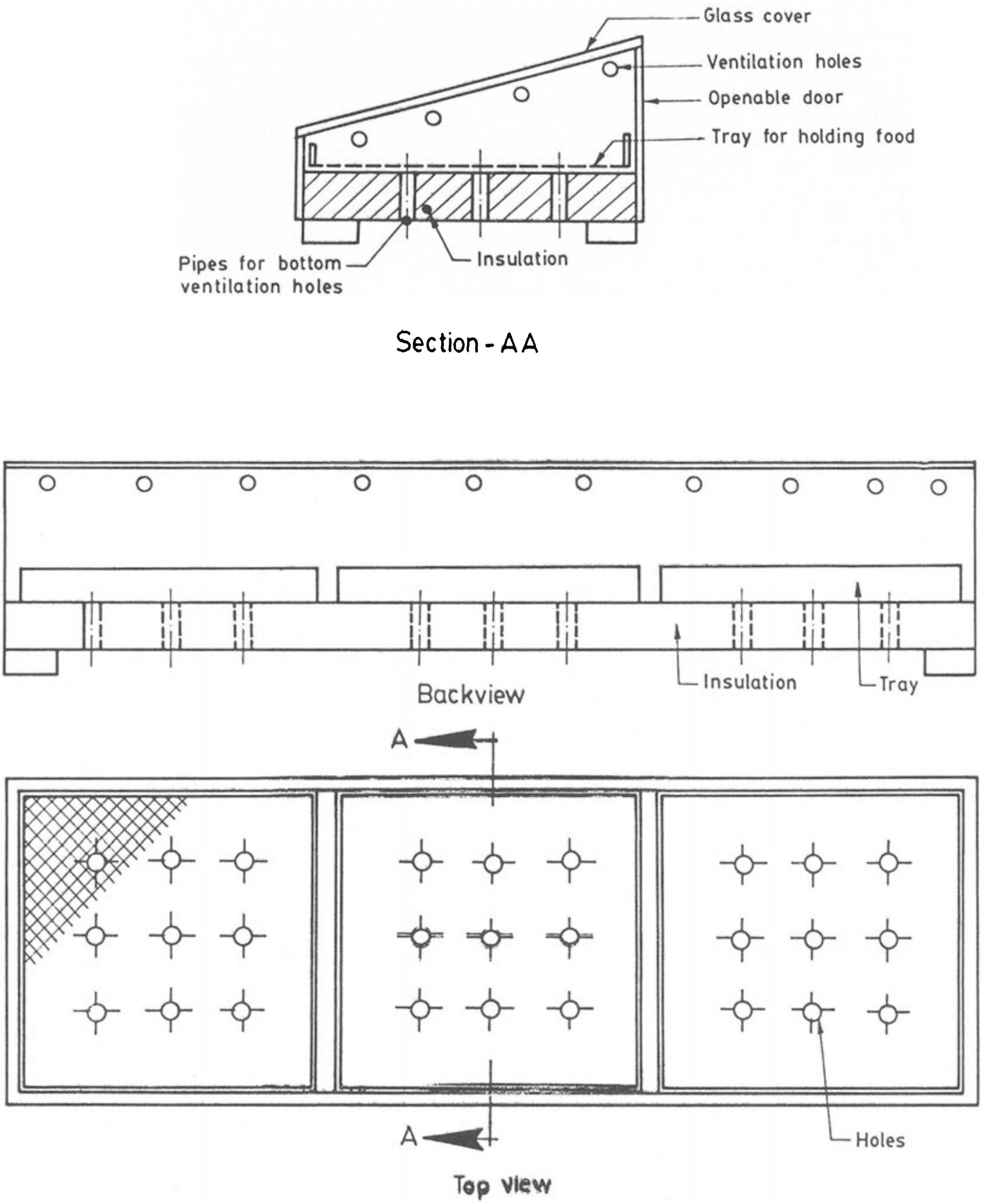


FIG.3.7 DETAILS OF SOLAR CABINET DRYER

and west below the drying platforms. This cap does not allow the rain and dust to enter the dryer and enhance the moisture evaporation from the product. The inside of the dryer as well as the trays are painted black. Fresh air in the dryer enters through the openings through shutters provided in the lower portion of the walls below the glass roof and above the drying platforms. Solar radiation penetrates through the glass roof, heats the product directly and absorbed within the dryer increasing the inside temperature. Sometimes to enhance the drying rate or in cloudy or rainy season, gas heaters are used which are kept below one of the platforms. These simple dryers are used in Brazil[11] on large scale for drying Cocoa.

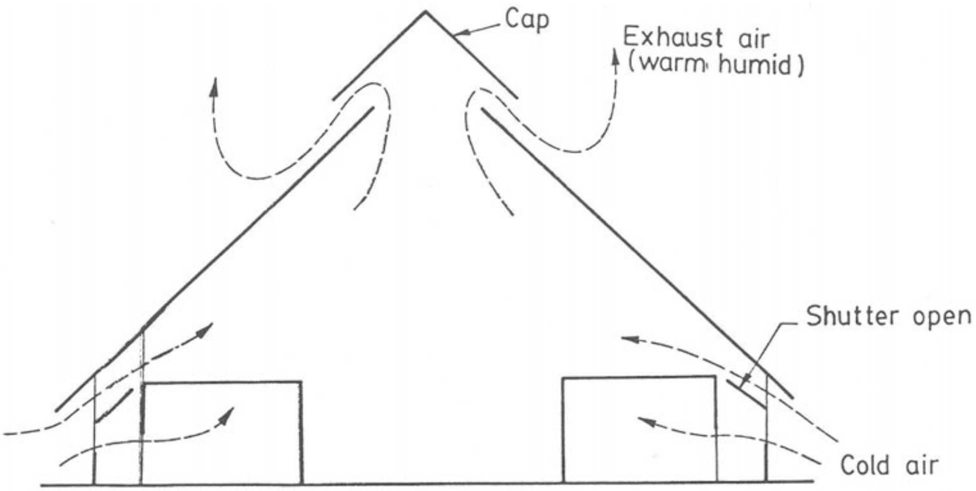


FIG.3.8. GREEN HOUSE TYPE SOLAR DRYER

3.4.2 Indirect type solar dryers

Indirect type of dryers are a little superior one than the direct type dryers since here the drying temperature, humidity, and drying rate can be controlled to some extent. These dryers use a drying chamber which may be either tray type, bin type, belt type, or tunnel type depending on the requirement and where food requires drying is placed, and somekind of solar air heater which is used to heat the air and therefore raising the temperature of the drying chamber and can be made use of some black painted mettalic sheet with or without insulation and glazing. Some of the dryers directly receives solar radiation and also heated air from the air heater while in other designs, the drying chamber receives hot air only from air heaters. Thus depending on the requirements and operation, these dryers are also of several types and a few of them will be described here.

3.4.2.1 Chimney type paddy dryer

This dryer named as 'Rice Dryer' was developed by Exell[55] in Bangkok, Thailand and which consists of a simple air heater, drying chamber, and a tall chimney used to increase the convection effect. The dryer as is schematically shown in fig.3.9 consists of solar air heater made of framework of bamboo poles and wire convered with 0.15 mm thick transparent PVC sheet and the ground is covered with burnt rice husk which absorbs the solar radiation and heat the air. The hot air in this air heater rises to the drying chamber kept at its top and the fresh outside air enters from the front openings of the air heater. The drying chamber may either consists of transparent PVC sheets on bamboo frame absorbing directly the solar radiation or with bamboo frame covered from all the four sides with some opaque material. The drying material(rice) is kept in the drying chamber on nylon netting of sufficient sized pores spread on bamboo matting. The drying material is kept on this nylon net tray in thin layer through which hot air heated from air heaters enters through its bottom and goes up in to the chimney. The chimney is a long cylinder made of bamboo frame covered with black PVC to keep the inside air warm. There is a cap at the top of the chimney leaving some space in between chimney top and cap to allow warm humid air to go out and protecting the product from rain and other foreign materials. The height of the chimney and the hot air inside it creates a pressure difference between its top and bottom and therefore creating a forced movement of air through the rice bed to the top of the chimney. Although this dryer is designed to dry rice only but other food products or grains which require slow-low temperature drying may also be dried. The drying rate will depend on depth of the bed, Initial moisture content of the material, solar insolation, ambient temperature, and the design of the dryer. It is experienced that if the material in the dryer remained untouched then the material in the lower layer gets overheated and overdried while at the top remained underdried. Therefore stirring of material and thin layer of material is recommended. This dryer has been studied both experimentally and theoretically[56,57] by scientists of the Asian Institute of Technology, Bangkok, Thailand.

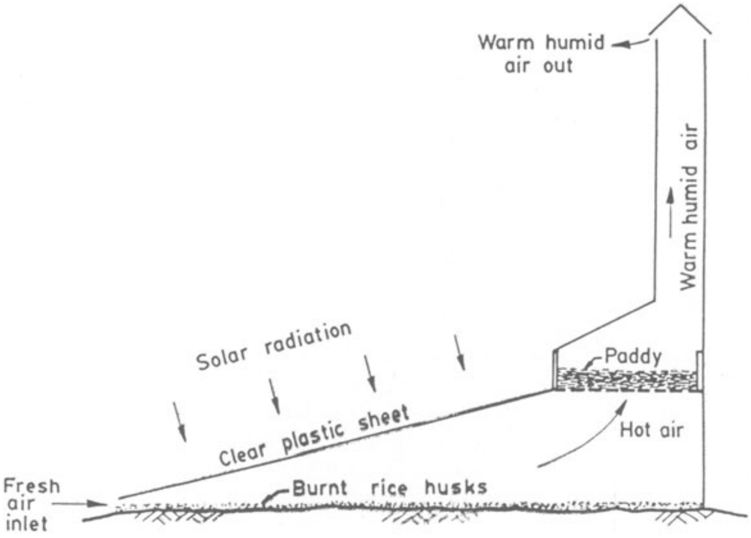


FIG.3.9 CROSS SECTION OF CHIMNEY TYPE DRYER.

3.4.2.2 Fruit and Vegetable dryer

As discussed earlier, the fruit and vegetables contain little more moisture compared to grains and therefore are to be dried quickly otherwise the material may get deteriorated. A fruit and vegetable dryer suitable for drying small quantities of product was developed in USA and the same is schematically shown in fig.3.10. This is also a combination of direct type and indirect type and the drying chamber is a long column consisting of wooden frame with three sides covered with durable transparent plastic sheet and rear side with openable wooden door. The top of the drying chamber is covered with translucent fibreglass sheet which also allows some solar radiation to go inside and heat the air at the top thus creating air movement in the dryer. Several drying racks one over the other spaced properly are kept in the drying chamber. The air heater consists of some rigid base may be some particle board at the bottom and a blackened metal sheet at the top with some air passage between the two. Fresh outside air enters through the inlet of the air heater, gets heated during its passage to the air

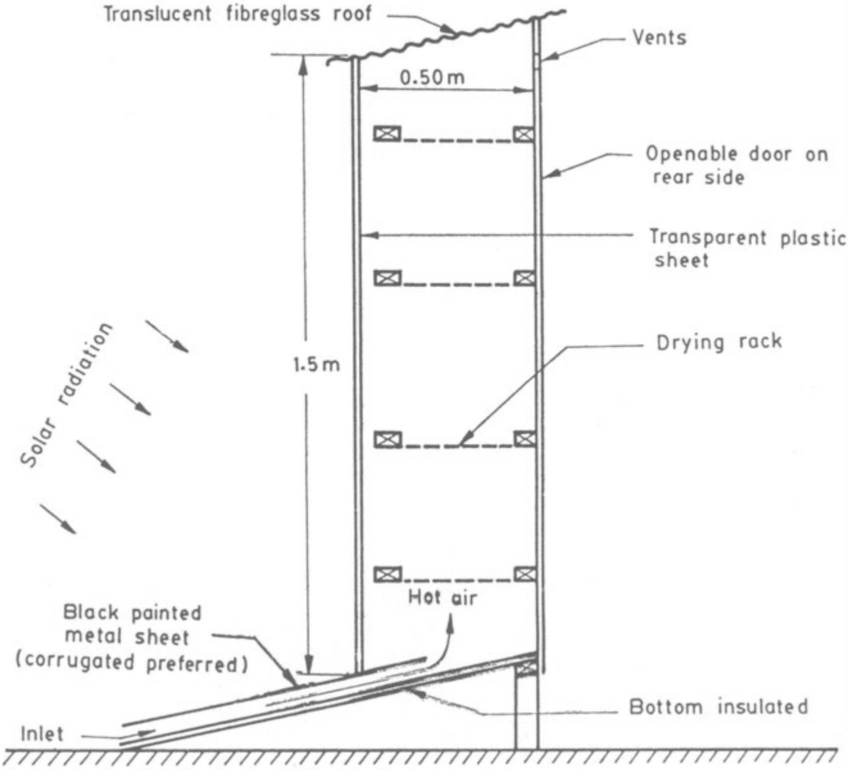


FIG.3.10 CROSS SECTION OF FRUIT AND VEGETABLE DRYER

heater. The heated air rises through the drying racks in the drying chambers and leaves the chamber at the top through vents. Thus the drying material gets heated directly by absorbing heat through the transparent walls and from heated air coming from solar air heater by natural convection.

3.4.2.3 Solar Wind ventilated dryer

The drying rate can be increased if the air flow rate is increased. The air flow rate can be increased either by using an electrically operated fan or wind operated fan. A

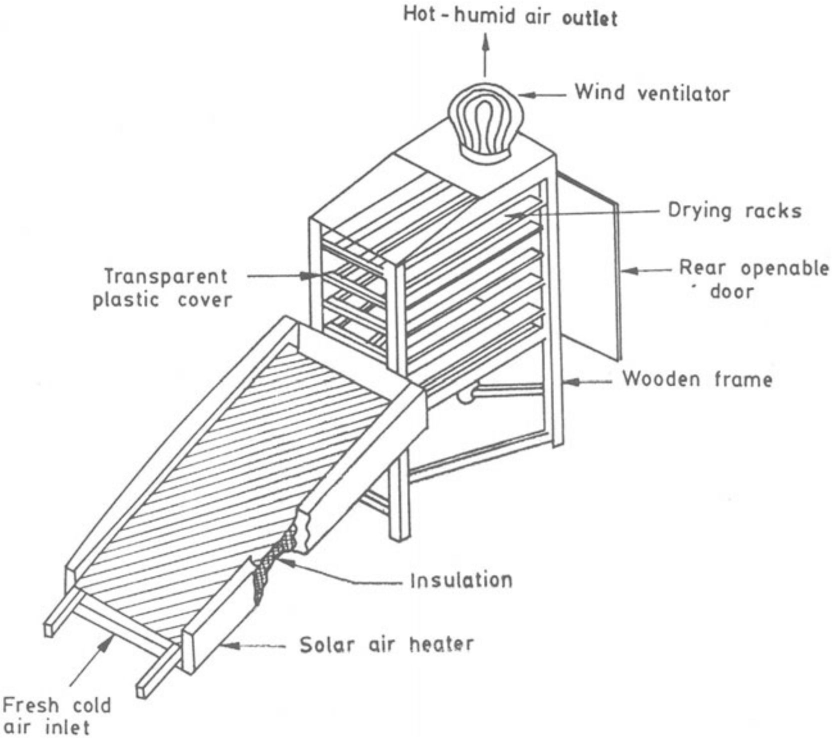


FIG.3.11 SCHEMATIC OF WIND-VENTILATED SOLAR DRYER.

dryer which uses a rotary wind ventilator at the top of the drying bin which increases the air circulation and hence the drying rate is described by Nahlawi[15] and the similar type is used for drying a variety of products in Syria[58], is shown in fig.3.11. As is seen from this figure, the dryer consists of a solar air heater, drying chamber, and a rotary wind ventilator. The solar air heater consists of a blackened hard board sheet with insulation on the rear side and covered by a single sheet of transparent plastic film. A perforated blackened wire mesh is placed between the glazing and the absorbing plate. Fresh outside air enters through the open bottom end of the air heater passes through the space between the glazing and the absorbing plate through the wire mesh, gets heated, reaches the top of the air heater, and enters through the bottom of the drying chamber. The drying chamber is made up of wooden frame with three sides, east, west, and south covered with transparent plastic film and on the rear side facing north is the wooden openable door. The bottom and the north side of the drying chamber is insulated. This drying chamber holds twelve trays placed in two adjacent six-tier stacks. Here also the product gets heated directly from solar radiation transmitted through walls of the chamber and also by the heated air coming from the solar air heater. A rotary wind ventilator is fixed at the top of the drying chamber which when spins in the wind expells air from the drying chamber. The height of the drying chamber should be large so that it provides a chimney effect and to provide more wind for the wind ventilator. Since the air heater operates at low temperatures, efficiency of air heater varies from 50 to 75 percent and the drying time is reduced to one half to one third compared to open sun drying.

3.4.3 FORCED CIRCULATION TYPE DRYERS

As the name implies, in these dryers some kind of blower for the circulation of air which is either operated electrically or mechanically is used. Such dryers are comparatively thermodynamically efficient, faster, and can be used for drying large agricultural products. These forced circulation type dryers are also categorised as direct mode forced circulation type dryers and indirect mode forced circulation type solar dryers. The direct mode forced circulation dryers are similar to the indirect type natural circulation dryers except that here circulation of air is made by forced circulation and therefore are not very efficient and not preferred. While indirect type or forced circulation dryers are very efficient, can be used at low as well as high temperatures, and for drying large quantities of agricultural products. These dryers are of bin type, tunnal type, belt type, column type, or rotary type.

3.4.3.1 Bin type Grain dryers

Solar energy is most ideal for drying grain since it is to be dried at low temperature and slow drying is generally preferred. Since grain is stored and dried in the same bin, this process is termed as in-storage drying. Sometimes it is also called as deep-bed drying or in-bin drying. A typical drying bin is shown in fig.3.12. In all drying bins there is a false or perforated floor which should have an open area equal to 15 percent or more of the total area. Warm air may be at a temperature of 5 to 10°C above the

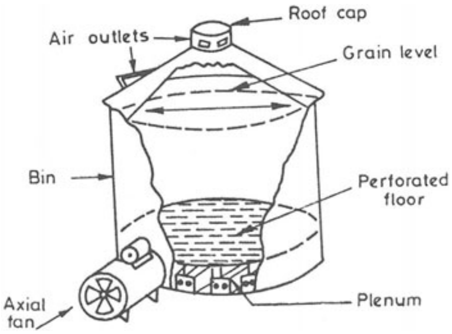


FIG.3.12 TYPICAL DRYING BIN

ambient temperature is drawn into the bin and forced up through the floor into the grain. This warm air during its passage picks up moisture from the grain goes up and passes out through the vent to the roof. Generally these bin dryers contain some auxiliary heating device such as electrical or propane heat source located after the fan. Sometimes drying can also be conducted by forcing the outside air through the grain. This in-storage drying is a low cost low capacity drying system compared to other solar drying systems. Several papers[41, 42, 43] on bin dryers are recently published.

There are two important components in the bin dryer, one is the solar collector and second is the bin itself. Generally two types of collectors both made of plastic sheets and materials such as inflated bag collector and Binwall collector are employed in-storage drying systems, since small air temperature rise is required. The inflated plastic solar collector which is commercially available in USA and is light-weight and collapsable consists of a large plastic bag with one fan on one side of the bag(Fig.3.13). This fan is used to keep the bag inflated. The transparent cover is made of UV stablized vinyl and the collector plate is made of two layers of vinyl. The second layer of vinyl is the absorbing plate which consists of a black opaque vinyl while the first layer(in the middle) is made of translucant vinyl. A part of the solar radiation after transmission through the transparent cover gets absorbed by the translucant plastic sheet and the rest is absorbed by the translucant plastic sheet and the rest is absorbed by the black vinyl sheet depending on its absorbtivity. The air picks up heat from the absorbing plate and the translucant sheet and is exhausted into the inlet to the drying bin with the help of the electric blower. There are several versions of these plastic inflated collectors. The advantages of these collectors are low in cost, collapsable, easy to store when not in use, large area can be covered and low pressure drop, while disadvantages are: high heat loss through the base of the collector since there is no insulation in base, and remains horizontal hence intercept less radiation during winter season when sun is low.

Another type of solar collector known as bin wall collector are studied by Peterson[59]. These bin wall collectors which do not need any much space and becomes almost a part of the bin are schematically shown in fig.3.14 for circular and rectangular bins. In bin-wall collectors, generally the bin wall is painted flat-black which forms the collector plate. In circular bins, the south half portion acts as the collector, and the bin wall is covered with a transparent UV stabilized plastic film spaced with the surface and held in position using intermittently spaced wood studs. In case of rectangular bins, the south wall as well as the south facing roof acts as a collector. Air is sucked by the fan through the space between the bin wall(collector plate) and transparent cover and is forced by the fan to the drying bin through the grain. Permanent covers like fibreglass sheets etc. can also be used in bin dryers. However, when drying is not required the cover is to be removed, otherwise it will result in very high temperature of bin wall resulting in convection currents in bin and therefore unnecessary moisture migration in the grain. This bin wall collector has an advantage that it does not need any additional space and intercepts more radiation in winter season compared to horizontal collector. The disadvantages are: the bin wall area sometimes is not sufficient to dry the grain in sufficient quantity and hence additional collector

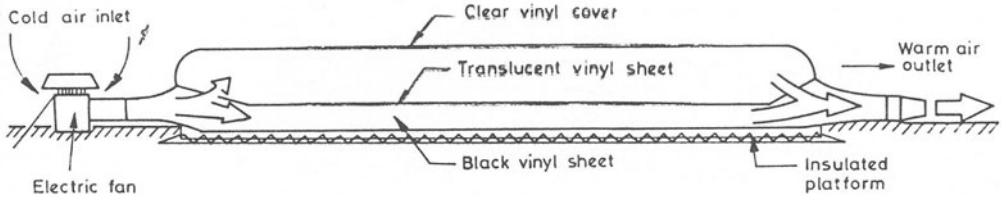
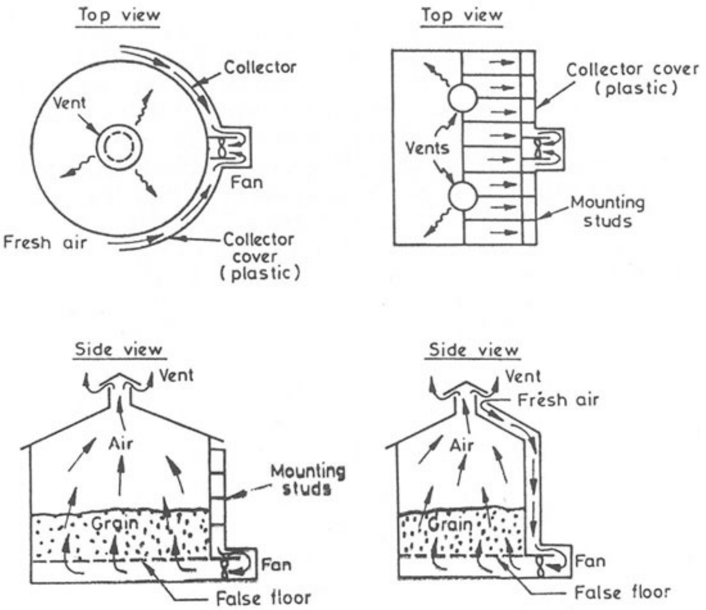


FIG.3.13. SCHEMATIC OF PLASTIC INFLATED COLLECTOR

area is required, and the collector is to be removed in the non-drying season which is a little difficult one.

Filling the drying bin with harvested grain is an important strategy since if it is not done scientifically



(a) Circular bin (b) Rectangular bin

FIG.3.14. CROSSECTION OF BIN WALL COLLECTORS FOR CIRCULAR BINS AND RECTANGULAR BINS.

then it may spoil the grain. There are three filling strategies: single filling, layer filling, and controlled filling. There are advantages and desadvantages of each filling strategy but the controlled filling is preferred. In the single layer filling which is known as fast filling which is done within 1 to 3 days, the drying is to be done at a faster rate otherwise there is a possibility that the drying front may not reach at the top layers in the allowable storage time when it should be at safe storage moisture content level and therefore the grain at the top level may get spoil. In the layer filling technique the bin is filled in layers as the harvest season progresses. The initial layer of grain which contains higher moisture is a single layer in the bin and gets dried quickly because of higher flow rates. The second layer which is at a slightly lower moisture content require comparatively less air flow rate and therefore gets dried. Finally the last layer of grain contains less moisture and requires less flow rate for drying and therefore gets dried in due course of time since lower layers are already dried. In the controlled filling strategy which is similar to the layer filling strategy, the second layer is not filled in the bin unless the first layer is fully dried. This strategy in no doubt reduces the chances of spoilage and filling proceeds as fast as the drying occurs, but increases the harvesting time.

There are basically three types of grain dryers[60]. In the non-circulating batch type dryer, the grain is loaded as a batch and it remains stationary throughout the drying period. In the re-circulating batch type dryers the grain is loaded and unloaded continuously or intermittently. These three types of dryers are available in stationary bins and portable dryers. The bin dryers of various capacities and types are available. The bin dryer should be sized in such a way that the grain harvested in a day should be dried in 24 hours. In the batch-in-bin process which is of low cost and which contains a fan, a heater, a perforated floor, grain spreader, sweep auger, and underfloor unloading auger, the heater and the fan unit is started as soon as the first layer of grain is filled in the bin and continues till this grain layer reaches to the equilibrium moisture content. The second layer of grain is dumped in the bin when the first is dried and it all depends on the initial moisture content of the grain and size of the drying unit. For efficient drying, air-flow rates of 125 litres per second per cubic metre of grain is suggested. The grain depth depends on the initial moisture content and the type of grain. Typcially[60] at moisture content below 20 percent grain depths for wheat, oats and barley is 1.5 m to 2.0 m. If moisture content is high then the grain depth should be low. As a matter of rule, lower and uniform layer of grain will increase the air flow and increase the drying rate. The heating of air is stopped when the drying front is about 15 cm from the surface, because rest of the drying will be done automatically when the grain is cooled for storage. Cooling can be done with the dryer fan itself or if aerated storage is available then hot grain can be transfered to the storage bin directly and it can be cooled by aeration fan. In any case the grain should be cooled to within 5°C of ambient air to prevent condensation or moisture migration [60].

There are some bin dryers, where the perforated drying floor which is cone-shaped holding the grain to be dried is located about one meter below the roof. The fan and the heater unit is also placed below the drying floor. When the grain gets dried it falls on the second perforated floor in the bottom of the drying bin where aeration fan is used to cool the grain. After the first batch is over, the second batch is loaded on the drying perforation floor and the same procedure is repeated. This process of drying is repeated till the bin is filled upto the level of heater unit with the dried and cooled grain and then the grain is transfered to the storage bin. All the process like drying, cooling and storage can continue simultaneously also. More uniform drying can be obtained if a vertical stirring auger is used in the drying bin. Stirring auger increases the drying rate and therefore grain depths upto three meter can be used. This also avoids the overdrying of grain in the bottom layers.

There can be a recirculating batch bin dryer also where the grain dries more uniformly than in a non-recirculating batch dryer. In these type of dryers either the grain is recirculated or the grain is supplied at a continuous flow in the bin. In one of the recirculating bin dryers, the perforated floor can be sloped towards the centre so that the grain flows in the centre of the bin from where it is picked up by a cential vertical auger and delivered at the top of the drying bin. The dried grain gets mixed up with the other grain and provides a more uniform drying.

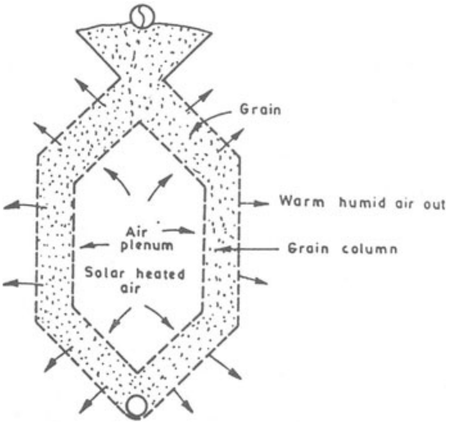


FIG.3.15. NON-RECIRCULATING TYPE BATCH DRYER.

There are portable bin dryers also which are on wheels and can be taken to farms for drying operations only and these are also of two types recirculating type or non-recirculating type. Fan type, capacity, and column width in a batch dryer are important parameters. Centrifugal fan will provide more uniform airflow rate with different grains and quiter in operation compared to axial fans. Lower column widths and large fan capacity will provide higher drying rate. But this will result in lower fuel efficiency. Batch type dryers are preferred over the continuous flow-dryers where relatively small amounts of different grains are to be dried. However, batch dryers require higher flow rates and therefore more pumping power is needed. The batch dryer can be non-recirculating type or recirculating type. In the non-recirculating batch dryer as shown[60] in fig. 3.15 there are two enclosed columns and the wet grain is loaded in the dryer from the top until it is filled. The solar heated air is passed through the grain as shown in figure till the grain gets dried. Since the grain is not re-circulated or does not move, the inside layer gets over-dried while the outermost layers may be underdried. After the drying cycle is over, the grain is either cooled in the dryer itself by putting the heating unit off or it is transferred to the aeration bin for cooling. In the recirculation batch dryer as is shown in fig. 3.16 there is a central vertical auger which is surrounded by a air plenum and which is surrounded by grain. The operation is similar to the non-recirculating batch dryer except that here the grain is continuously recirculated with the help of vertical auger throughout the heating and cooling processes. The auger picks up the grain from the bottom of the circular bin and delivers it at the top of the bin.

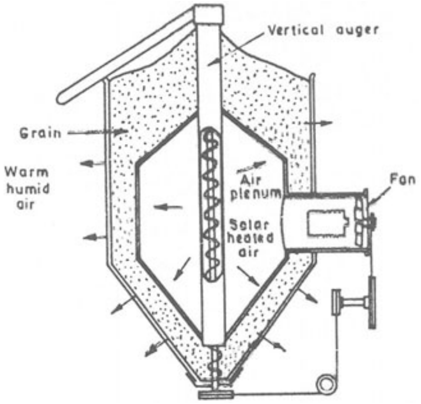


FIG.3.16. RECIRCULATING TYPE BATCH DRYER.

The continuous flow bin dryers are also of two types: the crossflow dryer and parallel flow drier. In the continuous cross flow dryer as shown in fig.3.17 there are two vertical grain columns and the hot air flows normal to the grain flow. Here also the wet grain is filled from the top of the dryer, moves down into the two hot air plenum chambers and finally at the bottom it is removed by the auger. The grain flow rate can be controlled either automatically or manually depending on the initial grain moisture content, column width, and the hot air temperature and its flow rate. Here also there is no mixing in the grain hence the grain on the inner layer gets overdried while on the outermost layer side remains underdried. In the parallel continuous-flow dryers as shown in fig.3.18, the air flow is parallel to the grain flow. In this design there is more uniform drying since all the grain layers get air at uniform temperature and grain gets mixed up while it moves down but it required air slightly at higher temperatures for drying.

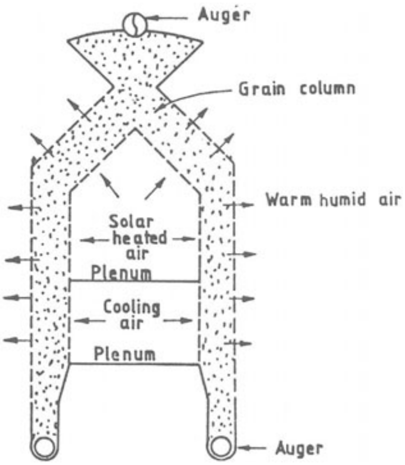


FIG.3.17. CONTINOUS CROSS-FLOW BIN DRYER

Another important parameter is the circulation of air. Generally in small dryers it is preferred to exhaust the warm humid air. But in commercial dryers, if the part of the exhausted warm humid air is recirculated, the efficiency of the system improves. It has been proved that even if the 50 percent of the warm exhaust humid air is recirculated through the drier, the dehydrator efficiency increases by about 30 percent but the drying rate decreases by about 10 percent. This can be explained on the psychrometric chart shown in fig.3.19. When no air recirculation takes place, the heating and drying can be shown by line A B and C. Here point A shows the temperature T_1 and humidity H_1 of the fresh air entering the dehydrator, point B represents the maximum air temperature after the heating. Thus line AB represents the rise in enthalpy of air. Now when there is no recirculation, the air at condition B will be cooled adiabatically along the line BC picking up moisture from food material and exhausted at point C. Now if a part of this warm humid air and fresh air is heated to point D at temperature T_2 and humidity H_2 and passed over the food it cools adiabatically along the line DE and air at condition E is achieved. Again a part of the air is exhausted and a part mixed with fresh air and heated to get a new condition F shown in fig.3.19. This procedure may continue again and

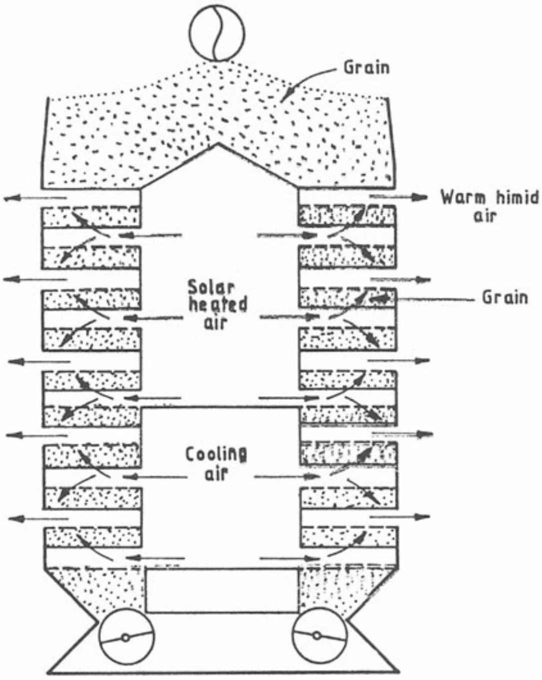


FIG.3.18. CONTINOUS PARALLEL-FLOW BIN DRYER.

again. Thus it is seen that although additional heat is required because of additional re-heating steps but the quantity of heat used for evaporating per kg of water evaporated gets reduced.

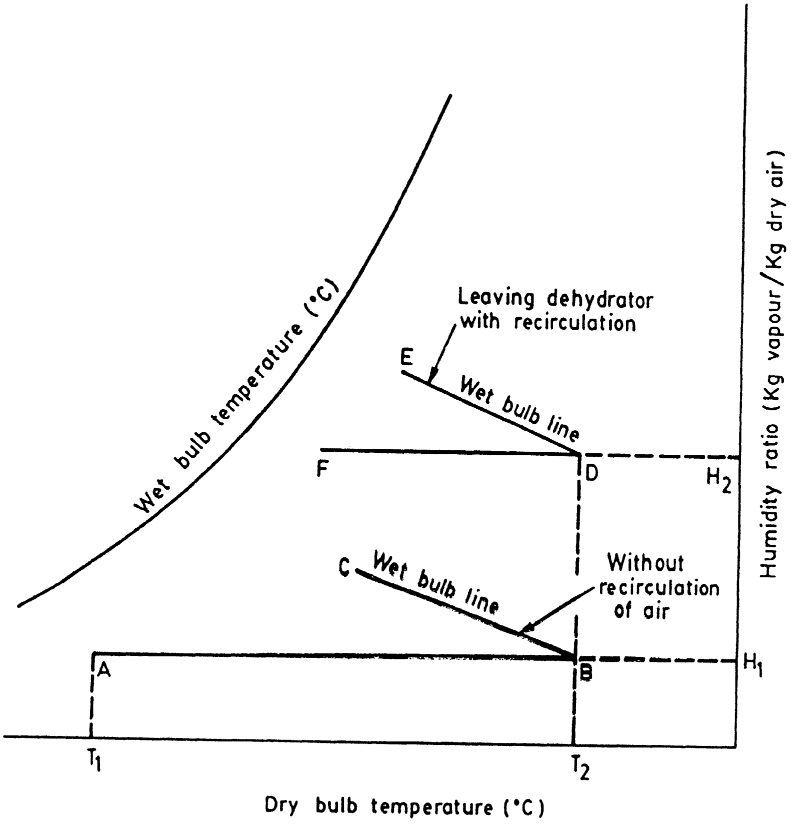


FIG.3.19. THE EFFECT OF RECIRCULATION OF AIR IN DEHYDRATOR.

3.4.3.2 Tunnel or Belt dryer.

Tunnel or belt dryers are large scale drying system consisting of an elongated enclosure through which trucks loaded with trays filled with material moved automatically through the dryer from one direction while solar heated air at 50°C to 80°C moves from the opposite direction. These trucks move continuously from one end to the other end and introduced periodically at one end of the dehydrator. In actual operation the food required drying is spread in uniform thin layers in trays which are stacked one over the other to a height of 1.5 to 2.0 m.

In the belt dryer, the prepared food is kept on belt spread on it in a uniform thin layer(10 cm) and the belt continuously moves in a direction opposite to the direction of hot air which is sufficiently at a high flow rate and high temperature (70 to 100°C). If the product gets sufficiently dried then for final drying it can be spread in thick layers (40 cm) and hot air at 40°C to 70°C can be employed for drying. Such tunnel or belt type dehydrator if retrofitted and Solar Energy/auxiliary fuel is used will prove to be economical.

3.4.3.3 Solar assisted or Hybrid dryers

Due to intermittent nature and low intensity of solar radiation, and auxiliary heating arrangement is always used. Storage of solar heat will make the system more dependable. Such drying systems where solar energy is used to supplement the auxiliary energy are known as solar assisted or hybrid drying systems. So in such hybrid dryers there are some kind of solar air heaters, drying bin, fan or blower, auxiliary energy supply unit and a thermal storage device. Auxiliary energy may be supplied either by electric heating or through oil or gas burners and used only when the solar air heaters or the heat from the thermal storage device is not sufficient to supply the necessary energy for drying the product. Several storage systems are proposed but the most preferred one is the rock bed storage system which stores the heat in the form of sensible heat and performs the dual function of storing the heat and acts as an heat exchanger also. The storage is used only when the solar air heaters are not able to supply the necessary heat required for drying. The storage is charged when the solar radiation is at the peak or when the drying is not required. Storage unit is put in series to the solar collectors.

Scientists of the California Polytechnic State University in collaboration with TRV Space and Energy Systems have set up [61] a large solar assisted fruit and vegetable dryer at Fresno, California. The solar contribution in this hybrid system is 1582 MJ/hr which is about 60 percent of the total heat requirements for drying. This solar dehydrator consists of several single glazed solar air heaters with a total area of 1950 m^2, a thermal storage (rock bed) device of about 350 m^3 volume, a novel rotary wheel type heat recovery unit, and a tunnel dehydrator in which 14 trucks loaded with prepared food moves at a rate of 24 hours per truck in one direction and the heated air is sent from the other direction. This solar dehydrator is schematically shown in fig.3.20. It is seen from the figure that the ambient air is first preheated in the heat recovery wheel by means of warm humid air coming from the dehydrator to be exhausted. This preheated air is further heated to the desired level either by passing it through the thermal storage unit or passing it through the auxiliary energy heating unit or by the combination of these two depending upon the availability of energy in the storage unit. In this case the control system will divide the air flow, one part going through the storage unit and second part going through the auxiliary heater part to raise the temperature of air at the desired level. This system is designed for a fixed air flow rate of 9.5 m^3/s to the dehydrator 24 hours a day. The drying temperature varies in different months say 60°C in the beginning of June to 66°C in August and September.

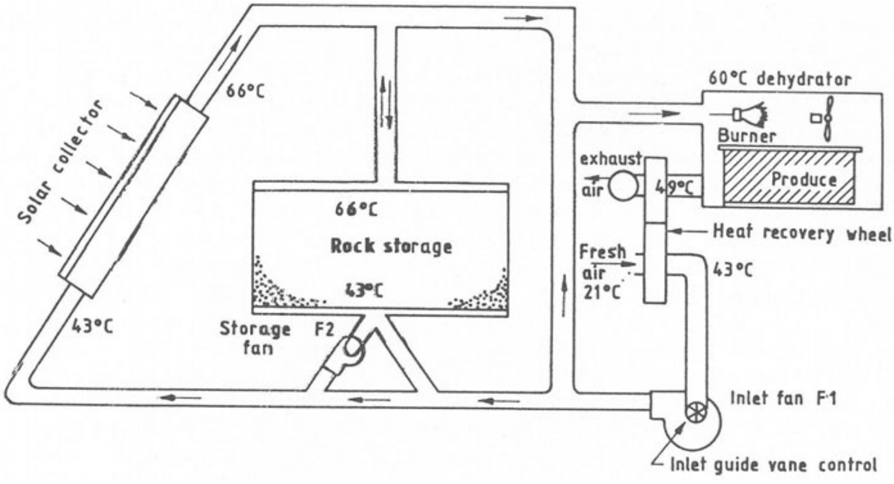
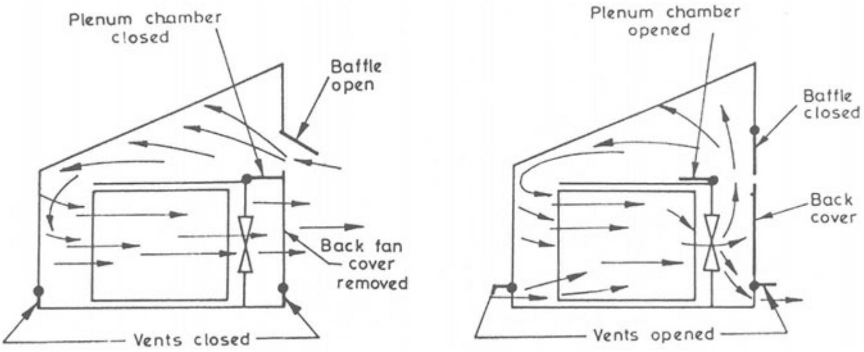


FIG.3.20. SOLAR CROP DEHYDRATOR AT FRESNCO, CALIFORNIA.

3.4.3.4 Solar Timber drying

Drying of lumber is required for its use in making furniture, doors, cabinets, floorings, wood carvings, etc. Air drying of lumber is the cheapest, and simplest but it takes longer time in drying since it gets effected with rain and varying degree of humidity and even the product is not superior. Therefore, kiln drying using fuel heated air is generally adopted. The use of solar energy for lumber drying can save the fuel and can be used to small units of low capital investment. It has been observed that solar dried lumber is better compared to open air dried lumber. The lumber dryer generally consists of a large green house generally rectangular with all the four walls and roof made of single or double covers of transparent plastic sheet or glass sheet. Inside the chamber the floor which is generally made of cement concrete is a bit raised one and on which the lumber is stacked in such a way that there is sufficient space for the circulation of air. An electrically operated fan is used for circulating the air inside the chamber through the stack. The inside wooden frame, ground etc, are all painted black.



(a) Single pass dryer.

(b) Recirculating type dryer.

FIG.3.21. TWO MODES OF OPERATING SOLAR KILN

Studies on solar lumber drying are conducted in India by Rehman and Chawla[16], and Sharma[21] et al who actually built solar timber seasoning kilns and experiments conducted on several species. Studies on solar lumber drying are conducted in many countries like USA[62,17], Japan[23], Taiwan[18], Uganda[63], Australia[64], Fizi[65], Philippines [66], etc. Almost all the solar kilns are similar except some small small variations. The idea is to utilize the low grade heat and to increase the drying rate without degradation of the timber. The solar timber seasoning kiln as described by Sharma et al[67] and shown schematically in fig.3.21 and 3.22 consists of a rectangular structure with frame work made of wood and long axis in the E-W direction. Tilted roof facing south at an angle of 24 deg. from horizontal was used in the present construction. All the walls except on the north side and roof is covered with two layers of transparent polyethylane sheet seperated by an air gap. In later designs glass sheets are employed in place of

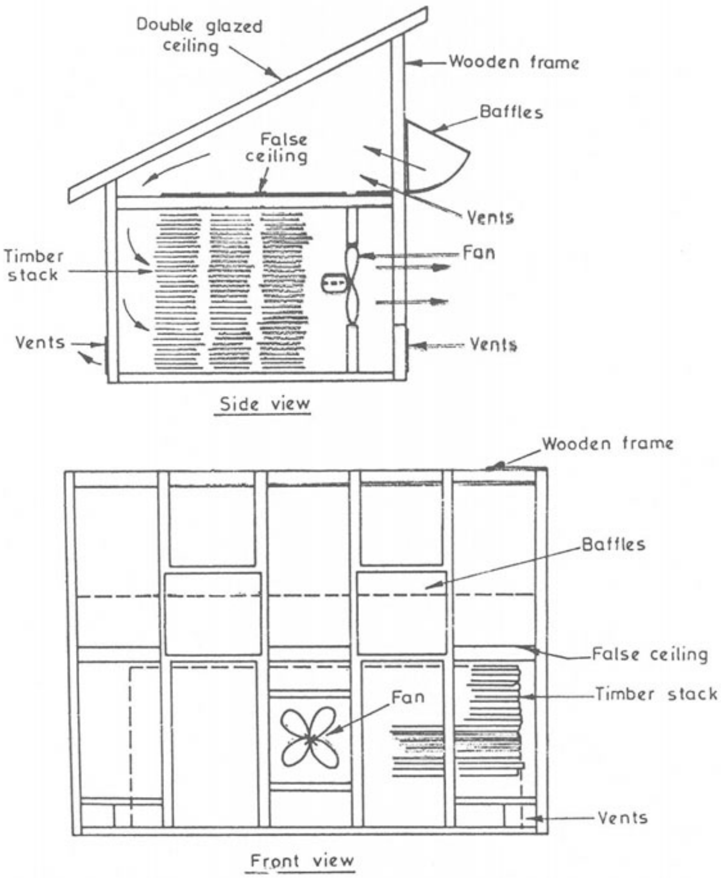


FIG.3.22. FRONT AND SIDES OF SOLAR KILN.

polyethylene sheets. There is a false ceiling in the kiln above the wood stacks. There is a another false north side wall extending from the wood stack level upto the false ceiling and at its centre a fan is fixed. All the interior surfaces are painted black. The kiln has a space to dry 7.1 m^3 of 25 mm thick planks on 25 mm thick crossers. The adequate humidity in the kiln is maintained with the help of a water spray humidifier provided on the north side of the wall in the upper protion of the false ceiling. With some adjustments the kiln can be operated either as a single pass flow through dryer or as a recirculating dryer. The fan of 1.5 KW is used for the circulation of air in the kiln.

3.5 THEORY AND SIMULATION MODELS [Ref. 3,43]

Drying simulation models are useful in predicting the performance of design variables and in knowing the contribution of solar energy in drying the product. In drying the heat and mass transfer occurs simulatneously. The necessary heat required to evaporate the moisture from the surface of the material is generally provided by heated air. As discussed earlier, most of the biological materials, initially dry in the period of constant rate moisture loss and then followed by falling rate drying period. Most of the cereal grains which contains less moisture, dry entirely in the falling rate period. Generally most food products/grains are either dried in single layer or in deep layer and the drying behaviour in both the cases is different and therefore discussed here seperately.

3.5.1 Single layer drying

As discussed earlier if the moisture content of the product is high, then the surface of material will behave like a thin layer of water and the internal resistance of moisture transport will be much less than the external resistance to water vapour removal from the surface and the product will dry in the constant moisture rate loss. The drying rate dM/dt in the constant drying rate period can be determined by either using equation(3.1) or (3.2) and the drying time tc can be determined by using equation(3.1) or (3.2). However, the only thing to be determined is the transfer coefficients h_D and h_C which sometimes is difficult to determine because of irregular shapes of the products.

In the falling rate period, the thermal resistance for the moisture movement within the product becomes more than the external resistance and therefore the driving potential $(P_{vwb}-P_{v\alpha})$ decreases and thus the drying rate decreases. In this falling rate period the product temperature increases and is more than the wet bulb temperature. In the falling rate period the rate of moisture evaporation is both a function of internal variables and external variables and therefore it is difficult to predict the drying rate. Only empirical or semiemprical methods are used in predicting the drying rate. Several mechanisms[3] are proposed to explain the movement of moisture in capillary porous products such as in grains. Some of the mechanisms proposed are: there can be liquid movement due to surface forces (capillery flow), there can be liquid movement due to moisture concentration difference (liquid diffusion), there can be vapour movement due to moisture concentration difference (vapour diffusion), there can be vapour movement due to temperature differences (thermal diffusion), there can be liquid and vapour movement due to pressure difference (hydrodynamic diffusion),etc. For the drying of capillary porous products, Luikov[68] has given a set of following partial differential equations:

$$\frac{\partial M}{t} = \nabla^2 K_{11} M + \nabla^2 K_{12} \Theta + \nabla^2 K_{13} P$$

$$\frac{\partial \Theta}{\partial t} = \nabla^2 K_{21} M + \nabla^2 K_{22} \Theta + \nabla^2 K_{23} P \qquad (3.5)$$

$$\frac{\partial P}{\partial t} = \nabla^2 K_{31} M + \nabla^2 K_{32} \Theta + \nabla^2 K_{33} P$$

Here K_{11}, K_{22} and K_{33} represents the phenomenological coefficients and other K's are the coupling coefficients. Although moisture M, temperature θ and pressure P effects the moisture flow inside the grain, but it has been observed that the moisture movement due to pressure graient is significant only at sufficiently high temperatures which is not within the range of grain drying, hence the above equations reduces to:

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M + \nabla^2 K_{12} \Theta$$

$$\frac{\partial M}{\partial t} = \nabla^2 K_{21} M + \nabla^2 K_{22} \Theta \qquad (3.6)$$

The above two equations are applicable to many food products. It is also observed that for most of the cereal grains the coupling effects of temperature and moisture is not very significant and hence equations (3.6) reduce to

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M$$

$$\frac{\partial \Theta}{\partial t} = \nabla^2 K_{22}\Theta \qquad (3.7)$$

Equations (3.7) can be very effectively employed to describe the drying and thermal behaviour of grains. However, it was observed that even the thermal diffusion effect is insignificant upto temperatures 120°C. So Luikov's equations finally leads to the following equation:

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M \qquad (3.8)$$

Where K_{11} is now termed as diffusion coefficient and is replaced by D, the diffusion coefficient. Now for a constant value of diffusion coefficient D, the equation (3.8) can be written as:

$$\frac{\partial M}{\partial t} = D\left(\frac{\partial^2 M}{\partial r^2} + \frac{C}{r} \frac{\partial M}{\partial r}\right) \qquad (3.9)$$

Here r defines the particle's coordinate and C is a constant and is zero for planar symmetry, C is unity for cylindrical body and C is two for a spherical body. Now equation (3.9) can be solved for any regular shape of the grain with the following initial and boundary conditions;

$$M\ (r,\ 0) = M_{in} \qquad (3.10)$$

$$M\ (r_o,\ t) = M_{eq} \qquad (3.11)$$

Where M_{in} and M_{eq} are the initial and equilibrium moisture content. Solving equation (3.9) using the above boundary conditions, the expression of moisture ratio $MR[=(M-M_{eq})/(M_{in}-M_{eq})]$ for a infinite plane is given as-

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\alpha} \frac{1}{(2n+1)^2} \exp.\left[-\frac{(2n+1)^2\pi^2}{4} x^2\right] \qquad (3.12)$$

and for a sphere the equation is

$$MR = \frac{6}{\pi^2} \sum_{n=0}^{\alpha} \frac{1}{n^2} \exp.\left[-\frac{n^2\pi^2}{9} x^2\right] \qquad (3.13)$$

and for an infinite cylinder the equation is

$$MR = \sum_{n=1}^{\alpha} \frac{4}{\lambda_n^2} \exp.\left[-\frac{\lambda_n^2}{4} x^2\right] \qquad (3.14)$$

where $x = A\,(D_t)^{1/2}/V$, λ_n is the roots of bessel function of zero order, A is area and V is volume of the body.

For products with high moisture content such as fruits and vegetables, first there will be constant rate period then there will be falling rate period. The drying of such high moisture products is modelled by Hussain et al[69]. Sarvacos [70] has expressed the diffusion coefficient as an exponential function of moisture content.

$$D(M) = D_o \exp(pM) \qquad (3.15)$$

Where p is a constant. It is also shown by Sarvacos[70] that the drying process can be explained well by three process : Constant rate, Ist falling rate, and 2nd falling rate (Fig.3.3). Therefore for three phases of drying, three different models are given as follows:

For contant rate drying where $Min \leq M \leq Mc$

$$\frac{\partial M}{\partial t} = \nabla^2 D_{eff}\, M$$

$$\frac{\partial \theta}{\partial t} = \nabla^2 K_{22}\, \theta \qquad (3.16)$$

For first falling rate period where $M_{hyg} \leq M \leq Mc$

$$\frac{\partial M}{\partial t} = \nabla^2 D_{eff}\, M \qquad (3.17)$$

$$\frac{\partial \theta}{\partial t} = \nabla^2 K_{22}\, \theta + K \frac{\partial M}{\partial t} \quad \text{where } K = \frac{L}{C_p}$$

For second falling rate where $M_{eq} \lesssim M \lesssim M_{hyg}$

$$\frac{\partial M}{\partial t} = e^{PM}\, \nabla^2 M + Pe^{PM} \left(\frac{\partial M}{\partial x}\right)^2$$

$$\frac{\partial \Theta}{\partial t} = \nabla^2 K_{22}\Theta + K\frac{\partial M}{\partial t} \qquad (3.18)$$

Depending upon the initial and boundary conditions, these equations can be solved.

There are empirical equations developed for various products under certain specific conditions to predict the drying rate in addition to the above theoretical equations. The drying time, t, for shelled corn in the temperature range of 60to 150°C was calculated by Thompson et al[71] and the same can be calculated from the following empirical equation:

$$t = A \ln MR + B(\ln MR)^2 \qquad (3.19)$$

where $A = -1.086178 + 0.00488(1.8\,\theta + 32.0)$
and $B = 427.3640 \exp(-0.055418\,\theta - 1.05632)$

Another empirical drying equation was developed by Flood et al[72] for corn in the temperature range of 2 to 22°C, which is given as:

$$MR = \exp[-K(t^{0.664})] \qquad (3.20)$$

where,

$$k = \exp(-xt^{y})$$

$$x = [6.0142 + 1.453 \times 10^{-4} (\phi)^2]^{0.5} - (1.8\,\theta + 32)[3.533 \times 10^{-4} + 3.0 \times 10^{-8} (\phi)^2]^{0.5}$$

$$y = 0.1245 - 2.197 \times 10^{-3}\phi + 2.3 \times 10^{-5}\phi\,(1.8\theta + 32) - 5.8 \times 10^{5}(1.8\,\theta + 32)$$

Where ϕ is the relative humidity, x and y are bed coordinates, and θ is grain temperature in °C.

The following formula is derived by Becker[73] from the drying rate data of wheat:

$$MR = 1 - 24.82\tfrac{1}{4}Dt)^{1/2} + 14.29\,Dt \qquad \text{for} \quad (Dt)^{1/2} < 0.034$$

$$\text{and} \quad MR = 0.509 \exp(-629.68\,Dt) \qquad \text{for} \quad (Dt)^{1/2} \geqslant 0.034$$

$$(3.21)$$

where $D = 76.8 \exp[-11080/\theta_{abs})$

Here θ_{abs} is in °R.

3.5.2. Deep-bed grain drying

Upto now we have considered only the drying of individual cereal grain Kernals or in thin layers which is done only when the moisture content in the product is high. However, most of the cereal grains contain low moisture and dried in large quantities and therefore deep bed drying is preferred. Several models are proposed for predicting the drying rate in deep-bed grain drying.

3.5.2.1 Logarithmic model

The first logarithmic model which is a empirical method of modelling low temperature drying is proposed by Hukill [74]. The assumptions made in this model are: (1) the latent heat of evaporation of moisture of grain is much more than the sensible heat required to heat the grain and removing the moisture, (2) during the drying process when moisture is added in the air, the increase in its sensible heat is negligible, (3) grain density is constant, and (4) during the drying process there is an equilibrium between the air and grain temperature. Based on these assumptions Hukill [43] has given the following equation:

$$G_aC_a \frac{\partial T}{\partial y} = \rho_g L \frac{\partial M}{\partial t} \qquad (3.22)$$

where Ga is the air mass flow rate. The solution of this equation is given as:

$$MR = \frac{2^{D'}}{2^{D'} + 2^{r'} - 1} \qquad (3.23)$$

where D' and Y' are the dimensionless depth and time variables, and are given as:

$$D = \frac{LK\rho_g\ (M_{in} - M_{eq})y}{G_aC_a(T_a - T_g)} = D'\ln 2$$

$$Y = K.t = Y'\ln 2$$

where Ta is the air temperature in the plenum, and Tg is the exhaust air temperature. Barre et al[75] obtained the following equation of moisture ratio MR, when he used the above logarithmic model and applied the boundary conditions.

$$MR = \frac{1}{D} \ln \left(\frac{e^{D} + e^{Y} - 1}{e^{Y}} \right) \qquad (3.24)$$

The above two models were tested by many workers[76] against the emperimental results and found that this logarithmic model is unable to describe the movement of drying zone.

3.5.2.2 Partial differential equation (P.D.E.) model.

The partial differential equation (PDE) model which is simply a set of partial differential equations used for modelling the drying process is more accurate compared to logarithmic model and is applicable to both at high temperature and low temperature processes. The assumptions made in formulating the PDE model are:
(1) during the drying process the volume shrinkage is negligible, (2) conduction from particle to particle is negligible, (3) within the individual particles the temperature gradient is negligible, (4) both the grain flow and air flow is plug type, (5) $\partial T/\partial t$ and $\partial W/\partial t$ are negligible compared to $\partial T/\partial x$ and $\partial W/\partial x$, (6) the bin walls have negligible heat capacity and are adiabatic, (7) during short time intervals the heat capacities of grain and moist air are constant, and (8) the moisture equilibrium isotherm and thin layer drying equations are accurately known. Now the analysis will be done for the fixed bed (stationary bed) and fluidized bed.

(A) Fixed bed model(Ref.3)

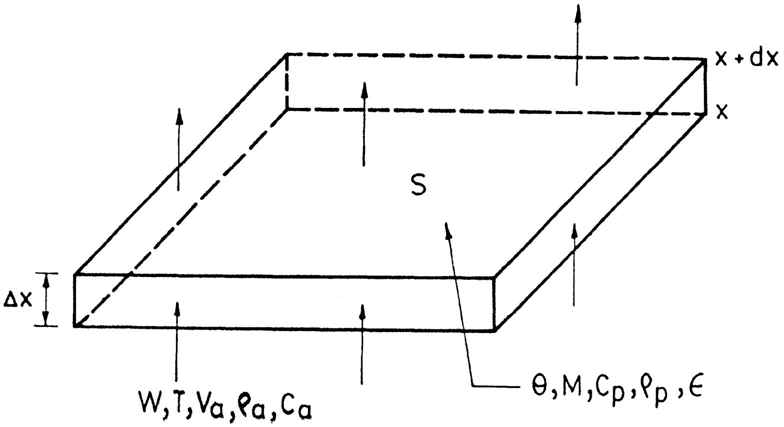


FIG.3.23. BED VOLUME

For making this model, we consider an elemental bed volume(Fig.3.23) located anywhere in the fixed grain bed. Now the drying characteristics require four unknowns: the moisture content M, the humidity ratio of air W, the air temperature, t, and kernal temperature θ. Now following Sodha and Kumar[77], four balances are made resulting in four differential equations.

(i) Enthalpy of air: The heat transfered by convection to the grain bed is equal to the sum of the enthalpy carried out of the volume by air and the change with respect to time in the enthalpy of air in the void spaces.

$$G_aC_a \frac{\partial T}{\partial x} = \varepsilon \rho_a C_a \frac{\partial T}{\partial t} = -h(T-\theta) \qquad (3.25)$$

where Ca is specific heat of moist air, Ga is mass flow rate of air, ε is bed porosity, ρa is air density and h is enthalpy.

(ii) Enthalpy of grain: The energy transferred by convection by hot air to the grain is used as sensible heat in increasing the grain temperature and temperature of evaporated moisture and as latent heat in evaporating the moisture from grain. Thus on the grain kernel the enthalpy balance equation is

$$\rho_g C_{gm} \frac{\partial \theta}{\partial t} = h(T-\theta) + L\,\rho_g \frac{\partial M}{\partial t} \qquad (3.26)$$

Here C_{gm} is the specific heat of wet grain (= C_g + MC_m), and ρ_g is the grain density.

(iii) Humidity of air: The moisture loss by the grain kernels is equal to the net amount of moisture carried out of air out of element plus the change in the humidity of the air in the void spaces. Thus we get

$$G_o \frac{\partial W}{\partial x} + \varepsilon\, \rho_a \frac{\partial W}{\partial t} = -\,\rho_g \frac{\partial M}{\partial t} \qquad (3.27)$$

where G_o is the mass flow rate of air at the outlet

(iv) Moisture Content of grain: The drying rate for a thin layer can be expressed either by diffusion type of expression(eq.3.8) or by empirical relation (3.19). Thus for this layer drying, the differential equation will be of the form.

$$\frac{\partial M}{\partial t} = \text{any thin layer drying equation} \qquad (3.28)$$

Now the three differential equations(3.25), (3.26), and (3.27) alongwith the equation(3.28) formulate the simulation model and can be used to study the drying behaviour of a deep stationary bed. The boundary conditions are $T(o,t) = T(\text{inlet})$, $\theta(x,0) = \theta(\text{initial})$, $W(0,t) = W(\text{inlet})$, $M(x,0) = M(\text{initial})$.

(B) Cross flow model:

In a cross flow dryer, the air and grain moves in perpendicular directions i.e. if air flows in x-direction, the grain moves in y-direction. Now considering the differential volume(dxdy) in any location in the bed and making all the assumptions as in fixed bed case, the differential equations will be:

$$\frac{\partial T}{\partial x} = - \frac{h_a\,(T-\theta)}{(G_aC_a + G_aC_{vw})}$$

$$\frac{\partial \theta}{\partial y} = \frac{h_a(T-\theta)}{(G_pC_p + G_pC_{wa}M)} + \frac{L + C_v(T-\theta)}{(G_pC_p + G_pC_{wa}M)}\, G_a\, \frac{\partial W}{\partial x}$$

$$\frac{\partial W}{\partial x} = - \frac{G_p}{G_a}\, \frac{\partial M}{\partial y} \qquad (3.29)$$

$$\text{and} \quad \frac{\partial M}{\partial t} = \text{a thin layer equation}$$

where G_a and G_m is the mass flow rates of air and product respectively, and 'a' is the partial surface area per unit of bed volume, and W is the humidity ratio. The boundary conditions are: $T(0,Y) = T(\text{inlet})$, $\theta(x,0) = \theta(\text{initial})$, $W(0,Y) = W(\text{inlet})$, $M(x,0) = M(\text{initial})$.

(C) Concurrent flow model:

Here in this dryer both the grain and the hot air moves in the same direction. Considering the elemental volume Sdx in the bed and making all the assumptions of fixed bed drying the set of equations will be:

$$\frac{\partial T}{\partial x} = \frac{- h_a(T-\theta\ )}{(G_aC_a + G_aC_vM)}$$

$$\frac{\partial\theta}{\partial x} = \frac{h_a(t-\theta)}{(G_pC_p + G_pC_{wa}M)} - \frac{L + C_v(T-\theta)}{(G_pC_p + G_pC_{wa}M)} . G_a \frac{\partial W}{\partial x}$$

$$\frac{\partial W}{\partial x} = - \frac{G_p}{G_a} \frac{dM}{dx}$$

$$\frac{dM}{dx} = \text{a thin layer equation} \qquad (3.30)$$

The boundary conditions are T(o) = T(inlet), (0) = (initial), W(0) = W (inlet), and M(0) = M(initial). The above equations are total differential equations and can be solved numerically.

(D) Counter-flow model:

In the counter-flow type dryers, the flow of the air and the grain is in the opposite direction, and here also as in earlier cases the energy and mass balances can be considered on an elemental volume(Sdx) of the system with assuming the flow of grain in the positive direction. Assuming all the earlier assumptions and steady state conditions the equations can be written as:

$$\frac{dT}{dx} = \frac{h_a(T-\theta)}{(G_aC_a + G_aC_vW)}$$

$$\frac{d\theta}{dx} = \frac{h_a(T-\theta)}{(G_pC_p + G_pC_{wa}M)} + \frac{L + C_v(t-\theta)}{(G_pC_p + G_pC_{wa}M)} . Ga \frac{dW}{dx}$$

$$\frac{dW}{dx} = \frac{G_p}{G_a} \frac{dM}{dx}$$

$$\frac{dM}{dt} = \text{a thin layer equation} \qquad (3.31)$$

The boundary conditions are:
T(L) = T(inlet), θ(0) =θ(initial), W(L) = W(inlet), and M(0) = M(Initial)

Although equations(3.31) appears to be similar to the equations(3.30) of the concurrent flow case except some changes in the sign but the solutions of equations (3.31) will be quite different from equations(3.30) because while the concurrent model is a single point boundary value problem but the counter-flow model is a two point boundary value problem.

Recently Thomson et al[78] formulated the mathematical model to predict the performance of three types of continuous grain dryers-Cross flow, Concurrent flow, and counter flow. It was observed that the performance characteristics of each of the three dryers are significantly different from each other. The grain gets overdried where the air enters and remains underdried where it leaves in case of crossflow dryers. In the concurrent type of dryers, most of the moisture was removed during the initial stages of drying. The counterflow dryers is the best compared to the other two dryers since it removes more moisture per metre of drying bed than the other two dryers.

3.6 ENERGY REQUIREMENTS FOR GRAIN DRYING

Table 3.7 Energy required(kwh/tonne) for drying corn from 24 percent to 14 percent, wet basis.

	Drying Method	Energy used by	
		Fan	Heat
1.	High speed drying at 90°C	3.2	225
2.	High speed drying at 90°C to 16 percent moisture level and then by dryeration	2.2	170
3.	High speed drying at 90°C to 20 percent moisture and then bin finish.	14.6	100
4.	Batch-in-Bin at 60°C	Fan + Heat	210
5.	In-Bin at 20°C	Fan + Heat	185
6.	In-Bin at low temperature $\Delta T = 4°C$	Fan + Heat	120
7.	Low temperature solar drying, Maximum $\Delta T=10°C$	Fan + Heat	80

The energy required for grain drying is very large and as discussed earlier in USA, liquified petroleum gas or natural gas is used. It has been estimated that for drying 150 million metric tons of crop in USA about 20 million barrels of oil equivalent is used[79]. As discussed earlier that there are a variety of methods used for drying grain and therefore it becomes essential to know that which method is very efficient. Although apart from energy efficient drying process, the other factors like drying capacity, reliability, and quality of the product are also very important. A good review of energy requirements by different drying methods are made by Peart et al[80] and this work is due to them only. The summary of energy required (Kwh/tonne) for drying corn from a initial moisture content of 24 percent to the final moisture constent of 14 percent by various drying methods is given in Table 3.7.

From table 3.7 it appears that from energy efficiency point of view solar drying is the best but solar drying is weather dependent and the calculations made are for central Indiana weather conditions for October, November and December. Another energy efficient system is the one where high speed drying at 90°C is done upto a 20 percent moisture level and then the grain is shifted to the storage bin with perforated floor and the drying is done at low temperature with natural air at a rate of 1 m^3/min/tonne. This system is no doubt energy efficient but required two separate drying systems and therefore the equipment cost is higher. In bin drying at 20°C which is a layer drying method in which the bin is partially filled, dried and then second and third layer is added and dried is also very energy efficient drying system.

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CHAPTER 4

SOLAR POWERED WATER PUMP

4.1 INTRODUCTION

In many developing countries of the world animate power and muscle power is still used for lifting water for crop irrigation or for drinking purposes. Both these methods are highly inefficient, time consuming and becoming costlier. The energy requirements of rural people in developing countries are quite low and are met largely by non-commercial energy sources like firewood, agricultural waste and cow dung cakes. The agricultural land is either irrigated by natural means like rains or by using animal or muscle power. The use of diesel or petrol operated water pumping sets or electric water pump is also increasing. With the increase in population, more land is to be brought under cultivation to increase crop production for meeting the demand of food for which water is an essential ingradient. Moreover, in developing countries where 40-50 percent GNP (Gross National Product) coming from agricultural sector alone, more energy particularly for pumping of water for irrigation is required. Efforts are being made in developing countries to provide electricity in rural areas but the progress has been slow mainly due to the reason that it is capital intensive and is difficult to connect remote scattered villages with the central electric grid system. Therefore decentralized energy systems like solar irrigation pump sets may be more appropriate in developing countries. Taking India as a typical example of a developing country, the energy requirements by human and animal power, diesel engine, and electric motors are assessed and the same are shown[1] in table 4.1 From this table it is seen that by 2000 AD there will be a considerable increase in the use of electric motors and diesel engines for pumping water. Inspite of large efforts made by government of India only 30 percent of the total villages are electrified and that too are not getting sufficient electricity. Very little percentage of villages having population less than 500 are electrified due to large capital investment.

Solar radiation is maximum in summer months when greater need of irrigation occurs. Moreover, intermittent nature of solar energy will make the water pumping intermittent and the pumped water can be stored in large ponds for irrigation when required. The development of a small solar pump for

Table 4.1 Table showing estimated energy for pumping water (million KWH) [From Garg (1)]

Year	Human and Animal power	Diesel Engine	Electric Motors	Total
1968-69	2746.6	1004.5	1543.9	5295.0
1973-74	2375.8	1813.2	3973.1	8152.1
1978-79	2178.0	1905.2	6778.4	10861.6
1983-84	1932.2	3264.51	7573.4	12770.1
1988-89	1642.9	2627.4	10234.2	14504.5
1993-94	1294.4	3107.4	12153.5	16555.3
1998-99	893.1	3620.9	14207.9	18721.9

irrigation purposes of 2 to 5 KW capacity can result in an agricultural revolution. Solar Energy can be used for pumping of water in two ways. In the direct conversion scheme, solar energy is directly converted into electricity using photovoltaic (solar) cells, this produced electricity is either stored in batteries or used directly in d.c. motors or converted into a.c. using inverter and then used in conventional water pumps (fig.4.1). In the thermodynamic

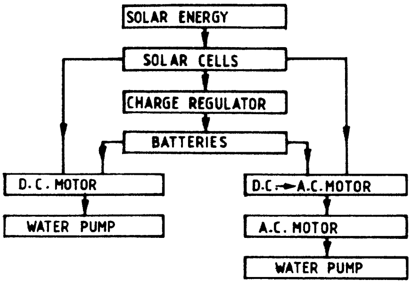

FIG.4.1. THE PHOTOVOLTAIC WATER PUMPING SCHEME.

conversion scheme shown in fig.4.2, solar energy is first converted into mechanical energy (shaft power) and then mechanical energy is used for pumping water employing water pump. In the thermodynamic scheme somekind of solar energy collectors like flat plate or concentrating type are used for heating a working fluid

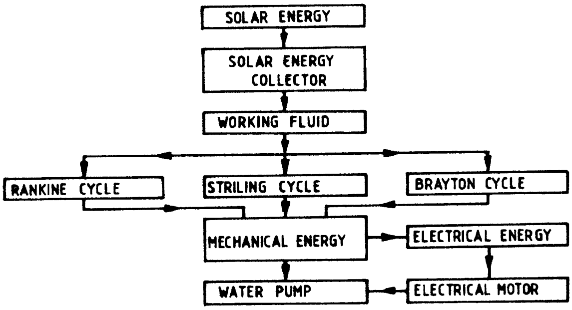

FIG.4.2. THE THERMODYNAMIC WATER PUMPING SCHEME

which is then used for operating a Rankine, Stirling, or Brayton engine producing mechanical power. The cost of solar water pump is very high which is due to low conversion efficiency of solar energy to mechanical energy and low production rate of machinery involved. Unfortunately the solar cells are also very expensive and the efficiency is low. With the renewed interest in photovoltaic materials and equipment development, it is hoped that the solar pumps would be cost competitive with the alternative pumping systems.

In this chapter, the history of solar pumps, types of solar pump, typical solar pump installations and types will be described.

4.2 HISTORY OF SOLAR PUMPS

The use of solar energy for pumping of water is not a new idea. Several efforts are made in the past to convert solar heat into mechanical power. A good review of solar water pumping is made by Pytlinski[2] and Newkirk[3].Perhaps the first historical attempt for pumping water using solar energy was made by a French Engineer, Salomon de Caux[4] (1576-1626) who developed an engine and pumped water using solar heated air. Another Frenchman, August Mouchot, with the backing of Napoleon III, developed and demonstrated [5-7] several solar water pumps (1860-1878). Mouchot developed his first solar engine in 1866 and demonstrated the same in Paris World fair in which he used a number of truncated cone reflectors (45° cones) to focus solar radiation on a copper tube converting water into steam and then steam engine was used for pumping water. The second engine was built by

Mouchot in 1875 with French government support in which a reflector of 4.0 m^2 and an axial boiler of 0.8 m long was used which produced steam at 50.7 x 10^4n/m^2 at 426 K and used for operating a rotary engine driving a water pump. This pump had produced a power of about 370 watts. The third solar engine was built by Mouchot in 1878 in which a reflector area of 5.2 m^2 was used. John Ericsson, a Swedish immigrant to America built several successful hot air engine which earned him in 1868 an honorary Ph.D. from the university of Lund, his native Place. Ericsson[8] in 1883 built a solar engine in which he used a parabolic trough of 3.3 m long and 4.9 m wide focussing solar radiation on a boiler tube, producing steam at a pressure of 24 x 10^4 N/m^2 driving a reciprocating engine to generate about 1.2 KW. An Englishman, Williem Adam [9,10], during the years 1876-78 in Bombay, India operated the first solar operated steam engine in which he used a hemispherical reflecting surface of about 12.2 m in diameter made out of small plane mirrors (25 cm x 42 cm) focussing solar radiation on a copper boiler producing steam continuously at a pressure of 20.7 x 10^4 N/m^2 and running a 1.8 KW steam engine and used for pumping water. In France, Abel Pifre[9] in 1878 used a parabolic reflector of 9 m^2 alongwith a rotary pump and was able to pump 99 litres of water in 14 min. from a depth of 3 m. A Frenchman Charles Albert Tellier[9] in 1885 used flat-plate collectors of 19.5 m^2 for vaporising ammonia from ammonia solution and the vapors pushed through a diaphragm the water out from a submerged iron cylinder. The ammonia was condensed and recycled and was physically seperated from the water using a flexible rubber diaphragm. This solar pump was able to pump about 1 m^3 of water per hour from a depth of 19.8 m in Autevil, France.

An American, A.G.Eneas built several solar engines[9] and in 1901 he demonstrated a solar water pump at the Ostrich Farm in Pasadena, California, USA, which was the largest pump ever built to that time. Eneas in his solar water pump used truncated, cone-shaped reflector with 10.2 m in diameter with a central opening of 4.6 m in the bottom consisted of small flat mirrors, reflecting solar radiation onto a tube boiler producing steam at a pressure of 10.3 x 10^5 N/m^2 driving a compound condensing engine coupled to a centrifugal pump. This solar pump was able to lift 5.3 m^3 of water per minute from a depth of 3.6 m thereby producing a peak power of 7.5 KW. H.E.Willsie[11] during the years 1902-1908 built several solar engines using first time the two fluid system. In 1904 Willsie built in St. Louis a 4.5 KW solar pump using flat-plate collectors with double glazing of about 55.7 m^2 area and an ammonia engine. In 1905 the Willsie Sun Power Company built another 15 KW pump using sulfur dioxide near Needles, California. An American, Frank Shuman[12] during the years 1907 to 1915 built several solar engines used for pumping water. In 1907 Shuman built in Tacony, Pennsylvania a solar pump using flat-plate collectors for heating water which in turn is used to evaporate ether and the resulting ether vapor was used to drive a vertical vapor engine of 2.6 KW capacity. In 1911, Shuman built another solar engine developing 24 KW power. One of the largest and most successful solar pump was operated by Shuman and C.Boys at Meadi, a Suburb of Cairo, Egypt in 1913 which used five parabolic troughs each of 4.06 m wide at the top and 62.2 m long with a total solar radiation collecting area of 1263 m^2 with a concentration factor of 4.6. These collectors were placed along the north-south direction and were rotated automatically in the east-west direction during the day. Along the focal line, a tube boiler was used producing steam which in turn produced a power of 37.3 KW giving an overall thermal efficiency of about 4.32 percent. J.Harrington in 1920 in New Mexico generated sufficient steam using solar energy concentrators which is used to run a steam engine and then pumping water upto a height of 6 m. In 1951, an Italian firm, Somor Ltd. of Milan[13] started manufacturing on a commercial scale solar pumps with capacities of 0.5, 1.0, 2.0, and 2.5 KW. Here also sulfur dioxide was used as a working fluid and it was estimated that about 1.5 m^2 collector area will produce about 0.7 KW. In 1940 F.Molero of the Heliotechnical Laboratory at Tashkent, USSR, used 10 m diameter parabolic dish to produce steam at a pressure of 2.03 x 10^5 N/m^2 which was further used for pumping water for irrigation and livestock watering. In 1955, d' Amelio at the University of Naples, Italy, developed a novel system in which heat is directly transferred from solar heated water to a liquid like ethyl chloride which is immisible in water without any seperate heat exchanger. The vapors of ethyl chloride, which are obtained by direct contact with the hot water, is passed to an expansion turbine. This turbine operates an irrigation water pump.

Although the Stirling engine was invented in 1816 by Scottish Clergyman, Robert Stirling and his brother, James but it was considerably improved and built by a Swedish engineer John Ericsson in 1826 which gave a very low efficiency at that time. The Philipps Company of Holland in 1946 considerably improved this engine, which operates on the Stirling cycle and this was used (1951-1955) by Ghai and Khanna of New Delhi, India for pumping water by using specially designed plane glass reflectors[14]. A 4 KW solar turbine using a binary Rankine cycle with monochlorobenzine as a working fluid was developed in 1961 by Tabor and Bronicki[15]. These vapor turbines produced under the name ORMAT Rankine power units are now available in the range of 100 watts to 15 KW and can be used for pumping of water.

In Dakar, Senegal, Masson and Girardier[16] during 1962 to 1966 developed two solar motors. The motor operating since 1962 lifted 8 to 10 litres water per minute from a depth of 10 metres which is equivalent to 21 watts. In another experiment in 1966 flat plate collectors of 300 m^2 were used and the solar engine pumped water at the rate of 40 m^3/hr from a depth of 8 to 10 m. During the years 1974 to 1980, a French Company, Society Francaise d'Etudes Thermiques et d' Energie solaire, SOFRETES[17,18] installed several solar irrigation pumps in many countries of the world. The first solar pump (1975) of 25 KW capacity using 1500 m^2 flat plate collectors was installed in San Luis de la Paz, Mexico which had given on output of 2600 m^3/day of water from a head of 10 m. Later a 50 KW solar pump was also developed by this firm. Here water is heated through flat plate collectors which in turn through heat exchanger boils the organic liquid such as butane or Freon Operating a Rankine cycle reciprocating engine or turbine. A 37 KW solar water pump delivering water at a rate of 38 m^3 per minute was operated[19] in 1977 at the Gila River Ranch near Phoenix, Arizona, USA in which parabolic reflectors of 564 m^2 were used for generating steam which in turn through heat exchanger vaporize Refrigerant 113 used as working fluid in a Rankine cycle power unit. A 19 KW solar water pump[20] using parabolic trough collectors (622.4 m^2) with caloria HT-43 as primary fluid, a storage unit of 22.7 m^3 with Caloria HT-43 as storage medium and a vapor turbine with Refrigerant 113 as working fluid was used near Willard, New Mexico, USA. This solar water pump was able to pump about 2.6 m^3 water per minute from a depth of 34 m.

A solar power generation [21-23] unit of 150 KWe with a technical support from Sandia Laboratory, Arizona Solar Energy Commission and University of Arizona in October, 1979 was built on the Dalton Cole farm South-west of coolidge in Central Arizona. The plant was completely designed by Acurex Corporation, California and used 2140.5 m^2 linefocus collector subsystem, a storage of 114 m^3 tank of hot oil, and an organic Rankine cycle turbine engine built by Sundstrand Corporation. This plant was operated for three years by the University of Arizona to characterize energy performance, identify needed equipment improvements and quantity operating and maintenance requirements. This plant was later deeded to the owner of the farm on which it is sited, Dalton Cole, Jr. A-100 KW solar thermal electric power station is in operation in Sulaibyh, Kuwait[24] since June, 1981 which is a joint Venture of Kuwait Institute for Scientific Research (KSIR), Kuwait, and Messers-Chmitt-Bolkow-Blohm (MBB) of Germany. The solar power station consists of 56 point focussing parabolic dishes, each of 5 m diameter with total collector area of 1025 m^2, a thermal storage tank and an organic Rankine cycle engine using toluene as working fluid and provides both electric and thermal energy for heating and cooling of greenhouses, desalination, irrigation, and pumping of brackish water. MacCracken[25] in 1955 described a novel solar pump known as thermopump which uses no moving parts and the heat supplied from a flat-plate collector can be used. In this system the heat is used to vaporise a low boiling point liquid like R-11, R-113, R114 etc. which pushes a floater down which in turn pushes a diaphragm forcing the water to go out. The vapors on cooling get condensed go to the generator and the water gets lifted from the reservoir. Swet and Fox[26] have discussed (1973) a representative device which pumps water by the direct pressure of solar heated air through low heads. A floating sheet metal housing serves both as solar collector and pumping unit. Minto (1976) has described[27] a vapor-power engine operating on a small temperature difference between a heat source and sink and the same is known as Mintowheel and which can be operated with solar energy. In the Minto solar wheel, a series of sealed containers fastened around the wheels rim with a low boiling point liquid such as R-11, R-22, R-113, R-114, R-500, propane, etc. in the lower containers are used. Minto solar wheel starts from the change of thermal energy to potential energy, and then from potential energy to mechanical energy. Lin and Bhardwaj[28] have recently done the analysis of the thermodynamic cycle of the Minto solar wheel. Rao et al [29,30] have developed (1976) two types of solar water pumps for lift irrigation which have no moving parts. This pump uses flat-plate collectors to vaporise a hydrocarbon fluid under pressure and vapors are used to force water from a closed tank, to a higher elevation. Burton[31] of Papua New Guinea in 1980 has described a simple solar water pump where flat-plate collectors are used to heat Refrigerant 113 and the vaporisation and condensation of this working fluid is used to pump the water using a diaphragm pump. This pump has no moving parts and gives an overall efficiency of 1.7 percent. A special mechanical valve is developed to pump the water.

Solar photovoltaic water pumps[32] are in operation in many parts of the world since 1968. It is impossible to know the number of pumps installed and the list of manufacturers. The largest solar photovoltaic water pump was made first time in USA which was of 25 KW in Nebraska and now pumps of this capacity are available in many countries. A few French firms have put up solar photovoltaic pumps in Senegal, Mali, Nigeria, Upper volta, Rwanda, Cameroon, Saudi Arabia, and Corsica. A large number of photovoltaic pumps are in operation in India also.

The interest in solar water pump is renewed with the shortage of food, electricity and diesel oil. A National Workshop on Solar Irrigation[33] was arranged in 1977 at Albuquerque, New Mexico, USA by ERDA and United States Department of Agriculture under the chairmanship of Wetherholt. Recently several review articles on Solar Water Pumping are written by Garg[1], Bahadori[34], Hofmann et al[35] and Derrick et al[36]. A technoeconomic analysis for the transfer of technology with a special case of solar pump is carried out by Parikh[37]. Analysis of photovoltaic solar pumps is carried out by Braunstein and Kornfeld[38], Matlin and Katzman[39], Evans et al[40], and Matlin[41].

4.3 COMPONENTS OF SOLAR ENERGY PUMPS

There are several components of a solar thermal energy water pumps such as collector array, thermal storage unit, heat exchangers, Rankine turbine, pump, electric storage batteries, etc. and therefore there are several design options also. Some of the important design options are discussed below:

4.3.1 Collector types

Solar energy collectors which are generally employed for mechanical power generation required for operating a water pump are: flat-plate collectors, solar pond(non-convective type), evacuated tube collectors, and concentrators. All these collectors, their design, performance, limitations, etc. are discussed by Garg[42-44] in earlier publications.Flat plate collectors of liquid type are generally preferred because of their simplicity and no need of suntracking arrangement but supply heat at below 100°C. Flat plate collectors of liquid type are used in solar pumps where a low boiling point liquid (60-90°C) is used and which gets expanded in a Rankine cycle engine like turbine. The efficiency of such a combination in no doubt is quite low. Some of the parameters need attention while designing a liquid flat plate collectors are : number and transmittance of glazing, absorptance and emittance of absorbing plate, materials of construction, size number, and location of manifold and tubes, heat transfer efficiency from absorber plate to fluid in tube; insulation properties; tilt, orientation and place; etc. For power production or water pumping applications a collector with single glazing with black chromium coating on absorber plate is sufficient. The efficiency equation for such a collector (liquid type) is of the form:

$$\eta = 0.82 - 4.2(\Delta T/I) \tag{4.1}$$

Where η is the efficiency of the collector, ΔT is the temperature difference (°C) between the collector inlet (T_{in}) and ambient air temperature (T_a), and I is the solar radiation incident on the collector plane (W/m^2). The final selection will depend on its conversion efficiency, operating temperature, and cost.

Evacuated tube collectors (tubular collectors) which supply fluid[43] in the temperature range of 100-150°C are also used in solar pumping units. Here the space between the inner absorbing tube and the outer glass tube is evacuated ($\simeq 10^{-4}$ torr). The outer surface of the inner tube is coated with a selective coating and thus the thermal losses from the whole unit gets considerably reduced. A number of such tubes generally spaced equal to outer tube diameter are arranged in a frame with either a white plane deffuse reflector on the rear side or a cusp reflector is placed behind the tubes to enhance the solar radiation. These collectors are now commercially produced in many countries.

Non convecting solar ponds where the heat loss by convection is reduced using salt concentration gradients which increase with increasing depth are used in Israel for power production and studied in many countries[43]. The depth of such ponds are generally 1 to 2 m and salts employed are NaCl or MgCl . Such salt graident or Non-convecting ponds collect and store the solar energy and are able to provide water temperature in the bottom upto 95°C. The main problem of these ponds are the maintenance of salt gradient concentration.

Solar concentrators of two or three dimensional geometries with different concentration ratios, various degree of sophistication, operating temperatures, and costs can be employed. There are two main advantages of these collectors: one is that these operate at high temperature resulting higher 'Rankine cycle efficiency, second these collect more solar energy during the daylong since they follow the sun. The disadvantages being: a sophisticated sun tracker is required which also uses auxiliary power, they do not collect diffuse solar radiation, etc. Stationary concentrators with a concentration ratio of about 3 may also be employed which require only seasonal adjustments. These concentrators may be either refractive type such as Fresnel lenses. Generally two dimensional reflector type concentrators known as linear concentrators or parabolic through concentrators (PTC) are employed in solar pumping units. There are three ways of orienting these PTC collectors: (i) axis of PTC remains horizontal in the north-south direction and tracking is done in the east-west direction during daytime, (ii) axis of PTC remains horizontal in the east-west direction and tracking is done in the south-north direction during daytime, and (iii) axis of PTC is tilted equal to the latutude angle in a polar mount. In summer months, the north-south arrangement collects more solar radiation during noontime throughout the year but the collection falls off sharply as the sun's azimuth angle departs from solar noon. The polar mounted PTC collector reduces 'Cosine losses' and therefore collects more energy on yearly basis compared to N-S or E-W oriented systems. The polar mounted system collects less solar energy in summer months compared to N-S oriented collector and its winter peak noon output is also less compared to the E-W oriented system. Moreover, the horizontal axis PTC's are simpler to install, requiring fewer support structures, and less piping.

4.3.2 Storage type

Generally in solar water pumping units, the thermal energy is not stored. However during non-irrigation periods or when the extraction rates from irrigation wells are limited the pump water is stored in an elevated pond or tank from where water is supplied to the fields by gravity flow. Water can be stored for long term storage in ponds and for short term storage in tanks.

If the water extraction rates from the well is limited then the excess solar energy collected should be stored for later use. If electricity is generated using turbine-alternator combination, then the same may be stored in electric batteries. If thermal energy is to be stored then the same may be stored in the form of sensible heat using water or high temperature fluids, as latent heat with a phase change material, or as a dual meadia i.e. combination of two. A good discussion on possible storage materials in different temperature ranges and associated problems are discussed by Garg etal[45]. The type and size of thermal energy storage depends on a life-cycle cost-benefit analysis.

4.3.3 Heat engines

Heat engines are used for converting solar thermal energy into mechanical power which powers the solar pump. The energy conversion cycles which are generally employed are: Rankine cycle, stirling cycle, and Brayton cycle[43]. The stirling cycle and Brayton cycle both operate with a gas (vapor) generally at a temperature more than 400^0C. While the Rankine cycle operates both with the liquid and the vapor phase of the working fluid. Moreover, in the temperature range generally available with the solar energy collectors flat plate and PTC i.e. 60 - 250^0C, the Rankine cycle is preferred in solar energy conversion over the other two cycles because of its superiority interms of its overall efficiency, component sizes, and high work ratio. In the solar pumping power requirement range which is less than 50 KW, the expanders available are turbines, reciprocating engines, and the rotary displacement engines. In this range turbines are preferred because of many reasons such as: smaller size, high efficiency with large capacity turbines,

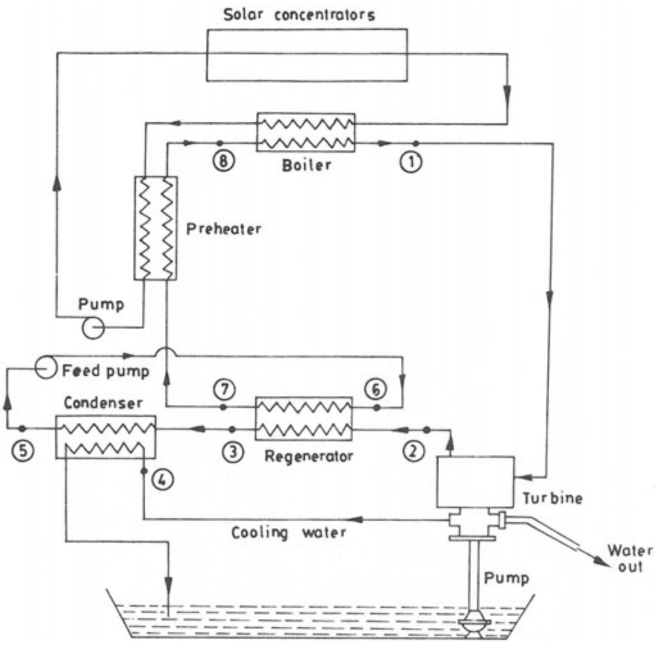

FIG.4.3. SCHEMATIC OF RANKINE CYCLE IRRIGATION PUMP

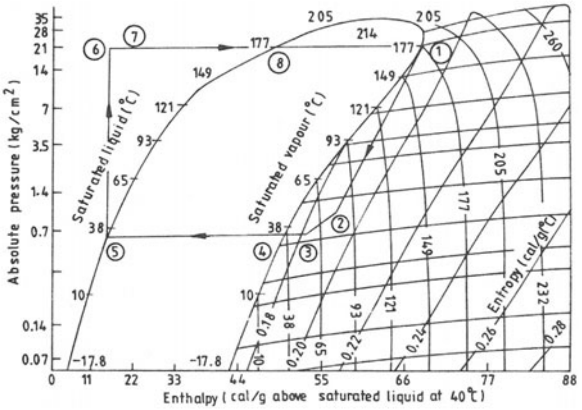

FIG.4.4. MOLLIER DIAGRAM FOR FREON-113

low maintenance and reliability, large expansion to condenser pressure, no internal lubriation is required, possibility of direct coupling with alternator, perfect balancing, etc. Both the 'drying type' fluid and 'wetting type' fluid can be used in a Rankine cycle turbine. Expansion of a fluid in the turbine going into the wet region should be avoided since this will damage the expansion device and therefore such 'wetting type' fluids should be superheated before expansion. However, a 'drying type'fluid may expend directly from the saturated vapor line but it would pass in the superheated state and therefore in this case a regenerator between the turbine and condenser is required which will recover the heat from the superheated fluid. The operation of a solar powered Ranking cycle was explained earlier by Garg[47] but the same is repeated again for convenience. A typical Rankine cycle irrigation pump is shown in fig.4.3 and its operation is shown on pressure-enthalpy diagram of fig. 4.4. As soon as the sun rises and the solar flux is enough, the solar concentrator start automatically tracking the sun's movement. Simultaneously an electric motor starts operating two small pumps: one pump starts circulating water through solar concentrators, boiler, preheater and back to solar concentrators, while the second pump starts circulating the working fluid (say in this case Freon-113) through various heat exchangers. As is seen from fig.4.3, the working fluid in the liquid condition is pumped at high pressure by the feed pump through regenerator and preheater where it is partially heated and then to the boiler. In the boiler, the working fluid gets vaporised by hot water coming from solar concentrators. The high pressure vapor gets expanded through turbine producing shaft power which can be used for generating electricity using alternator or for pumping water using a pump. The low pressure and low temperature vapor passes through regenerator transferring some of the heat to the high pressure working fluid and then liquified through condenser. The cycle points from 1 to 8 shown in fig.4.4 relate to the cycle points shown in fig.4.3. The cycle points 1 to 2 on fig.4.4 show the expansion of fluid in the turbine. Points 2 to 3 shows that some heat is transferred from the low pressure and low temperature vapor by the regenerator to the liquid fluid from the low pressure and low temperature vapor by the regenerator to the liquid fluid from points 6 to 7. The vapor gets condensed in the condenser by cooling water from point 3 to 5. Points 5 to 6 show that the feed pump raises the pressure of the liquid. The preheater raises the pressure of the liquid from points 7 to 8. The boiler converts the hot liquid into gas from point8 to 1. A little amount of water pumped is used to cool the condenser. The pumping of water or electricity generation continues throughout the day if there is enough sunshine or if the wind speed does not exceed the design point. During sunset hours or when the wind speed exceeds the design speed then the collector array will automatically turned to the stowed position. A survey of organic Rankine engines was conducted by Curran [46]. He collected data on 2150 Rankine engines which use 16 different organic fluids providing power in the range of 0.1 to 1120 KW and were operational for different durations upto September 1979.

4.3.4 Working fluid.

The choice of a working fluid in the Rankine cycle depends on the operating temperature in the boiler and condenser and the type of engine. The efficiency of the system will very much depend on the properties of the working fluid. Generally two different fluids on the primary fluid in the solar collector loop and second the secondary fluid in the power loop is employed. For low temperature operations water is used as a primary fluid but for high temperature operations high temperature stable fluids such as Caloria HT-43 are employed. Steam is the most widely used working fluid in heat engines due to its low cost, high chemical stability, universal availability and better cycle efficiency. But due to some technical and operational reasons, generally organic fluids are used as working fluids and are selected based on their physical and thermodynamic properties. The working fluid should be cheap, thermally and chemically stable, nonflammable, non-corrosive, non-toxic, small number of atoms in the molecule and of high molecular weight. A longlist of suitable working fluids in different temperature ranges is prepared by Curran[46]. Thermodynamic properties of a few typical working fluids suitable for solar Rankine cycle operations are given in table 4.2.

4.4 TYPICAL SOLAR PUMP SYSTEMS.

During the last twenty years several solar irrigation pumps ranging from 1 KW to 200 KW are built in many countries. Photovoltaic solar pumps are also made in the range of 200 watts to 5 KW and are more successful so far as the performance is concerned compared to thermodynamic type of solar pumps. A few typical solar irrigation pumps which differ in concepts, size, type of solar collector used, etc. are briefly discussed in this section.

4.4.1 The Coolidge, Arizona, 150 KW Solar thermal irrigation pump.

A deep well solar irrigation plant was put to operation in November 1979 at the Dalton Cole farm, south of

Table 4.2 Thermodynamic properties of few working fluids

Fluid	Formula	Molecular weight	Critical point (°C/KPa)	Freezing point (°C)	Approx. thermal stability (°C)	Vapor pressure at 40°C (KPa)
Acetone	C_3H_6O	58	235	-95	-	52
Ammonia	NH_3	17	133/11429	-	-	1554
Butane	C_4H_{10}	58	152.6	-	-	410
Toluene	C_7H_8	92	321/4254	-95	480	7
Freon-11	CCl_3F	137	198/4413	-111	120	159
Freon-12	CCl_2F_2	121	112/4114	-	-	958
Freon-22	$CHClF_2$	86	96/4978	-160	200	1455
Freon-113	$C_2Cl_3F_3$	187	214/3441	-35	175	76
Freon-114	$C_2Cl_2F_4$	171	146/3261	-94	175	317
Tetrachloro ethylene	C_2Cl_4	166	347/9640	-22		

Coolidge, Arizona. This 150 KWe solar thermal power (21-23) plant is a joint effort of University of Arizona, Sandia Laboratories, US Department of Energy, Acurex corporation, Sundstrand corporation, and Sullivan and Masson Consulting Engineers. This plant has already been discussed by Garg [48] and repeated here for convenience. The coolidge solar thermal electric plant is shown schematically in fig.4.5 which consists of an array of solar collectors, thermal energy storage unit, and a power conversion subsystem. The details of the plant are listed in table 4.3. The collector field with total area of 2140.5 m^2 of line-focussing parabolic trough collectors, manufactured by Accurex Corporation, California, is arranged in 8 north-south oriented loops, each containing 48 collectors. Each collector trough is of about 1.8 m wide and 3 m long and originally had aluminium reflective surface which was later (spring 1981) laminated with aluminium acrylic film (FEK-244) to improve their performance. The collector receiver tubes, located at the solar collector focus, are coated with black chrome selective coating and surrounded by a pyrex glass tube. The concentration ratio of the collector receiver system is about 36. A heat transfer oil, Caloria HT-43, is pumped through the receiver tube by a pump at a controlled flow rate such that the outlet oil temperature reaches to 288 °C.

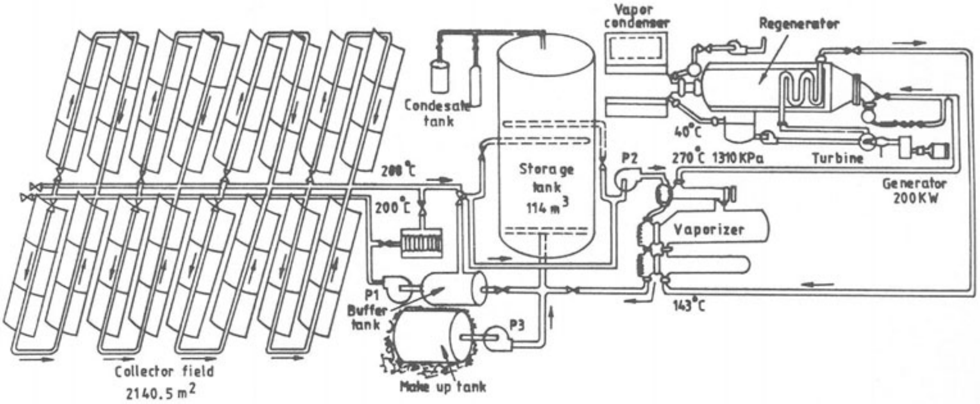

FIG.4.5 FLOW DIAGRAM OF COOLIDGE 150 KWe SOLAR POWER PLANT

Table 4.3 Summary of the 150 KW coolidge solar thermal power plan (From Larson[22])

1.	**Collector**	
	Type	: Parabolictrough collectors (1.8 x 3 m)
	Reflector material	: Polished aluminium, aluminized mylar (FEK-244)
	Number and area of collectors	: 384 collector in 48 groups, 2140.5 m^2
	Orientation of collectors	: N - S axis
	Receiver coating	: Black chrome
	Concentration ratio	: 36
	Collector fluid	: Caloria HT-43
	Temperatures	: Inlet temperature = 200°C Outlet temperature = 288°C
	Design conditions	: g_i = 600 W/m^2 m = 7167 Kg/hr system efficiency = 38.6 percent
2.	**Storage**	
	Type	: Stratified Liquid (thermocline) (sufficient for 5 hrs operation)
	Size	: 4.16 m diameter and 14.93 m high tank (114 m^3 usable storage)
	Storage medium	: Caloria HT-43
	Storage temperature	: 200°C to 288°C
	Insulation thickness	: 30 cm (Fibreglass)
3.	**Cooling system**	
	Type	: Vapor Condenser
	Water (makeup)	: 2270 litres/hr
	Condensing temp.	: 40°C
4.	**Power generation**	
	Type	: Organic Rankine cycle
	Working fluid	: Toluene
	Gross efficiency	: 20 percent

Heated caloria at 288°C is returned to the top of the 114 m^3 insulated storage tank which is 4.16 m in diameter and 14.93 m high and provides sufficient energy to operate the power conversion subsystem for more than 5 hrs. A thermocline separates the heated caloria at the top of the tank from the cooler caloria at the bottom of the tank. The power conversion unit consists of a heat exchanger transfering heat from heated caloria to the working fluid toluene, single stage impulse turbine made by Sundstrand Corporation, sychronous generator for generating electric power, and evaporative cooling tower for condensing the toluene.

Thus basically there are three closed heat transfer loops. In the first loop warm caloria from the bottom of the storage tank is extracted, circulated through the receiver tubes of the collector field and the heated caloria is returned at the top of the storage tank. In the second loop hot caloria from the top of the tank is extracted, circulated through the vaporizer heat exchanger and returned to the bottom of the storage tank. In the third heat transfer loop, the high pressure vaporized toluene from the heat exchanger is sent to the turbine to produce shaft work, the vapor expands which is condensed in an evaporative cooling tower and then sent to the inlet of the vaporizer heat exchanger for further vaporization. An automatic control subsystem monitors and controls the tracking and collection of solar energy, flow rates of caloria and storage of heat, flow rates of caloria in heat exchanger and flow rates of toluene in the power conversion unit, and the generation and supply of electric power. The control unit also protects the solar thermal electric power plant arising due to system related anomalies or due to natural means. A natural gas fired auxiliary heater is also provided for testing purposes in case of low insolation values.

This plant was operated daily except during periods of collector testing, equipment modification activities and other breakdowns and repairs. During the year 1980, 1981, and 1982 the collector subsystem operated 89,93 and 98 percent of the possible operating hours respectively. The power conversion subsystem operated about 90,97, and 97 percent of the possible operating hours during the year 1980, 1981 and 1982 respectively. Daily data on available solar energy (compiled only that direct radiation which is more than 300 W/m^2), collected thermal energy, and electrical energy generated have been compiled for 1980,81 and 82. It was found that average monthly collection efficiency ranges from 7 percent in winter to 27 percent in spring and fall to 35 percent in summer. Some collector efficiency tests are conducted on clear days near winter and summer solastice; and spring and autumnal equinox.

The total energy produced during the years 1980, 81 and 82 is 114930, 163410, and 178030 KWh respectively. This increase in electric power production is due to some equipment and collector improvements and operating experience.

The maximum electrical power was produced in June 1982, which was 27350 KWh, and 17000 KWh in September and only 3000 KWh in December. On a single clear June day in 1982, the system has produced about 1300 KWh electricity. The average thermal to electrical energy conversion efficiency ranges from 9 to 12 percent in winter months and 12 to 18 percent in summer months. During January 1980 tests, the thermal to electrical conversion efficiency at 200 KW design point was 19.7 percent. The parasitic power requirement (for running various pumps, auxiliary equipments, cooling tower operations, etc.) was about 24 KW thereby showing a net cycle efficiency of 17.3 percent for power conversion subsystem. During the peak irrigation season the plant was used to provide power to the well pumps giving an output of 88 l/s from a depth of 115 m and surplus electricity was sold to the local electric utility grid during the off season.

4.4.2 Gila Bend, Phoenix, Arizona, 37 KW Solar powered irrigation pump.

A 37 KW solar-powered irrigation pump was designed [48,49] and built by the Columbus Laboratories of the Battelle Memorial Institute (BMI) for Northwestern Mutual Life Insurance Company (NMI) of Milwaukee, Wisconsin for installation at their Gila Band Ranch, South-west of Phoenix, Arizona. The pump which is capable of pumping 38 m^3/min of irrigation water at peak operation from an average depth of 3.7 m was installed during the early months of 1977 and completed during April, 1977. The NMI/BMI solar irrigation pump is schematically shown in fig. 4.6. As is seen the system consists of parabolic single axis tracking solar collector array (564 m^2), a Rankine cycle power unit comprised of a turbine/gearbox, boiler, condenser, re-generator, preheater, and a low lift high volume flow propeller pump.

The parabolic trough collectors with a total aperture area of 564 m^2 were supplied by Haxcel Corporation in Casa Grande, Arizona and have the orientation towards north-south with automatic tracking during the daytime in the east-west direction. This orientation and tracking has delivered more water on daily basis during summer months. The reflecting surface used over the parabolic-shaped aluminium honey comb panels is acrylic covered aluminized mylar sold under the trade name 'Scotchal' and supplied by Minnesota Mining and Manufacturing Company in St. Paul, Minnesota. A radial-inflow Rankine turbine manufactured by Barber-Nechols Engineering Company in Arvada, Colorado, with Freon-113 as the working fluid was used. This turbine has a outside wheel diameter of 11.9 cm with a speed of 30500 rpm which is reduced using a gearbox to the output shaft to 1760 rpm. The overall efficiency of the turbine/gearbox assembly was of about 75 percent. A low head, high volume flow propellor irrigation pump with a static pumping head of 3.7 m was selected. This layne and Bowler 16-P propeller pump with a 37 KW input has delivered about 0.63 m^3 of water per second. In the power cycle[50], four heat exchangers; a regenerator, a boiler,a preheater, and a condenser are used. All the heat exchangers except that of regenerator were commercially available and used and were of the shell-and-tube type heat exchangers. The heat exchanger used in regeneration was specially made by using multiple row, tube-and-fin type heat exchanger core. Apart from the above main components there are several other components like: (1) three electric motors, one used to circulate the fluid through collector, boiler, preheater and back to collectors; the second to circulate the freon-113 through boiler, turbine, regenerator, preheater and back to boiler; and the third circulates the water to the condenser, (2) pressure relief valves, (3) high wind speed sensors and high temperature sensors to shut down the collectors, (4) battery operated collector tracking mechanism, (5) expansion tank connected in the collector water loop, and (6) in case of emergency a manually operated control unit.

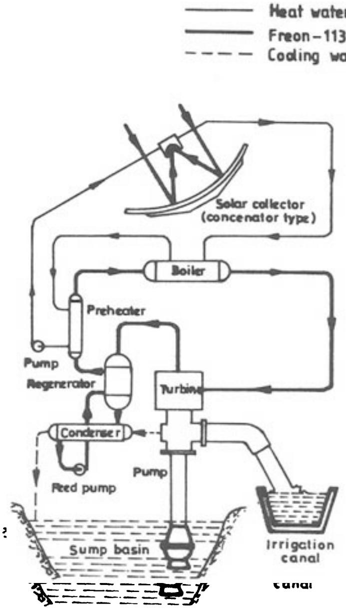

FIG.4.6. SCHEMATIC OF NML/BMI SOLAR POWERED IRRIGATION PUMP

Over a period of 18 months only the whole system was conceieved, designed, built and put to operation which involved system analysis using computer modelling in the design of components and in optimizing the system. The irrigation pump was completely monitored for its performance for the year 1977 and was observed that the system worked for about 7 hrs per day in winter and about 9 hrs per day in summer clear days. The water delivered varied from day to day depending on the availability of solar radiation. On an average clear day the system pumped over 11000 m^3 of water. On one longest day (9.5 hrs) in arizona which happened to be a clear day also, the system pumped about 21000 m^3 of water. The overall output observed was not as predicted earlier due to mainly three reasons : (1) The output of the collectors deteriorated with time and it was not as per expected, (2) the cooling water temperature of the sump used in condenser was found higher than anticipated, and (3) due to large flow lines, bends and flow meters there was a large flow losses.

4.4.3 Willard, New Mexico, 19 KW Solar thermal water pump.

The Sandia National Laboratories, Albuquerque, New Mexico in collaboration with New Mexico State University (NMSU) Las Cruces, New Mexico with assistance from specific contractors designed and fabricated a 19 KW solar water pump with the financial assistance from Energy Research and Development Administration (ERDA) of USA. This pump was installed on Jan.1, 1979 at a commercially operated farm (Estancia valley) near Willard which is about 100 km southeast of Albuquerque, New Mexico[20,50-52]. The scientists of Sandia Laboratories were responsible for the systems modelling and design analysis of the solar irrigation pump while the scientists of New Mexico State University were responsible for procuring the equipment for the demonstration with specific responsibility for the solar collector field, the agriculture experiments, monitoring of the irrigation pump, and the dissemination of information. The climatic and Geographical details of the Estancia valley the place of installation are given in table 4.4.

Table 4.4 Climatic and geographical details of Estancia Valley, Willard, New Mexico,

Latitute of place	34.2 deg. N
Longitude of place	106.1 deg
Elevation of place	1835 m
Temperature range	-28.9 to 43.3°C
Peak wind load	177 Km/hr
Average wind load	16.5 Km/hr
Solar insolation	631 w/m^2

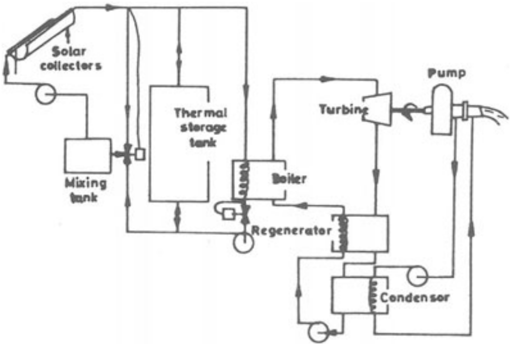

FIG.4.7. SCHEMATIC DIAGRAM OF WILLARD SOLAR IRRIGATION PUMP

Table 4.5 Major components of solar pump and supplier

Component	Description	Supplier
Solar collectors	Parabolic trough north-south oriented full trackingshielded receiver tubes	Acurex Corporation, Mountain view, California, USA and Solar Kinetics,USA.
Heat storage	Oil tank, Thermocline 6000 gallon, designed by Sandia Laboratory	Albuquerque Tank Company Albuquerque, New Mexico,USA
Rankine engine	Turbine and gearbox working fluid freon 113	Barber Nichols Company, Denver, Colorado, USA
Irrigation pump	Deep well turbine Johnson12 cc,1200rpm	T.P. Pump Company, Albuquerque, New Mexico, USA.

The whole solar irrigation system was built with commercially available components. The whole system is schematically shown in fig. 4.7 and consisted of four major components, solar collector field, heat storage unit, a Rankine engine, and an irrigation pump. The name of suppliers of these four components are given in table 4.5. The detailed specifications of the four components are shown[52] in table 4.6. It is seen from this table that parabolic trough collectors with an aperture area of 1276 m^2 with automatic single axis tracking (East-west) and fixed axis in the north south direction are used. Parabolic trough collectors of 651 m^2 were supplied by Solar Kinetics and 625 m^2 were supplied by Acurex Corporation. The thermal storage subsystem utilized a thermocline and consists of two cylindrical tanks each of 26 m^3 capacity using Caloria HT 43 oil as the storage media and also the heat transfer media from the solar collector field. This results in about 40 litres of storage volume for 1 m^2 of collector aperture area. The organic Rankine cycle heat engine was supplied by Barber-Nichols Engineering Co. and uses R-113 as the working fluid and provides 36300-rpm at a fluid temperature of 163°C, pressure at 1550 KPa and fluid flow rate of 29 1/min. A conventional water pump with 1173 rpm obtained using a gear box is used and sprinkler irrigation unit is employed for efficient operation. A water pond of 0.55 hectare-m (5551 m^3) capacity for the irrigation water was used to store irrigation water and also to boost the water pressure from 70-80 kpg availably at the well head to the 140-200 kpg required for sprinkling irrigation system. Whenever irrigation or mechanical power was not required the electrical power was generated using a belt driven induction generator. The oil circulation scheme is shown in fig. 4.8. The control unit provides four modes of operation: Collector array recirculation, collector array recirculation and hot oil-to-storage, storage hot oil-to-heat engine, and hot oil from collector array-to-heat engine and hot oil to or from storage. As soon as the temperature of oil (caloria HT 43) reaches to 216°C at the outlet of the collector, the valves 1 and 2 are opened and the heated oil flows either to the storage tank or directly to a boiler/heat exchanger. In the boiler/heat exchanger, the heated oil transfers heat to Freon R-113 reaching a temperature of 163°C and 1550 KPa. This high pressure freon vapor drives the turbine at 36300 rpm which powers the water pump.

Over a period of 1.5 years of operation, the heat engine worked for about 560 hrs. The average collector efficiency during summer months was of about 25 percent while that of heat engine Rankine cycle efficiency 15 percent. By including the other system losses the overall system efficiency on clear summer days was about 3 percent while on clear winter days only 1.5 percent. This low efficiency is attributed to the very low reflectivity of the parabolic collector system, high receiver losses,working at low temperature, and non modular unit resulting high losses.

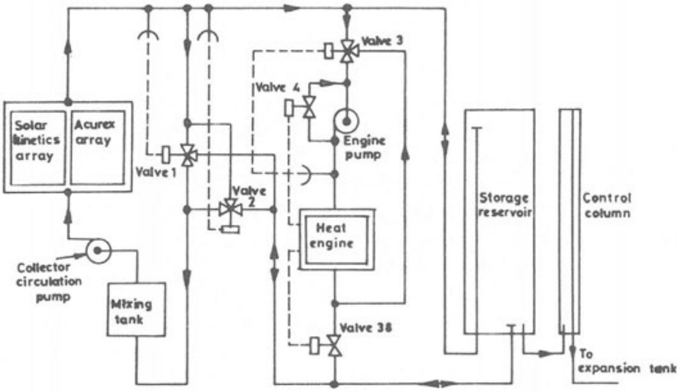

FIG.4.8. SCHEMATIC DIAGRAM OF WILLARD SYSTEM OIL CIRCULATION SYSTEM (From Fenton et al[52])

Table 4.6 Specifications of Willard Solar irrigation pump (From Fenton et al[52])

1. Solar Energy	Parabolic trough, north-south axis, Collection: east-west tracking; maximum recirculation temperature, 216°C; heat transfer fluid, Caloria HT 43 oil. Solar Kinetics: Collector array area, 651 m^2; module width, 239 cm; Aperture width 2.1 m; module length, 6.2 m; initial mirror reflectance, 0.84; reflective surface, metalized azcrylic film; mirror shape, 90 deg. parabolic; receiver tube, 3.8 cm carbon steel; selective surface, black chrome; receiver cover, glass; pylon drive mechanism, hydraulic cylinder and rod assembly activated by central supply unit; tracking system, shadow band controlled.

Table 4.6 contd....

	Acurex: Collector array area, 625 m^2; module width, 193 cm; aperture width, 1.8 m; module length, 3.2 m; initial mirror reflectance, 0.70; reflective surface, polished aluminium; mirror shape, 90 deg. parabolic; receiver tube, 3.2 cm carbon steel; selective surface, black chrome; receiver cover, annealed Pyrex glass; pylon drive mechanism, worm gear to large spur gear segment; tracking system shadow band controlled, reversible AC motor drive with desteer circuit.
2. Thermal Energy	Two cylindrical tanks with Storage: individual capacity, 26.0 m^3 storage fluid medium, Caloria HT 43 oil; insulation, adjacent to tank-20 cm fiberglass, outside-5 cm urathane, aluminium protective jacket; air vent for oil level control, 8 mm diameter; make-up oil provided by fill pump and underground storage.
3. Power System:	Total output power, 19 kw (25 hp); output speed, 1800 RPM; mechanically coupled to irrigation pump; alternative output, induction generator driven by cog belt, one-way clutch prevents generator driving heat engine turbine.
	Barber-Nichols Engineering Organic Rankine Cycle Heat Engine: Working fluid, R113; peak boiler conditions 163°C and 1550 kPa; working fluid flow, 29 liters/min; condenser conditions, 30°C and 55 kPa; condenser water flow, 270 liters/min turbine, full admission unit with fast-acting pilot valve for over-speed and AC power loss protection, single-stage, radial-inflow, reaction type, 99 mm diameter, 36300 RPM rotational speed; gearbox, two-stage.

Table 4.6 contd....

4. Irrigation:	pumping depth, 32 m; irrigation pump, 5 stages, 1173 RPM, 83 percent efficiency, Johnson Model 12 cc; holding pond capacity, 5560 m^3; sprinklers, side roll type; nozzled for 1.3 cm irrigation water per hour at 450 kpg; field area, 49 hectares.

4.4.4 SOFRETES SOLAR PUMP

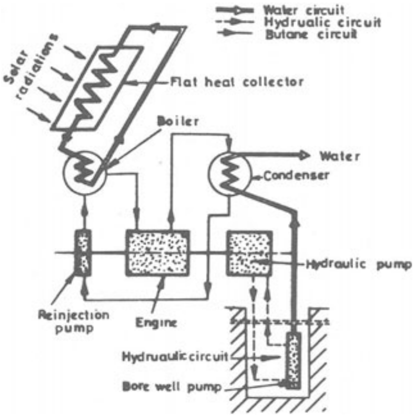

FIG.4.9. SCHEMATIC DIAGRAM OF A SOFRETES SOLAR PUMP

A low temperature solar engine (LTS engine) has been developed in France for lift irrigation purposes and SOFRETES[16,17] has already installed 25 1-K W solar pumps in Africa and Latin America. A schematic diagram of the pump is shown in fig. 4.9. In this solar pump a large number of flat-plate collectors are used which heat water upto about 70°C by thermosyphon action in a heat exchanger.

Here the hot water gives its heat to the low boiling liquid like methyl chloride or butane which evaporates and produces high pressures. These vapours at a high pressure actuate a reciprocating engine to which a pump is connected. This engine runs a hydraulic press which finally operates a pump immersed in the water in the well. The vapours after doing the mechanical work at low pressure reach the condenser which is cooled by the pumped water and then liquid methyl chloride is pumped back for the next cycle by a small re-injection pump coupled to the engine. These pumps are fabricated by the French Research Organisation SOFRETES. This pump uses a number of heat exchangers and four pumps and therefore the overall efficiency of these pumps is very low-of the order of only 1 percent.

A unit which has been working quite effectively since 1968 is the one installed at Institute de Physique Meteorologique de Dakar, Senegal. This pumping unit uses flat-plate collectors of 88 m^2 area supplying water at a temperature of 70-80°C. The motor runs at an effective speed of about 80-90 rpm pumping about 6 m^3/hr of water from a depth of about 25 m.

Another unit operating in Algerian Republic has the following specifications. Collector area 350 m^2, pumping rate 21.5 m^3/hr, pumping head 30 m, and working time 5 to 6 hours.

4.4.5 Bakel, Senegal, 32.4 KW solar powered irrigation system.

A solar thermal irrigation system of 32.4 KW capacity with a nominal pumping capacity of 6400 m^3/day of water was installed[53] in the Sahel region of Africa, Bakel, Senegal by the SOFRETES, Montargis, France in collaboration with Thermoelectron Corporation, Waltham, Massachusetts, USA. The system as schematically shown in fig. 4.10 consists of a bank of flat-plate collectors with 1872 m^2 area, a thermal storage tank of 320 m^3 capacity, an organic single stage Rankine turbine of 32.4 KW capacity of 5500 rpm using Freon-11 as working fluid, a 25 KW alternator for generating electricity, an electrically operated water pump pumping about 6400 m^3/day of water through a height of 10.2 m. The specifications of the irrigation system are shown in table 4.7.

In this system flat-plate collectors with aluminium absorber plates coated with black chrome with absorptivity of 0.92 and emissivity of 0.2 are used. The collector panels which are 25 in numbers with each having an aperture of 72 m^2 and overall dimensions of 6.3 m x 13.7 m are employed and are put on the roof of a building facing south with an inclination of latitute of the place. The water at 88°C enters the collectors loop and leaves at 95°C. This hot water either goes to the organic Rankine cycle thermal loop or to the 320 m^3 water storage tank which is parallel with the collector loop and used for energy storage. Two separate water circulation pumps, one in the storage-collector loop with variable speed is used and second in the boiler-collector loop is used. A single stage axial flow impulse turbine which operates at 5500 rpm with inlet pressure of 590 KPa, inlet temperature of 86°C and outlet pressure of 155 KPa giving a power output of about 32.4 KW is used with a Freon flow rate of 2 Kg/sec. Freon-11 is used as the working fluid in the thermal power loop consisting of a boiler, turbine, and a condenser. The condenser is cooled with the irrigation water at a nominal temperature of 29°C.

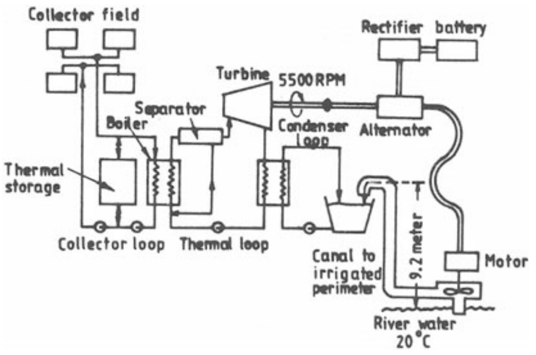

FIG.4.10. SCHEMATIC DIAGRAM OF A 32.4 KW SOLAR POWERED IRRIGATION SYSTEM AT BAKEL, SENEGAL

In the earlier programme, the turbine shaft was to be directly connected through a gear box to a mechanically driven irrigation pump. But due to the shifting river bed and non-availability of water in the well in sufficient quantity, a floating, electrically driven 550 m^3/hr water pump was used. The electricity generated using a 25 KW alternator was mostly used for pumping the water and a little was used for operating the various electric pumps used for circulating the fluids and also for charging the storage batteries meant for startup in the morning. Additionally 20 KWh/day was made available for other local use like lighting and refrigeration.

Table 4.7 Specifications of 32.4 KW solar powered irrigation system at Bakel, Senegal.

1.	Collector	
	Type	Flat-plate
	Coating	Black chrome
	Area (total)	1872 m^2
	Number of panels	26 panels each of 72 m^2
2.	Thermal Storage	
	Capacity	320 m^3
	Storage material	water
3.	Turbine	
	Type	Single stage, organic fluid
	Inlet temp. and pressure	86°C, 590 KPa
	Output power and efficiency	32.4 KW, 67 percent
	Available pump power	20.7 KW
4.	Pump (Electrically driven)	
	Average head	10.2 m
	Pumping capacity	550 m^3/hr
5.	Plant efficiency	
	Carnot efficiency	17.9 percent
	Cycle efficiency	5.6 percent

4.4.6 TRISAIA CNEN, Rome, Italy, 3 KW solar water pumping plant.

A 3 KW solar water pumping plant using flat-plate collectors is installed at the TRISAIA CNEN Centre in the South of Italy[54]. The climatic and geographical details of the place given are in table 4.8. As is shown in fig. 4.11 the whole solar water pumping plant consists of two loops:

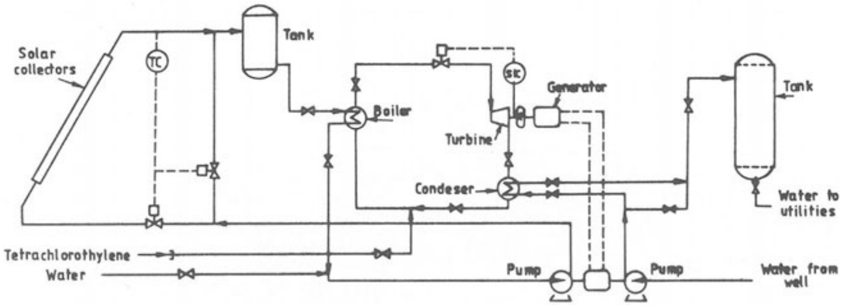

FIG.4.11. SCHEMATIC DIAGRAM OF 3 KW SOLAR WATER PUMPING PLANT AT CNEN, ITALY

in the first loop a bank of flat-plate collectors (168 m^2) are used to heat water upto a mean temperature of 78°C and this heat is transferred to the working fluid (tetrachloroethylene, C_2Cl_4), in the second loop which is the power loop a boiler, condenser, and a single stage axial turbine of 3.5 KW shaft power is employed. An alternator is used to convert mechanical energy into electrical energy and which is used for pumping the water at a rate of 100 m^3 /day from a head of 30 m with a working period of 5 hrs/day.

Table 4.8 Climatic and geographical details of CNEN-Trisaia Centre

Latitude of place	40.15 deg. N
Longitude of place	16.63 deg E
Elevation of place	50 m
Mean temperature in summer	25°C
Mean wind speed in summer	18 Km/hr
Daily Insolation (mean)	
June	18.7 MJ
July	18.5 MJ
August	16.6 MJ

A number of flat-plate collectors with a total area of 168 m^2 and having single glazing are used in the system. The absorber plate is of stainless steel which is coated with a selective coating of absorptance 0.9 and emittance 0.10. The organic Rankine cycle turbine is a single stage, axial flow reaction type turbine giving a shaft power of 3.5 KW at a rpm of 15000. The efficiency of the turbine is 0.8 at a C_2Cl_4 flow rate of 589 Kg/hr with inlet and outlet temperatures of 75°C and 30°C respectively and inlet and outlet pressure of 23.1 and 3.1 KPa. Both the boiler and condenser heat exchangers are of the same type and shape and are shell and tube type. The pumped water is used to cool the condenser. The electricity generated is used to pump the water. This plant will be able to pump about 20 m^3/hr of water from a depth of 30 m.

4.4.7 Special solar pumps

Apart from the above conventional solar water pumps which are studied extensively there are special designs also which need some mention here. Practically in all these special pumps the principle of liquid vaporisation and condensation is employed. When a liquid vaporises its volume increases which displaces a volume of water to a higher elevation and when this liquid condenses its volume reduces resulting in suction of water from a depth. The volume of water pumped is equal to the change in volume of the liquid in changing phase.

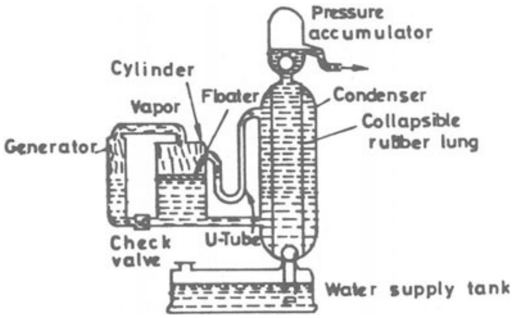

FIG.4.12. A SAMPLE THERMOPUMP

A simple solar thermopump as suggested by MacCracken [25] is shown in 4.12. In this pump there is a generator, a cylinder carrying a floater (piston), a U-tube, a condenser with rubber diaphragm, and a pressure accumulator. In the generator (boiler) when solar energy is applied a low boiling point organic fluid vaporises, pushes the floater (piston) in the cylinder down, pushing the collapsible rubber lung in the condenser and thereby forcing the water to go out through the pressure accumalator at the top. When the floater reaches to the bottom of the cylinder, the vapor escapes through the vapor U-tube and gets condensed in coming in contact with the liquid which has been cooled by pumped water through rubber lung. When all the vapor gets condensed, a vacuum is created in the rubber lung sucking the water from a water supply tank at a lower level and the floater moves up blocking the entrance of the vapor tube and thus the generator and cylinder is again filled with liquid. This action continues intermittently. Any organic fluid with low boiling point may be employed in this system. This pump may be suitable for lifting water through a height of 1 to 2 m only.

A solar Minto-wheel[27,28] can also be employed for pumping water. The schematic diagram of a solar Minto wheel is shown in fig. 4.13. As is seen a large wheel is used which consists of a series of sealed metallic containers fastened around the wheel's rim. The diametrically opposite containers are connected through tubes. A low boiling liquid such as Freon or Propane is filled in one lower container of each pair and the opposite upper container is evacuated.

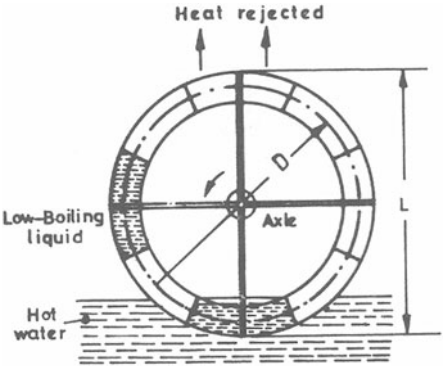

FIG.4.13. SCHEMATIC DIAGRAM OF MINTO SOLAR WHEEL

Solar heated water can be used to heat the lower container containing liquid. The liquid vaporises in this container and the vapor pressure forces the remaining liquid to move to the upper container through the connecting tube. This movement of liquid in the top containers make the top heavier and the bottom lighter resulting the wheel to start turning. This process repeats continuously since each pair of containers shuttles its liquid mass back and forth. This Minto wheel does not operate on the Rankine cycle and in this process first the thermal energy is converted into potential energy and then potential energy into the mechanical energy. The thermal efficiency of the Minto wheel very much depends on the properties of the working fluid but it is very low and the wheel runs very slowly.

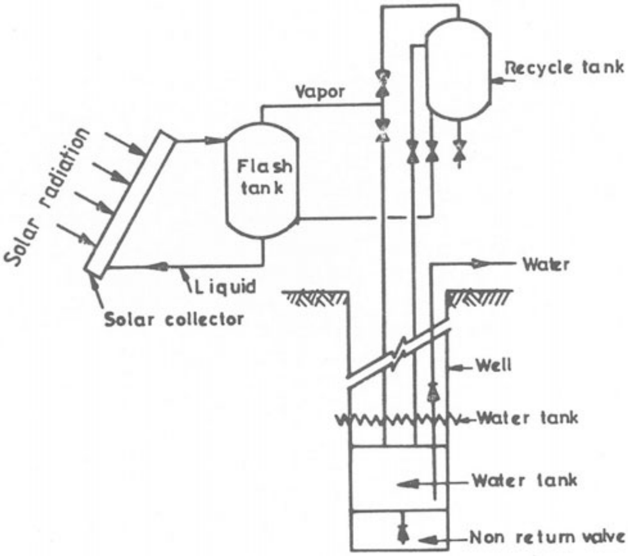

FIG.4.14. SCHEMATIC DIAGRAM OF A AIR COOLED PUMP

A simple solar pump with no moving parts has been developed by Rao and Rao[29] and studied extensively by Sudhakar et al[30]. This pump is based on the principle that when a pressure is applied on the surface of the water in a closed well, the water comes out to the other end and thus can be pumped to great heights. The air cooled pump as developed consists of a battery of flat-plate collectors used for heating low boiling point liquid like pentane, a flash tank used as a storage for working fluid (Pentane) and vapour separator, a recycle tank used for sucking the condensed vapours back, a big tank located in the well and a number of valves as shown in fig. 4.14. In this system the liquid pentane by gravity flows into the collector from the flash tank. The pentane gets vapourised, goes into the flask tank and then into the tank full of water located in the well. As the vapour pressure goes on increasing at the water surface, the water goes on rising in the delivery pipe and finally pumped out. At night the collectors get cooled and the vapours condensed during the daytime in the tank flows back in the collector and then goes on the flash tank. At this time the tank in the well will again by filled with water through non-return valve. Thus in this system one cycle can be completed in 24 hours and thus can be named as day-night cycle. A water cooled pump has also been developed by Rao and Rao[29] in which several cycles can be completed during the daytime.

A low head solar pump capable of pumping small amounts of water has been studied by Swet and Fox[26]. In this concept as is shown in fig.4.15 a large floating metallic container is used both as a solar collector and a pumping unit. An external hose pipe is connected to its bottom. The top surface of the container serves as a solar collector which is painted with selective coating and a single clear polycarbonate film is used at the top. The other sides are covered with urethane foam insulation. The air inside the chamber (container) gets heated by conduction, convection, and radiation from the top surface during daytime. In the bottom of the air heating chamber projecting downwards,there is a transfer well in which water enters through the ball fill valve and then the water leaves through the outer hose pipe. A plastic float actuates the vent valve and also supports the spray cooler. During daytime, air in the chamber goes on heating and the increased pressure makes the water level in the transfer oil to rise and thus closing the vent valve and also to settle the fill valve ball against its seat. Now the further increase in pressure forces the water further in the hose pipe and exerts more pressure on to the vent valve. At this stage water from the transfer well enters the spray cooler through another valve and thus compresses the trapped air. When the discharge line is filled completely, the discharge begins and continues till the air temperature continues to rise. When the air starts going through the discharge line, the internal pressure drops and the vent valve opens by gravity releasing the pressurized cooling water gets sprayed and cools the inside air almost to ambient air. It also allows the water again to enter the transfer well through fill valve and lift the float to begin next cycle.

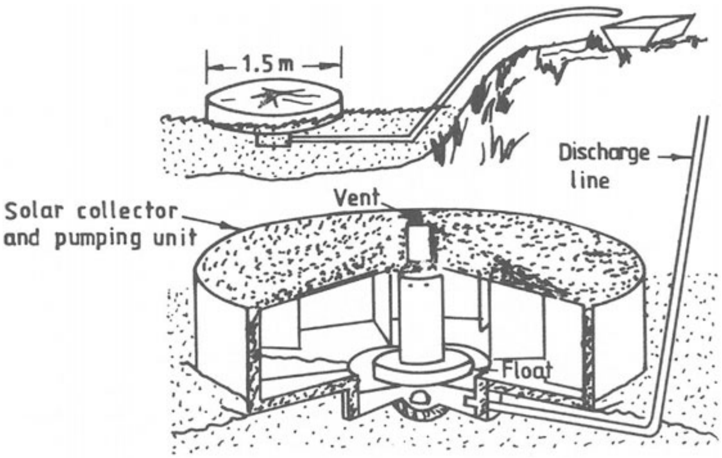

FIG.4.15. CONFIGURATION OF LOW HEAD SOLAR PUMP

4.4.8 Mead, Nebraska, 25 KW photovoltaic powered irrigation pump.

A 25 KWe peak power photovoltaic operated plant develope[55,56] jointly by MIT/Lincoln Laboratory and the University of Nebraska-Lincoln under ERDA sponsorship was made operational in the summer of 1977 at the Mead Experimental Station at Nabraska, USA. This photovoltaic system was designed to operate a 7.5 KW irrigation pump for 12 hrs per day operation to irrigate about 32 hactares of corn in summer season and for grain drying during non-irrigation portions of the year like fall and winter season. As is seen from fig. 4.16, the power unit consists of an array of photovoltaic panels, a battery storage unit, and a power conditioning control unit. The whole photovoltaic unit consists of 28 flat panels, each of 2.5 m high and 7.6 m long using about 100000 single crystal silicon cells each of 5.5 cm diameter and each of them was preassembled and wired into 2212 modules. The photovoltaic panels are arranged in two rows facing south each having 14 panels and arranged in such a way that individual panel could be elevated upto 65 deg. from horizontal. One row was put at about 1.5 m lower than the other to avoid shadow falling on cells. These panels are wired to provide 6.3 amps at a maximum voltage of 150 volts.

Power from the photovoltaic array is going to two shelters - one housing large number of rugged 6 volt lead-acid batteries which can store upto 85 KWh of energy for off-peak power use and the other housing the power conditioning/control unit. This unit is designed to combine the power onto a DC bus, upon which are floated the batteries. A switching unit is used to provide a DC power at 120 volts or 3-phase 60 HZ power at 240 volts using 22.5 KVA inverter. Lead-acid batteries 38 numbers each of 6 volts and nominal capacity of 375 ampere hours with a total storage capacity of 85 KWh are used. These batteries are connected in two rows each of 14 batteries giving a nominal voltage of 115 volts. For cloudy weather periods a 3-phase battery charger is used to supplement the array. The three inverters used in the system are controlled by a single master circuit to maintain a proper phase relationship. The whole system is controlled automatically using microprocessor and is programmed to extract maximum energy from the photovoltaic array.

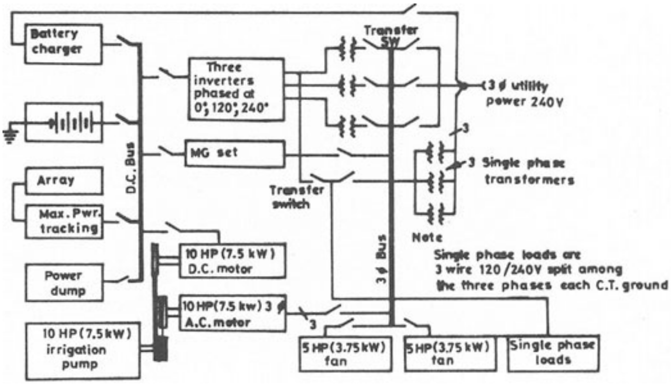

FIG.4.16 BLOCK DIAGRAM OF POWER SYSTEM USED IN MEAD, NEBRASKA 25 KW PHOTVOLTAIC PLANT.

A data acquisition system is used to measure the all input and output variables. The irrigation pump, 7.5 KW, was interconnected with a gated pipe irrigation system and worked 12 hrs a day and pumped 3.8m^3/min of water out of an irrigation reservoir. The irrigations were scheduled through UN-L's aggricultural computer Net work (AGNET). Grain drying experiments are also conducted using two each of 3.8 KW centrifugal fans. Two grain bins each of holding 150 tons of grains to be dried were built near the site. These fans are powered with solar electricity and each provided 0.001 m^3 of air per minute per kg of corn.

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CHAPTER - 5

SOLAR GREENHOUSES

5.1 INTRODUCTION

Solar greenhouses are the enclosures where crops, vegetables, or flowers are provided proper environment under adverse climatic conditions for plant growth and production. Certainly all greenhouses receive necessary sunlight from the sun required for photosynthesis and also supplementary heat during cold months from sun. In tropical countries, the solar insolation and ambient temperatures are quite high and therefore summer greenhouses can be designed in such a way that the inside temperature remains low and the plants receive sufficient of sunlight required for photosynthesis. Greenhouses are also now a days used for growing vegetables and flowers throughout the year even if their season is not there since the light and temperature in the greenhouses can be controlled. Some greenhouses are also designed to conserve the water resources. Naturally, each plant type requires a little different type of environment for best production, but basically the desirable needs are moderate temperature, light, carbon dioxide, oxygen, mineral nutrients, air movement and water. The greenhouses are generally made to provide two energy related needs which are moderate temperature and light. Temperature is a dominant environmental factor in plant growth and optimum temperatures must be maintained to obtain optimum conditions during all stages of plant growth. The temperature can be high but it should not be so high as to cause the metabolic change. The optimum temperature can be altered by changes in water relations, light intensity, etc. and is related with environmental factors. The light is absolutely essential for plant growth and development and the light intensity, light spectral distribution and its duration affects the plant growth. Therefore one of the most essential requirement of a greenhouse is the light transmission of solar radiation through the greenhouse covers (glazings). Since in cold climates during the night times the inside temperature can go quite low, auxiliary heating is required for maintaining the optimum temperature,therefore the greenhouse structure should be well insulated thermally to reduce the cost of auxiliary heating. Moreover, the greenhouse structure should have adequate strength to withstand the forces of wind, hail, and snow.

In a solar greenhouse, it is not only the light which is maintained at a desired level but the solar heat is to be stored for use at night and for cloudy days, and therefore it differs from the ordinary glass house. In solar greenhouses, the solar energy is collected and stored in a variety of ways and therefore the solar greenhouses differ in their designs. Moreover, the solar collection storage system depends on many factors like climate, greenhouse size, plant type, orientation, economics, and weather a new green house is to be planned or existing is to be modified.Further there can be a design difference if the collection-storage and distribution system is by passive means or by active means. The former greenhouses where the energy is stored directly in heavy brick walls or rock walls and/or water pools or water containers exposed to solar radiation and heat is distributed inside the greenhouse by natural means are known as passive greenhouses. In greenhouses where solar energy is collected and stored and distributed and where some auxiliary energy is employed either for circulation or for distribution or for both are known as active type. Generally a combination of both active and passive features are employed in a solar greenhouse with an objective to minimize the use of auxiliary energy either for heating the greenhouse or for collection-storage-distribution system. Another class of greenhouse is known as the attached-greenhouse where a greenhouse is made onto a house (house-attached) and where a free exchange of air between residence and greenhouse takes place maintaining the house temperature at comfortable temperature and reducing the heat losses from the greenhouse.

One unique advantage of a solar greenhouse is the less use of the auxiliary energy required to maintain the indoor air temperature required for plant growth compared to that required in the conventional greenhouse. Other advantages of a solar greenhouse are: growing season can be extended practically for a year at a much lower operating cost than conventional greenhouses, relatively easy to build, uses simple technology and low in cost because of the use of low cost materials.

There are many materials recently developed, techniques perfected and designs developed which make a greenhouse cost effective in certain situations. The parameters effecting the plant growth, material properties, techniques modifying the greenhouse environment, types of greenhouses, economics, few typical greenhouses and their performance prediction models are described in this chapter.

5.2 HISTORY

It appears that greenhouse industry was first developed in Holland during the middle of seventeenth century. The farmers of Netherlands grow vegetables, grapes, flowers, and lettuces out of season in greenhouses and the Netherlands has the largest greenhouse industry today in the World. In western Holland, grapes were grown along rock walls under glass enclosures which permitted early crops of grapes. In the western part of Netherlands, cut flower and vegetables are grown in large scale in greenhouses. These cut flowers and out of season vegetables were sent to many countries like Great Britain, France, Germany, etc. from Amsterdam. During the years 1800-1900 several environmental control techniques were developed and in Europe and North America greenhouses were used to grow two crops of lettuces followed by a crop of tomatoes or cucumbers in a single year[1]. During the year 1889-91, a greenhouse at Cornell University, USA was used to grow tomatoes as a midwinter crop and as a spring and early summer crop. Only those crops which have a short season, heavy yield, large demand, perish rapidly, and can fetch more price can be economically justified to be grown in greenhouses. Around 1850, in Boston, Massachusetts, USA, which used to be the Center of the horticultural industry in USA, farmers used to use glass slashes for making low height glasshouses[2]. During the years 1875-1890 in USA considerable improvements in the glass house designs were made and hot water and steam heating systems were introduced for heating the greenhouses. During the years 1900 large area green houses with timber frame construction in multi-3 meter span blocks covering each an area of 0.8 hactares with thermosyphon heating were constructed in USA and used for growing several vegetable and flower crops. Large span green houses were also suggested from light transmission point of view but because of high maintenance and capital cost these greenhouses were not accepted. Upto 1950, only horticultural glass or float glass was used as a glazing material for greenhouse. With the availability of PVC plastic films in 1950s, the growers started using these plastic films in place of glass sheets due to their low initial capital cost, easy handling, and convenient design of greenhouse.

Greenhouses are becoming popular for commercial production of vegetables and flowers in many countries like USA [3], Holland, Australia[4], Canada[5], Switzerland[6], USSR [7], Kuwait[8], France[9], Japan[10], Greece[11], U.K.[12], Sweden[13], Abu Dhabi[14],Saudi Arabia[15], Turkey, Lebanon, China, South Korea, and North Africa. Looking to its importance and good economics recently several review articles[1, 16-21], monographs and books[22-30] are written on greenhouses. In USA, almost every year a conference on greenhouses is arranged[31-34].

Greenhouse architecture varies greatly throughout the world. In some poor countries, a greenhouse consists of thatch(straw) roof supported by bamboo or wooden poles. This system may protects the plants from excessive solar radiation, rain, snow, or excessive cold. In some rich countries and even where solar insolation is quite high greenhouses with sophisticated structures with double glass as coverings and mechanical heating and cooling devices are used. Greenhouses are of several designs including the conventional quonset shapes, A-shape frame, and vertical towers. Transparent coverings used are of glass sheets or plastic sheets. Glass sheet covered greenhouses are used exclusively in north western Europe and plastic films or fibreglass reinforced plastics (FRP) are used in temperate areas such as the Mediterranean region. Transparent cover properties suitable for use in greenhouses are discussed by Bond et al[35]. Several parameters are to be considered in designing a greenhouse. The parameters and the design analysis of greenhouse are discussed by Zornig[36], Businger[37], Nisen[38], Selcuk[39], Hare et al[1], Nelson[28], McCullagh [26], Aldrich et al[27], Gray[21], Walker and Duncan[40], and Fuller et al[41,42]. The design of glass greenhouses are quite different from the plastic greenhouses. Some of the designs of glass greenhouses are described by Hare et al[1], Nelson[28], McCullagh[26], Courter[18], Wiebe and Barrett[19],Bauerle and Short[43], and Maghsood[44].

Several methods of heating the greenhouses and energy conservations are described in the literature such as by Nelson[28], McCullagh[26], Hare et al[1], Short et al[45-48], Badger and Poole[3], Mears et al[49,50],Roberts[51], Simpkins et al[52], Walker and Duncan[53], Aldrich and coworkers[54,56], Albright and co-workers[57-60], Johnson et al [61], Roberts and Mears[62], Blackwell et al[63], Kanthak [64], Click and Pile[65], Critten[66], Fohner and White[67], Silverstein[68], Tilford969], McCormic[70], Baird and Mears [71], Liu and Carlson[72] and Lawand et al[5]. Except on some higher latitude stations, cooling of green houses in summer is required otherwise high temperatures will result in low production, loss of stem length and flower size and delay in flowering, etc. Various mechanical and passive cooling techniques are proposed such as by Walker and Cotter [73], Nelson[28], Malik[8], Walker and Duncan[74], Bartok [75], Fuller and Meyer[76], Abdelmohsen[77], Hodges[78], and Peck et al[79]s.

For reducing the energy need in a greenhouse to maintain its temperature, a energy storage device is required. Many techniques of solar energy collection and storage for greenhouses have been proposed and tested. Some of the energy storage techniques suitable for greenhouses are proposed by Morrison[80], McCullagh[26], Jaffrin et al[81,84], Schneider et al[82], Blackwell and Garzoli[83], Kimball[85], Nash and Williamson[86], Akridge[87], and Dale et al[88]. In a winter greenhouse, the heat losses from the inside to the outside are to be minimized and the heat gains from the outside are to be maximized. Heat loss from the greenhouse can be calculated by any of the methods described in the literature[89-91]. There are several variables outside and inside the greenhouse which influence the thermal environment of the greenhouse and finally the crop yield. Several attempts are made in the past to develop mathematical model representing functional relations among the variables and the greenhouse environment in the hope to help the designer for a better greenhouse.

An analytical procedure is outlined by Walker[92] for the prediction of temperatures within both heated and ventilated greenhouses as environmental conditions or airflow rate is changed and the results are velidated with the observations made on full size greenhouse. A computer program was developed by Rotz et al[93] to simulate the performance of conventional and alternate systems for greenhouse heating. It shows that by using thermal insulation and solar heating, the fossil fuel requirement for heating the greenhouse was reduced as much as 90 percent of the conventional heating requirement. Roberts[94] reported simplified heat balance equations useful for the practical design of heating and ventilating systems. Computer simulation studies on a commercial greenhouse are carried out by McCormick[95] to analyse the performance characteristics of solar heating systems for economic optimization. A rigorous computer simulation model expressing the outside climatic parameter as Fourier series and including the plant transpiration, soil moisture evaporation, and condensation on the cover material was developed by Takukura et al[96] and used for predicting the temperature variations in various greenhouse constituents. Thermal radiation terms were linearised and iterative techniques are used for obtaining the solution.Seiginer and Ievav[97] have described various analytical and simulation greenhouse models developed. A quasi-one dimensional model was also developed by them where the greenhouse has been considered as horizontally homogeneous and the time variation of inside air temperature is expressed as Fourier series.

A mathematical model is developed by Froehlich et al [98] to predict steady-periodic thermal behaviour of glasshouses. This analytical model which gives the solution in closed form is able to predict internal air-water vapor mixture, plant canopy and floor surface temperatures with reasonable accuracy. A transient analysis to predict heating and cooling loads and moisture addition or removal required to maintain predetermined conditions within a green house is developed by Chandra et al[99]. The model appears to be quite general and flexible and greenhouse geometry, materials, environment conditions, future modifications etc. can be included without much difficulties. Selcuk[100] using unsteady state heat balance equations and numerical techniques of solution developed a greenhouse model which assumed infinite thermal conductivity of greenhouse cover material, uniform plant properties and saturated soil. The effect included were soil moisture evaporation, condensation on the cover, and plant transpiration. Iterative techniques are used to solve for air, plant and floor temperatures and radiation terms were linearized for simplicity. Initially a steady state thermal analysis was used to develop design criteria for solar residence/greenhouse combination by Zornig et al[101]. Later a dynamic thermal analysis was carried out by Zornig et al[102] to check various design parameters under varying outside and inside conditions. Recently Tiwari[103] has analysed the performance of a controlled environment greenhouse system and the effect of various parameters like ventilation/infiltration, relative humidity, movable insulation, etc. on the performance of greenhouse have been studied.

A dynamic mathematical model for the performance prediction of greenhouse and crop yield has been developed by Cooper and Fuller[104]. The model consists of five separate models for five main components of a greenhouse, namely the cover, air space, crop, growing medium, and floor. When combined interactively, the transient operation of the greenhouse can be simulated. This model can be used for determining the amount of photosynthate produced by a crop since the model responds to photosynthetically active radiation, leaf temperature, and carbon dioxide level.

Thus the traditional greenhouses used in cold climates are different in designs from the ones suitable under hot arid climates. The greenhouses for colder regions are designed to maximize the heat loss while the greenhouses for hot arid regions are designed to reduce the solar heat gains but sufficient light is admitted required for plant growth and designed to minimize the rate of water vapour loss from the plant and the soil in the greenhouse.

5.3 BASICS OF PLANT GROWTH

As discussed earlier there are many parameters effecting the plant growth and the important ones are light intensity its spectral quality and photoperiod, temperature of surroundings, humidity of surroundings, air temperature, CO_2, nutrients, etc. Greenhouse can provide such an environment for plants such that these can take maximum advantage of each of the parameters e.g. controlled and optimum dose of CO_2 can increase the yield considerably compared to the open outside environment. Therefore it is essential to know the basic requirements of a plant so that proper environment in the greenhouse can be created.

5.3.1 Light Intensity

Visible light energy, CO_2 and water is used by plants to convert them into carbohydrate and Oxygen, the process is known as photosynthesis and occurs in the green chloroplasts within cells.

$$\text{Light energy} + \text{water} + CO_2 \rightarrow \text{carbohydrate} + \text{Oxygen.}$$

Now this carbohydrate alongwith water and other nutrients from fertilizing materials is used in the growth of the plant which can be seen by dry matter. In the respiration process which is reverse of photosynthesis the energy in the plant is released which is used by the plant for various functions of growth such as nutrient uptake, protiens formation, division of cells, etc.

$$\text{Carbohydrate} + \text{Oxygen} \longrightarrow CO_2 + \text{energy} + \text{Water.}$$

When all the parameters like CO_2 level, temperature, and water are optimized for the photosynthesis process in a plant, then it is the light intensity which affects the plant growth. The light intensity varies from place to place but it generally varies from 0 at the begining of the day to about 100000 to 150000 lux (lumen/m^2) at the time of noon. Light intensity on clear and cloudy days goes quite low and some of the plants can not grow properly. At low or high light intensity than the optimum level, the process of photosynthesis (growth) slows down limiting the plant growth and yield because the chloroplasts are injured. Different plants need different light intensities for efficient photosynthesis. Plants can grow quite well even at a light intensity of 25000 lux which is about one fourth of the maximum light available in a day as is seen[105] in fig.5.1 Some plants like cucumber etc. need high light intensity while other plants like spanish, lettuce, tomato, etc. can be grown even at low light intensity. Since greenhouse structure cuts considerable light intensity, the light available in a greenhouse on a clear day rarely exceedcs 50000 lux. Therefore not more than two clear glazings in a greenhouse is recommended otherwise the necessary visible and near infrared light required for plant growth will not be enough. Additional light beyond a certain limit will also not help in the additional plant growth as can be seen from fig5.2 where three crops corn, tomato, and collard are shown. In areas where light intensity is low, the amount of light can be increased by painting the interior supports, walls and roof white and by using large area glazings using less sash bars. The light intensity can also be increased by using good quality glass or plastic sheet, orienting them properly and by keeping them clean. Supplemental lighting

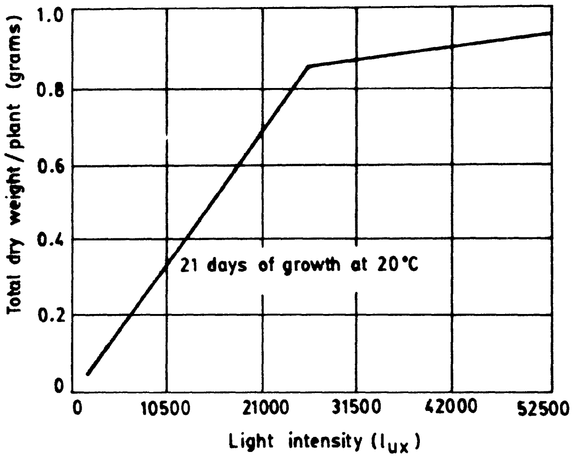


FIG.5.1. EFFECT OF LIGHT ON GROWTH OF MARQUIS WHEAT(From ASHRAE[105])

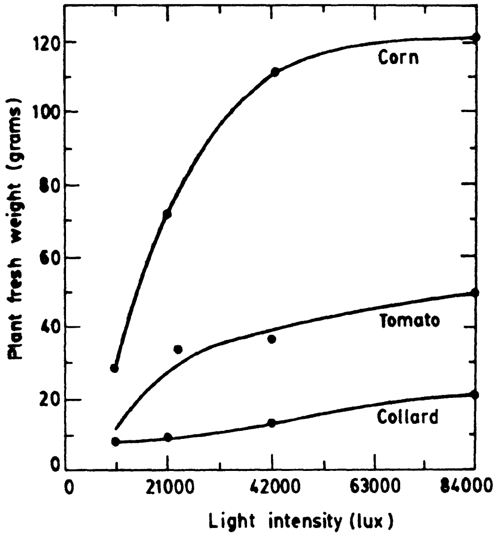


FIG.5.2. EFFECT OF LIGHT ON PLANT GROWTH(From ASHRAE[105])

may be necessary in some darken areas to increase either the light intensity or to increase the duration of light. The supplemental lighting is more effective when the plants are just germinating than these are old. Electric lamps of all kinds are used in greenhouses. Basically three types of lamps: incandescent, flourescent, and high intensity discharge (HID) are used. Incandescent lamps are not recommended for use in greenhouses. flourescent lamps with some kind of reflectors can be used in greenhouses. The high intensity discharge (HID) lamps such as high pressure mercury discharge type HID lamps, High pressure metal halide type HIE lamps, and high pressure sodium type HID lamps are recommended for supplemental lighting in greenhouses since these convert large percentage of electrical energy into visible light. The solar radiation on the earth surface lies in the wavelength range of 0.2 to 3 micrometer while for photosynthesis plants need light in the visible and in the near infrared region only. The photosynthetic activity is observed to be higher at some peaks in the red and blue bands of light. If more infrared light is available to plants, the internodes become long resulting in tall plants. Ultraviolet radiation in sunlight or from lamps can kill plants. More blue light on plants may make the growth short and may make them dark in colour.

The day length and night length i.e. photoperiod also affects the plant growth. The relative day-night lengths may affect the rooting of cuttings, initiation of flowers and fruits, bulbing and tuber formation, advent and cessation of dormancy etc. There are plants which require short day lengths, longday lengths and some are day-neutral plants. Spinach and radishes flower only when the daylengths are longer while chrysanthemums and pomsettias flower only when the daylength is shorter. There are plants like rose who do not respond to day-night lengths. In a greenhouse, the photoperiod can be increased or decreased by the use of artificial light or by using curtains.

5.3.2 Temperature

For every crop there is an optimum temperature at which the enzymes which is heat sensitive and responsible for biochemical reactions in the plant are optimally active. Photosynthesis and respiration are the two processes by which the plants grow. If the photosynthesis exceeds the respiration the plants grow, if it equals the growth stop and if it reduces the plants finally die. Temperature of plant surrounds and soil temperature required for plant growth is very much dependent on light intensity,CO_2 intake, humidity of surrounds, and air velocity. Thus the temperature may affect the movement of minerals, water and food in roots, stems and leaves, and can effect the photosynthesis process. For different stages of plant development, like germination, growth, flowering, fruit setting, different ideal temperatures are required as shown[105] in fig.5.3. However, the optimum temperature required can be altered slightly by changing the light intensity, water level, etc. The ideal temperature range, for winter crops is from 5 to 15°C but a variation of 2 or 3°C on either side will not affect the growth. However, if very low or very high temperatures continue for long durations then the growth will not be proper. Similarily for warm season crops, the optimum temperature range is 20°C to 30°C and 5°C temperature drop will not effect the plant growth. However, prolonged low temperature will result in loss of flowers and fruits and result in slow-down in growth while prolonged high temperature will result in loss of flowers, fruits, and burning of leaves and lowering in plant growth.

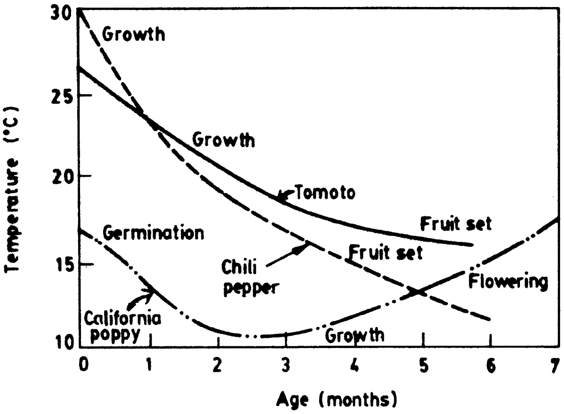


FIG.5.3. OPTIMUM NIGHT TEMPERATURE FOR GROWTH AND REPRODUCTION (From ASHRAE[105])

Soil temperature also affects the plant growth because it affects the absorption of water from the soil by the plant. The optimum soil temperature for most of the plants is of 20 to 25°C. The plants which grown in warm soil will not grow well in cool soil and vice versa. When the plants are germinating or are still young high soil temperatures above the optimum are desirable. Soil temperature will depend on many parameters including shading produced by plant leaves, solar intensity, etc. If the temperature difference in the soil and the air during the daytime and night time do not change much, the plants behave as it is grown at the mean temperature. Since in a solar heated greenhouse there is a temperature variation from floor to the roof, the warm crops can be placed near the roof and the cool crops can be located near the floor. Thus plant temperatures can be changed either by growing them on ground level beds or on benches or on shelves or in hanging pots.

5.3.3 Humidity

The relative humidity of air between 30 and 70 percent is ideal for plant growth. Vary high relative humidities (more than 90 percent) will provide better environment for pathogenic organisms making the plant sucesptible to diseases. High relative humidity alongwith high temperature are even more harmful, since for keeping the plant cool from overheating, the plant must lose moisture by transpiration which will not happen because of high relative humidity. The sapplings and germinating seeds need very high humidity ($\approx$ 100 percent) but as these grow and become younger the relative humidity should be gradually reduced. As the temperature increases, the requirement of high humidity increases. Low relative humidity is also harmful for plants since it increases the evapotranspiration rate which increases the water requirement. The low relative humidity alongwith high temperature will result in burning of tips and reduction in plant growth. In environmentally controlled chambers generally relative humidities between 55 to 65 percent and temperatures between 20 to 25°C is maintained. The relative humidity in a greenhouse can be lowered by ventilating it which suits most in spring and the fall but in summers the ventilation may make the greenhouse dry. In winters, ventilation should be avoided since it only removes the heat from inside and brings cool dry air but the dry air produces cooling in the greenhouse because of moisture evaporation. Therefore in winter water should be sprayed on to the plants and soil which on absorbing sunheat keep the inside a little warm.

5.3.4 Air movement

Although air movement does not directly affect the plant growth but due to its affect on transpiration, evaporation of water from soil, CO_2 availability, tearing of leaves, cooling effect, etc. the plant growth gets effected. The air velocity affects the boundary layer thickness of the leaves of the plant through which the plant transpired and water vapour diffuses into the outside air and through which atmospheric CO_2 enters into the plant required for photosynthesis. The affect of wind speed on the plant growth is shown[105] in fig.5.4. From this figure it is seen that at very low windspeeds (<0.05 m/s and at high wind speeds (>0.75 m/s) the growth of plant decreases. The optimum growth takes place between the wind speed of 0.10 to 0.35 m/s. Studies have shown that at a wind speed of about 2 m/s the growth of plant gets considerably affected and at a speed of 4 m/s the plant may die in few days. Since air movement in the greenhouse affects the soil temperature and evaporation of water from soil; leaf temperature and transpiration and relative humidity and air temperature; the air velocity is an important design factor for the greenhouse. The relative position of pots and plants and their height etc. all changes the air velocity in the greenhouse. The affect of wind direction on the plant growth is found negligible.

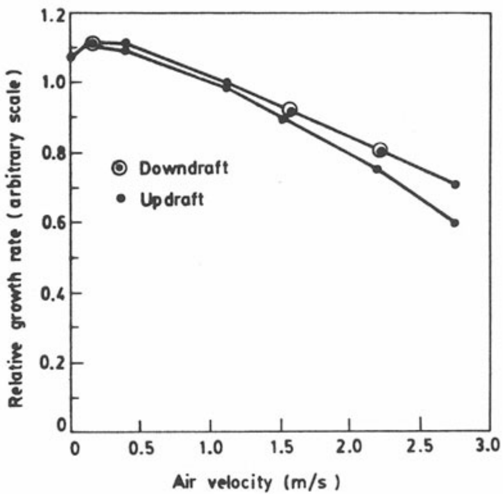


FIG.5.4. EFFECT OF AIR VELOCITY ON LEAF GROWTH (From ASHRAE[105])

5.3.5 Carbon dioxide

The amount of CO_2 present in the plant environment considerably effect the plant growth. The CO_2 present in the normal outside atmosphere is 0.03 to 0.04 percent and which is essential for photosynthesis. The amount of CO_2 required for optimum plant growth depends on the plant type, state of development, temperature, light intensity, leave areas, air velocity, humidity, water stress, etc. and the concentration of CO_2 in a greenhouse depends on the diffusion of air into and out of greenhouse structure, soil respiration, rates of photosynthetic uptake, and respiratory production. In case of an airtight greenhouse, the plant growth will be limited due to shortage of CO_2 and the growth can be enhanced by supplying CO_2 either by supplying outside air using somekind of counterflow heat exchanger or by some supplementary methods such as by using organic manure in green house or by combustion of sulphur free fossil fuels such as liquid petroleum, natural gas, propane, kerosene oil, etc. or by supplying CO_2 directly from CO_2 cylinders. The requirement of CO_2 for optimal growth is different for different plants. Some plants even can take CO_2 when it is 0.01 percent while others at 0.02 percent.

There are some small pores on the leaves known as stomata which absorb CO_2 from the atmosphere. The stomata are closed during night time when CO_2 is not used or when the CO_2 concentration is high even when there is light. Thus for optimal plant growth there is an optimal CO_2 concentration depending on the plant type. In an airtight greenhouse with full of plants, the CO_2 will be depleted in no time and hence attached greenhouse will have an advantage since the CO_2 left by inhabitants can be infiltrated from the house to the greenhouse. The effect of CO_2 concentration from 0.03 percent to 0.13 percent depending on the light intensity and temperature may effect the photosynthetic rate significantly as can be seen[105] from fig. 5.5. The stomata opening and

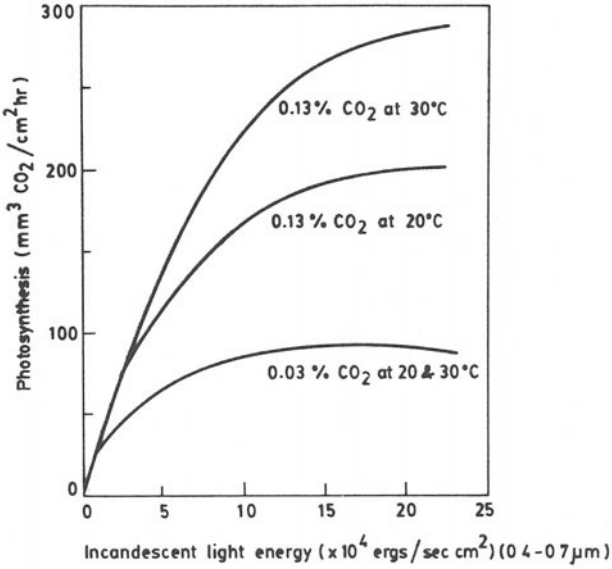


FIG.5.5. PHOTOSYNTHESIS OF CUCUMBER LEAF WITH CO_2 CONCENTRATION UNDER INCANDESCENT LIGHT(From Ashrae[105])

closing also depends on the water stress depending on water supply and water intake and transpiration. Many researchers have shown that by enriching the greenhouse atmosphere by CO_2, the crop yield increases, the quality of product improves, and the crop gets matured early. It is observed in case of lettuces and other crops that if the CO_2 concentration is 2000 ppm, light intensity 25000 lux, and temperature of 30°C for about 16 hours per day, the crop gets matured in half the time. Moreover these plants were heavier and of better appearance due to sturdier stem and leaves and increased branching. The plant will utilize the CO_2 more effectively, if the same is supplied during the time of more sunlight hours i.e. during 9.0 a.m. to 4.0 p.m. In winter season, when the light intensity is low the enrichment of CO_2 will produce the larger leaves helping receiving large amount of light. Generally CO_2 in the greenhouse is supplied by venting the greenhouse air. For providing sufficient CO_2 in a greenhouse a complete air change after approximately every ten minute is recommended. During spring and falls when the inside temperatures are not low, venting can be a good source of CO_2. But in winter direct venting is not recommended.

5.3.6 Nutrients

Plants need nutrients for growth. In a typical plant about 90 percent is water and the rest 10 percent which is known as drymatter consists of 17 essential nutrient elements.The three essential elements which are not provided by fertilizer are Carbon(C), Hydrogen(H), and Oxygen(O) and these three elements alone constitute about 90 percent of the dry matter. The remaining fourteen elements constitute the 10 percent of the dry weight and are available naturally in the soil and can be provided through fertilization programme. Carbon and a little Oxygen are derived by the plant from CO_2 while hydrogen and some Oxygen are derived from water (H_2O). In a greenhouse if CO_2 supply is not adequate there can be a shortage of carbon. Since the requirement of hydrogen and oxygen by plants are very small, their shortages are never felt even if the water is in short supply. Water stress may harm the plants in other ways only. The nutrients which are available in the soil through fertilization programme are divided into two categories, the macronutrients which are available in plants in large quantities, and micronutrients which are available in small quantities. The macronutrients are: Nitrogen(N) 4.0 percent, Phosphorus (P) 0.5 percent, Potasium (K) 4.0 percent, Calcium(Ca) 1.0 percent, Magnesium (Mg)0.5 percent and Sulfur (S)0.5 percent of the dry matter. The micronutrients are :Iron(Fe) 0.02 percent, Manganese(Mn) 0.02 percent, Zinc(Zn) 0.003 percent, Copper(Cu) 0.001 percent, Boron(B) 0.006 percent, Molybdenum

(Mo), 0.0002 percent, Sodium(Na)0.03 percent, and Chloride(Cl) 0.1 percent of the drymatter.

Nitrogen which is an essential nutrient for plant growth comes from the atmosphere and is being fixed in the soil by some legumes or is available to the soil due to decaying of organic matter like manure, hay, blood meal etc. The nutritional needs in a greenhouse can be seen through testing of soil. It is recommended that the greenhouse soil should be tested atleast once in three months. For most greenhouses a pH of the soil between 6.2 and 6.8 is recommended. The soil is neutral at pH 7.0, acid if below, and alkaline if above. If the pH of the soil is low then the supply of nutrients like phosphorous, Calcium, magnesium, and molybdenum are low and the supply of nutrients like Iron, Manganese, Zinc and Copper are more. Some of the common fertilizers which can be used to maintain the soil pH are : manure, dried blood, cotton seeds meal and tankage which are the organic fertilizers; Ammonium Sulphate, Ammonium phospate, Ammonium nitrate, Urea, Potasium nitrate, Potasium sulphate, Potasium chloride, Sodium nitrate, Calcium nitrate, Superphosphate, and Diammonium phosphate which are the inorganic fertilizers.

5.3.7 Watering

Watering of plants is considered to be the easiest operation generally done by an unexperienced person but if it is not properly applied like application at wrong time or in less or more quantity may affect not only the quality of the crop but also it may be spoiled. If water is not applied in sufficient quantity, the photosynthesis process will retard resulting in small size plants, small number of leaves, shorter stem internodes, hardened look of plant, and slow growth. If the water stress prolong, the leaves may drop off and the plant may die. If water is applied more frequently and in large quantities then the plant may become unnecessary taller, resistance to diseases reduced, and the lack of oxygen in the root system may damage the roots.

The water requirement and its frequency of application depends on the plant type, its density, time of year, plants moisture needs, etc. It is difficult to know when to irrigate and amount of water to be used but experience helps a lot. Now a days irrigation meters which are based on principle of conductivity are commercially available which can be used as a guidline for irrigation. In all cases the soil should be watered thoroughly otherwise with the evaporat-ing water the salts from the unused fertilizer will migrate to the soil surface, get accumulated and may injure plant roots.

5.4 GREENHOUSE DESIGN

Many parameters are to be considered in the design of a greenhouse. A few parameters are discussed below:

5.4.1 Orientation and tilt

The design of a solar greenhouse mainly depends on the type of plants to be grown in the greenhouse, the light and heat requirements of the plants, size of the business, season in which greenhouse is to be used, degree of automation desired, topography, local climate, and materials for construction. In a winter greenhouse, where the average outside air temperature is much lower than the optimum temperature required for the plant growth, the shape of the greenhouse is so optimised, that it receives adequate sunlight required by plant and minimize the heat losses. Since in northern hemisphere at high latitude stations, sun never shines on the north side, hence most of the glazings in the greenhouse should be provided on the south side. For winter operations only, the long axis of the greenhouse should face east-west direction, admitting more sunlight in winter season. A north-south oriented greenhouse will provide more sunlight over the complete year compared to east-west oriented greenhouse. If due to local conditions, it is not possible to orient the greenhouse in the east-west direction i.e. facing south then upto 20 deg. on either side of south direction will not significantly affect the receipt of sunlight. If the slope of the greenhouse roof is between 35 to 60 deg. even 45 deg. off south orientation will change the sunlight availability by 18 to 20 percent only.If the percentage of diffuse radiation is more, then effect of off-south orientation will be much less. In some areas where nights are very cold and after noons are generally cloudy, the greenhouse is oriented towards east to receive more solar radiation in morning. Therefore the local weather pattern is very important in deciding the orientation of a solar greenhouse. Since very little solar radiation enters through the north wall in a east-west oriented greenhouse, the north wall and north roof is generally opaque and made of solid material and insulated.

From the solar radiation receipt point of view, the angle of the roof of greenhouse is important. The slope of the greenhouse roof should be so selected that the angle of incidence of sun rays remains within 30 deg. If the angle of incidence becomes more, the reflection and absorption losses increases. Since more solar radiation comes through south facing surface and the solar radiation intensity is more during midday, the slope is optimized for south surface only. For winter use, the optimum angle of tilt of south roof from horizontal can be taken as latitude of the place plus fifteen degrees[106]. For best year round performance the slope of the south roof can be 0.9 times the latitude. Since most heating is required only in winter therefore the slope is generally decided on winter basis. The rear insulated wall if given proper slope and with reflector lining will reflect sunlight onto the plants in the greenhouse. This slope can be equal to the solar altitude at noon on June 21. Whatever may be the shape and slope of the north wall/roof it should be provided with reflective lining to enhance the solar radiation input. A very steep slope of the roof will unnecessary increase the area resulting in higher heat loss and the cost of the material.

5.4.2 Modes of heat transfer

The greenhouse should be designed to maximise the input of solar radiation which will require large glazing area. Increasing the glazing area would mean increasing heat loss from greenhouse to outside. Therefore the glazing area should be such that the solar radiation is enough to provide adequate sunlight and heat required by the greenhouse. Since the solar radiation is intermittent and is available only during the daytime a provision of storage should be made to store the solar heat required during night time or whenever the heat is required. There are several ways of

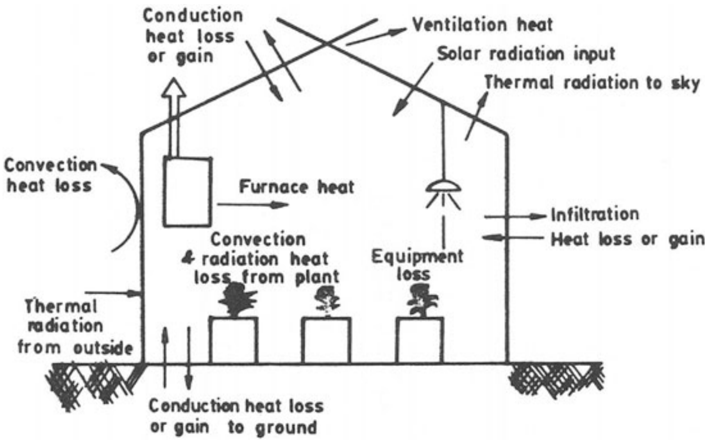


FIG.5.6. ENERGY FLOW IN A GREENHOUSE

heat loss from a greenhouse as is shown in Fig.5.6. The heat inside the greenhouse is received by solar radiation, by heat loss from electrical appliances, from auxiliary heat sources like furnace, by infiltration from outside air to inside air which may happen during daytime, by conduction process from the ground, and by thermal radiation from the walls in case wall is at a higher temperature. Heat is lost from the plants in the greenhouse by convection, transpiration, and radiation processes. Heat is also lost from the greenhouse through the ground which is generally through the edges. The temperature in the ground at about 3.5 meters depth is practically constant. After a sufficient of time there will be no heat loss from the greenhouse into the ground and the temperature in ground gets stablized which is equal to the average temperature of the greenhouse. If the edges of the building of the greenhouse are properly insulated, then there will be practically no heat loss from the greenhouse to the ground. Therefore the prefabricated greenhouse models and the greenhouses made on concrete slabs are not preferred since the edge losses in these case become quite high.

The convection and infiltration heat losses from the greenhouse which depends on the design of a greenhouse, cracks, and out side wind speed are also quite significant. If there are more cracks or leakages in the greenhouse, then the water vapour from the greenhouse can be carried away by the wind resulting in high heat losses. Therefore it is advisable that in a greenhouse there should not be any leakages. A large amount of heat is lost from the greenhouse by the process of conduction through walls and roof. In summer months when outside temperature is higher than the greenhouse temperature heat will flow into the greenhouse by conduction through walls and by infiltration through leakages. The inside plants and other materials in the greenhouse will reradiate the heat in the long wavelength region which can be transmitted by some of the plastic glazing materials. The use of such plastic glazing materials which are transparent in the short wavelength region (solar range) and long wavelength region (thermal radiation) also should not be used as a glazing material in a greenhouse. Glass and fibreglass materials which are transparent for short wave radiation and opaque to long wave radiation are desired glazing materials for greenhouse. But glass is a good conductor of heat and therefore single glazing is not preferred.

Since the thickness of the glazing material is very small the resistance to heat loss becomes very small and therefore multiple glazing with some air space in between is used to reduce the heat loss. Since little resistance is offered by the glazing for the heat loss through it, the glazing area should be kept minimum or provision should be made to reduce convection, conduction, and radiation heat loss through it such as by using multiple layers of glazing, using movable insulation during night time or even during day time when the solar radiation is quite low. The multiple layers of glazing not only reduces the heat loss by the process of conduction and convection but also by radiation because the glazing temperature goes on decreasing. The trapped air spaces reduce both the conductive and convective heat losses. Generally two glazings are preferred in colder regions either of the same material or with the outer layer made of glass and inner layer of plastic.

During night time considerable amount of heat is lost through glazing which can be reduced by using movable insulation. The movable insulation which can be of a curtain type generally consists of rolls of canvas covered with insulation and which can be unrolled down on the greenhouse at night time and rolled up again in the morning is used. The arrangement of a movable insulation should be made in such a way that it should remain in position and should not be effected by wind and snow. Use of Beadwall system during night time developed by Zomeworks in Albuquerque, New Mexico in which the dead air space between the glazing is filled with the help of a compressor with very small tiny plastic beads during night time and the same are removed through a vacuum pump (reversing the compressor operation) during daytime is also quite effective. This system appears to be very effective but is not feasible and practical at all places and therefore removable interior insulation consisting of styrofoam or other insulation with a backing of rigid sheets such as plywood and masonite is recommended. This system will also help in controlling the sun in hot summer months. Venitian blinds can also be used for controlling the sun in an efficient manner but can be effective in combination with some insulating material.

The use of metal frames such as aluminium frames is not desirable since this will conduct more heat and therefore wooden frames are preferred. The heat loss through the opaque surfaces and walls can be reduced by using insulating materials or by using cavity walls. Several insulating materials such as fibreglass, thermocol, extruded polystryene, polyurethane foam, polystyrene microfoam, etc. are suggested for use in greenhouses.

Generally the heat loss through the material is represented in terms of heat transfer coefficient, 'U' which is defined as the heat transfer per unit area per unit of temperature difference from inside to outside. For convenience 'R'values which is the reciprocal of 'U'and is the resistance to heat flow are given in books and are more convenient to use. Low 'R'values mean low resistance to heat flow and high "R" values of materials mean high resistance to heat flow. The values of "R" for various materials used in the construction of greenhouses are given[3] in table 5.1.

Table 5.1 Heat resistance values for some greenhouse construction materials (From Badger and Poole [3])

	Material	R values** (m^2 $^oc/w$)
1.	Glass, single layer	0.155*
2.	Glass, double layer 6 mm space	0.271*
3.	Glass, triple layer, 6 mm space	0.375*
4.	Clear polyethylene film, single layer, (2,4 or 6 mil)	0.153*
5.	Clear polyethylene film, double layer, separated (2, 4 or 6 mil)	0.252*
6.	Polyethylene film, double layer, separated over glass	0.352*
7.	Fibreglass	0.176*
8.	Double acrylic (acrylite SDP)	0.313*
9.	Double polycarbonate (Tuffak-Twinwal)	0.283*
10.	Face brick, 10 cm thick	0.077
11.	Concrete Block, 20 cm	0.345
12.	Concrete Block, 20 cm plus 2.5 cm foamed urethane	1.354
13.	Concrete Block, 20 cm plus 2.5 cm foamed polystyrene	0.977
14.	Concrete, poured 15 cm	0.234
15.	Cement asbestos board, 6 mm	0.160
16.	Cement asbestos board, 6 mm plus 2.5 cm foamed urethene	1.257
17.	Cement asbestos board, 6 mm plus 2.5 cm foamed polystyrene	0.838
18.	Microfoam 6 mm thick	0.190
19.	Polystyrene(beadhoard or loose fill), thick 12 mm	0.369
20.	Polystyrene (beadboard or loose fill) 18 mm thick	0.537
21.	Polystyrene (beadboard or loose fill), 2.5 cm thick	0.704
22.	Extruded polystyrene (styrofoam) 2.5 cm thick	0.951
23.	Polyurethane foam (applied at site), 2.5 cm thick	1.285
24.	Plywood, 1.2 cm	0.109
25.	Plywood, 2.5 cm	0.220
26.	2.5 cm nominal softwood	0.315
27.	Expanded vermiculite (60-100 Kg m^3, 2.5 cm thick)	0.352

Curtain Materials

28.	Al/Temp. Aluminium down	0.252
	Aluminium up	0.208
29.	Duracote 2425 (Foylon)	0.463
30.	Black Sateen	0.271
31.	Black Polyethylene, 6 mil	0.185
32.	Reemy, spunbound polyester, 2016	0.146
33.	Vinyl(aluminized polyester laminated vinyl), 4.5 mil.	0.378
34.	Al/Blac	0.241

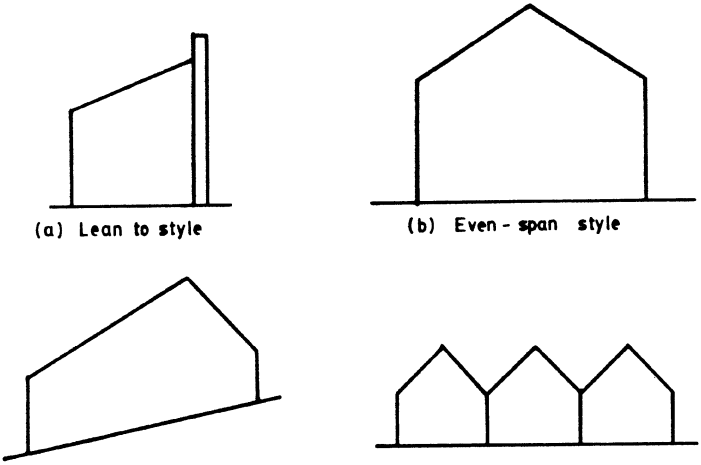
** The R value represents the resistance to heat flow at the thickness listed. The higher the R value the better the insulating property.

* Includes effects of surface coefficients.

5.4.3 Glass or plastic Greenhouses

As discussed earlier both the glass and plastic greenhouses are made but plastic greenhouses are now a days preferred because of their low initial capital cost. Before the year 1950 only glass greenhouses were existed. The life of glass greenhouses can be even more than hundred years but the cost involved is so high compared to plastic greenhouses that their cost per year comes out to be much higher . The glass greenhouse styles depend on a number of parameters including size of glass sheet available, climatic conditions of the place, light and heat requirements of the greenhouse, type of automation required in the greenhouse, crop to be grown in the greenhouse, season in which the greenhouse is to be used, the type and material of frame to be used, etc. Some basic styles of greenhouse[28] are given in fig.5.7. In the lean-to design as shown in fig. 5.7a, the greenhouse is put against the wall of a building and thus makes use of maximum sun light and minimum roof support structure. For single small greenhouse on a levelled ground an even-span greenhouse as shown in fig.5.7b is preferred. In this design the roof is of tent like structure with equal slope and width. If the land is not levelled and can not be levelled easily such as in case of near the side of a hill, uneven-span greenhouse as shown in fig.5.7c is used where the two roofs are of unequal width. This design although has its advantages but is not adaptable to automation. These individual greenhouses as shown in fig.5.7 (a, b, c.) are in use. In a large area greenhouse, ridge-and-furrow type arrangement where several greenhouses generally of even-span type are connected are used as shown in fig.5.7d.

Fig.5.6. Energy flow in a greenhouse.



(a) Lean to style

(b) Even - span style

(c) Uneven - span style

(d) Ridge - and furrow style

FIG.5.7. BASIC GREENHOUSE STYLES

In the ridge-and-furrow type greenhouse the heat loss gets reduced because there are no intermediate side walls, automation is possible which can be done at a low cost, and the cost gets reduced. In this design snow can be a problem and can not slide off the roofs as can happen automatically in case of individual free standing greenhouses, therefore heating pipes are generally used in the gutter to melt the ice.

Greenhouse frames are also made of different materials like that of wood, iron and aluminium. Details of some of the commercially available glass greenhouse frames in U.K. are shown schematically[1] in fig.5.8. Depending on the width of the structure, a particular type of frame and its material selected. If the width of the structure is less than 6 m, then wood frame is preferred. If the width of the greenhouse structure is between 6m and 15m then iron frame is recommended. In a iron frame structure the truss is made using steel pipes or angle iron of flat steel welded together and the angle iron perlins running the length of greenhouses are bolted to each of the truss. Now-a-days iron frame structures in greenhouse are widely used because they can be prefabricated by automatic machines and are economical in the long run. The glass sheets are attached to the iron or wooden frames with the help of sash bars which are generally made of durable wood. These wooden sash bars require maintenance. Now a days even aluminium sash bars are also used in fixing the glass with the metal frames. The advantage of aluminium sash bars are : maintenance is low, available in prefab condition, and are stronger than wood sash bars and therefore large size glass

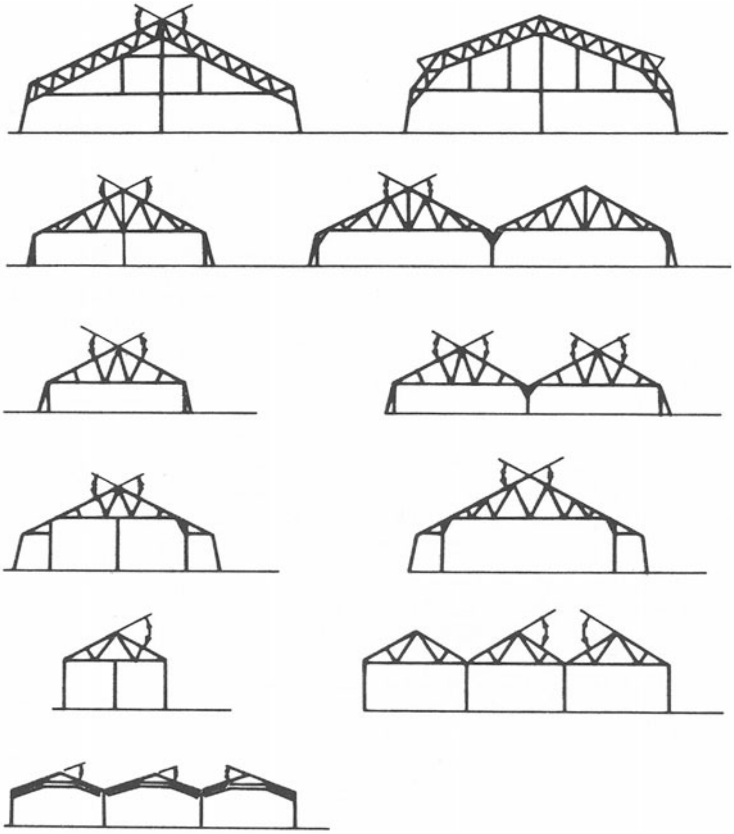


FIG.5.8. TYPICAL GLASS GREENHOUSE FRAMES USED IN UK (From Ref.1.) (Reproduced with permission from Robinsons of Winchester Ltd Hampshire, UK)

sheets can be used reducing shadows in the greenhouse due to frames. Generally glass sheets of 1m x 0.5m are used in case of aluminium sash bars. Plastic film covered greenhouse are now a days in use in many countries. Because the plastic films are available in variety of thicknesses and sizes and because of their low weight, a large variety of frame designs are available for use with the plastic materials as covering. Some of the plastic greenhouseframes

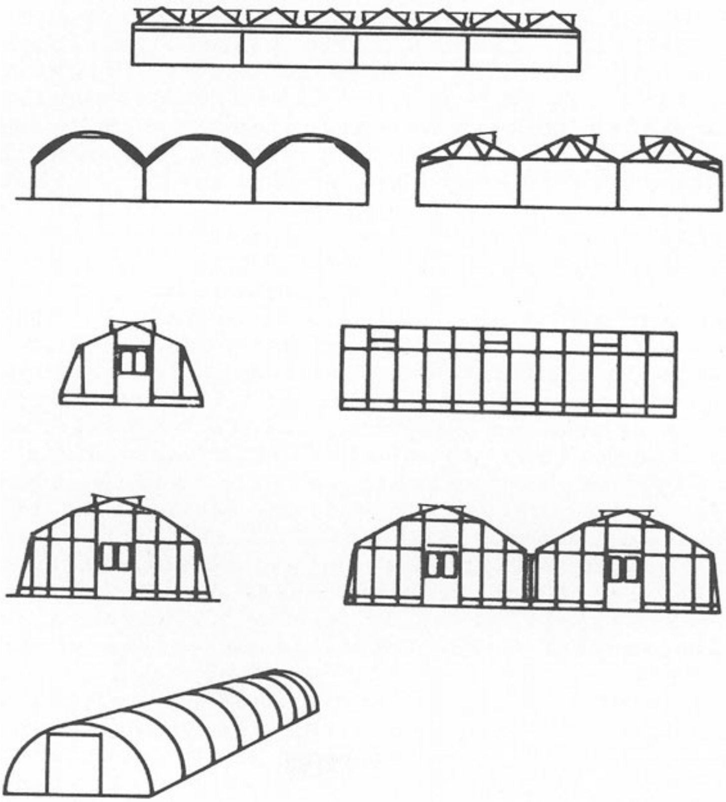


FIG.5.9. TYPICAL PLASTIC GREENHOUSE FRAMES USED IN UK.(From Ref.1) (Reproduced with permission from Robinsons of Winchester Ltd Hamshire, UK.)

are shown[1] in fig.5.9. If the plants are to be grown only for a very short duration such as for growing of seedlings, the plastic greenhouse will prove to be more economical compared to glass greenhouse the cost of which can not be justified. Films which are generally used in a greenhouse are mylar, vinyl, polyethylene, etc. Polyethylene film is used as a covering material in greenhouses and such greenhouses are in use in U.K. and U.S.A. The only disadvantage with the plastic film is of its short life may be 1-2 years depending on its thickness and weather. The plastic film greenhouse frames can also be made inexpensively by using soft wood such as pine or using iron. To reduce heat loss from the greenhouse two layers of plastic with an air gap in between of about 3 to 5 cm are used. Virtually almost all the plastic greenhouses now-a-days use air inflated system in which a plastic film is applied directly on top of the other from the outer side and the space between them is maintained by supplying air at a low positive pressure. The pressure between the sheets should be small to keep the 2 sheets apart and should not be very large.

Rigid plastic sheets such as polyvinylchloride (PVC) and fibreglass reinforced plastic (FRP) sheets are also used as glazing materials in the greenhouse. Because of poor weathering of PVC sheets, high cost of installation and high initial cost, these sheets are not used. FRP sheets which are available in different shapes and sizes are used widely as a greenhouse covering material. The choice of cover materials depend on many parameters such as: short wave (solar radiation) transmission, long wave (thermal radiation) transmission, resistance to ultraviolet degradation, weathering properties, temperature limitations, coefficient of expansion, mechanical strength, availability, material and installation cost, and weight. A list of cover materials used in solar greenhouses in USA as discussed by Bond et al[35] is given in Table 5.2 which also include their longwave(>2.8 µm) transmittance values when these are used only as a single sheet. As discussed earlier single glazing material is not very effective and therefore two cover materials with some airspacing in between are used. Transmission properties of some cover combinations when outer cover is polyethylene and inner of other materials are given in Table 5.3 and when the outer is glass and inner of some other materials are given in table 5.4.

5.4.4 Heat Storage in the Greenhouse

The temperature in the green house can be maintained and the energy can be conserved by using a suitable thermal energy storage device. Heat can be stored inside the greenhouse or it can be stored in a storage bin outside the greenh house. Generally in-built-heat storage device in the greenhouse is preferred and used. The different heat storage materials proposed for use in the greenhouse are sensible heat storage materials like water, oil, rock, adobe, masonary walls,soil, steel rods, graphite, etc. and latent heat storage materials such as wax, salt hydrates and their eutectics. Some of the energy storage techniques

Table 5.2 Tranasittance values of single cover materials

Cover material	Longwave transmission (percent)	Shortwave transmission at normal incidence (percent)
Glass(double strength),3.2 mm	3	89
Polyethylene, 0.1 mm	80	92
Flat fibreglass, o.63 mm	12	87
Polyester, 0.13 mm	32	88
Corrugated Fibreglass,1.0mm	8	83
Polycarbonate, 1.6 mm	6	86
Polyvinyl flouride, 0.08mm	43	93

Table 5.3 Transmission values of double cover materials when top cover is of polyethylene.

Cover combination	longwave transmission (percent)	Shortwave transmission (percent)
Polyethylene-polyethylene	63	83
Polyethylene - glass	1	81
Polyethylene-flat fibreglass	5	77
Polyethylene-polyester	21	81
Polyethylene-corrugated fiberglass	4	72
Polyethylene-polycarbonate	2	78
Polyethylene-Polyvinylflouride	31	86

Table 5.4 Transmission values of double cover materials when top cover is of glass.

Cover combination	Longwave transmission (percent)	Shortwave transmission (percent)
Glass-glass	1	80
Glass-polyethylene	2	80
Glass-Flat fiberglass	1	69
Glass-Polyester	1	78
Glass-corrugated fiberglass	1	71
Glass-polycarbonate	1	76
Glass-polyvinylflouride	2	83

suitable for greenhouses are proposed by Morrison[80] MeCullagh[26], Jaffrin et al[81, 84] Schreider et al[82], Blackwell and Garzoli[83], Kimball[85], Nash and williamson[86], Akridge[87], and Dale et al[88]. A review of thermal energy storage systems is recently done by Garg et al[107]. The position of thermal storage mass in the greenhouse is very important in efficient storing and distributing the heat. If the storage mass is exposed directly to the solar rays than it will absorb and distribute the heat more effectively. Because in a greenhouse plants occupy large areas therefore the space left for the placement of heat storage system is limited. The capacity of plants and the material in the greenhouse except the ground and the walls is very little and therefore the heat storage by them is used for heating and humidifying the air only and which is difficult to store. Therefore large amounts of massive materials which are cheap like drums filled with water and rocks are used to store the heat and which creat a thermal "flywheel", absorbing the heat during the daytime and releasing the same when it is required such as during night time. Moreover, a thermal coupling between the storeage and air in the greenhouse is required which will help in direct absorption of solar energy by the storage material and distributing the same to the air in the greenhouse effectively.

Since there are large number of plants in the greenhouse and which may be tall and bushy also, there will be very little space left in the greenhouse where the storage mass can be placed and exposed to the direct sunlight. The geometry of the greenhouse may be able to solve this problem in which case it can be designed in such a way that the glazing hight on the south side can be kept as equal to the greenhouse depth and the east-west dimension two or three times the north-south dimension. In such a design the sunlight from the south wall having glazing at 45 to 60 deg will allow the sunlight to fall on the north wall where the storage mass such as water drums can be stacked. Generally water is stored in a number of 208 litres (55 gallon) steel drums which are stacked one over the other forming a wall near the north wall or at any other convenient place where these can be exposed to the sun. Small metal or thin plastic containers with a capacity of 15 to 20 litres filled with water and stacked one over the other can also be used to store the heat. These water filled containers should be stacked in such a way that the heat is transferred and extracted from them efficiently.

Rocks or masonary walls are also used for storing the heat in greenhouses. the disadvantages of these solid sensible heat storage materials are of low thermal capacity and poor heat transfer properties compared to water. The only advantage of these materials is that these can form a part of the greenhouse construction. All masonary walls which can be solid or bins and pellets of loose stones which are directly illuminated by sunlight are used for storing the heat. Several methods of improving the heat conductivity of the walls and increasing the heat capacity are suggested such as embedding steel tubes or rods in the concrete wall at some optimum spacings, mixing iron filings which is a waste material from steel mills in the cement concrete, making use of graphite material in making the wall, etc.

The ground in the greenhouse when exposed to the sun also stores the heat and the amount of heat storage depends on the moisture content of the soil, organic mineral in the soil, and soil colour and covering, etc. The daily cycle of heat penetrates from 20 cm to 30 cm. The heat absorbed in the soil which is about 20 to 40 percent of the solar heat falling on it is lost by convection and radiation into the air of the greenhouse during night time. In summers, when the heat gain in the soil is more than the heat loss, the heat cycle penetrates to depths from 3 m to 10 m. To prevent heat loss from the ground to outside, the perimeter of the greenhouse should be properly insulated.

Several latent heat storage materials such as waxes and salt hydrates and their eutectics are also proposed for use to store heat in the greenhouse. These materials when properly used are able to release and absorb enormous amount of heat by changing from one phase to another phase. Jaffrin and Cadier[81] have used 13.5 tons of calcium chloride hydrate in 9000 flat bags each of one dm^3 containing 1.5 Kg salt and piled up on five levels in a tunnel burried in the ground. These bags are made of polyster-aluminium-polyethylene complex and are made airtight by properly sealing. Small centrifugal fans are used to circulate the air through these bags for charging and discharging purposes.

5.5 ENERGY CONSERVATION TECHNIQUES

By properly designing and applying various energy conservation techniques the solar greenhouse can be maintained at the desired temperature even on cold winter days without the use of fossil fuel energy or with very little use of fossil fuel. Several energy conservation techniques are described by Short etal[45,47], Badger and Poole[3], Rebuck etal[55], Seginer and Albright[59], Silverstein[68], Johnson etal[61], Critten[66], Fohner and White [67], and Aldrich and White[54]. The various energy conservation techniques suggested by Badger and Poole (Ref.3) can be grouped as either modification, maintenance, or miscellaneous techniques. The modification techniques include both the structural modifications and the heating system modifications.

Table 5.5 Summary of Potential Annual Savings for Energy conservation Methods (From Badger and Poole[3])

Method	Annual percent savings (Range)
0. Glass	0 (base)
A. Major Modifications continous	
1. Double plastic film over glass	40-60
2. Glass-lap-sealants	5-40
3. Single plastic film over glass	5-40
4. Double layer plastic film	30-40
Periodic	
5. Curtains	20-60
6. Polystyrene pellets	60-90
7. Liquid foam	40-75
B. Other Modifications	
1. Sidewall insulation	5-10
2. Foundation insulation	3-6
3.Insulating ventilation fans	1-5
4. Heating systems:	
a. Automatic firetube cleaners	6-20
b. Turbulators	8-16
C. Maintenance	
1. Structure	3-10
2. Heating system	10-20
D. Miscellaneous Factors	
1. Windbreaks	5-10
2. Greenhouse orientation	5-10

The various conservation techniques and the resulting percentage annual savings as calculated by Badger and Poole[3] are given in Table 5.5. The Ohio Agricultural Research and Development Centre(OARDC) has suggested the use of double-plastic-over-glass (DPOG) and studied its effect on the energy savings and its effect on plant growth. It has been shown that DPOG reduces the annual fuel requirement by 57 percent. Another modification suggested by OARDC for conserving energy in a green house is replacing glass with a rigid double wall acrylic sheet and glass lap-sealants. The use of silicone sealant between glass laps reduced the infiltration of cold air into the glass greenhouses. In old greenhouses the use of silicone sealant will realize the most savings. The energy in the greenhouse can also be conserved by the use of thermal-curtains to the greenhouse interior which reduces heat losses resulting from convection, radiation and infiltration. Studies on thermal curtains have been done by Simpkin etal[52], Seginer and Albright[59], Rebuck etal[55], and Albright etal[58]. The thermal curtain which are used at the night time reduces air staratification and the amount of the space to be heated. The thermal curtains should be sealed tightly at the edges otherwise it will not be very effective. Commercially available single layer thermal curtains are able to stop up to 60 percent of heat loss during night time. If the thermal curtain also uses a reflected surface than there will be a further 10 to 15 percent savings in energy loss compared to a non-reflective thermal curtain. Generally a solid thick curtain with reflector lining on one side with a automatic opening and closing mechanism operated with the help of photocell or time clock is preferred over the multi-layered one with both reflectorized surfaces. Apart from insulation and reflection characteristics of the thermal curtains the other requirements are ease of fabrication and handling, weatherability, cost, tear strength, flammability, and longevity. sometimes an air-inflated blanket system is also used which is mounted on the inside of the roof. This air inflated blanket can also be used on side and end-walls. By using such air-inflated blankets fuel savings upto 40 percent can be achieved.

5.6 HEATING AND COOLING OF GREENHOUSES

Heat should be supplied to the greenhouse at a rate at which it is lost to the outside to maintain at the desired temperature. Heat loss from the greenhouse takes place mostly by transmission through the covering materials of the greenhouse, infiltration through the cracks and leakages, and radiation from warm inside objects to the outside. Various methods in the literature are discussed to heat the greenhouses using solar energy. Some of the methods are discussed here.

Scientists at the Cook College, Rutgers University, New Jersey, USA have developed several systems to heat a greenhouse through the floor. These systems are: (i) The Rutgers solar heating system[49,50) (ii)Using condensor cooling water from power plants(108), (iii) In floor placement of plastic pipe for warming porous concrete floors[62], and (iv)The use of plastic pipe and plastic grids in floors of various materials(109). In one of the most successful solar heating system of greenhouse, four major elements are employed. One element is a movable insulation curtain system which is used during the night time and reduces the heat loss. The second element is a composite floor which performs the dual function of storing the heat and dissipating it to the greenhouse. The composite floor consists of four layers, the bottom layer is made of polystyrene board insulation, the next layer is a vinyl swimming pool liner, the third layer is a gravel bed which is flooded with the hot water, and fourth and the last layer which is at the top is a cap of porous concrete. this porous concrete floor serves the propose of heat exchange and also allows the excess irrigation water to drain. The gravel bed which is flooded with water serves the purpose of thermal storage and the [3]vinyl layer holds the water. The third element is the vertical curtain heat exchanger which helps in transferring heat efficiently into the greenhouse from the stored hot water. The heat exchanger is formed by making use of a trickle irrigation hose which is tied to a horizontal support and a plastic film draped over the support. This support is attached to the curtain insulation system and the vertical curtain can be dropped to the floor when not in use. Hot water from the ground bed is pumped through the trickle hose, flows between the two plastic sheets releasing heat to the greenhouse and the water returns to the storage through the porous concrete floor.

The fourth element is a solar colector heating water which is made up of a frame covered with five layers of plastic film. The middle black layer is a rigid plastic film absorbing solar radiation while the other two layers on either side of this black layer are of transparent polyethylene film. The spaces between the two clear plastic films are maintained using air pressure. The collector is mounted at an optimum tilt near the green house facing south and the water is introduced through a pipe manifold at the top. The water gets heated during its passage from top to bottom and the hot water is collected in a return gutter at the bottom and by gravity flows into the floor storage. The auxiliary heat is provided with the help of an oil-fired burner. A differential controller thermostat is used to control the collector pump operation which circulates the water when the collector is at a temperature of 5-6°C more than the floor temperature. If the greenhouse air temperature falls below a certain set temperature, the circulator pump starts circulating hot water through the curtain heat exchanger. If the floor temperature falls below the set temperature sensed by the thermostat then the heat is added to the greenhouse using oil-fired burner.

The greenhouse used in this study is about 5.2 m by 7.3 m with a total useful floor area of 33.4 m^2 and the exposed roof and wall area of 80 m^2. The solar collector area is 33.8 m^2 and the exposed heat transfer area of the verticle curtain heat exchanger is 37.27 m^2. The system was found quite effective and economical.

In Australia[83] systematic work has been done on heating of greenhouses using solar energy. Heat loss due to infiltration was stopped using neoprine sealing strips at the edges of each cladding sheet and silicone sealant at all sheet overlaps. A thermal screen made of aluminised polyster was also used at night time. To Provide additional solar heating, three systems are tested. In system 1, a single-skin polyethylene tunnel of 6m x 12m alongwith an insulated 10m^3 rockpile thermal storage system and a fan capable of delivering 2500 m^3/hr. against a pressure of 7.5 mm w.g. were used . Hot air from the highest point near the end wall of the greenhouse was drawn and passed through the rock pile so long as the temperature of the air entering the pile was higher than that leaving. At night with the help of thermostat set at 6°C the pump starts extracting heat from the rock pile. This simple system was able to maintain a 6°C differential against an outside minimum of 1.7°C.

In system II, the polyethylene cover was removed and instead a single skin of fibreglass reinforced polyster was used. In this system, a solar air heater made of standard galvanised roofing material with a total area of 24 m^2 was used. Five galvanised iron sheets were overlapped forming 10 air channels with flat base and sides closed. The upper surface is painted black. The cover is the same transparent fibreglass as is used for cladding the greenhouse. The fan is the same as is used in system I, which draws air from the greenhouse allows it to pass through all the 10 channels of the solar air heater and then returns the air to the top of the rock pile. The solar air heater assembly was bolted to the trusses of the greenhouse with the channels running horizontally along its length and mounted in such a way that the angle of inclination of the absorber varied from 21.5 deg. at the northern edge to horizontal at the apex. The volume of the rockpile is 10 m^3 and charging and discharging of the rockpile was done in the same direction i.e. always downwards for simplicity reasons. This system was able to maintain an air temperature of 9°C inside the greenhouse against an outside minimum of 1.1°C.

In system III, called as low energy greenhouse, the cover material used is double skin of fluted-acrylic sheet with enclosed air channels of 5 mm x 5 mm. The south wall of the greenhouse is made up of concrete blocks which is also the wall of the two identical 20 m^3 rockpiles. The solar air heaters (23 m^2) are made by rivetting two sheets of standard aluminium roofing profiles back to back producing 12 air channels for each rockpile and fixed at an angle of 60 deg. on the rockpile and form one wall of the upper and lower fan chambers. The air heater uses 2.5 cm formaldehyde foam insulation on the rear side and transparent corrugated acrylic sheet on the exposed side. Each rockpile is provided with a 0.33 KW electric motor driving a fan delivering 8000 m^3/hr. against a pressure of 24 mm w.g. This system was able to maintain a inside air temperature of 10°C against the outside minimum of 1°C.

The Boeing Company of USA has proposed a unique system for heating a greenhouse using solar energy. The greenhouse heating system as described by Deminet[110]uses all glass collectors utilizing glass structure containing partially evacuated cells and enclosed passages. The solar energy is absorbed directly by a blackened working fluid. It is also proposed to use a water solution containing 2.5 percent of $CuCl_2$ circulating through the collector which absorbs electromagnetic radiations in the infrared region and is transparent to the visible wavelength. This water solution picks up the heat from the glass solar collector and the hot water is stored in a tank from where the heat is supplied to the greenhouse as and when desired.

A similar system was proposed byDamagnez et al[111] where the solar collector consists of a double sheet of rigid plastic covering the entire south facing surface of the greenhouse. The water containing a little CuCl circulates between the two sheets absorbing solar radiation and the hot water solution is stored in an insulated storage tank kept underneath the greenhouse. During night this hot water solution is recirculated through the spacing between the two plastic sheets as was done during the day time and thus heating the greenhouse. The main advantage of the system is that no additional space is required for solar collectors.

A full scale greenhouse located[71] at Bradenton, Florida is heated using solar flat plate collectors, an insulated hot water storage tank, water-to-air heat exchanger in the greenhouse, and automatic controls. The greenhouse used in this study is the conventional one using glass as the cover material with a total greenhouse floor area of 135 m^2 and glass are of 230 m^2. The hot water tank is of 7570 litres capacity and is insulated with 12.5 cm thick urethane foam. Aluminium roll-bond flat-plate collectors with an area of 10 m^2 are used on the roof of the greenhouse and 16 more collectors with a total are of 45 m^2 are used on the ground near the greenhouse. A differential controller thermostat controls the flow of water in the collector storage loop. Depending on the requirements of heat in the greenhouse sensed by the greenhouse thermostat, hot water from the hot water storage tank is circulated through the water to air heat exchanger thereby heating the greenhouse.

McCormick[70] of Lockhead-Huntsville Research and Engineering Centre, USA has described a solar heating system for a greenhouse using simple liquid solar collectors separated from the greenhouse. For computer simulation studies a small greenhouse with a floor area of 26 m^2 with a double cover of polyethylene is used. simple liquid flat plate collector, 18.5 m^2, made of an aluminium extrusion with a single glass cover and tilled at an angle of 60 deg. from horizontal and put near the greenhouse is used. Two insulated hot water storage tanks each of 950 litres are used. One pump is used in the collector storage loop and circulates the water through the collector only when the differential controller thermostat senses that the collector outlet temperature is higher than the water temperature in the bottom of the storage tank. Depending on the demand of heat of greenhouse which is sensed by the greenhouse thermostat, the pump in the storage tank-greenhouse loop circulates the water through a standard water/air heat exchanger and thereby heating the greenhouse. More than 75 percent of the heat requirement of the greenhouse is supplied by the solar heating system. An electrical air heater is used for back up.

The Solar Energy Research Corporation[112], Colorado, USA is using a 185 m^2 of Thermo-Spray solar collector for heating a double poly-covered quonset greenhouse with a total area of 223 m^2. The thermo-spray collector consists of two clear plastic covers seperated apart using air-inflation techniques. The absorber plate is of black high density plastic. Solar radiation is absorbed by the absorber plate facing south and its temperature is sensed by a probe which gives a signal to the controller operating a water circulating pump. Depending on the set temperature of the probe water is sprayed through nozzles on the absorbing plate, collecting the heat and storing the hot water in a hot water storage tank. Floating insulation is used inside the tank to reduce the heat loss from the top surface of the water. This hot water from the top of tank is circulated through a heat exchanger inside the greenhouse thereby heating it. During daytime when solar radiation alone is enough to heat the greenhouse, the entire water in the storage tank is heated using Thermo-Spray solar collector and therefore only one pump i.e.in the collector storage loop will be working. During night time or when the heating of greenhouse is required, only the pump in the storage-greenhouse loop will be circulating hot water between storage tank and the heat exchanger. In the entire one winter season about 66 percent of the heating load of the greenhouse was met with this solar heating arrangement.

Lawand[17] has described a greenhouse with a long axis in the east-west direction so that the glazing is in the south side and the north wall is insulated to reduce heat loss and is tilted towards the sun at an angle of 68 deg. to prevent shadows at the summer solstice (at 45 deg. latitude). The north wall which is insulated is also covered with a reflective lining which enhances the solar radiation reaching the plant Canopy. The south-facing glazing is inclined at an angle of 35 deg. which is not an optimum tilt for the latitude but is kept from convenience point of view so that the operator in the greenhouse can work conveniently. A fan is also used during the day time for blowing warm air from the growing space through air ducts burried in the soil under the plants. In this way the excess day time heat is stored in the ground. At night, the fan is used to circulate the warm air from the underground pipe to the growing space.

A nonconvective solar pond of 3.6 m depth and 155 m^2 surface area with sodium chloride as the salt was constructed in late April 1975 at the Ohio Agricultural Research and Development Centre, Wooster, Ohio, USA to study its potential for space heating, greenhouse heating, and heating of rural residences. Such solar ponds are in operation in Israel for power production. The use of this solar pond for greenhouse heating was proposed by Short et al[48]. It is hoped that such a solar pond which acts as an integrated solar collector and heat storage can be proved to be economical for heating greenhouses and homes.

Liu and Carlson[72] have proposed a conceptual design in which several factors such as (i) placing the solar collector inside the greenhouse to increase efficiency and reduce cost, (ii) Using transparent collector if possible as all or part of the greenhouse glazing, (iii) Using a water-rock dual storage system inside the greenhouse and kept underground for year round heating and cooling by transfering water or air mass or both. (iv) Using hot water heater for auxiliary heating, and (v) Nocturnal evaporative cooling are included. The main object of this project was to provide both the heating and cooling requirements of the greenhouse by using solar energy alone.

White et al[113] have developed a solar energy heating system for commercial greenhouses. The greenhouse which was designed for the study used a high grade corrugated fiberglass cover coated with the 'tedlar' which is extended to a sill about 90 cm above ground level and asbestos cement polyurethane sandwich panels extended from the sill to a 30 cm below ground level. Thermal blankets are used during night time to conserve the energy.

Staton[114] has described the details of the solar heating of an Ohio commercial greenhouse. The greenhouse has a floor area of 803.6 m^2 using single glass as a cover material for the greenhouse roof and upper side walls. The bottom 30 cm of the side walls consist of fiberglass siding. Low cost liquid collectors of about 558 m^2 area are mounted on wooden supports external to the greenhouse to be heated. A 95 m^3 in the ground concrete insulated tank is used for hot water storage. A liquid to air heat exchanger is used to transfer heat in the greenhouse. This system was able to provide 60 percent of the heating requirements of the greenhouse.

Several authors like Zornig et al[36], Jensen and Hedges[115], Davis et al[116], Peck et al[117], Smith et al[118] etc. have presented design criteria for a combined greenhouse-residences. The main advantage of such a combined greenhouse-residence combination is to reduce the costs of food and providing comfortable conditions for living. The design proposed by Zornig et al[36] consists of a roof top solar collector serving both the greenhouse and residence. Pre-heated air from the greenhouse passes through the solar collector and then it is allowed to go into the underfloor rock storage system or can be supplied directly into the house. During summer, the greenhouse is shaded and vented to the outside for cooling.

Jensen and Hodges[115] have actually built a combined greenhouse-office area at the Environmental Research Laboratory for the University of Arizona. Four advanced concepts are tried in this system: (i) A venetian blind solar collector, (ii) Rock storage for heating or cooling air, (iii) Newer methods for evaporative cooling, and (iv) Liquid foaming of a greenhouse acting for night time insulation. The window-blind solar collector forms the south wall of the greenhouse and collects the solar energy during day time which is stored and used either for the heating of office or residential spaces during night time hours. In this facility a two-stage evaporative cooling for summer use is also provided.

A residence-greenhouse combination is described by Smith et al[118] in which the greenhouse is provided on the south side of the structure with a solid wall separating it from the residence. Hot air from the greenhouse is forced to flow through flat plate solar collector and the heat is stored in a rock bed for night time use.

In several countries like USA, USSR, UK, West Germany, Canada, Holland, etc. waste heat from power plants or other industries is used for heating commercial greenhouses. The use of waste heat from electrical power generating plants is very attractive for heating greenhouses because in a typical power plant more than 60 percent of the fuel energy consumed by the plant ends up as waste heat which is generally dumped into the atmosphere or flowing water. In U.K. at Drax a 80,000 m^2 of greenhouse located near the power plant is heated using condenser cooling water from the station. At St.Laurent des Eaux in the Loire Valley, the glasshouses are heated using waste cooling water from nuclear power stations. USSR is also planning to have 30,000 ha of greenhouses to be heated using reject heat from the power stations. Several studies are conducted in USA for heating greenhouses using warm water from industries. Some of the greenhouses are located at Alabama as described by Burns et al[119], Minnesota as described by Ashely et al[120], and Alberta as described by Shaw and Trimmer[121]. In all these studies it has been reported that the temperature in the greenhouse can be controlled using waste heat but the acceptable relative humidities are difficult to maintain. Several feasibility studies[56] have been carried out for heating greenhouses with power plant waste heat.

Several problems are pointed out by Hare et al[1] for the widespread use of waste heat for greenhouse heating such as: (i) Low quality and poor reliability of the waste heat, (ii) Use of special low temperature heat exchanger requirement in such plants, (iii) matching the waste heat demands of greenhouse with the cooling tower of the power plant, (iv) Requirement of a auxiliary heat source for heating the greenhouse in case of power plant is unoperative, etc.

At places where solar insolation is high, cooling of greenhouse instead of heating is required. Cooling in the greenhouse can be provided in many ways but generally evaporative cooling systems which are also known as fan and pad cooling are used for many years. This evaporative cooling system is based on the principle that for evaporation of water heat is absorbed. In this system a pad consisting of excelsior (wood shreds) is used which is placed in vertical position and always remains wet. An exhaust fan placed on the opposite wall is used to draw outside air throgh the wet pads. The water from the pads evaporates for which heat is absorbed from pad frame and air and thereby leaving the air passing through the pad cool. If the humidity is low, such evaporative coolers can reduce the environmental temperature from 5 to 10°C.

Since a greenhouse is a controlled environment where enrichment of carbon dioxide is required, the cooling produced by venting or above evaporative methods are not justifiable. Fuller and Meyer[76] have described a closed cooling system for a sealed greenhouse using special heat exchanger alongwith a water spray. This system extracts both sensible and latent heat from an air stream if the counter flowing air stream is lower in both temperature and water vapour content. Air is drawn from the greenhouse which passes through a slowly rotating wheel absorbing both water vapour and sensible heat from the air stream. The resulting cooled and dried air is returned to the greenhouse. The absorbed enthalpy is transferred into a counter flowing air stream drawn from ambient and exhausted to ambient. A spray chamber is also provided if the greenhouse air temperature still remains above the design limit.

5.7 TYPICAL GREENHOUSE DESIGNS

The main purpose of the greenhouse is to grow plants in a controlled environment. Therefore the structure and the covering of the greenhouse should be such that it must always be subserviant to the primary purpose of a greenhouse. It is not only the shape of the greenhouse which affects its indoor environment but there are several paramaters[112] such as: Location and orientation of greenhouse; shape and overall dimensions of the greenhouse; number of cover and type of cover materials; type of heating system and fuel used; variation of air temperature in the greenhouse due to ambient air temperature amplitude and solar insolation; ventilation; optimum utilization of space within the greenhouse; use of movable insulation during night time; use of air to air heat exchanger; utilizing newer concepts like use of thermal curtain at night time and using insulation on the north side walls alongwith some reflecting material on the inner side; using storage system in the greenhouse, etc.

For growing small quantities of food and also for providing comfort using solar energy, attached greenhouse are generally preferred. These attached greenhouses are relatively inexpensive and are easy to maintain. For providing large agricultural produce and for optimum use of solar energy for heating the greenhouses, free standing greenhouses are preferred. There are several greenhouses made all over the world designed for growing varieties of crops and suited to the local climatic conditions varying in large design variables. In this section a few typical greenhouse designs are discussed.

5.7.1 The Brace Greenhouse Design

The scientists[17,122,123] at the Brace Research Institute, Quebec, Canada have developed an experimental small greenhouse at Laval University with the aim to reduce the fuel costs for heating the greenhouse in colder regions. The greenhouse as shown in fig.5.10 is of about 6.1 m long, 6.5 m wide and 4.72 m high with its major axis in the east-west direction such that the transparent wall and roof face the south. The north wall is insulated and is tilted towards the sun at an angle of 65 deg. and is of 5.26 m long. This insulated wall is a sandwich of polystyrene between two layers of masonite. The outer masonite layer

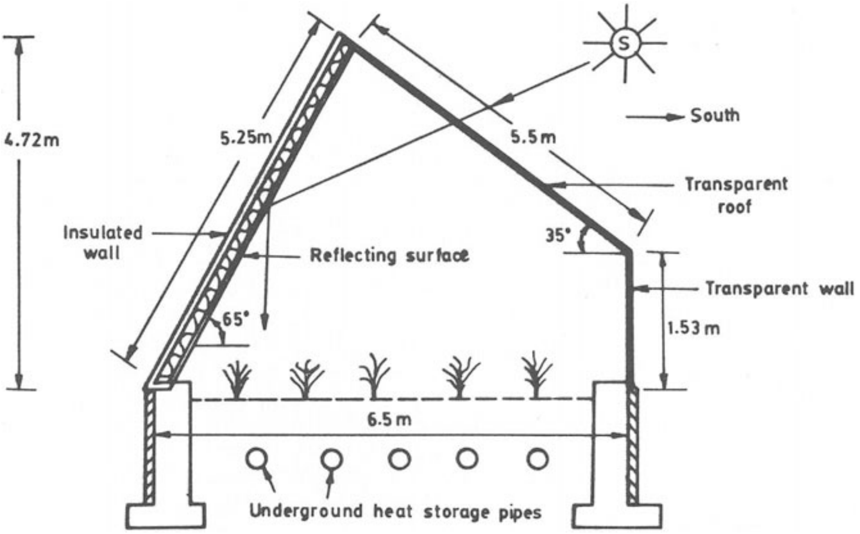


FIG.5.10. BRACE EXPERIMENTAL SOLAR GREENHOUSE

is covered first by tar paper and on to it an aluminium foil is pasted. The inner masonite layer is also first covered with tar paper and then a aluminium foil is pasted over it so that the same may reflect solar radiation on to the plant canopy. The south side of the greenhouse is made completely transparent by using a double layer of U-V stablised 0.11 mm thick clear polyethylene film. The space between these two layers is maintained by 5 x 5 cm wood spacers. The south side consists of a vertical wall of 1.53 m hight and a sloping roof of 5.5 m long making an angle of 35 deg. from the horizontal. The entire frame of the greenhouse is of wood. The foundation posts are made of 10 x 10 cm wood and embeded in the concrete. The frame and chevrons are all made out of 5 x 10 cm and 5 x 15 cm wood membranes. The end walls facing east and west uses a single layer of rigid transparent fiberglass sheets. In one of the latest designs pipes are burried in the soil under the plant through which warm air during the day time is blown which is drawn using fan from the growing space. In this way the surplus heat during the day time is stored in the ground. At night the same fan can be used to warm the air in the growing space by blowing it through the ducts again.

By providing an insulated north wall and using a reflector lining, the heat loss through the north side is reduced considerably and additional light is directed towards the plant canopy. The tilt angles of the south roof and north wall are optimized to allow the maximum penetration of incident solar radiation in to the greenhouse and distribution of reflected solar radiation on to the plant canopy. The area of the transparent cover surface is also kept minimum to minimise the heat loss.

In this greenhouse several parameters like ambient air maximum and minimum temperatures, greenhouse maximum and minimum temperatures, global and diffuse radiation intensities, the amount of fuel used for maintaining the temperature, temperature of the soil, relative humidity etc. are measured. This greenhouse has shown about 30 to 40 percent improvement in terms of heating requirements compared to a standard double layered plastic covered greenhouse. Moreover, in winter due to higher luminosity the productivity of tomatoes and lettuces was observed to be higher compared to the standard greenhouse.

5.7.2 A low energy Australian Greenhouse.

The scientists at the CSIRO Centre of Irrigation Research, Griffith, Australia[4,41,42,76,83,124] have developed a low energy greenhouse. As discussed earlier following three systems are studied.

System I : Single polyethylene skin tunnel with rockpile storage.
System II : Fiberglass reinforced polyester clad tunnel with solar air heater and rockpile storage.
System III : Low profile double skin fluted-acrylic greenhouse with structural integration of solar air heaters and rockpile.

The greenhouse of system III is schematically shown in fig. 5.11 and its details are given below:

(i) The greenhouse has a floor plan of 12 m x 12 m with a total greenhouse volume of 432 m^3.
(ii) The roof of the greenhouse has a slope of 5 deg.. The north wall is of 2.5 m high and south wall is of 3.5 m high.
(iii) The roof, north end and side walls are consisting of double skin of fluted-acrylic sheeting of 6 mm thickness with enclosed air channels of 5 mm x 5 mm. The frame is all made of aluminium.
(iv) Two simple solar air heaters with overall dimensions of 75m x 2m, each consisting of 12 channels formed by rivetting two sheets of standard aluminium roofing

profiles back to back giving 12 air channels for each rock pile and mounted at a tilt of 60 deg. to the horizontal are used. The glazing to the air heaters is a corrugated acrylic sheet and the insulation on the reverse side is 2.5 cm urea formaldehyde foam.

(v) Two rock piles, each 5m x 2m x 2m high containing 1.9cm diameter crushed basalt rock in concrete block bins lined with 5 cm thick polystyrene foam sheets are used. The two rock piles form the south wall of the greenhouse.

(vi) Two axial flow fans rated at 850 watt, each with a capacity of $3m^3/s$ at 150 Pa are used in the system.

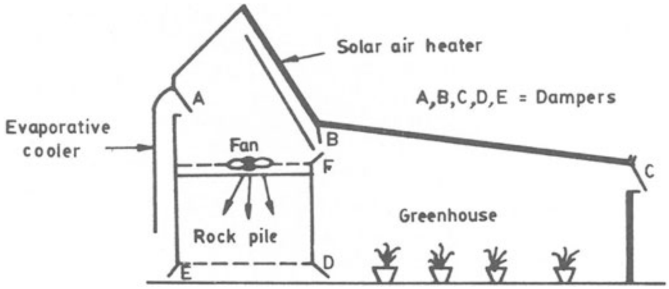


FIG.5.11. CSIRO LOW ENERGY GREENHOUSE

In winter during day time the dampers A,E,C and F are closed and dampers D and B are opened. Warm air heater via damper B is allowed to flow through the rock pile charging the rock pile with solar heat during day time and entering green house via damper D. During night time when heating in the greenhouse is required the dampers A,B,E and C are closed and damper D and F remain open. Warm air from the rock pile enter the greenhouse through damper D and cool air from the greenhouse top enters the rock pile through damper F.

In summers during night time the dampers A,E and C remain open while B,F and D remain closed. The greenhouse during night time gets cooled due to ventilation through vents C. The rock pile during night time is charged with coolth by passing evaporatively cooled air from evaporative cooler through damper A which passes down through the rock pile and then discharged to the outside through damper E.

In summers during day time when cooling in the greenhouse is required the dampers B,F, and E remain closed and dampers A,E and C remain opene. Outside air gets first cooled by evaporative cooler and then further cooled in passing through the rock pile and then enters the greenhouse through damper D cooling the greenhouse and finally gets discharged to outside through damper C.

Simulated performance of this greenhouse was carried out for climatic conditions of Griffth(Australia) and Hamburg(West Germany). It was found that in Griffth 100 percent of the heating requirements of the greenhouse during autumn and spring was met by solar energy alone. In winter more than 75 percent of the energy requirements was met by solar energy. It was assumed while doing this simulation that the greenhouse temperature was maintained at 25°C and 17°C during day time and night time respectively.

5.7.3 The Rutgers University Solar Greenhouse

The Scientists at the Cook College, Rutgers University, New Jersey, USA have developed a complete solar heating system for greenhouses using low cost components[49,50,62]. As discussed earlier in section 5.6 the solar heating system consists of four major elements and all of them are necessary for maximum conservation of fossil fuel. These components are as follows:

(i) An insulation curtain used during the night time over the crop to reduce the heat loss. Various curtain materials like 4 mil clear vinyl, 6 mil black vinyl, 6 mil black vinyl laminated to one half mil aluminized mylar, 4 mil clear vinyl laminated to one half mil aluminized mylar and 4 mil clear vinyl printed with white dots covering 25 percent of the curtain area. On sunny days the shade curtain consisting of 4 mil clear vinyl printed with white dots covering 25 percent of curtain area can be used as a control shading curtain which can be pulled over the crop and on cloudy days the same can be removed. It has been observed that a clear vinyl curtain 4 mil thick laminated to a half mil thick aluminized mylar sheet can reduce the heat loss during night time considerably.

(ii) The second element is the composite floor which performs the dual function of storing the heat and of heat exchanger. The floor consists of four layers. In the bottom there is a polystyrene board insulation over which there is a vinyl swimming pool liner, the next layer is gravel which will be flooded with water and the top layer is a cap of porous concrete. This porous concrete forms the floor of the greenhouse, a heat exchanger surface and also allows the excess irrigation water to drain. The water in the gravel bed stores heat along with the gravel and also acts as a heat transfer fluid for the solar collector. The vinyl liner holds the concrete gravel and water. The porous concrete is made with aggregate, cement and water and no sand is used. For one cubic meter of mix about 1660 Kg. of 0.95cm size aggregate, 7.8 bags of cement and about 110 liters of water is used. The void ratio of the gravel is 50 percent and a cubic meter of gravel weighs about 1680 Kg and contain about 510 Kg of water. The total heat storage capacity of the water-gravel bed is 3550 J/m^{3}K

(iii) The third element is the vertical curtain heat exchanger which is used to transfer heat from the stored warm water in the floor to the greenhouse. A 5 cm steel pipe is used for structural support and supply manifold fittings located every 6 m connected to a 19mm polyethylene pipe. This plastic pipe has 2 mm holes drilled 7.5 cm on centre along the top of the pipe. This system sprays water on the inside of the vinyl curtain which is draped over both pipes. A 12mm diameter PVC pipe is connected on the lower side of the curtain which holds the curtain down. A string/pulley is used to roll the curtain up when it is not required. Warm water from the floor storage unit is pumped into the trickle hose which flows between two sheets of plastic, releasing its heat to the greenhouse and the water is drained to the storage through the porous concrete.

(iv) The fourth element is a solar collector which consists of a frame covered with 5 layers of plastic film. The solar collector is of about 3 m high and 7.2m long and is designed in such a way that its angle can be adjusted. The middle layer is a black plastic layer acting as an absorbing plate and the outer two layers on either side of it are clear polyethylene film. The outer two layers and the rear of two layers are inflated and black layer is pressed between the two inflated sections. The water is allowed to flow from the top of the collector from a pipe manifold at the top. The hot water is collected in a return gutter at the bottom of the collector and goes to the floor storage by gravity.

Several greenhouses utilizing the above concept are made in USA and also in other countries. The performances have been very good. In one of the greenhouses made for experimental purposes at the Rutgers University, New Jersey, all the above four concepts are utilized. This experimental greenhouse has the floor dimensions 5.2 m x 7.3 m with a useful floor area of 33.4 m^2 and the exposed roofs and wall area of about 80 m^2. The exposed solar collector area is of about 33.8 m^2. The heat transfer area of the vertical

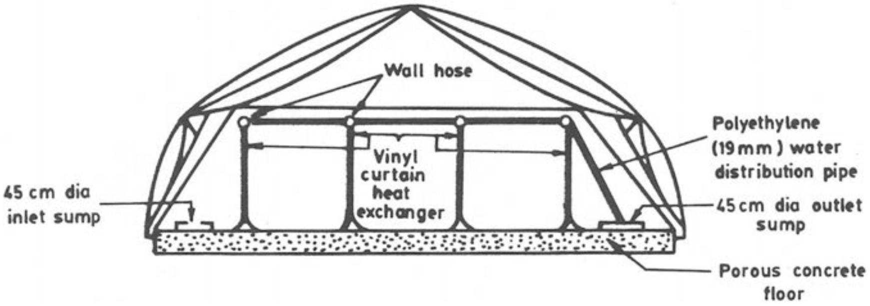


FIG.5.12. RUTGERS UNIVERSITY EXPERIMENTAL SOLAR GREENHOUSE

curtain heat exchanger is 37.2 m^2. A schematic diagram of the greenhouse is shown in fig. 5.12. This system has been run continuously automatically since August, 1976 and the performance of each components has been monitored. The auxiliary heat to the greenhouse when solar energy was not able to maintain the greenhouse temperature was supplied by an oil-fired burner.

The temperature in the growing area of the greenhouse was maintained during the heating season at a minimum temperature of about 15.6 °C which was possible only when the water in the floor was at a temperature of 22 °C or more. For many nights when the outdoor temperature fell below-18 °C, the temperature in the growing area was maintained at 14.4 °C below the black polyethylene insulating curtain while above this curtain temperature has gone to near freezing.

5.7.4 A Commercial Solar Greenhouse at Tennessee

A commercial solar greenhouse was designed and built by McGowan and Black[125] at Tennessee (36° N) at an elevation of 183 m. Out of the three building shapes, a shape as shown in fig. 5.13 was selected for the greenhouse. The greenhouse is 8.2 m wide 29 m long and 6 m high. The floor area of the greenhouse is about 237.8 m^2 and occupy a volume of 850 m^3. The greenhouse is designed using materials which are locally available. The post and beam framing of wood is used. The floor of the greenhouse is gravel fill on top of clay and the foundation walls are well insulated with rigid insulation board. The vertical wall and sloped roof on the south side of the greenhouse which is of about 223 m^2 uses fiberglass reinforced acrylic of 1 cm thick and backed by

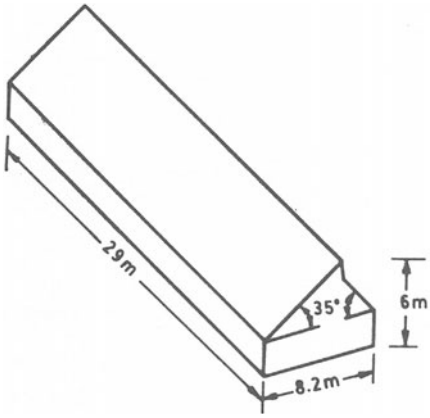


FIG.5.13. DIMENSIONS OF A GREENHOUSE AT TENNESSEE USA

polyethylene sheet. The flat glazing sheets are bowed in the middle to provide rigidity to the structure and resistance to wind. The flat glazing sheets are bowed in the middle to provide rigidity to the structure and resistance to wind. The north wall of the greenhouse uses a insulation of R-19 fiberglass batts and covered with aluminium foil which reflects solar and infrared radiation. The east, west, and end walls are also insulated with R-19 fiberglass board behind 12mm thick sheetrock painted white so that it can diffuse and reflect the light and thus helps in distributing the light.

Heat in the greenhouse is stored in 150 storage drums each of 208 litres capacity which are filled with water and an anti-corrosion compound. Most of these drums are put near the north wall with three drums one over the other. a few drums are also put near the south wall supporting the plant racks and a few drums are also scattered throughout the greenhouse.

The auxiliary heat in the greenhouse on very cold night or on cloudy days was provided with single wood stove located at the centre of the greenhouse. This wood stove was capable of providing 50 MJ/hr. Whenever there is a temperature drop in the greenhouse this wood stove starts sending hot air in the centre of the greenhouse and radiates heat from the long stovepipe.

The average temperature difference between the inside and outside of the greenhouse was of about 10.8°C during the first five months in the winter season. The total heat loss from the greenhouse from November through March was about 110 GJ out of which solar energy supplied 85 GJ and wood fuel supplied 25 GJ.

In summer the cooling was provided by natural ventilation and also by storage drums. It was observed that in summer the greenhouse temperature was lower than the air temperature outside in the shade due to the reason that the high thermal mass of the drum dampen out daily high and low tempeatures. Moreover, the design of the north roof was such that it gives shade to the north wall drums during the middle hours of the day in summer months.

5.7.5 New Alchemy Institute Solar Passive Greenhouse

A completely passive system greenhouse for growing vegetables for family use was built at Falmouth (Cape Cod), Massachusetts, USA, which uses a large volume of water for heat storage. This family-sized greenhouse is 7.7 m long, 4.7 m wide and 3.6 m high. The growing area is about 14 m^2. The south clear wall sloped to within 30 cm of ground level. The opaque roof slopes steeply down to a 1.2 m deep wall in back. The east and west walls are also double glazed. This greenhouse was made around the existing fish pool of about 4.6 m x 4.6 m and 1.2 m deep. The floor and walls of the water pool are made of 10 cm thick concrete slab. All walls are insulated with about 8.5 cm thick fiberglass board. The concrete block and fish tank bottom are all insulated with 5 cm thick foam on the outside.

The south wall as well as the end walls are glazed with kalwall plastic sheets. Behind the kalwall there are three layers of thin tedlar-like-film. The transmittance of these three plastic films is quite high and is comparable to that of polyethylene film. The three dead air spaces help in reducing the heat loss from the greenhouse to the outside. The water tank contains about 25550 litres of water. The water became black in colour to absorb solar radiation because of algae growth. About 21 m^2 of pool area receive direct radiation all day long. Even on very cold winter nights the water temperature in the pool remained close to 5°C. The soil inside the greenhouse also receives direct radiation and stores the heat which also helps in maintaining the temperature in the greenhouse. This greenhouse is one of the most intensively planted and productive solar greenhouse where many crops like cabbage, onions, lattuce, chard, kale, beets, turnip, etc. are grown. Based on the experience of this greenhouse two other greenhouses with larger capacities were built in USA and are operating with satisfaction.

5.7.6 The KISR Greenhouse for Warm Climates

The requirement of a summer greenhouse is different from that of the winter greenhouse. In a winter greenhouse the main requirement is in the reduction of heating load and utilizing solar energy to maximum possible extent. In a summer greenhouse the requirement is in the reduction of cooling load and also to provide enough solar radiation. In hot humid area, the outside temperatures goes so high that it becomes difficult to grow crops year round. By using a summer greenhouse it is possible to keep the inside temperature low enough to grow crops year round. By using a summer greenhouse it is possible to keep the inside temperature low enough to grow crop even with little use of irrigation water. Some studies on such summer greenhouses are conducted by Malik et al[8] at the Kuwait Institute for Scientific Research, Kuwait and they have successfully developed and demonstrated small experimental summer greenhouses.

Two greenhouses were built for summer use in the campus of Kuwait Institute for Scientific Research, Kuwait with each having an area of about 10 m^2. The cross-sectional view of greenhouse No.1 is shown in fig. 5.14. The south wall of

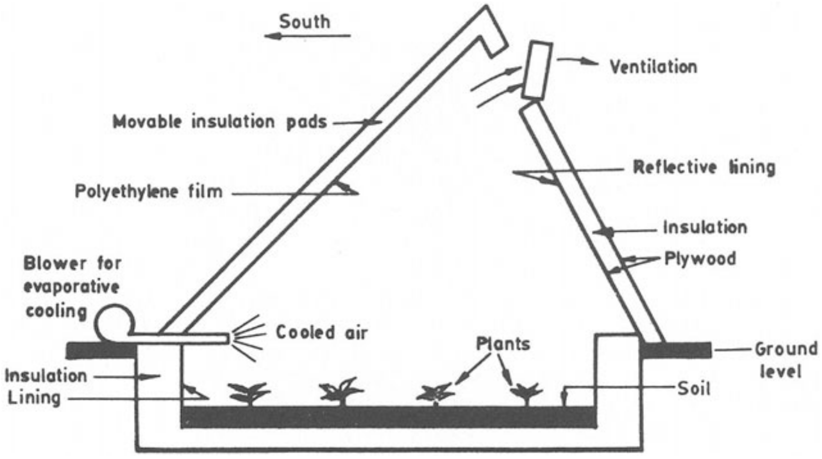


FIG.5.14. KISR SUMMER GREENHOUSE

this greenhouse is covered with U-V stabilised polyethylene (125 micron thick) film which in turn is covered by movable white 7.5 cm thick styrofoam insulation blocks. These insulation blocks can be conveniently and selectively moved to admit solar radiation into the greenhouse whenever it is required. Solar radiation can also be admitted through east and west transparent walls of the greenhouse whenever it is required by removing the plywood sheets. Solar radiation was allowed to enter in the greenhouse only in the morning and evening hours. The objective of movable insulation is to allow only the absolutely essential amount of solar radiation required for the plant growth. The north wall consists of 10 cm styrofoam sandwiched between two 1.9 cm plywood sheets. The inside surface of the north is provided with a aluminium reflector to distribute the solar radiation on plant canopy. A part of the greenhouse is sunken in the ground to take advantage of the ground cool and constant temperature. The surface of the greenhouse which is below ground level are also insulated with styrofoam insulation which is lined with aluminium foil. In the bottom there is a 1.9 cm thick plywood sheet. There are two sets of windows on the south as well as north wall of the greenhouse which are used to cool the greenhouse by free convection from April to June. When the outside temperature becomes quite high the windows on the south wall are closed and the greenhouse was evaporatively cooled passing outside air through evaporative pads using a blower. The blower was sized to provide one air change per minute in the greenhouse.

This greenhouse was tested for its performance during the summer of 1977 at Kuwait. The parameters measured are inside and outside temperature, relative humidity, soil temperature, solar insolation, wind speed and direction and amount of water consumed by plants. These parameters were continuously recorded for one complete growing season and it was observed that plants could be successfully grown inside the greenhouse in the hot and humid climate of Kuwait. The evapotranspiration rate was observed to be of the order of 10 percent compared to that of outside irrigation which appears to be significant from the point of view of scarcity of water. The movable insulation pads were adjusted from time to time based upon visual observations of the plant growth. A reduction of cooling load of about 80 percent was observed compared to that of a conventional greenhouse. In mild summers even free convection of air movement was able to provide cooling and bean crop was grown in the month of June without using evaporative coolers. By using evaporative coolers temperature in the range of 30 to 35°C was maintained.

5.7.7 U.A.E. Plastic Greenhouse for Warm Climates

A plastic tunnel type greenhouse[126] suitable for warm climates was developed at Ras Al Khaimah, United Arab Emirates which can be made easily and cheaply with local materials. The plastic tunnel greenhouse is shown in fig. 5.15. The plastic tunnel is of 6 m wide, 3 m high and 36 m long. The arches are made in four sections using 19 mm nominal diameter galvanized iron pipes. Each section of the arch is 2.3 m long, 6 m wide and 3 m high. The joining pieces are made of steel bars of about 20 mm diameter. The cover material used in the greenhouse tunnel is U-V stablized polyethylene film. The tunnel is oriented along the direction of the prevailing wind. The doors, one on each end of the tunnel are made of plastic film and plywood strips.

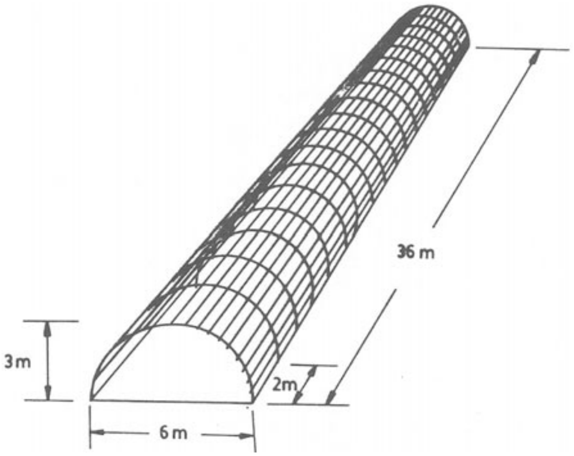


FIG.5.15. UAE TUNNEL GREENHOUSE FOR WARM CLIMATES

When the outdoor temperature and the air temperature in the tunnel becomes quite high then some kind of cooling is required. If the outdoor air temperature is lower then the inside air temperature of the greenhouse, then the greenhouse can be cooled by ventilation alone. The overheating in the greenhouse can also be reduced by using some kind of shading. Shading is suggested by using a lime paint on the covering material. In the summer season the white lime paint can easily be washed off by rain or can easily be brushed off with a soft brush to allow the solar radiation to enter in the greenhouse in autumn. Lime paint is found very effective for shading the greenhouse. Screens can also be used for selective shading. Shading plastic materials with different degrees of light transmittance are now a days available in the market. If the inside air temperature remains quite high inspite of ventilation and shading, the evaporative cooling system can be used. The evaporative cooling system called 'Fan and Pad' which reduces the temperature and increases the humidity is found to be quite effective and economical under UAE conditions compared to mechanical cooling systems. It is observed that for 7 to 9 months of the year i.e. between September 15 and June 15 in UAE, all types of vegetable can be grown in this plastic tunnel greenhouse.

5.7.8 Residential attached greenhouse

Attaching a greenhouse to a residence on its south side with a common intermediate wall can significantly reduce the heating requirement of the residence and the greenhouse performance also gets improved because of reduced heat loss from the greenhouse due to the presence of the residence. Moreover, crops can be grown on a year-round basis in the greenhouse and therefore the residential attached greenhouse concept has caught public interest.Such residential attached greenhouses are common in USA since this concept can be utilized in a new or existing residence without adding much cost.

The residence can be of common construction with a greenhouse made on its south side with a transparent wall and roof and which is exposed for winter sunlight. During a winter clear day the greenhouse temperature may become quite high while at night the temperature may drop well below the acceptable limit due to excessive heat losses from the greenhouse. The excessive heat in the day time of the greenhouse is removed by removing air from upper portion of the greenhouse using a fan and supply it either directly to the house or through the rock bed storage system provided in the basement of the residence attached greenhouse.

A greenhouse attached residence was constructed[118] at the Colorado State University, Colorado, USA with the objective to determine the compatibility of residential and garden greenhouse spaces combined in the same structure and using solar energy as the primary heating source. The residence and greenhouse have the total floor area of about 59.5 m^2 and the solar energy is collected using 47 m^2 flat plate solar air heaters and the heat is stored for night time or cloudy days use in a 11.2 m^3 rock bed storage unit. The greenhouse has a glazed area of about 47 m^2 and the hot air from the upper portion of the greenhouse is first allowed to flow through the collectors and then the hot air goes to the storage unit. Warm air from the storage unit is supplied to the greenhouse and the residence independently and gas furnaces are used to supply auxiliary heat when necessary. The design details of this combined greenhouse-residence structure along with the method of collection, storage, and distribution of solar heat has been described by Smith and Bedford[127]. Various techniques of reducing heat loss such as use of double glazing, caulking, and perimeter insulation etc. are employed in the greenhouse. The roof of the greenhouse consists of 0.9 x 2 m double glass units which are supported on 10 x 10 cm wood rafters on 0.9 m spacing making an angle of about 40 deg. from the horizontal. The space between the two glazing is about 1.5 cm and the same is completely sealed. The south wall upto 1 m high and end walls of the greenhouse are made of double thickness corrugated fiberglass sheets. Butyl rubber strips are used to weather seal between fiberglass sheets. Silicone caulking is used to fill all the cracks and hole in the wall to stop air infiltration. Styrofoam insulation of 5 cm thick sandwiched between 2 pieces of 1 cm thick asphalt impregnated sheathing is used to reduce perimeter heat losses.

The residence is having about 59.4 m^2 ground level and an open attic-space and both can be heated with a heating load of about 1.4 kwh/°C day. The house walls and roofs are heavily insulated. Five windows with a glazing area of 9.4 m^2 are towards the greenhouse while two windows with an area of 3.7 m^2 are openable to the outside.

Solar heat is stored in a rock bed unit built into the residence and supported on a 15 cm concrete slab located at about 60 cm below grade. This storage unit required about 2.4 x 1.8 m of floor space. The rock is of about 2 to 4 cm in diameter, heat capacity of 0.84 KJ/Kg°C and a fill density of 1.8 tons/m^3. The total volume of the rock bed unit is 10 m^3 containing 16 tons of rock.

The solar air heater with a total exposed absorbed area of about 42 m^2 are used. The solar collector consists of a 22 gauge steel plate coated with an ordinary black paint. Below the absorber plate an air duct of about 1.2 cm deep is formed though which air at an air flow rate of about 10 litre/sec m^2 is allowed to flow. These collectors used double glass glazing on the exposed side which are sealed and insulated on the back side. The solar collectors are mounted in the same plane as of the greenhouse roof and are installed using cap strips and gaskets preventing water leakage and thus forming the weather proof roof of the building. These collectors are internally manifolded with four duct penetrations through the building sub-roofs to bring air out of the collectors. Air from the greenhouse top can enter through the collectors after passing through four backdraft dampers which allow the air to flow only in one direction.

Heat loss from the roof of the greenhouse was reduced by using two systems: one by using aluminized cloth curtain which is drawn beneath the roof at night time covering about 85 percent of the roof area, and second by using bead wall system filling the space between two panes of glass by small styrene beads filling 10 percent of the roof area.

A two-stage thermostat set at 14.5°C and 12.2°C is used for heating operation. The heat from the storage unit is supplied at a thermostat set temperature of 14.5°C. If the greenhouse temperature falls below 12.2°C the additional heat is supplied through natural gas burner. In summers when greenhouse gets overheated the cooling is provided either by ventilation or by using evaporative coolers. A two-stage cooling thermostat set at 26.7°C and 32.2°C is used. At a temperature of 26.7°C a fan starts ventilating the greenhouse with outdoor air. At a temperature of 32.2°C the evaporative cooler starts working. An experiment for soil heating and irrigation water heating was also conducted by heating water by passing through the air-to-water heat exchanger placed in the air stream leaving solar collectors.

Several experiments on this combined greenhouse residential unit was conducted during the years 1976 to 1979. In winters more than 85 percent of the heating requirement of the combined residence and greenhouse was supplied by solar energy. Out of this total solar heat supplied, about 87 percent was derived from solar collectors and 13 percent was obtained from the greenhouse. A wide variety of vegetables and flowering plants were produced in the greenhouse throughout the year.

5.8 PERFORMANCE PREDICTION OF CROP YIELD AND THERMAL ENVIRONMENT IN GREENHOUSE (REF 104)

As discussed earlier there are several variables outside and inside the greenhouse which influence the thermal environment of the greenhouse and finally the crop yield. Several attempts are made in the past to develop mathematical models representing functional relations among the variables and the greenhouse environment in the hope to help the designer for a better greenhouse. The attempts made in this direction are due to Walker[92], Rotz et al[93],Roberts [94], McCormick[95], Takukura et al[96]. Seginer and Levav [97], Froehlick et al[98], Chandra et al[99], Sclcuk[100], Zornig et al[101,102] and Tiwari[103]. Recently Cooper and Fuller[104] have developed a generalized computer model for predicting the performance of greenhouses applicable to a wide range of climatic conditions. This model can be used for determining the amount of photosynthate produced by a crop since the model responds to photosynthetically active radiation, leaf temperature, and CO_2 level. This generalized model[104] which is modular in nature and incorporates both solar heating and evaporative cooling system alongwith a rockpile storage unit is described here in brief.

Because of the complexity of the heat and mass transfer mechanisms in a greenhouse it is very difficult to model the greenhouse as a single component and therefore the greenhouse components like growing medium, floor, crop, greenhouse air, and greenhouse cover are modelled independently and their interaction with each other is facilitated by the organizational nature of TRNSYS[128] program which is still a powerful simulation program. Referring to Fig.5.16 the energy balance equations on various components of a greenhouse can be written[104] as follows.

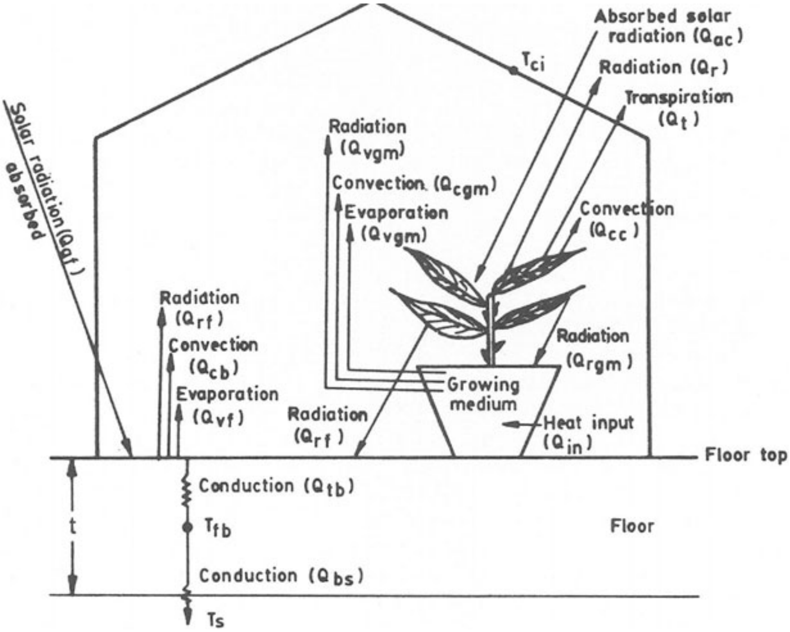


FIG.5.16. ENERGY TRANSFER MECHANISM IN A GREENHOUSE

The energy balance equation on the growing medium is written as:

$$Q_{sgm} = Q_{in} - Q_{cgm} - Q_{vgm} - Q_{rgm}$$

$$= M_{gm} C_{pgm} \frac{dT_{gm}}{d\Theta} \qquad (5.1)$$

Where Q_{in} is the energy added to the growing medium directly. Here Q_{cgm} is the energy transferred from the growing medium to the greenhouse air by convection alone and is given as:

$$Q_{cgm} = h_{gma} A_{gm} (T_{gm} - T_{gh}) \qquad (5.2)$$

and Q_{vgm} is the energy transferred from the growing medium by evaporation and is given as:

$$Q_{vgm} = h_{dgm} (W_{gm} - W_{gh}) A_{gm} h_{fg} \qquad (5.3)$$

and Q_{rgm} is the energy transferred from the growing medium to the crop by radiation alone and is given as:

$$Q_{rgm} = \varepsilon_{gmc} \sigma A_{gm} (T_{gm}^4 - T_c^4) \qquad (5.4)$$

Here A_{gm} is the area of the growing medium; h_{gma} is the convective heat transfer coefficient from the growing medium to greenhouse air; T_{gm}, T_{gh}, and T_c are the temperatures of growing medium, greenhouse air, and crop temperature respectively; h_{dgm} is the mass transfer coefficient for growing medium and can be taken as approximately equal to ratio of heat transfer coefficient (h_{gma}) to the specific heat of fluid (1.005); W_{gm} and W_{gh} are the absolute humidity ratio of saturated air at the temperatures of growing medium and greenhouse air respectively; h_{fg} is the latent heat of vaporization of water; ε_{gmc} is the radiation exchange factor between growing medium and crop; M_{gm} is the mass of growing medium; C_{pgm} is the specific heat of growing medium; and Θ is the time.

The floor or ground of the greenhouse can be divided into two parts; the floor top where the solar radiation is absorbed and the heat is lost by evaporation, convection and radiation to the greenhouse and by conduction to the bulk floor and the bulk floor which has large thermal capacity. The expression for the energy stored, Q_{st}, in the bulk floor is given as:

$$Q_{st} = Q_{tb} - Q_{bs}$$

$$= M_f \, C_{pfb} \frac{dT_{fb}}{d\theta} \qquad (5.5)$$

Where Q_{tb} is the energy transferred by conduction from top of floor to the main mass of floor and is given as:

$$Q_{tb} = (2 \, K_1 \, A_f/t) \quad (T_{ft} - T_{fb}) \qquad (5.6)$$

and Q_{bs} is the energy transferred by conduction between main mass of floor and ground sink and is given as:

$$Q_{bs} = (K_2 \, A_f/y) \quad (T_{fb} - T_s) \qquad (5.7)$$

The solar energy absorbed by the top floor Q_{af}, is given as:

$$Q_{af} = I_f \alpha_f \, A_f \qquad (5.8)$$

The expression for energy transfer by convection from floor top to the greenhouse air, Q_{cf}, is given as:

$$Q_{cf} = h_{fa} \, A_f \, (T_{ft} - T_{gh}) \quad (1-w) \qquad (5.9)$$

The expression for energy transfer by evaporation from floor top to the greenhouse, Q_{vf}, is given as:

$$Q_{vf} = h_{df} \, w \, h_{fg} \, (W_{ft} - W_{gh}) \, A_f \qquad (5.10)$$

and the expression for energy transfer by radiation from floor top to the crop, Q_{rf}, is given as

$$Q_{rf} = \varepsilon_{fc} \, \sigma \, A_f \, (T_{ft}^4 - T_c^4) \qquad (5.11)$$

Here A_f is the area of the greenhouse floor; T_{ft}, T_{fb}, T_{gh} and T_c are the temperatures of floor top, floor bulk, greenhouse air, and inner cover temperature respectively; h_{fa} is the convective heat transfer coefficient from floor to greenhouse air; h_{df} is the mass transfer coefficient of floor and is the ratio of heat transfer coefficient (h_{fa}) to the specific heat of fluid (1.005); W_{ft} is the absolute humidity ratio of saturated air at floor top temperature; w is the fraction of floor with free water available for evaporation; ε_{fc} is the radiation exchange factor between floor and crop; I_f is the solar radiation reaching the floor; α_f is the absorptance of floor for solar radiation; K_1 and K_2 are the thermal conductivities of floor top and bulk floor material respectively; t is the floor thickness; and y is the distance from middle of main mass of floor to ground sink.

The crop in the greenhouse receives solar radiation and this heat is lost by convection to the greenhouse air Q_{cc}, transpiration to the greenhouse Q_t, radiation to the growing medium Q_{rgm}, radiation to the floor Q_{rf}, and radiation to the sky. The expression of solar radiation absorbed by the crop, Q_{ac}, is given as:

$$Q_{ac} = I_c \alpha_c A_c \qquad (5.12)$$

the heat loss by convection from crop to the greenhouse air, Q_{cc}, is given as:

$$Q_{cc} = h_{ca} A_c L_i (T_c - T_{gh}) \qquad (5.13)$$

the heat loss by transpiration from crop to the greenhouse, Q_t, is given as:

$$Q_t = K_t (L_i/1.8) A_c (W_c - W_{gh}) h_{fg} \qquad (5.14)$$

the heat loss by radiation from crop to the growing medium, Q_{rgm}, is given as:

$$Q_{rgm} = \varepsilon_{gmc} \sigma A_{gm} (T_c^4 - T_{gm}^4) \qquad (5.15)$$

the heat loss by radiation from cop to the floor, Q_{rf}, is given as:

$$Q_{rf} = E_{fc} A_c (T_c^4 - T_{ft}^4) \qquad (5.16)$$

and the heat loss by radiation from crop to the sky through cover, Q_r, can be determined using a procedure described in reference 104 and depends on following parameters:

$$Q_r = f (T_c^4, T_{ci}^4, T_{cio}^4, T_{sky}^4, Z_{clw}) \qquad (5.17)$$

Where A_c is the horizontal crop area; T_{ci}, T_{cio} and T_{sky} are the cover inside, outside and sky temperature respectively; I_c is the solar radiation striking the crop; α_c is the solar absorptance of crop; h_{ca} is the convective heat transfer coefficient from crop to air; L_i is the crop leaf area index; K_t is the crop transpiration coefficient; W_c is the absolute humidity ratio of saturated air at crop temperature; and Z_{clw} is the longwave transmittance of cover.

In air in the greenhouse, there can be a infiltration heat loss and heat can be added through solar heaters or the air can be cooled through evaporative coolers.The expression of energy transferred into the greenhouse air by infiltration of outside air, Q_i, is given as:

$$Q_i = \dot{L} V C_{pa} \rho_a (T_{gh} - T_a) \qquad (5.17)$$

The expression of energy transferred due to natural or forced venting with ambient air, Q_{ve}, is given as:

$$Q_{ve} = \dot{m}_v C_{pa} (T_{gh} - T_a) \quad (5.18)$$

and the expression for energy transferred due to cooling device, Q_h, is given as

$$Q_h = \dot{m}_h C_{pa} (T_{gh} - T_h) \quad (5.19)$$

Where C_{pa} is the specific heat of air; T_h is the air stream temperature supplied by cooling device; $\dot{m}_h$ and $\dot{m}_v$ are the mass flow rate of cooling device and mass flow rate due to natural or forced venting to outside air respectively; $\dot{L}$ is the number of air changes per hour due to infiltration; V is the greenhouse volume; ρ_a is the density of air; and T_a is the ambient air temperature.

In the greenhouse air there is no radiation exchange and the thermal capacity is negligible and the state of air at any instant is given by its temperature and absolute humidity ratio.

The mass transfer equations in the greenhouse are written as:

$$M_h = \dot{m}_h (W_{gh} - W_h) \quad (5.20)$$

$$M_{ve} = \dot{m}_v (W_{gh} - W_a) \quad (5.21)$$

$$M_i = \dot{L} V \rho_a (W_{gh} - W_a) \quad (5.22)$$

$$M_{co} = (h_{coa}/1.005) A_{co} (W_{gh} - W_{ci}) \quad (5.23)$$

$$M_{vgm} = (h_{gma}/1.005) A_{gm} (W_{gm} - W_{gh}) \quad (5.24)$$

$$M_c = (h_{ca}/1.005) A_c K_t (L_i/1.8)(W_c - W_{gh}) \quad (5.25)$$

$$M_{vf} = (h_{fa}/1.005) A_{fw} (W_{ft} - W_{gh}) \quad (5.26)$$

Where M_h and M_i are the mass transferred due to cooling device and infiltration of outside air respectively; M_{ve}, M_{vf} and M_{vgm} are the mass transferred due to natural or forced venting with outside air, evaporation from floor, and evaporation from growing medium respectively; M_c is the mass transferred due to transpiration of crop; M_{co} is the mass transferred due to condensation on cover; $\dot{m}_h$ and $\dot{m}_v$ are the mass flow rate out of cooling device and mass flow rate due to natural or forced venting of outside air respectively; W_h, W_a and W_{ci} are the absolute humidity ratio of air stream supplied by cooling device, absolute humidity ratio of ambient air, and absolute humidity ratio of saturated air at cover temperature respectively; h_{coa} is the convective heat transfer coefficient between cover and greenhouse air and A_{co} is area of cover.

In the greenhouse there is a single or double cover and there can be a thermal screen used during night time to reduce heat loss. The cover receives solar radiation and this heat is lost to the outside by convection and radiation and also to inside the greenhouse by convection and radiation. The thermal capacity of the cover can be assumed negligible. The equation for energy absorbed by the cover Q_{aco}, is given as:

$$Q_{aco} = I_{co} A_{co} \alpha_{co} \tag{5.27}$$

In case of a single cover, the energy transferred by convection between outside air and cover, Q_{cco}, is given as:

$$Q_{cco} = A_{co} h_{coo} (T_{co} - T_a) \tag{5.28}$$

The expression for energy transferred by convection between greenhouse air and cover Q_{cci} is given as:

$$Q_{cci} = A_{co} h_{coa} (T_{gh} - T_{co}) \tag{5.29}$$

The expression for energy transferred by condensation to the cover, Q_c, is given as:

$$Q_c = A_{co} (h_{coa}/1.005)\, h_{fg} (W_{gh} - W_{ci}) \tag{5.30}$$

and the energy transferred by radiation from inner cover, Q_{ri}, is a function of:

$$Q_{ri} = f(T^4_{ci}, T^4_{sky}, T^4_c, T^4_{co}, Z_{clw}) \tag{5.31}$$

If there are two covers or one cover and a thermal screen then the equations of heat loss from the outer cover will be as follows:

$$Q_{cco} = A_{co} h_{coo} (T_{co} - T_a) \tag{5.32}$$

$$Q_{cio} = A_{co} h_{ct} (T_{ci} - T_{co}) \tag{5.33}$$

$$Q_{aco} = I_{co} A_{co} \alpha_{co} \tag{5.34}$$

and $$Q_{ro} = f(T^4_{co}, T^4_{ci}, T^4_c, T^4_{sky}, Z_{clw}) \tag{5.35}$$

Where I_{co} is the solar radiation incident on the cover; A_{co} is the horizontal cover area; α_{co} is the solar absorptance of cover material; h_{coo} is the convective heat transfer coefficient from outer cover to ambient air; and h_{ct} is the combined convective heat transfer coefficient between inner and outer cover.

The environment around a crop is responsible for the crop growth and crop yield. If the environment changes the photosynthetic rate and hence the yield of the crop changes. The photesynthetic uptake of CO_2 for spray carnations is given by the relation:

$$F = [0.3116(I_{PAR}\alpha_c)^{0.789} (C_{CO_2})^{0.241} (T_c)^{0.167} - (5.673 + 5.182\ Z)_2 (T_c - 20)/10] \times 10^{-5}\ KgCO_2\ (m^{-2}\ leaf)\ hr^{-1} \qquad (5.36)$$

$$\text{where } Z = \left|\begin{array}{l} \ln\ (I_{PAR}A_c) \text{ during daylight hours} \\ \ln\ (l_{PAR}A_C) \text{ during following night} \end{array}\right.$$

where F is the net CO_2 uptake; I_{PAR} is the photosynthetically active radiation; C_{CO_2} is the CO_2 concentration in v.p.p.m.; and $(\overline{I_{PAR}A_c})$ is the average rate of absorption of photosynthetically active radiation over the previous day. Now as suggested by Enoch[129] and Acock et al[130] the crop yield Y in kg/h is given as:

$$Y = 7(FA_cL_i\ 0.66) \quad Kg/h \qquad (5.37)$$

The above models are incorporated by Cooper and Fuller [104] in the standard TRANSYS program[128] and the crop yield and the thermal performance was predicted of a greenhouse built at Griffith, Australia.

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CHAPTER - 6

SOLAR CELLS

6.1 INTRODUCTION

Solar photovoltaic field is getting priority in countries like USA, USSR, Japan, England, France, Germany, India etc. and there is a considerable interest, research effort and funding. This worldwide interest is attributed to a variety of factors such as search for new energy sources due to heavy pressure on conventional fuels; simplicity, cleanliness, and direct conversion into electricity by solar cells; and a fast growth of technical material. Photovoltaic cells or the so called solar cells generate electromotive force as a result of absorption of ionizing radiation. The advantages of solar cells are manyfold compared to conventional methods of power systems such as:

1. Solar cells directly convert the solar radiation into electricity using photovoltaic effect without going through a thermal process.
2. Solar cells are reliable, modular, durable, and generally maintenance free and therefore suitable even in isolated and remote areas.
3. Solar cells are quiet, benign, compatible with almost all environments, respond instantaneously with solar radiation, and have expected lifetime of 20 years or more.
4. Solar cells can be located at the place of use and hence no distribution network is required.

Solar cells suffer from some disadvantages also like other solar devices, such as:

1. The conversion efficiency of solar cells is limited to 25 percent. The solar intensity is also low. Hence large areas of solar cell modules are required to generate sufficient useful power.
2. The present costs of solar cells are very high making them economically uncompetitive with other conventional power generation methods for terrestrial applications particularly where the demand of power is very large.
3. Solar energy is intermittent and solar cells produce electricity when sun shines and in proportion to solar intensity. Hence somekind of electric storage is required making the whole system more costly. In large installations, the electricity generated by solar

cells can be fed directly into the electric grid system.

Solar cells are the standard source of power for space vehicles and satellites for the last 25 years and is still one of the important applications, while their use for supplying electricity for terrestrial applications will be inevitable if the problem of economic availability of solar cells has been solved. The chalanges of producing reliable and competitive electrical power for terrestrial applications have led to intensive research activities in almost all advanced countries during the past one and a half decade and are expected to continue to do so. There are several semiconductor material which can be converted into solar cells. Among these materials only Si (Silicon) and CdS (cadmium sulphide) have given encouraging results. The single crystal Si solar cell has given an efficiency of about 20 percent at AM-1 insolation, but still due to its high cost, it is not used widely for terristrial applications. This high cost of silicon cells is not only due to its expensive fabrication techniques but also due to expense of assembling large numbers of cells into a large area and making them durable and weatherproof. The thin film cells like CdS cells are no doubt operated at much lower efficiencies but are also less costlier compared to silicon solar cells. The basic material cost in CdS cells is low and large area cells can be fabricated on more or less continuous fashion, but these are not stable and therefore limit their applications. Therefore attempts are made to reduce the cost of silicon solar cells or to try some other combination of materials. Successful attempts have been made in recent years to develop vacuum evaporated polycrystalline Si thin film cells. The ribbon techniques are attempts at improving the costly and slow operation of wafering. Efficiencies upto 8.5 percent at AM-1 insolation with a cell area of 30 sq.cm. have been obtained in case of polycrystaline silicon solar cells which are much cheaper than single crystal silicon solar cells. Encouraging results have also been reported in recent years on the fabrication of low cost thin film amorphous silicon solar cells which can be produced by a variety of methods such as glow discharge decomposition of silane (SiH_4), ion bombardment of single crystal silicon, cathode sputtering, electrolytic deposition, vacuum evaporation, etc. Some of these techniques perfected have resulted high efficiency and low cost silicon solar cells.

Schottky barrier cells of platinum/amorphous silicon layer on a stainless steel substrate are easy to make and a cell are of 1 sq.cm. has shown an efficiency of 5.5 under AM-1 conditions. The metal-insulation-semiconductor (MIS) cells with titanium oxide (T_iO_x) as the insulating layer of area 0.02 sq.cm. have also been constructed and have given an efficiency of 4.8 percent under AM-1 conditions. After silicon cells, GaAs cells have received the most attention as a single crystal semiconductor and these have achieved the highest measured efficiencies of any solar cell. The highest efficiency reported with GaAs solar cell under 200 suns at 28°C is about 23.7 percent. The CdS/Cu_2S cell which is made from polycrystalline material and is much thinner than the single crystal silicon cell holds great promise from commercially viable point of view and the maximum reported efficiency is 9.2 percent. Thin film CdTe cells with a single crystal n-CdS/nCdTe/p-CdTe have shown a highest efficiency of 10.5 percent while polycrystalline thin films of screen printed cell and vacuum deposited cell have shown efficiencies of 8.1 and 8.7 percent respectively. Extensive studies are in progress on new semiconductor materials suitable as solar cell and on advanced technologies to make the cell cheaper and efficient. Some of the cells studied are InP cells, Zn_3P_2 cells, WSe_2 cells, Cu_2O cells, CdSe cells, etc. It appears that silicon cells (single crystal, polycrystaline, amorphous), GaAs cells (Single crystal, polycrystaline) and CdS/Cu_2S cells hold great promise and are to be used in the near future.

In order to supply the required electrical power for a particular demand of a given load, solar cell should not be seen as a single identity but as a whole system where the solar collector called photovoltaic array will be consisting of a large number of cells connected in series to provide desired voltage level or parallel to provide increased current, a voltage regulator, a storage (electrical) unit, an inverter, and other subsystem. The required electrical load may be very small to be used as single purpose device like as individual family residences, navigation lights, small irrigation pumps (less than 500 watts), etc. or medium load such as for commercial or public buildings, street lights, etc. or for large loads such as by industries or an entire utility network. In this chapter the progress in various solar cell types, fabrication techniques, new developments, photovoltaic array design, concentrated systems, etc. will be discussed.

6.2 HISTORY

The photovoltaic technology remained the province of research scientists only untill the advent of the space program. Although the basic material selenium[1] was discovered in 1817 by Berzelius, but the full understanding of the operation of solar cells took nearly 100 years. The photovoltaic effect was first observed in electrolytic cells by a French scientist Bacquerel in 1839 who found that more current can be generated if more light is allowed to fall on the cell. He also discovered that the increase in current is dependent on the wavelength of light. The photoconductivity in selenium was discovered by Willonghby in 1873. In 1876 Adams and Day observed the photovoltaic effect in solid-state selenium structure and also the spectral sensitivity of selenium photoconductors. The first selenium photovoltaic cell was described by Fritts in 1883 and who also in 1885 simulated the human eye response with the combined response of selenium cells and color filters. In 1887, Hertz discovered that ultraviolet light altered the lowest voltage capable of causing a spark to jump between two metal electrodes. In 1904 Hallwacks observed that a combination of copper-cuprous oxide structures were photosensitive. By 1905 it was known that the number of electrons emitted from an element is dependent on the intensity of light at a given wavelength and that the maximum kinetic energy of the emitted electrons varied with the wavelength of light.

Later Einstein published his famous paper in which he explained the emission of electrons and precisely formulated the maximum kinetic energy of the emitted electrons which was later proved experimentally by Millikan in 1916. First time in 1914 the existance of a barrier layer in photovoltaic effect was proved. A new interest emerged with the development of copper/copper-oxide rectifier which led to the development of new devices mainly for photometery and light control systems. But the fast and perfect developments in selenium devices had quickly replaced the copper /copper-oxide photovoltaic devices. In 1941, the Bell Telephone Laboratory of USA using a technique called a 'grown p-n junction' prepared a single-crystal silicon photovoltaic device. But it was exactly after 10 years i.e. in 1950 a team of scientists like Chapin, Fuller, Pearson and Prince at Bell Telephone Laboratories and Rappaport,Loferski and Jenny at RCA developed an impurity diffusion method for p-n junction formation which pushed the efficiency upto 6 percent. With the improvement in the design of the device, fabrication process, and understanding the theory have led the silicon cell to give an efficiency of 14 percent in 1958. By this time many big electronic companies like RCA, Texas Instruments and International Rectifier entered the field and started the production of solar cells with the hope for their terristrial use world over. During 1955 the Western Electric even started selling commercial licences for silicon photovoltaic technology.

The first major contribution of solar cells was appeared in the space programme when on March 17, 1958 the USA had launched his first space craft, 'Vanguard I' powered by Solar cells containing 6 small arrays of 108 silicon chips providing power to a 5-milliwatt radio transmitter. After only 2 months i.e. in May 1958, the USSR launched a much bigger space craft, 'Sputnik' powered by solar cells. Thus the photovoltaic system soon established their dominance over all other space power systems in terms of reliability and economics for satellites for the coming years. Presently all the satellites used in all countries in the world are powered by photovoltaic systems. Although many technological advances were made during the next decade but the photovoltaic systems had an application only in space programms and almost all these systems were made with silicon cells and the power output varied from few watts to 20 KW depending on the satellite requirements. By 1970, there was sufficient improvement in the energy conversion efficiencies of photovoltaic systems and there was a reawakening of interest in their uses. In 1970, several articles started appearing evaluating photovoltaics for photovoltaic applications. During this year the volume of cells produced for terristrial applications had completely out stripped that for space use. The commercial and large volume production resulted in significant reduction in solar cell costs. By this time several manufacturers in countries like USA, France, Japan, Australia, West Germany, England, India started manufacturing and marketing photovoltaic devices but some of them have gone out of production because of high cost of photovoltaic system and poor demand.

In October 1973, the National Science Foundation[2] had organized a Workshop to assess the potential of photovoltaic systems for terristrial applications and to establish goals for both technology and costs. This 1973 Workshop evolved a National Photovoltaic Programme which became a part of ERDA and DOE and established a 10 year cost goal of trying to achieve photovoltaic power systems that would sell for 50 cents (US cents) per peak watt. This was later converted into the national programme to be achieved in 1986. This goal appeared to be a significant reduction since the terristrial photovoltaic array was selling at US Dollars 50-80 per peak watt in 1970. In view of above the research work on several thin film materials such as silicon films (polycrystaline and amorphous), copper sulfide-cadmium sulfide, copper sulfide-cadmium zinc sulfide, gallium arsenide, cadmium telluride, cadmium selenide, zinc phosphide, copper oxide, copper ternaries, Indium phosphide-cadmium sulfide, cadmium indium selenide-cadmium sulfide, zinc silicon arsenide, cadmium silicon arsenide, boron arsenide, organic materials, etc. with various cell structures such as p-n junctions, hetero-junctions, schottky barriers, metal insulator semiconductor (MIS), semiconductor insulation semiconductor (SIS)etc. was extensively started. Technical literature in terms of review articles describing the physics, technology, modelling, advantages, applications, etc. of solar cells started coming[3-25). Recently several books [26-40) are also written on photovoltaics alone which shows the potential of this field. The photovoltaic field is so exploding and fascinating that the IEEE (Institute of Electrical and Electronics Engineers Inc. New York) is arranging a photovoltaic Specialists Conferences at 18 months intervals and the 18th IEEE photovoltaic specialists conference was held[41] in 1985. The EEC (European Economic Community) is also arranging[42] seperately photovoltaic specialists conferences at 18 months intervals, with the first one held in Luxembourg (September, 1977), second in Berlin (April, 1979), and the sixth in London in April 1985. As discussed earlier there are several semiconductor materials which can be used in different structures. A chart showing the various semiconductor materials more suitable as solar cells is given in fig. 6.1. Several articles are recently written on suitable solar cell materials [43-52]. Instead of single crystal cell, polycrystalline material may also be used which will be cheaper but have shown comparatively low efficiency. A series of review articles on the possibilities and successes of polycrystalline solar cells are also written [53-63] by many scientists. Large area cell can be prepared cheaply if the material is used in the amorphous form and therefore many hundreds of articles on this topic

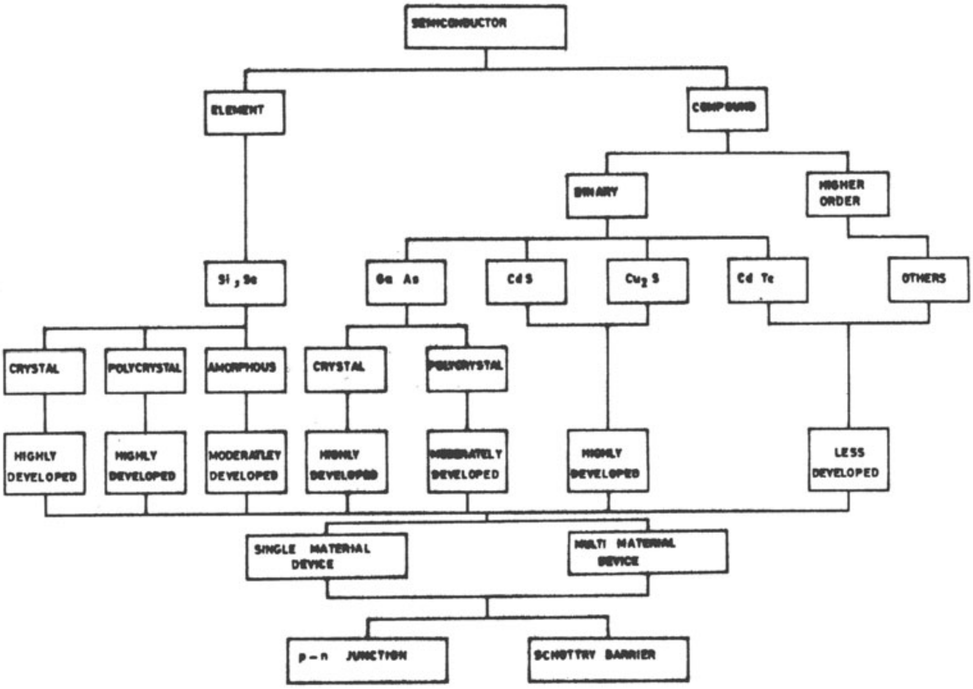


FIG.6.1. DEVELOPMENT CHART FOR SOLAR CELLS

have appeared during the last only 12 years. A few important review articles dealing with the basics of amorphous solar cells are referred here [64-84]. Large area, low cost but low efficiency solar cells can be prepared using materials like Cadmium sulphide/copper sulphide and several review articles are written[85-93] on this topic also. High efficiency solar cells can be prepared using materials like GaAs which can be operated at high temperatures also[94-98] and therefore in order to reduce the overall cost several types of photovoltaic concentrators have also been studied[99-111] in the recent past. Instead of a p-n junction, a junction called as Schottky junction named after its discoverer can also be established between a semiconductor material and a metal layer. Such metal-insulator-semiconductor junction cells have various advantages and also limitations [112-118]. Research is continuing both for making cheaper and reliable solar cells and also for finding new terristrial applications. In USA alone there are 15 large companies who are engaged in the manufacture of solar cells but all of them face the same problems of small market. Solar cells are not only for specialized applications and their use both in the space and on earth have very clearly shown that these can survive under very harsh space conditions such as high vacuum, high radiation, large temperature differentials, etc. and on earth such as dirt, water, wind, hail, dampness, chemical smog, etc. Photovoltaic systems of different capacities from few watts to 10 MW are working beautifully for the last many years on earth.

6.3 FUNDAMENTALS OF PHOTOVOLTAIC CONVERSION

Depending on the ability of the material to carry the current, the materials are grouped into three categories : conductor, insulator, and semiconductor. In a conductor, the electrons in the outer shell are free to move and are not bound to specific site and readily conduct electricity. The conductivity of a metal (conductor) is of the order of 10^6 mho/cm. In an insulator, the outer shell of the atom contains six or seven electrons and therefore the electrons are tightly bound and are unable to carry electric current. The conductivity of an insulator is of the order of 10^{-10} mho/cm. In a semiconductor which lies between these two extremes, the atoms may have three, four or five electrons in the outer shell, and these electrons can be freed only if some additional energy is supplied. These semiconductors conduct the current slightly and have a conductivity near unity. The conductivity of a semiconductor can be changed by orders of magnitude by introducing new foreign elements called dopants. The conductivity of a semiconductor,silicon, can be changed from 1000 to 0.001 mho/cm. Another property of a semiconductor is that in it the electric current can be carried by electrons (negatively charged) or holes (positively charged).

6.3.1 Semiconductor materials

Like any other material, the semiconductors can also be in the crystalline, polycrystalline or amorphous form. In the crystalline form the atoms or molecules are arranged in a ordered array and the array is periodic throughout the bulk of the sample. In a polycrystalline sample, the atoms within a subsection are symmetrically arranged like in crys-

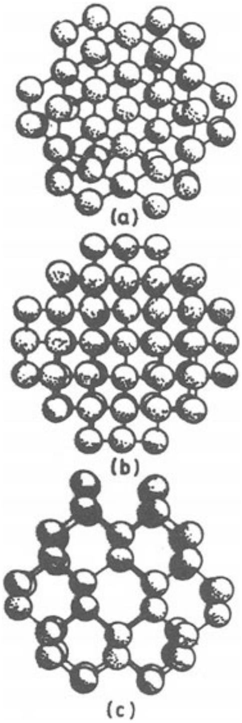


FIG.6.2. MODEL OF SILICON (DIAMOND) SEMICONDUCTOR CRYSTAL (A) VIEW FROM THE 111 DIRECTION (B) VIEW FROM THE 100 DIRECTION AND (C) VIEW FROM 110 DIRECTION

talline form while the subsections (crystallites) are jumbled and the atomic order and regularity is totally irregular. In an amorphous form of a material (semiconductor) the atoms are not arranged in an orderly pattern on any macroscopic scale. All the properties of the semiconductors will not be discussed here except to those related to solar cells hence readers are referred to read text books meant and dealing only with fundamental properties of semiconductors[119-127].

Single crsytal silicon cell is widely studied and used and therefore will only be discussed here to understand the fundamentals of solar cells. Silicon p-n junction crystalline solar cell works the same way as other solar cells and therefore can be considered as an illustrative model. A pure commercial silicon (intrinsic) contains impurity atoms with concentrations of less than $10^{18} m^{-3}$ and electrical resistivity of 2500 Ωm with four valence electrons which are shared with adjacent silicon atoms in convelent bonding. In fig.6.2 the atomic arrangement of a silicon (or diamond) crystal from three different directions is shown which shows the crystal order in these directions. The top atomic structure is when it is viewed in the 111 direction, the middle from 100 direction, and the bottom from 110 direction. These physical arrangement of atoms in different directions create electrical and physical differences in the

(a) Silicon at absolute zero (0°K)

(b) n-doped silicon (excess electron)

(c) p-doped silicon (defficient electron)

FIG.6.3. SCHEMATIC OF SILICON CRYSTAL LATTICE

properties of the crystal and therefore may fundamentally change the performance of a solar cell when made from these crystals. Hence it is always said a silicon with crystal as being 111, 110 or 100 material is used in solar cell. Some basic properties of silicon are shown in table 6.1. In a silicon crystal, each atom is surrounded by four equidistant atoms and each atom has four valence electrons and each of the four valence electrons in the crystal lattice is shared by one of its four nearest neighbours as is seen from fig.6.3. At absolute zero (0 K), all the four electrons are firmly bound, and the silicon crystal will be an insulator and no electrons will be free and therefore there will be no conduction as is seen in fig.6.3(a). But if some energy is added from outside which is sufficient to break the convalent bond called the bond energy or energy gap given as E_g which in case of silicon is 1.1 eV, the covalent bond can be broken. When an electron breaks away the covalent bond, it leaves behind a space called hole acting as a positive charge carrier. But if the silicon crystal is doped with an impurity such as phosphorus which occupies the same lattice sites but has five valence electrons, then the doped crystal will have valence electrons in excess of a pure crystal-one for each of the phosphorus atoms. These excess electrons can be separated from the phosphorus atoms by thermal energy and are free to move in the crystal and therefore make the system electron conducting or n-type semiconductor as shown in fig. 6.3(b). But if silicon is doped with boron atom which has three valence electrons, it leaves a vacancy of one electron in the lattice known as hole, with positive charge which can be filled with electron. The electron vacancy or hole is a positive charge carrier and is free to more in the crystal and thus making the crystal as hole conducting or p-type semiconductor as shown in fig. 6.3(c). If the p-type and n-type semiconductors are joined together, a p-n junction is made at the boundary because the electrons in the n-type portion would diffuse across the joining boundary in the p-type region and similarly the holes in the p-type portion will diffuse across the joining boundary in the n-type region until a voltage equal to the sum of the diffusion potentials of the electrons and holes was established across the p-n junction. Therefore in the region of the junction a permanent electric field gets established. Such p-n junctions in practice can be realised in several ways including ion implanting, diffusing, or growing n-type impurity in p-type crystal or p-type impurity in n-type crystal.

Table 6.1. Properties of silicon

Pure, Intrinsic material

Density	2329 kg/m^3;atoms $5x10^{28} m^{-3}$
Melting point	1412°C
Boiling point	3145°C
Heat of fusion	12.1 Kcal/mole
Heat of vaporization	71 Kcal/mole at boiling pt.
Specific heat capacity	0.694 KJ/Kg K
Thermal conductivity	157 W/m k
Critical Pressure	1450 atm.
Critical temperature	4920°C
Refreactive Index	3.5 (at λ = 1.1μm)
Temperature coefficients of elastic constants	$K_{C11} = -75 \times 10^{-6}/°C$ $K_{C22} = -24.5 \times 10^{-6}/°C$ $K_{C44} = -55.5x10^{-6}/°C$
Energy gap	1.11 ev (at λ = 1.11μm, temp.=200°C) 1.14 ev (at λ = 0.97μm, temp.=27°C)
Electron mobility	0.135 m^2/Vs
Hole mobility	0.048 m^2/Vs
Electron diffusion coefficient	35×10^{-4} m^2/s
Hole diffusion coefficient	12×10^{-4} m^2/s
Relative permittivity	11.7
Effective density of states in conduction band	3×10^{25} m^{-3}
Effective density of states in valence band	1×10^{25} m^{-3}

Si homojunction p-n/p^+ solar cell

P-layer thickness	250 - 350 μm
Dopant concentration in p layer	$\leq 10^{24}$ m^{-3}
n^-layer thickness	0.20 - 0.5 μm
Dopant concentration in n layer	$\leq 10^{26}$ m^{-3}
P^+ layer thickness	0.45 μm
Dopant concentration in P^+ layer	$\geq 10^{24}$ m^{-3}
Minority carrier lifetime	~10 μs
Minority carrier path length	~ 100 μm
Minority carrier diffusion coefficient	10^{-3} m^2/s
Surface recombination velocity	10 m/s

6.3.2 Photon energy

Since light is responsible for photovoltaic effect in a semiconductor, hence a little knowledge of solar spectrum is required. The solar intensity outside the earth's atmosphere remains practically constant known as solar constant and its value is 1353 w/m^2 and 98 percent of the energy radiated from the sun is confined within the spectral region of 0.25 to 2.5 μm. The solar spectral irradiance curve above the earth's atmosphere known as air mass zero (AM-0) curve is shown in fig.6.4. During the day due to variation in zenith angle of sun, the path length of sun beam varies and is given as air mass (AM). Air mass zero (AM-0) means solar radiation at sea level when the sun is at zenith. It means that AM-0 conditions correspond to solar flux density of 1353 w/m^2 and AM-1 conditions correspond to a solar fluse density of 1070 w/m^2. The solar light is composed of tiny bundles of energy called photons which moves at an extremely

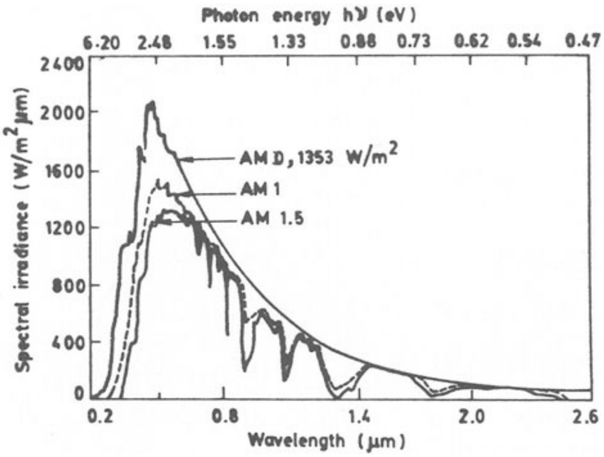


FIG.6.4. SOLAR SPECTRAL IRRADIANCE AS A FUNCTION OF WAVELENGTH AND PHOTON ENERGY

high but finite speed and the energy of the photon known as photon energy is the product of its mass and speed. When photons strike an atom they interact with the electrons and absorbed. This added energy may drive one of the atom's outer electron off. Depending on the number of photons and their energies, the electrons will be freed. Therefore it is essential to know, the number of photon and the corresponding energy in the solar radiation. The photon energy in different wavelength bands for AM-0 and AM-1 solar spectral irradiance is shown[28] in table 6.2.

Table: 6.2. Photon energy and solar spectral irradiance in different spectral bands at AM-0) and AM-1 (From Neville[28])

Wavelength (μm)	Energy (eV)	Solar Spectral Irradiance (w/m^2)	
		AM-0	AM-1
- 1.15	0 - 1.08	317.7	252.4
1.15 - 1.00	1.09 - 1.24	95.1	84.1
1.00 - 0.90	1.25 - 1.38	82.9	60.2
0.90 - 0.80	1.39 - 1.55	99.3	83.5
0.80 - 0.70	1.56 - 1.78	123.7	80.5
0.70 - 0.60	1.79 - 2.07	151.5	132.5
0.60 - 0.50	2.08 - 2.49	177.0	143.0
0.50 - 0.40	2.50 - 3.11	187.7	151.0
0.40 - 0.30	3.12 - 4.14	101.7	79.1
0.30 - 0.20	4.15 - 6.22	16.3	3.7
0.20 - 0.00	6.23 - ∝	0.1	0.0
	Total	1353.0	1070.0

From table 6.2 it is seen that in the far infrared region i.e. greater than 1.15 μm there is a significant portion of solar irradiance and this energy is not used as energy source by solar cells which is one of the reason of low efficiency of solar cells.

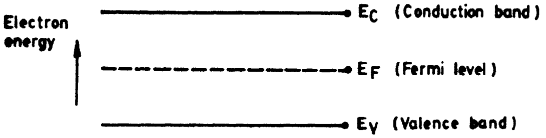
6.3.3 Electron-hole concentration and Fermi level

In a equilibrium state of a crystal, the electrons are constantly seeking the lower energy levels but are constantly being exited to higher state by interactions such as with phonons and photons. The Pauli exclusion principle limits the number of electrons that can exist at any allowed energy level. This principle implies that each allowed energy level can be occupied by, at most, two electrons, each of opposite spin. This energy level is termed as Fermi

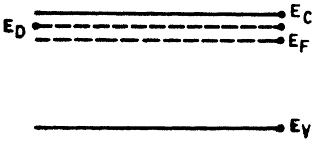
Level E_F. If the temperature increases, some of the electrons gain energy in excess of Fermi level and the electrons distribution in the allowed levels can be described using Fermi-Dirac distribution function f(E), given as;

$$f(E) = \frac{1}{1 + \exp[(E-E_F)/KT]} \qquad \ldots(6.1)$$

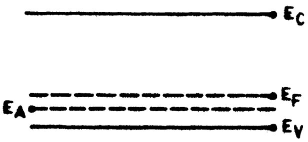
Where E is the energy of an allowed state, E_F is the Fermi energy, K is the Boltzmann's constant, and T is the absolute temperature. At absolute zero, f(E) is unity upto an energy equal to E_F and then it becomes zero above energy E_F. By definition, the Fermi energy level, E_F is the energy at which the probability of a state being filled by an electron is exactly one-half. In a pure semiconductor (intrinsic semiconductor) the free electrons in the conduction band and the free holes in the valence band are only due to thermal excitation across the band gap. While in an extrinsic semiconductor, the additional electrons in the conduction band are due to ionized donor imperfections or additional holes are present in the valence band due to ionized



(a) An intrinsic semiconductor



(b) Extrinsic n-type semiconductor



(c) Extrinsic p-type semiconductor

FIG.6.5. ENERGY LEVEL DIAGRAM OF SEMICONDUCTORS

acceptor imperfections. The energy band diagram for these three cases is shown in fig 6.5. In a intrinsic semiconductor, the Fermi level is exactly in the middle of the energy gap i.e. $E_F=E_g/2$ and there are equal number of electrons and holes. The Fermi level in an extrinsic semiconductor gets shifted towards the donor level E_D (if the impurity added yields electrons it is called donor) or towards the acceptor level (if the impurity added yields excess holes it is called acceptor) E_A. However, the exact location of the Fermi level in these extrinsic material depends on the impurity atoms per cubic centimeter (doping level) and the absolute temperature. The difference in energy, (E_C-E_D) is of the order of KT, the thermal energy, and hence the electron gets sufficient thermal energy to get excited into the conduction band where it acts as a charge carrier. In an acceptor, the energy of an electron is E_A which is approximately KT above the valence band which means that the electrons from the valence band can easily be thermally excited onto the acceptor atom leaving behind a mobile hole in the valence band. In thermal equilibrium the number of electrons, n, in the conduction band per unit volume of crystal is given as

$$n = N_C \exp\left[(E_F - E_C)/KT \right] \tag{6.2}$$

Where N_C is called the effective density of states in the conduction band and is given as:

$$N_C = \frac{\sqrt{\pi/2}}{\pi^2 h^3} (m_d k)^{3/2}\ T^{3/2} \tag{6.3}$$

Here m_d is the effective mass for the electrons in the conduction band and h is the Planck's constant. Similarly the density of holes, P , in a p-type material is given as

$$p = N_V \exp\left[(E_V - E_F)/KT\right] \tag{6.4}$$

Where N_V is called the effective density of states in the valence band and is given as

$$N_V = \frac{\sqrt{\pi/2}}{\pi^2 h^3} (m_V k)^{3/2}\ T^{3/2} \tag{6.5}$$

Here m_V is the effective mass for the holes in the valence band. For a pure semiconductor, n equals to p hence

$$n = p = n_i \text{ (intrinsic carrier concentration)} \tag{6.6}$$

and therefore the product of the number of electrons and holes (np) is constant for a semiconductor under thermal equilibrium i.e.

$$np = n_i^2 = N_c N_v \exp [- (E_c - E_v)/KT] \qquad (6.7)$$

$$= N_c N_v \exp [- E_g/KT] \qquad (6.8)$$

Where E_g is the width of the forbidden gap between the conduction band and valence band and is known as band gap energy. From equations (6.6) and (6.7), E_F is given as

$$E_F = \frac{E_c + E_v}{2} + \frac{KT}{2} \ln \left(\frac{N_v}{N_c} \right) \qquad (6.9)$$

Which clearly shows that in a pure crystal the Fermi level is exactly in the middle of valence and conduction band and gets shifted to either side depending on the density of states in the conduction and valence bands.

The addition of donor or acceptor impurities do not change the overall macroscopic change neutrality of a semiconductor crystal and hence satisfy the following condition:

$$(p + N^+{}_D) - (n + n^-{}_A) = 0 \qquad (6.10)$$

Where $N^-{}_A$ is the concentration of ionized acceptor atoms and $N^+{}_D$ is the concentrator of ionized donor atoms and are given as:

$$N^-{}_A = \frac{N_A}{(1 + \exp [(E_A - E_F)/KT])} \qquad (6.11)$$

$$\text{and} \quad N^+{}_D = \frac{N_D \exp [(E_D - E_F)/KT]}{1 + \exp [(E_D - E_F) /KT]} \qquad (6.12)$$

Where E_A is the energy of the electron on the acceptor atom, E_D is the energy of the electron on the donor atom, N_A is the concentration of acceptor impurities, and N_D is the concentration of donor impurities.

The position of the Fermi level can be established using equation (6.2) and (6.4) depending whether the material is doped with donors or acceptors respectively. Thus using equation (6.2)

$$n = N_D = N_c \exp [(E_F - E_C)/KT]$$

$$E_F - E_C = KT \ln (N_D/N_C) \qquad (6.13)$$

and

$$p = N_A = N_V \exp [(E_V - E_F)]$$

$$E_V - E_F = KT \ln (N_a/N_V) \qquad (6.14)$$

The electrical conductivity σ of a semiconductor depends on the number of charge carriers and is given as:

$$\sigma = q (n\mu_e + p\mu h) \qquad (6.15)$$

Where q is the electronic charge, and μe and μh are the election and hole mobilities respectively given as

$$\mu = V/E \qquad (6.16)$$

Where V is the velocity of charge carrier and E is the applied electric field in volts per cm. and σ is the electrical conductivity of semiconductor in mho per cm. In a semiconductor, the electron or hole can not accelerate indefinitely and in the way collision takes place with the atoms of the material, atoms of the impurity material, and other charge carriers. If the electric field is small, the mobility is assumed to be independent of electric field and depends on impurity concentration and temperature. If the semiconductor is heavily doped, the mobility will reduce and will depend on the level of dopants N (in cm^{-3}) and in such a case following emperical equations as given by Caughey and Thomas [128] can be used for electron and hole mobilities:

$$\mu_e = 65 + \frac{1265}{1 + (N/8.5 \times 10^{16})^{0.72}} \ cm^2/V_s \qquad (6.17)$$

$$\mu_h = 47.7 + \frac{447.3}{1 + (N/6.3 \times 10^{16})^{0.76}} \ cm^2/V_s \qquad (6.18)$$

6.3.4. A p-n junction

If a semiconductor is doped with a donor impurity increasing the number of electrons in the conduction band then it is known as n-type material. If the semiconductor is doped with an acceptor impurity leaving the excess holes then it is known as p-type material. The energy versus distance diagrams for a n-type and p-type semiconductors with positions of Fermi level as determined by equations (6.13) and (6.14) are shown in figs 6.5 (b) and 6.5 (c) respectively. If these n-type and p-type crystal are joined then according to the definition of the Fermi level, the Fermi levels in the two regions should be at the same energy which leads to a energy displacement configuration as shown in fig 6.6. Due to the bending of the energy bands a strong electric field develops in the junction. Now the p-type portion contains disproportionate amount of elections and is at a much higher negative potential causing a field across the junction. Therefore a charge dipole is created in the vicinity of the junction and no net current flows in the dipole in thermal equilibrium. The electric field at the junction counter balances the strong tendency from a large diffusion current from p-region to n-region (fig 6.6). This p-n junction thus provides an inherant electric field which will accelerate electrons which may drift through the junction into the n-type material. Now suppose a voltage is applied across this p-n junction in the mode as shown in fig 6.6 (a) known as 'reverse bias condition', the motion of electrons from right to left and of holes from left to right will make the inherent electric field even stronger resulting in no flow of current. The small current which will flow through the p-n junction will be due to flow of electrons from the p-side and holes from the n-side. If the voltage is applied in the opposite direction as shown in fig 6.6(b) called as 'forward bias condition' the internal energy barries will be reduced and the electrons from the n-material will find a least barrier to enter the p-material and similarly the holes from the p-material will enter without much resistance to n-material. Since many electrons

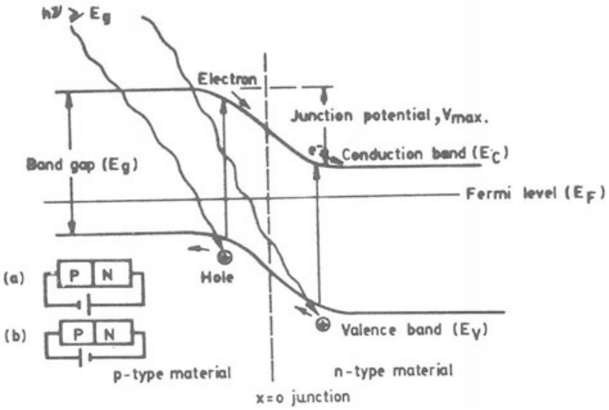


FIG.6.6. ENERGY BAND STRUCTURE OF A p-n JUNCTION

are available on the n-side and many holes on the p-side to cross the barrier the current flow increases sharply. In the absence of light, the relationship between the flow of junction current I_j with imposed voltage V in a p-n junction is given as:

$$I_j = I_o \, [\exp \, (qV/KT) \, -1] \qquad (6.19)$$

Where q is the electronic charge and I_o is the saturation current also called as dark current as shown in fig 6.7. This saturation current is obtained when large negative voltage is applied across the diode. This saturation current I_o is dominated by diffusion of minority carriers and is given [28] as:

$$I_o = \frac{qD_h p_{no}}{L_h} + \frac{qD_e n_{po}}{L_e} \qquad (6.20)$$

Where n_{po} and p_{no} are the thermal equilibrium densities of electrons on p-side and holes on the n-side of the junction respectively; L_e and L_h are the electron diffusion length on p-side and hole diffusion length on n-side respectively; and D_e and D_h are the electron and hole diffusion constant respectively. These diffusion constants are given as:

$$D_e = \frac{KT}{q} \mu_e \qquad (6.21)$$

and

$$D_h = \frac{KT}{q} \mu_h \qquad (6.22)$$

and densities of electrons and holes are given as

$$n_{po} = \frac{n_i^2}{N_a} \qquad (6.23)$$

and

$$p_{no} = \frac{n_i^2}{N_d} \qquad (6.23)$$

Where N_a and N_d are the p-region and n-region impurity concentrations and n_i is the intrinsic carrier concentration. The electron and hole diffusion lengths are given as:

$$L_e = (D_e \tau_e)^{1/2} \tag{6.25}$$

and $$L_h = (D_h \tau_h)^{1/2} \tag{6.26}$$

Where τ_e and τ_h are the electron and hole lifetimes as minority carriers. When light (photons) is incident on the junction, the electron hole pairs are generated and electric current will be the difference between the normal diode current and the light generated current I_L (fig. 6.7) i.e.

$$I = I_L - I_j \tag{6.27}$$

Curve (a) in fig.6.7 shows the voltage-current characteristics when the junction is not illuminated while curve(b) shows the current-voltage characteristics of a p-n junction when it is illuminated. From photovoltaic energy conversion point of view the power quadrant shown on right hand bottom quadrant in fig 6.7 is very important which gives the ideal current voltage output of a p-n junction solar cell.

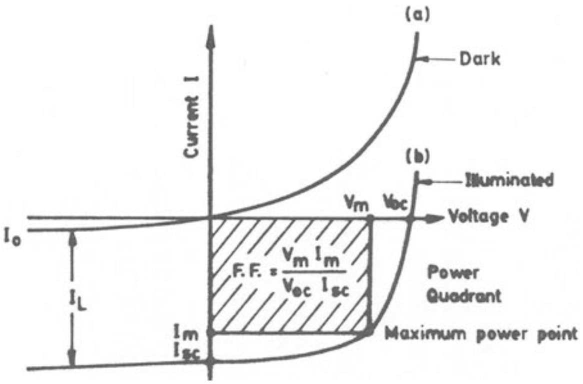


FIG.6.7. TYPICAL CURRENT-VOLTAGE CHARACTERISTICS OF A SOLAR CELL

The behaviour of a solar cell can be characterized using three parameters [27], the open circuit voltage V_{oc}, the short circuit current I_{sc}, and the fill factor FF as shown in fig 6.7 (power quadrant). The open circuit voltage V_{oc} is defined as the voltage output from a photovoltaic cell when the load impedence is much larger than the device impedence which mean no current is flowing and it is the maximum possible voltage. The short circuit current I_{sc} is the current output when the load impedance is much smaller than the device impedance i.e. the maximum possible current. The fill factor FF is the ratio of maximum power a photvoltaic cell can produce ($V_m I_m$) to the theoretical limit ($V_{oc} I_{sc}$) if both voltage and current were simultaneously at their maximum.

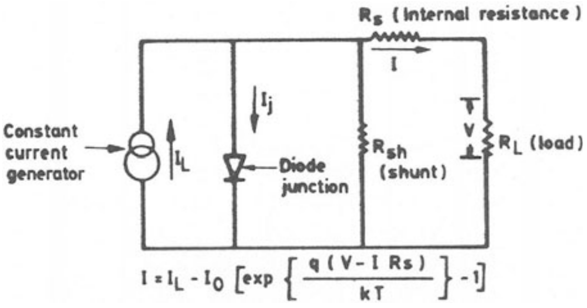


FIG.6.8. EQUIVALENT CIRCUIT OF A SOLAR CELL.

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \qquad (6.28)$$

A simplified steady state equivalent circuit of a solar cell is shown in fig 6.8 in which R_L is the load resistance. The modified equation of the current flow will thus be

$$I = I_L - I_o \left[\exp\left(\frac{(V - IR_S)q}{KT}\right) - 1\right] \qquad (6.29)$$

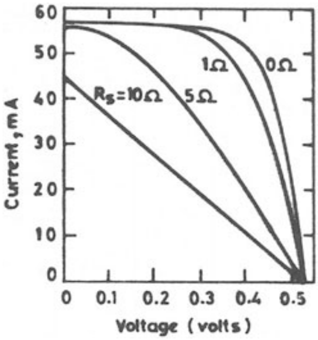


FIG.6.9. THE EFFECT OF SERIES RESISTANCE R_s ON THE CURRENT VOLTAGE CURVE FOR A TYPICAL SILICON SOLAR CELL.

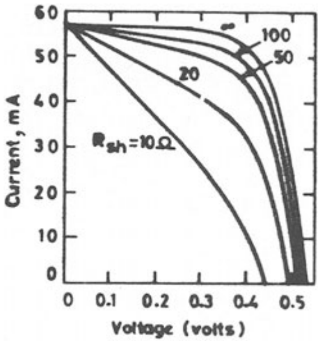


FIG.6.10 THE EFFECT OF SHUNT RESISTANCE R_{sh} ON THE CURRENT VOLTAGE CURVE FOR A TYPICAL SILICON SOLAR CELL.

The series resistance R_s which is due to the resistance to conduction in the thin diffused layer on the top of the photovoltaic cell should be reduced to zero which can be done by proper design of metalization and the conductivity of the material. The effect of series resistance R_s and shunt resistance R_{sh} on the voltage-current characteristics for a typical silicon cell with 2 Sq.cm. area and illuminated with 1000 w/m^2 are shown in figs. 6.9 and 6.10 respectively. From fig 6.9 it is seen that the open circuit voltage is not affected but the fill factor gets considerable reduced. The open circuit voltage also gets affected. From fig 6.10 it is seen that as the shunt resistance decreases the fill factor and open circuit voltage gets reduced while the short circuit current is not affected. The series resistance can be reduced by making the diffusion region thin, heavily doped and by optimizing the design of the ohmic contact grid design pattern giving least resistance with covering 5 to 10 percent of the surface.

The open circuit voltage, V_{oc}, of a p-n junction is related to the band gap, E_g, and is generally expressed (27) in terms of short circuit current, I_{sc}, the dark current I_o, and the junction perfection factor A_o:

$$V_{oc} = A_o(KT/q)\ \ln\left[\ (I_{sc}/I_o) + 1\ \right] \qquad (6.30)$$

The value of A_o is unit for a perfect junction. The dark current I_o is a function of band gap of the material and temperature. With the increase in band gap and decrease in temperature, the dark current I_o decreases and open circuit voltage V_{oc} increases. The short circuit current, I_{sc} depends on the spectral response of the photovoltaic cell and the spectrum of the light. The spectral response of the photovoltaic cell depends (27) on many parameters including optical absorption coefficient α , junction depth X_j, width of depletion region W, the life times and mobilities on both sides of the junction, surface recombination velocity S, the presence and absence of electric field. The fill factor FF can be determined by knowing magnitude of open circuit voltage V_{oc}, the junction perfection factor A_o and the series and shunt resisrtances R_s and R_{sh}. The expression (6.20) of diode saturation current (37) can also be written as:

$$I_o = A \left(\frac{qD_e\ n_i^2}{L_eN_a} + \frac{qD_h\ n_i^2}{I_hN_D} \right) \qquad (6.31)$$

For maximum value of V_{oc}, the diode saturation current should be as small as possible. From equation (6.31) it is seen that saturation current I_o is a strong function of square of the intrinsic concentration, n_i2, which is given as:

$$n_i^2 = N_cN_v \exp\ (-\ E_g/KT) \qquad (6.32)$$

Therefore the expression for minimum value of saturation current, I_o, in terms of band gap can be written as:

$$I_o = 1.5 \times 10^5 \exp\ (\ -\ E_g/KT)\quad A/cm^2 \qquad (6.33)$$

This expression indicates that as the energy band gap increases, the maximum value of V_{oc} decreases which is opposite to that of I_{sc} suggesting that there is an optimum band gap semiconductor for maximum efficiency. The maximum open circuit voltage V_{oc} also decreases with increasing temperature and the power output decreases relative to the input of solar energy. The maximum conversion theoretical efficiency as calculated using above equation with energy band gap for several semiconducting materials is shown in fig 6.11. The efficiencies calculated here do not consider any losses such as reflection, transmission, nonideal junctions, cell resistance, collection efficiency, etc. It is seen from fig. 6.11 that the maximum efficiency is a strong function of operating temperature and with the increase in temperature, the optimum band gap shifts upward. At room temperature, (at about 298 K) the peak efficiency occurs between the band gap in the range of 1.4 and 1.6 eV with efficiency increasing from 26 to 29 percent. The band gap for silicon (1.1 eV) is lower than the optimum while the band gap for GaAs is near optimum i.e. 1.4 ev even than the silicon cell efficiency is quite high.

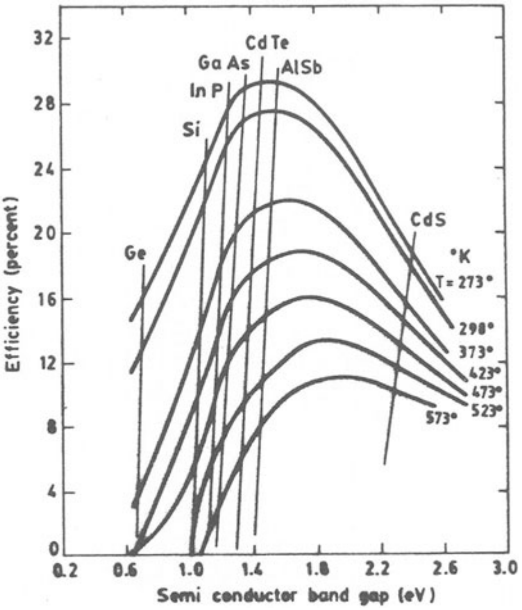


FIG.6.11. SEMI-CONDUCTOR EFFICIENCY LIMITS AS FUNCTION OF BAND GAP AND TEMPERATURE

The open circuit voltage V_{oc} is a strong function of temperature while the short circuit current I_{sc} is not so dependent on operating temperature. The short circuit current is related with the open circuit voltage with the following relation:

$$I_{sc} = I_o \left[\exp (qV_{oc}/KT -1 \right] \qquad (6.34)$$

Which can also be written (37) as follows by neglecting small negative term

$$I_{sc} = AT^{r} \exp (- E_{go}/KT) \exp (qV_{oc}/KT) \qquad (6.35)$$

Where A is area and is independent of temperature T, E_{go} is the band gap at zero temperature, and γ determines the temperature dependence of other terms determining I_o which lies between 1 to 4. Now on differentiating equation (6.35) and puting $V_{go} = E_{go}/q$ and neglecting the effect of temperature on short circuit current, one find

$$\frac{dV_{oc}}{dT} = - \frac{(V_{go} - V_{oc} + \gamma\,(KT/q)}{T} \qquad (6.36)$$

From this expression it is seen that with increasing temperature, the open circuit voltage, V_{oc} decreases linearly. The effect of temperature on maximum voltage V_{max} is shown in fig 6.12 and on maximum current is shown in fig 6.13. From these figures also it is clear that with the increase in temperature the percentage decrease in V_{max} is greater than that in I_m and also the temperature effect on the efficiency is less for semiconductors of high band gap.

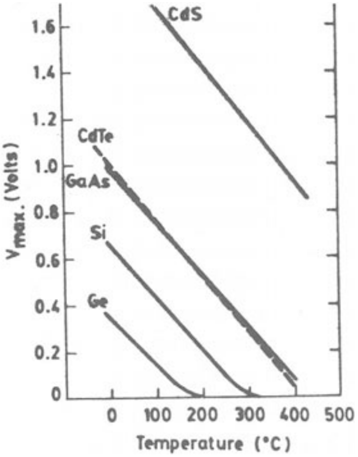


FIG.6.12. EFFECT OF TEMPERATURE ON THE MAXIMUM VOLTAGE FROM A SEMICONDUCTOR.

For silicon the open circuit voltage decreases by about 0.4 percent for each degree °C rise in temperature and the power output decreases by 0.4 to 0.5 percent per °C. The GaAs cells which have high band gap are only about half as sensitive to increase in temperature as are silicon cells. The light intensity also affects the solar cell performance and the optimum design at low and high intensities can be quite different. The effect of light intensity on the open circuit voltage and short circuit current in case of a silicon solar cell is shown in fig 6.14. From this figure it is seen that the short circuit current increases linearly with the increase in light intensity while the open circuit

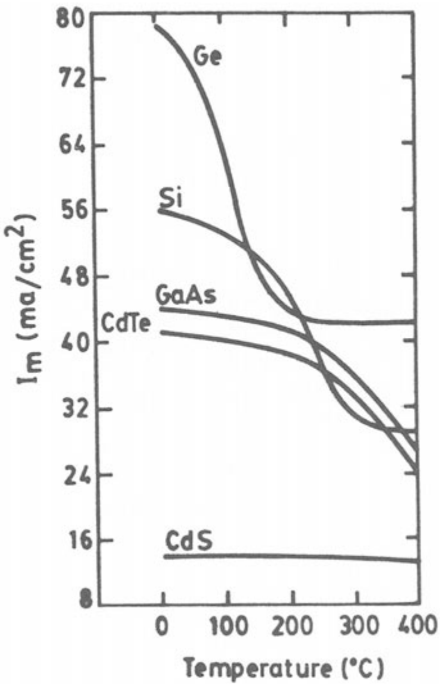


FIG.6.13. EFFECT OF TEMPERATURE ON THE MAXIMUM CURRENT FROM A SEMICONDUCTOR

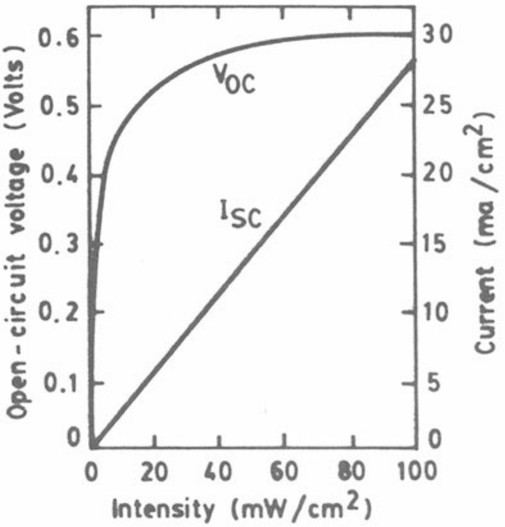


FIG.6.14. EFFECT OF LIGHT INTENSITY ON THE CURRENT AND VOLTAGE FOR A SILICON SOLAR CELL

voltage increase very rapidly and then becomes constant with the increase in light intensity. At low intensities the series resistance becomes unimportant and the shunt resistance has a strong effect while at high intensities the shunt resistance becomes unimportant and series resistance has a strong effect.

6.3.5 Absorption in a semiconductor

Generally it is assumed that all the light incident on the semiconductor having energy more than band gap E_g gets absorbed and converted into electron-hole pairs or heat. If the semiconductor is thin, a number of photons may pass entirely through the semiconductor. The absorption of light in a semiconductor is a function of wavelength of light and is related with the photon flux f_0 (λ) at a distance $x = 0$ in the absorbing media as:

$$f(\lambda, x) = f_0(\lambda) \exp [- \alpha(\lambda) x] \qquad (6.37)$$

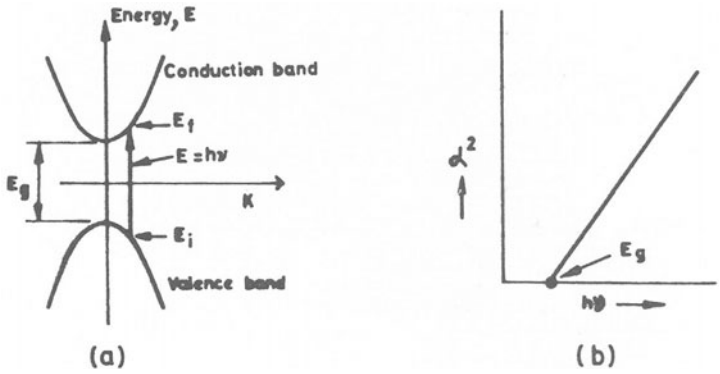


FIG.6.15 OPTICAL ABSORPTION IN A DIRECT BAND SEMICONDUCTOR (A) DIRECT OPTICAL TRANSITION FROM VALENCE TO CONDUCTION BAND (B) PLOT OF ABSORPTION COEFFICIENT α WITH PHOTON ENERGY.

Here the photon flux is measured in mw/cm^2 or photons/cm^{2}s. The intrinsic absorption are of two types: direct and indirect absorption. The absorption process in a direct-band gap semiconductor is shown in fig 6.15 (a). In this case since the photon momentum k $(=h/\lambda)$ is small compared to the crystal momentum, the later is conserved in the transition. The absorption starts at $h\nu$ (photon energy) =

E_g and the electron is transferred vertically from valence to conduction band without a change in momentum. The absorption coefficient α near the minimum energy for absorption E_g is given as:

$$\alpha = C\,(h\nu - E_g)^{1/2} \qquad (6.38)$$

Where C is a constant and for allowed transitions it is given as:

$$C = 3.38 \times 10^7\, n^{-1}\,(m_e/m_o)^{1/2}\,(E_g/h\nu) \qquad (6.39)$$

Where n is the refractive index, and m_o is the free electron mass. The absorption coefficient for forbidden transitions is given as:

$$\alpha = C'\,(h\nu - E_g)^{1/2} \qquad (6.40)$$

Where C' is a function of energy.

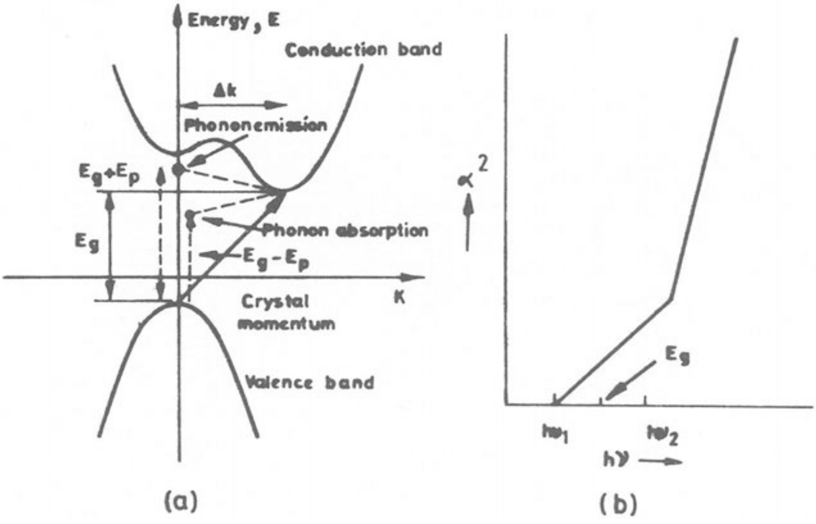


FIG.6.16 OPTICAL ABSORPTION IN AN INDIRECT BAND SEMICONDUCTOR (A) INDIRECT OPTICAL TRANSITION FROM VALENCE BAND TO CONDUCTION BAND (B) PLOT OF ABSORPTION COEFFICIENT WITH PHOTON ENERGY.

A plot between the photon energy $h\nu$ and α^2 is made in fig 6.15 (b) which is a straight line for direct absorption and a cut on the absicca (photon energy) gives the direct band gap of the semiconductor material.

In an indirect band gap semiconductor, the maximum energy in the valence band and the minimum energy in the conduction band occur at different values of crystal momentum as is shown in fig 6.16 (a). For the direct transition of electrons from valence band to the conduction band photons of much higher energy than energy band are required. Transition of electrons from maximum energy valence band to the minimum energy conduction band can take place with photons of suitable energy and in the presence of phonon. As compared to photon, the phonons have high momentum but low energy. Hence in this case the minimum photon energy required to excite an electron from valence band to conduction band is

$$h\nu = E_g - E_p \qquad (6.41)$$

Where E_p is the energy of the absorbed phonon of required momentum. In an indirect absorption, the absorption coefficient is low and it is to pass a reasonable distance before it is absorbed. The absorption coefficient is given as

$$\alpha = \alpha_a + \alpha_e$$

Where α_a is due to phonon absorption and becomes zero if $h\nu < (E_g - E_p)$, and the second term is the contribution due to phonon emission and can be taken as zero if $h\nu < (E_g + E_p)$. These are given as:

$$\alpha_a = \frac{A\,(h\nu - E_g + E_p)^2}{\exp(E_p/KT) - 1} \qquad (6.42)$$

and

$$\alpha_e = \frac{A\,(h\nu - E_g - E_p)^2}{1 - \exp(-E_p/KT)} \qquad (6.43)$$

Where A is a constant. In case of a forbidden indirect transitions

$$\alpha = A'\,(h\nu + E_p - E_g)^3 \qquad (6.44)$$

Where A' is a function of energy and temperature.

If a plot between the photon energy $h\nu$ and $\alpha^{1/2}$ is made in case of indirect absorption, we get two straight line segments as shown in fig 6.16 (b). The upper line intercept $h\nu_2$ on the photon energy axis corresponds to emission of a phonon while the lower line intercept $h\nu_1$ corresponds to absorption of phonon. The indirect band energy E_g and the phonon energy E_p is thus given as

$$E_g = \frac{1}{2}(h\nu_1 + h\nu_2) \quad \text{and} \quad E_p = \frac{1}{2}(h\nu_1 - h\nu_2) \tag{6.45}$$

The optical absorption coefficient for a number of interesting semiconductor materials as a function of photon energy is shown in fig 6.17. The direct band gap is small in case of materials like Cds, CdTe, GaAs, InP, etc. whereas the indirect band gap is small in case of Si and AlAs. In case a indirect gap material is used for solar cells, then a large material thickness will be required to absorb most of light and since large carriers are generated away from the collecting junction, long minority diffusion lengths are required for the carriers to reach the junction before recombination. To absorb most of the solar spectrum, typical thickness in such indirect gap material is in the range of 20 to 50 μm. While in case of a direct gap material, the typical thickness to absorb most of the solar

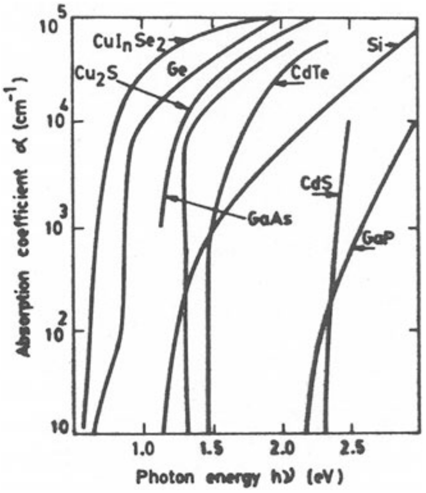


FIG.6.17. OPTICAL ABSORPTION COEFFICIENT AS A FUNCTION OF PHOTON ENERGY FOR A FEW SEMICONDUCTOR MATERIALS OF INTEREST TO SOLAR CELLS.

spectrum can be 1 to 3 µm. Therefore in such a thin material, the homojunction should have very small area on the surface so that light can penetrate to the junction. Therefore the direct band gap material homojunctions shows higher surface recombination losses.

Some of the problems are overcome by using a heterojunction structure of larger band gap material on the direct band gap absorbing material. The optical absorption phenomena in semiconducting materials has been studied by Moss et al [129], Dass and Newman [130], Marinuzzi et al[131], Bager and Paduchikh [132], Mitchell et al [133)] and Cardona and Herbeke [134]. Neville [28] has computed the power available from six commonly used semiconductors as solar cells under two conditions i.e. AM-0 and AM-1 using the absorption data available in the literature for these materials and the band gap. The results are given [28] in table 6.3. While making the calculations, it has been assumed that all the photons having energy more than E_g are absorbed. But generally cells can not be made very thick because of costly material. For example to have complete optical absorption silicon of about 1000 µm thick is required while for other materials like GaAs, CdSe, CdTe, AlSb complete absorption may take place in a thickness of below 50 µm. Even a silicon of thickness 150 µm will convert only 37.6 percent under AM-1 conditions and 38.6 percent under AM-0 conditions which is about 10 percent less than in case of complete absorption.

6.3.6 Solar cell materials

As discussed earlier there are many semiconductor materials which can be used as solar cells. But some semiconductor will perform better (produce high efficiency) while others perform a little inferior. Apart from many material properties the efficiency of a solar cell is a function of spectral distribution of incident light and the temperature. The silicon is the most commonly used material for solar cell and nearly all the cells used commercially are silicon cells. The electrical properties of the silicon depends on the type and amount of dopants. The dopants which are generally used in silicon are given [3] in table 6.4. The dopant selected should have a suitable energy level, solubility and an acceptable diffusion constant. From these considerations, P and B are the widely used donor and acceptor dopants in silicon. The electron and hole mobility changes with the donor and acceptor concentration (N_e and N_h) as shown in fig 6.18. Here it is seen that upto a donor or acceptor density of 10^{16} cm^{-3}, the mobility is practically constant but after that it decreases fast in case of electron mobility and a little less in case of hole mobility. Moreover, a large concentration of dopants will

Table 6.3 Solar Cell Usable Energy and Spectral Power (mW/cm^2)

λ	Sun		Si		InP		GaAs		CdTe		AlSb		CdSe	
(μm)	AMO	MMI	AMO	AMI	AMO	AMI	AMO	AMI	AMO	AMI	AMO	AMI	AMO	AMI
1.15	31.77	25.04	0	0	0	0	0	0	0	0	0	0	0	0
1.14 1.00	9.51	8.41	6.20	5.43	0	0	0	0	0	0	0	0	0	0
0.99 0.90	8.29	6.02	6.98	5.33	4.97	3.66	0	0	0	0	0	0	0	0
0.89 0.80	9.93	8.35	7.41	5.95	8.71	6.92	8.24	6.84	6.98	4.80	0	0	0	0
0.79 0.70	12.37	8.05	8.29	5.20	9.60	6.09	10.35	6.65	10.63	6.81	7.35	4.38	3.90	2.72
0.69 0.60	15.15	13.25	8.66	7.49	10.18	8.79	10.97	9.47	11.32	9.81	12.75	11.02	13.38	11.58
0.59 0.50	17.70	14.30	8.64	7.20	10.09	8.38	10.88	9.05	11.12	9.38	12.62	10.53	13.25	11.00
0.49 0.40	18.77	15.10	7.53	5.88	8.80	6.87	9.49	7.4	9.82	7.67	11.02	8.61	11.58	9.05
0.39 0.30	10.77	7.91	3.24	2.00	3.78	2.34	4.08	2.52	4.24	2.61	4.75	2.94	4.99	3.07
0.29 0.20	1.63	0.56	0.42	0.13	0.49	0.15	0.53	0.16	0.55	0.17	0.62	0.19	0.65	0.20

Table 6.3 contd...

0.19 0.00	0.01	0.01	--	--	--	--	--	--	--	--	--	--	--	--
Total	135.30	107.0	57.37	44.6	56.6	43.2	54.53	42.0	54.66	41.25	49.1	37.67	47.72	37.62
% of possible	100	100	42.4	41.6	41.8	40.4	40.4	39.2	40.4	38.6	36.3	35.2	35.2	35.1

decrease the minority carrier life-time due to lattice distortion and complexing.

Table 6.4 Dopants which are used in silicon

Dopant	Type	Energy below the conduction Band (ev)	Energy above the Valence Band (ev)
Al	p	-	0.057
As	n	0.049	-
B	p	-	0.045
Ga	p	-	0.065
Li	n	0.033	-
Sb	n	0.039	-
P	n	0.044	-
Bi	n	0.069	-
Ag	n	0.330	-

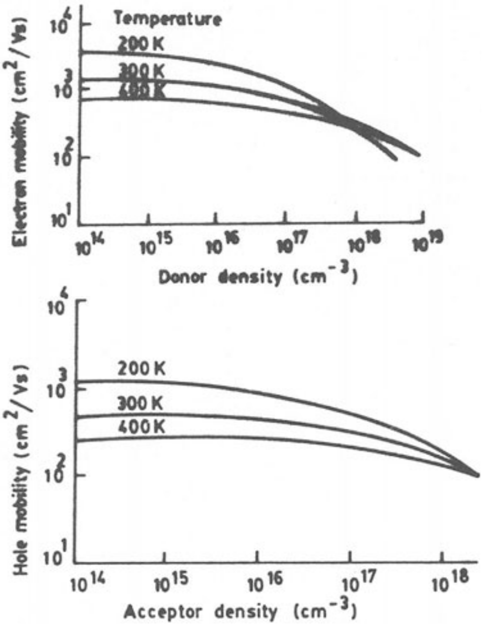


FIG.6.18 MOBILITIES OF ELECTRONS PHOSPHOROUS DOPED SILICON AND HOLES (BORON DOPED SILICON) VERSUS DONOR AND ACCEPTOR RESPECTIVELY

The first order parameter affecting the choice of semiconductors for photovoltaic application is the energy gap, E_g, and the affect of energy gap on the light to electricity conversion efficiency is already shown in fig. 6.11. Table 6.5 shows the energy gap values (E_g in ev) for some of the materials considered as candidate materials for solar cell.

The main hurdle in the terrestrial use of solar cells as discussed earlier is the cost of cells, which can be reduced by analysing the total system including the semiconductor material used,its thickness and fabrication technique. The cost can be reduced using thin film technology and thin films are not used in photoelectrically active layer but also such as antereflective coating, transparent conducting coating, for electrical contacts,window materials, etc. There are several techniques of film deposition such as vacuum evaporation, chemical vapor deposition, reactive and non-reactive sputtering, molecular and electron beam evaporation, epitaxial layer growth from liquid or vapor, spray pyrolysis, electrochemical crystallization. Single crystal solar cells of Si and GaAs have shown efficiencies at near about 20 percent while several others are nearly at about 5 to 10 percent only. A summary of major criteria for the selection of suitable semiconductor material is made by Fahrenbruch and Bube[38] and the same is given in table6.6.

Table 6.5 Energy gap for some candidate material for photovoltaic cells

Material	Energy gap (ev)	Material	Energy gap (ev)
Si	1.11	InP	1.27
SiC	2.60	In_2Te_3	1.20
$CdAs_2$	1.00	In_2O_3	2.80
CdTe	1.44	ZnO	3.30
CdSe	1.74	Zn_3P_2	1.60
CdS	2.42	ZnTe	2.20
$CdSnO_4$	2.90	ZnSe	2.60
GaAs	1.40	AlP	2.43
GaP	2.24	AlSb	1.63
Cu_2S	1.80	SnO_2	3.80
CuO	2.0	As_2Se_3	1.60
Cu_2Se	1.4	Sb_2Se_3	1.20
$CuInSe_2$	1.01	Ge	0.67
$CuInS_2$	1.50	Se	1.60
$CuInTe_2$	0.90		

Table 6.6 Criteria for Choice of system for photovoltaic cells (From Fahrenbruch and Bube [38]

Property	Criteria
Band gap of smaller band-gap material	Band gap near 1.4 eV to material maximize absorption of solar radiation, while minimizing diode current that limits Voc. Direct optical absorption so that carriers are generated close to the junction. Long minority-carrier diffusion length.
Band gap of larger band-gap material	As large as possible while material maintaining low series resistance.
Conductivity type	Smaller band-gap material should usually be p-type because of longer electron diffusion length.
Electron affinities	Materials should be chosen such that no potential spike occurs at the junction for the minority photoexcited carriers.
Diffusion voltage	As large as possible, since the maximum V_{oc} proportional to the diffusion voltage.
Lattice mismatch	As little mismatch in lattice constant between the two materials as possible (this appears to minimize interface state density and recombination losses through such states).
Deposition methods	Suitable deposition methods for thin-film formation and control should be available
Electrical contacts	It should be possible to form low-resistance electri-

	cal contacts to both n-and p-type materials.
Material availability	Supplies of the material should be sufficient to allow large-area cell production.
Material cost	Cost of the material should be competitive with alternative systems.
Material toxicity	Materials should be nontoxic, or control of toxicity should be possible.
Cell stability and lifetime	Cell must have an operating lifetime sufficient to pay back economic and energy costs required to produce it.

6.4 EFFICIENCY LOSSES

A typical p-n junction solar cell showing the physical arrangement of the major components is schematically shown in fig 6.19. Here the p-n junction provides an inherent field separating the charges created due to absorption of solar light. This p-n junction is generally made by putting a p-type base material in a diffusion furnance containing gaseous n-type dopant thereby the n dopants get diffused

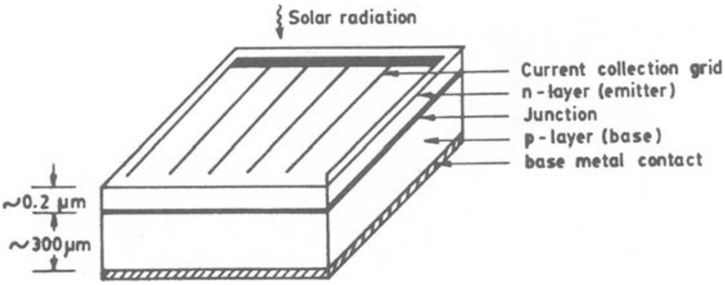


FIG.6.19. TYPICAL p-n JUNCTION SOLAR CELL.

into the surface upto a depth of about 0.2µm. Thus this junction is made near the surface and the electrons and holes created due to absorption of sunlight moves towards the front and back of the cell. The back of the cell is completely covered by a metallic contact and the charges are collected by it. A fine grid of very narrow metallic fingers are put on the front side of the cell which collects the charge from the front side. The area covered by this current collection grid is generally about 5 percent to the total cell area to allow more solar light to fall on the active cell area. Reflection of light from the front surface is reduced by using antireflective coating.

The solar cells do not operate at the theoretical maximum efficiency because of several limitations out of which some are avoidable but others are intrinisic to the cell. Some of the limitations can be independently tackled while the others are interrelated. Some of the parameters have advantages and disadvantages also. The following factors limit the efficiency [25] of a photvoltaic solar energy conversion device:
(1) Reflection losses at the top surface.
(2) Shade due to current collection grid at top surface.
(3) Incomplete absorption of photon energy.
(4) Incomplete use of excess photon energy.
(5) Collection loss.
(6) Voltage factor loss.
(7) Curve factor loss.
(8) Series and shunt resistance loss.

These losses or limitations are discussed below briefly.

6.4.1 Reflection losses

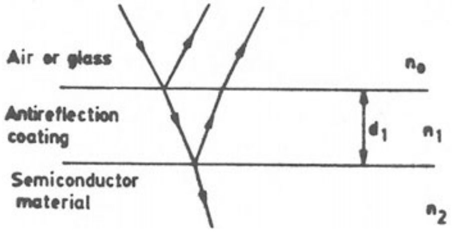


FIG.6.20. EFFECT OF ANTIREFLECTIVE COATING

The reflection losses from a bare, clean semiconductor material surface can be quite high (^{2}20 to 40 percent) which can be reduced by using antireflective coating (quarter wavelength) and by texturing the surface. Consider a three layer system as shown in fig 6.20, a film of semiconductor material of refractive index n_2, an antireflective film of refractive index n_1 of thickness d_1, and finally a sheet of glass or air of refractive index n_0, then the expression for the fraction of radiation reflected, R (reflectance), from the system is given as:

$$R = \frac{r_1^2 + r_2^2 + 2r_1\, r_2 \operatorname{Cos} 2\theta}{1 + r_1^2\, r_2^2 + 2\, r_1\, r_2 \operatorname{Cos} \theta} \qquad (6.46)$$

Where θ is the angle of incidence given as:

$$\theta = \frac{2\pi\ n_1\, d_1}{\lambda} \qquad (6.47)$$

and r_1 and r_2 are given as:

$$r_1 = \frac{n_o - n_1}{n_o + n_1} \quad , \quad r_2 = \frac{n_1 - n_2}{n_1 + n_2} \qquad (6.48)$$

The reflectance R would be minimum if $n_1 d_1 = \lambda_o/4$, where λ_o is the wavelength at which the layer is a quarter wavelength in optical thickness, and the minimum reflectance is given as:

$$R_{min} = \left(\frac{n_1^2 - n_o\, n_2}{n_1^2 + n_o\, n_2}\right)^2 \qquad (6.49)$$

From this expression, it is seen that the reflectance will be zero if the refractive index of the antireflective film (n_1) is the geometric mean of the refractive indexes of the film on either of its side (n_0 and n_2), or when

$$n_1 = (n_o\, n_2)^{1/2} \text{ at } d_1 = \lambda_o/4n_1 \qquad (6.50)$$

Thus there will only be one wavelength at which the above condition will be fulfilled while in practice, the reflectance is to be reduced for a broad band of wavelengths. For silicon where the refractive index in air is approximately 3.9 the antireflective coating for minimum reflectance should have a refractive index of 1.9 and of thickness 0.08 μm. This antireflective coating will provide a broad band reflectance of only about 6 percent which can be reduced to 3 percent by the use of multiple thin layers. Green [37] has made calculations for reflectance from a bare silicon, silicon with antireflective coating in air, and silicon with antireflective coating with glass encapsulation as a function of wavelength, and the results are shown [37] in fig 6.21. The antireflective coating has a refractive index of 1.9 and which gives a minimum reflectance at a wavelength of 0.60 µm. When the antireflective coating is put under glass (n_0 =1.5), the optimum value of refractive index of antireflective coating increases to 2.3. All these effects can be seen from fig. 6.21. Several materials have been tried as antireflective coating on solar cells such as M_gF_2 (n_1 =1.3-1.4), SiO (n_1=1.8-1.9), SiO_2 (n_1=1.4-1.5), Al_2O_3 (n_1=1.8-1.9), TiO_2 (n_1=2.3), ZnS (n_1=2.3-2.4), Ta_2O_5 (n_1=2.1-2.3), Si_3O_4 (n_1=1.9). The reflectance can be further reduced by using multiple layer coating. Studies on antireflective coatings for solar cells are conducted by Wang et al [135], Seibert [136], Kern and Tracy [137], Yeh et al [138], Gandham et al [139], and Berning [140].

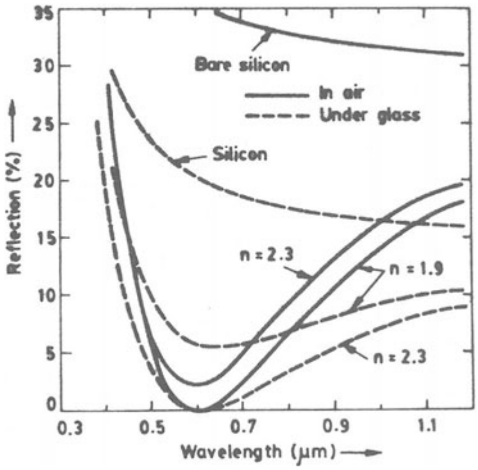


FIG.6.21. SPECTRAL REFLECTANCE FROM A BARE SILICON, SILICON COATED WITH ANTIREFLECTIVE COATING IN AIR AND SILICON COATED WITH ANTIREFLECTIVE COATING WITH GLASS AT THE TOP (From Green[37])

The reflection from the face of the solar cell can also be reduced using textured surface on the face of the cell material using selective etching which gives an appearance of pyramids on the surface and the light reflected from the face of the pyramids is directed towards the cell and therefore the light has atleast two chances of being coupled into the cell. Generally dilute caustic soda (NaOH,4 percent) is used for selective etching on silicon; H_2SO_4 or HCL or NaOH for GaAs; H_2SO_4 or HCL for CdS; HNO_3, H_2SO_4, HCL, for CdTe; KCN for Cu_2S; CH_3OH for InP; and aqua Regia for $CuInSe_2$. There are disadvantages also of using the textured surfaces as pointed out by Coleman et al[141] such as careful handling, overheating of cell due to absorption of unwanted solar light, poor top contact metallization, etc.

6.4.2 Shade due to current collection grid

A metal bar grid is always put at the top of the cell to collect the carriers for the flow of the current.Although a metal grid of suitable design is a must but it adds three problems e.g. it increases the series resistance in the form of grid metal resistance, it gives a surface contact resistance between metal grid and semiconductor, and it reduces the light transmission reaching the semiconductor. Therefore while designing a grid it should be sufficiently thick giving low resistance, should make a good contact with the semiconductor giving good ohmic contact, and also the width of the grid or the area covered by the grid should be very small compared to the front area of the cell giving little shade. The width of the metal fingers and their interspacing depends on the deposition-fabrication technique. Grid line widths upto 20 μm is possible using evaporation through photo-lithographic technique and upto 50 μm using screen printing techniques. Generally the sheet resistance and the transmission factor of the metal grid are considered while designing a suitable metal grid.

6.4.3 Incomplete absorption of photon energy

We see from the solar irradiance curve that there is significant portion of spectrum where the photon energy $h\nu < E_g$ (energy gap) and therefore this portion will not generate electron-hole pairs and will not be absorbed in the semiconductor. In case of silicon where the energy gap E_g is 1.1 ev, the inactive wavelength is $\lambda \geq 1.1$ μm and which constitutes about 23 percent of the AM_1 insolation. If this energy gets absorbed in the semiconductor then it will heat the material and unnecessarily increase the temperature which will result in low efficiency. These photon can either be removed using special kind of filters or the heat generated in a photvoltaic panel can be collected by active means which can be used for other applications.

6.4.4 Excess photon energy loss

The photon energy required for generating a electron-hole pair is equal to the energy gap. There are large number of photons having energies larger than the energy gap and this excess energy of the photons unnecessarily add to the lattice vibrations resulting in heating the semiconductor. Wolf[25] has done good analysis of the energy loss and calculated the number of photons in the solar spectrum which have energy more than the energy gap E_g with different energy gap values like 2.25 ev, 1.45 ev. 1.07 ev, 0.68 ev, and 0.34 ev which are given in fig 6.22. Generally one election-hole pair is absorbed with one photon absorbed. But under high photon flux two-low energy photons can collide with a single electron and can excite it to jump the forbidden gap. This phenomena has actually been observed in GaAs, CdTe, CdSe and CdS under high flux densities. A single energetic photon can excite two or even more electrons to jump the energy gap. For generating two electron-hole pairs the enrgy required by a photon should be about 3

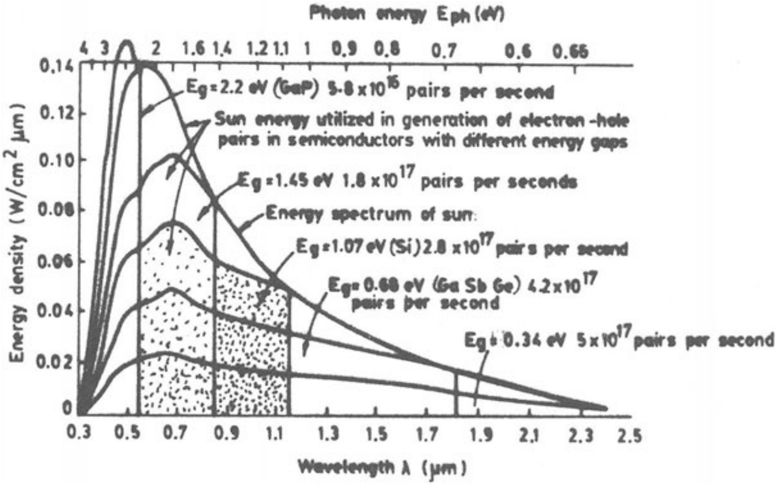
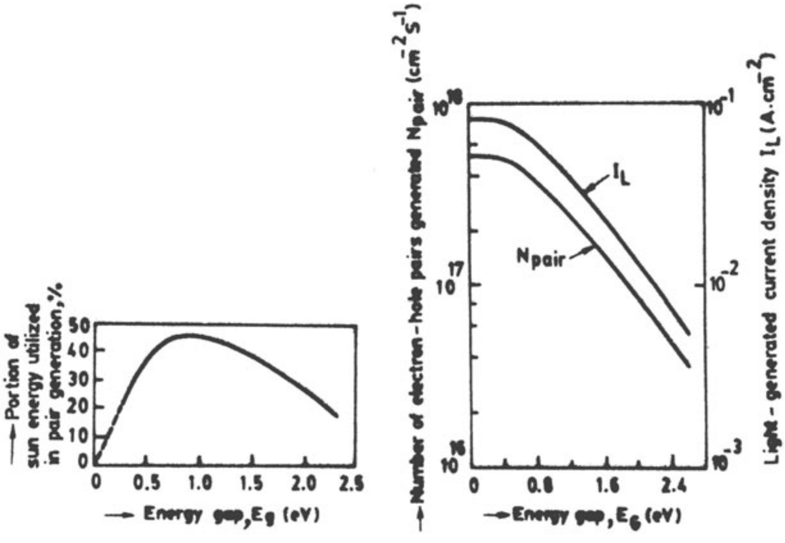


FIG.6.22. THE SOLAR IRRADIANCE CURVE FOR AM-I CONDITIONS AND SHOWING THE PART OF THE SPECTRUM UTILIZABLE OF DIFFERENT ENERGY GAPS AND THE NUMBER OF ELECTRON-HOLE PAIRS GENERATED (From Kreider and Kreith[25])

E_g which is generally not considered in the design of the solar cell. Depending on the energy gap, a portion of the solar spectrum will not be utilized in generating electron-hole pairs and its effect is shown [25] in fig 6.23 (a). From this figure it is seen that maximum energy utilized is only 46 percent and which is at a energy gap of 0.9 ev. The effect of energy gap on the number of electron hole pairs generated and the maximum current generated is shown [25] in fig 6.23 (b). From here also it is seen that both are maximum at 0.9 ev.



(a) (b)

FIG.6.23. EFFECT OF ENERGY ON THE SOLAR SPECTRUM UTILIZATION FOR GENERATING PAIRS, NUMBERS OF PAIRS GENERATED AND CURRENT DENSITY (From Kreider and Kreith[25])

6.4.5 Collection loss

It has been discussed earlier that if the semiconductor material is not of sufficient thickness then most of the light may be transmitted without generating the electron-hole pairs. Moreover in a cell all the electron-hole pairs are not generated within the space-charge region of the p-n junction where the strong electric field affects the separation of the charges. The photons of short wavelength (high absorption coefficient) are absorbed in the diffused region i.e. between the surface and the space charge region while the photons of low absorption coefficient are absorbed in the base region. If the electron-hole pairs are generated within the distance of two or three diffusion lengths[25] from the space charge region, then the minority carriers may reach the space charge region, being pulled across it by the built-in-field, and being, as a majority carrier will not be allowed to recombination. The minority carriers which recombine before reaching the space-charge region will reduce the cell efficiency. The collection process will therefore depends on the location of electron-hole pairs generation, the location of space charge region, the resistivity effecting the mobility and lifetime of minority carriers, and built in electric fields. The collection efficiency is a wavelength dependent function and is generally above 90 percent.

6.4.6 Voltage factor loss

The open circuit voltage, Voc, as defined earlier is the largest voltage obtainable from a solar cell and is given as:

$$V_{oc} = \frac{KT}{q} \ln (I_L/I_o + 1) \qquad (6.51)$$

Here I_L is the light generated current (photocurrent), and I_o is the saturation current which for a p-n junction is given as:

$$I_o = A \left(\frac{qD_h n_i^2}{L_h N_D} + \frac{qD_e n_i^2}{L_e N_A} \right) \qquad (6.52)$$

Here it has been assumed that the light generated current I_L is much greater than the diode saturation current I_o so that the diffusion current dominates the current-voltage equation in all types of cells. Once the open circuit voltage becomes equal to the internal barrier voltage, the internal barrier to current flow will be no more and the saturation current increases. The internal barrier voltages V_B for different cells are given below:

For a p-n junction

$$V_B = \frac{1}{\lambda} \ln (N_A N_D/n_i^2) \qquad (6.53)$$

Where λ is the wavelength of the photons.

For a heterojunction solar cell, the internal barriers voltage V_B is given as

$$V_B = \Delta E_g - (X_2 - X_1) \qquad (6.54)$$

Where ΔE_g is the difference in band gaps between the two semiconductors used in a heterojunction, and X_2 and X_1 are the electron affinities of the two semiconductors.

And for a schottky barrier or MOS cell it is given as

$$qV_{Bi} \leq q\,\Phi_B - \frac{q}{\lambda}\,\mathrm{In}\,(N_{eff}/N) < (X_2 - X_1) \qquad (6.55)$$

Where Φ_B is the effective metal-semi conductor barrier height, and N_{eff} is the effective density of states in the semiconductor either in the conduction band or valence band. In all these cases the upper limit for a internal potential barrier is the energy gap of the semiconductor. From equation (6.52), the minimum value of saturation current density I_o is given as:

$$I_o = 1.5 \times 10^5 \exp (- E_g/KT) \ A/cm^2 \qquad (6.56)$$

From this it is clear that if the energy gap E_g decreases the maximum value of open circuit voltage V_{oc} decreases while the trend is opposite to short circuit current I_{sc} implying that there is an optimum energy gap semiconductor for maximum efficiency. However in practice the open circuit voltage V_{oc} is always less (about 1/2 to 3/4 of E_g) than the energy gap E_g because of the following two reasons:

(i) The barrier height is equal to the maximum forward voltage and is determined by the difference in Fermi levels in the p and n type material on either side of the p-n junction. The fermi levels are located in the energy gap and are the functions of impurity concentration and temperature of semiconductor.

(ii) The highest voltage i.e. equal to the barrier height is obtainable only at very high injection levels which is not possible with the photon absorption from direct sun light.

6.4.7 Curve factor loss

As discussed earlier, the maximum power is obtained at the point where the largest rectangle can be inscribed into the current-voltage characteristic curve (fig.6.7) and these points are given by V_m and I_m on the curve. The ratio of V_mI_m to $V_{oc}I_{sc}$ is called the fill factor which depends on

$V_m I_m$ to V_{oc} I_{sc} is called the fill factor which depends on the open circuit voltage, series and shunt resistances, and slightly on recombination of carriers in the space-charge region. The fill factor which measures the squareness of the I - V curve is given as:

$$FF = V_m \left[\frac{1 - (I_o/I_{sc})\ (\exp(qV_m/nKT) - 1)}{(nKT/q)\ \ \text{In}\ (\ (I_{sc}/I_o)\ +\ 1\ )} \right] \qquad (6.57)$$

$$= \frac{V_m}{V_{oc}} \left[1 - \frac{\exp(qV_m/nKT) - 1}{\exp(\ V_{oc}/nKT) - 1} \right] \qquad (6.58)$$

In deriving the above equations of FF it has been assumed that there is no series or shunt resistance effects. Thus the fill factor can be broken into two parts:

$$FF = (CF)(AF) \qquad (6.59)$$

Where CF is the curve factor and can be determined from the equation of diffusion current and is the characteristics of the potential barrier, and AF is the artifacts factor which accounts for the softening of the I-V characteristic happening due to series and shunt resistance and non ideal barrier characteristics. Both the curve factor and the voltage factor is a function of energy gap and both increases with the energy gap.

6.4.8 Series and shunt resistance loss

The current generated in the cell is to pass through the bulk material before it reaches to the contact (ohmic) grid. On the rear side of the cell the whole area can be covered with a collection grid reducing the series resistance to be almost zero. Since the front area is to receive the sun light also, so the area of cell should be covered by the grid to the least possible value. This will cause considerable long current path lengths introducing large series resistance. Therefore the series resistance will constitute the bulk resistance of the semiconductor material of the cell, bulk resistance of the metallic grid, and the contact resistance. With the improved thin film technology, it is possible to reduce the series resistance to a very low value. The series resistance, R_s, of about 0.1 ohm with a cell of about 20 ohm at peak power can be produced with modern techniques.

The shunt resistance R_{sh} in a cell is caused due to crystal defects, foreign impurities, and the leakage across the p-n junction around the edge of the cell. Both the series and shunt resistances reduce the fill factor and their affects are shown in fig.6.9 and 6.10 respectively. Approximate expression of changed fill factor due to series resistance and shunt resistance are derved by Green[37] and the same are given below:

The effect of series resistance on the fill factor FF is given as:

$$FF = FF_o \ (1 - r_s) \tag{6.60}$$

Where FF_o is the ideal fill factor in the absence ofseries resistance, and r_s is the normalised resistance given as:

$$r_s = R_s/R_{CH} \tag{6.61}$$

Where R_{CH} is the characteristic resistance given as:

$$R_{CH} = V_{oc}/I_{sc} \tag{6.62}$$

Similarly the affect of shunt resistance on the fill factor FF is given as:

$$FF = FF_o \left[1 - \frac{(\nu_{oc} + 0.7)}{\nu_{oc}} \left(\frac{FF_o}{r_{sh}} \right) \right] \tag{6.63}$$

Where FF_o is the ideal fill factor in the absence of shunt resistance R_{sh}, and r_{sh} is the normalised shunt resistance given as:

$$r_{sh} = R_{sh}/R_{CH} \tag{6.64}$$

and ν_{oc} is the normalised voltage given as:

$$\nu_{oc} = V_{oc}/\ (nKT/q) \tag{6.65}$$

Generally shunt resistance in cells is very small and therefore its affect is negligible.

6.5 EFFICIENCY OF SOLAR CELL

The efficiency of a solar cell in converting light in a given spectral range into useful power is defined[27] as:

$$\eta = \frac{V_m I_m}{P_{in}} \tag{6.66}$$

where V_m and I_m are the voltage and current at the highest power point as shown in fig. 6.7 and P_{in} is the power input given as:

$$P_{in} = A_t \int_0^{\propto} (hc/\lambda) \; f\,(\lambda)\, d\lambda \qquad (6.67)$$

where A_t is the total area of the cell, F (λ) is the number of photons per Sq.cm per sec per unit bandwidthincidenton the surface of the cell at wavelength λ and (hc/λ) is the energy of photon. The spectrum F (λ) for AMO, AMI and AMI.5 is shown in fig. 6.4. Now the equation of power output is given as:

$$P_{out} = V_m I_m = (FF)\,(V_{oc})\,(I_{sc}) \qquad (6.68)$$

Now, if the series and shunt resistances are neglected, the expression for the cell efficiency will become as:

$$\eta = \frac{FF(A_oKT/q)\ \mathrm{In}\ ((I_{sc}/I_{oo}) + 1)\ qA_a \int_0^{\propto} F(\lambda)\ SR(\lambda)_{ext}\ d\lambda}{A_t \int_0^{\propto} (hc/\lambda)\ F\ (\lambda)\ d\lambda} \qquad (6.69)$$

Where A_o is the junction perfection factor, I_{oo} is the dark current preexponential term in single exponential approximation, A_a is active area, and $SR(\lambda)_{ext}$ is the external spectral response which is just the internal spectral response modified by reflection of light from the surface of the device. The efficiency expression can also be written in terms of average number of carriers collected and the average number of photons in the spectrum:

$$\eta = Q\ (I_m/I_{sc})\ (V_m\ qn_{ph}\ (E_g)/N_{ph}E_{av})\ (A_a/A_t)\ (1-R) \qquad (6.70)$$

Where N_{ph} is the total number of photons in the source spectrum per Sq.cm per sec, E_{av} is the average energy of photons, $n_{ph}(E_g)$ is the number of photons having energy greater than E_g per Sq.cm per sec, Q is the average collection efficiency given as the ratio of number of carriers collected to N_{ph} (E_g), R is the average reflectivity, and A_t is the total device area. Thus the solar cell efficiency is a function of V_{oc}, FF, and I_{sc}.

It is therefore seen that in a solar cell lot of power gets loss due to various reasons as discussed above. Table 6.7 shows the various losses in case of actual silicon and $CdS-Cu_2S$ solar cells. These energy loss calculations in solar cells are made by Rothwarf and Boer[142] and Wolf [143]. It has been shown earlier that the band gap of a semiconductor should match the solar spectrum and optimum band gap is in the range of 1.1 to 1.4 ev for getting high efficiency from the cell with high open circuit voltage and high photocurrent. Moreover, the absorbance of the cell should be such that it should be able to absorb all the photons in the solar spectrum, which is possible only if we use a series of solar cells with varying band gaps and arranged in a multilayer or tandem structure. This can also be achieved by using filters splitting the solar spectrum into different spectral regions and directing the spectral beam of desired spectral range towards individual cells which have spectral response and bandgap suitable to that spectral range. These concepts have been utilized and tandem solar cells approaching an efficiency of about 28 percent have already been achieved. Theoretically if 36 semiconductors with appropriate band gaps are arranged in cascade, then it is possible to obtain an efficiency of as high as 72 percent[144].

Table 6.7 Loss of efficiency of two types of cells.

	Energy loss due to the factor	Percent of light not converted into Electricity	
		Silicon cell	CdS- Cu_2S cell
1.	No photons absorption ($h\nu < E_g$)	23	28
2.	Excess photon energy ($h\nu > E_g$)	33	24
3.	Surface reflection	0.5	1.5
4.	Voltage factor	17.6	26
5.	Fill factor	4.8	5
6.	Series resistance	0.5	1
7.	Curve factor	2	3
8.	Collection efficiency factor	4.6	5
	Total	86.0	93.5

The simplest way of measuring the solar cell efficiency is the outdoor measurement which involves the measurement of solar irradiance using standard pyranometer and the electrical power of the cell being generated at the maximum power point. The main problem in this procedure is the variance in the spectral behaviour of the sunlight which depends on air mass and on many variables in the atmosphere like water vapor, aerosols, ozone, and other gases. Therefore this method is considered to be inaccurate for comparing the solar cells performances.

Therefore, three methods are approved[145] by NASA-Lewis in collaboration with Department of Energy (DOE) for the testing of solar cells which are known as 'reference cell' methods. In this reference cell method, the reference cells are calibrated by central test authority under standard illumination conditions which in this case is defined as AM-1.5 spectral distribution curve. The performance of the cell under test is then compared with the reference cell. This reference or standard cell should be made from the same materials as the test cell using the similar processing technique and should have the similar spectral response. The reference cell is calibrated in units of short circuit current output per unit of radiant energy input i.e. A/mwcm^2. The NASA/DOE standard test conditions are: an irradiance of 100 mw/cm^2, cell temperature of 28 ± 2°C. All measuring instruments like potentiometric recorder, digital voltmeter should have an accuracy of ± 0.5 percent over the range of 0-100 mv. The short circuit current should be measured with a precision load resistor with no more than 20 mv drop across the resistor and the open circuit voltage with a voltmeter having internal resistance of atleast 10^4 ohm/v. In making the calculations, the entire cell area including the grids and contacts is to be taken.

Both the outdoor and indoor tests are recommended in the NASA/DOE procedure. In the outdoor tests, it should be ensured that during the testing the solar intensity should remain constant within ± 0.5 percent and should be more than 80 mw/cm^2. In this procedure, both the reference cell and test cell are put in the same plane and held perpendicular to the solar radiation such that both are uniformly illuminated. The current-voltage characteristics of both the cells are simultaneously recorded. Since in outdoor tests the solar intensity and cell temperatures are not the same as specified in the test procedure, a correction factor can be applied and the whole data is transformed to standard conditions and then the cell efficiencies can be compared.

In an indoor test, a light source with spectral characteristics similar to that of AM-1.5 conditions is used. For this purpose three lamps are recommended (i) an ELH lamp (ii) Xenon lamp with appropriate filters, and (iii) a long arc pulsed xenon lamp. In an indoor test both the cells, the reference and test cells are maintained at a temperature of 28 ± 2°C and the collimated light from any of the above standard light source is allowed to fall on the test plane. The light should be stable and nearly at 100 mw/cm^2 during the test period. A four point contacting technique in which voltage and current leads to the cell are kept seperate can be used which avoids the affects due to series resistance of leads and associated contact resistances.

The measurement of spectral response of solar cell is also essential since its spectral response may help in further performance improvement strategy. The spectral response of the test cell can be measured by knowing its current-voltage characteristics under monochromatic light. In the test setup, a steady state source of monochromatic light from a monochromator or white light after passing through a narrow band optical filter is allowed to illuminate the cell uniformly and the cell output is amplified and phase-sensitivity detected by a lock-in amplifier. The reference cell is used which provides the reference signal to the lock-in amplifier.

6.6 BASIC MODELLING OF SOLAR CELLS (From Ref.3,27,28).

We have discussed earlier that the photons of energy more than energy gap impinging on the semiconductor will produce electron-hole pairs which if not encouraged to drift apart will eventually recombine in a time dictated by the lifetime of the material. These electron-hole pairs if seperated by applying electric field will produce space charge resulting voltage across semiconductor called photovoltage. The photocurrent will flow if these seperated charged carriers are allowed to flow in an external circuit. The three methods for generating internal electric field to seperate the election-hole pairs are: (i) doping impurities in a semi-conductor (homojunction or p-n junction), (ii) using semiconductors of different energy gaps (heterojunction), and (iii) using a semiconductor and a metal base (Schottky junction). There are other techniques also for generating the internal electric fields such as: (i) introducing strains or any other local impurity variations, (ii) the photomagneto electric effect the, so called Hall effect, (iii) anomalous photovoltaic effect, and (iv) Dember effect which is due to differential diffusivities of the charge carriers. We shall here discuss the electrical characteristics of only the p-n junction, the heterojunction, and the Schottky junction which are commonly used.

6.6.1 The p-n junction

The characteristic and the energy band diagram of a p-n junction has already been shown in fig. 6.6. As discussed earlier the p-n junction is made by the diffusion of a dopant (an n-type) into a base material containing another kind of dopant(a p-type). A p-n junction is formed at the interface where the dominant dopant changes to the opposite type and in this region a space charge is created that maintains the net electron and hole currents at zero. This region is called the depletion region which remains indefinitely and accelerates all charge carriers to one side or the other and is typically 10^{-6} to 10^{-4} cm wide. The junction is located at a place at which the Fermi energy level is halfway between the valence and the conduction band. The expression for short circuit current delivered to the load, I_L is given as:

$$I_L = q n_{ph}(E_g)\ (1-R)\ [1-\exp\ (-\alpha l)\ ]\ Q \qquad (6.71)$$

Where $n_{ph}(E_g)$ = number of photons incident who have energy more than the energy gap E_g (no/cm^{2}s),

R = average reflection coefficient.

α = absorption coefficient(cm^{-1})

l = thickness of cell (cm),

Q = average collection efficiency.

Since most of the parameters in equation (6.71) are the function of wavelength of photons, hence it can be written as

$$I_L = q\int_0^{\infty} n_{ph}(E_g)\ (\lambda)\ [1-R(\lambda)]\ [1-\exp(\ -\alpha(\lambda)l)]\ Q\ (\lambda)d\lambda \qquad (6.72)$$

The wavelength dependent efficiency $Q(\lambda)$ can be written as $SR(\lambda)$ and is called the spectral response of the cell. Now the expression of the total current I_L will be the sum of the current in the three regions i.e. p-region, n-region, and the depletion region i.e.

$$I_L = I_h + I_e + I_{DR} \qquad (6.73)$$

Now the continuity equation in the n-region is written as:

Rate of change of excess holes = rate of diffusion per unit volume + rate of gain due to electric field + rate of generation of hole-rate of recombination

$$\frac{\partial(h-h_o)}{\partial t} = D_h\ \nabla^2\ (h-h_o) + [\ \mu_h E\ \nabla(h-h_o)] + G(x) - \frac{(h-h_o)}{\tau_h} \qquad (6.74)$$

Where D_h = diffusion coefficient of holes in n-region(cm^2/s)

μ_h =mobility of holes in n-region ($cm^2/v.s$),

E = electric field (v/cm)

G(x) = rate of generation of holes due to photon absorption ($holes/cm^3.s$)

τ_h= lifetime of holes (s)

Now if p_o is constant then equation (6.74)canbe written as

$$\frac{\partial h}{\partial t} = D_h \nabla^2 h - \mu_h E \nabla h + G - \frac{(h-h_o)}{\tau_h} \qquad (6.75)$$

Where G as a function of λ and can be written as:

$$G(\lambda) = n_{ph}(\lambda)\,[1-R(\lambda)]\exp[-\alpha(\lambda)x]\ \alpha(\lambda) \qquad (6.76)$$

under steady stated conditions with uni-direction casewith no electric field in n-region

$$D_h \frac{\partial^2 h}{\partial^2 x^2} + \alpha(\lambda)\, n_{ph}(\lambda)\,[1-R(\lambda)]\exp[-\alpha(\lambda)\,x] - \frac{h-h_o}{\tau_h} = 0 \qquad (6.77)$$

Now we know that the hole diffusion length is $L_h=(D_h\,\tau_h)^{1/2}$, then the solution of above equation for a particular wavelength will be:

$$(h-h_o) = A\cosh\left(\frac{x}{L_p}\right) + B\ \mathrm{Sinh}\left(\frac{x}{L_p}\right) - \frac{\alpha\, n_{ph}(1-R)\tau_h}{\alpha^2 L_h{}^2 - 1}\,[\exp(-\alpha x)] \qquad (6.78)$$

Where the boundary conditions are that at the surfaces on both the sides of cell complete recombination takes place i.e.

at x = 0

$$S_h\,(h-h_o) = D_h \frac{dh}{dx} I_h \Big|_{x=0} \qquad (6.79)$$

and at X = H (Back of cell)

$$S_e\,(e-e_o) = D_e \frac{dn}{dx} \qquad (6.80)$$

Also in the depletion region, the excess carrier density reduces to zero i.e. at $X = X_j$, $(h-h_o) = 0$, and at $X = X_j + W$, $e-e_o = 0$. Now by applying the above boundary conditions the expression for current due to holes in the n-region becomes as:

$$I_h = \left[\frac{q n_{ph}\ (1-R)\ \ \alpha L_h}{(\alpha^2\ L_h{}^2\ -1)}\right]$$

$$\left[\frac{\left(\frac{S_h L_h}{Dh} + L_h\right) - \exp\left(-\ \alpha x_j\right)}{\frac{S_h\ L_h}{D_h}\ \mathrm{Sinh}\ \frac{X_j}{L_h} + \mathrm{Cosh}\ \frac{X_j}{L_h}}\right.$$

$$\left.\left(\frac{S_h L_h}{D_h}\ \mathrm{Cosh}\ \frac{X_j}{L_h} + \mathrm{Sin}\ \frac{X_j}{L_h}\right) - \alpha L_h\ \exp(-\ \alpha x_j)\ \right] \qquad (6.81)$$

With similar arguments, the expression for current due to electrons in the p-region can be written as:

$$I_e = \left[\frac{q n_{pe}(1-R)\ \ \alpha L_e}{(\ \alpha^2\ L_e{}^2\ -\ 1)}\ \exp\ (\ -\ \ \alpha(x_j\ +\ w))\right]$$

$$\left[\frac{\alpha L_e\ -\ \frac{S_e L_e}{D_e}\ \left(\mathrm{Cosh}\frac{H'}{L_e}\ -\ \exp(-\alpha h')\right)\mathrm{Sinh}\frac{H'}{L_e} + \alpha L_e\ \exp\ (-\alpha H')}{\frac{S_e L_e}{D_e}\ \mathrm{Sinh}\ \frac{H'}{L_e} + \mathrm{Cosh}\frac{H'}{L_e}}\right] \qquad (6.82)$$

The current in the depletion region of width W can be determined on the assumption that all the carriers in width W are collected and the lifetime is long compared to the time the carriers are removed by the field. Then one get

$$I_{DR} = q n_p\ (1-R)\ \exp\ (\ -\ \alpha x_j)\ [\ 1-\exp(-\ \alpha\ w)] \qquad (6.83)$$

The spectral response therefore now can be calculated as

$$SR(\lambda) = \frac{I_L(\lambda)}{qn_p(\lambda)\,[\,1 - R(\lambda)\,]}$$

$$= \frac{I_h(\lambda) + I_{DR}(\lambda) + I_e(\lambda)}{qn_p(\lambda)\,[\,1 - R(\lambda)\,]} \qquad (6.84)$$

6.6.2 The Heterojunction

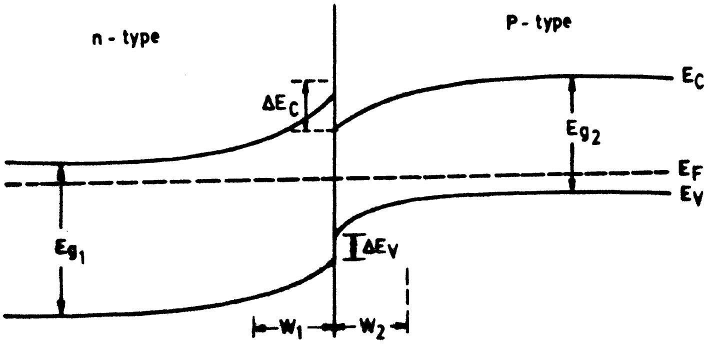


FIG.6.24. ENERGY BEND DIAGRAM OF A n-p HETEROJUNCTION CONSISTING OF TWO SEMICONDUCTORS OF ENERGY GAPS E_{g1}&E_{g2}

A simple energy band diagram of a heterojunction is shown in fig. 6.24. In this process a technique of gaseous or liquid epitaxy is employed where materials of desired dopants are grown into a base crystal by deposition from a gas or liquid. As is seen from fig. 6.24 there are two barrier heights for the two types of carriers. It is also seen that there are two notches, one in the conduction band and one in the valence band and their heights are given as:

$$\Delta E_c = x_2 - x_1 \qquad (6.85)$$

and $$\Delta E_v = E_{g1} - E_{g2} - \Delta E_c \qquad (6.86)$$

where x_2 and x_1 are the electron effinities of the two semiconductors. Like in a p-n junction cell, here in the heterojunction cell also there are three main current mechanisms : (i) diffusion current which is due to injection of minority carriers from each side of the junction which is similar to p-n junction, (ii) current within the space charge region due to generation-recombination, and (iii) current due to tunneling.

The expression for diffusion current for n-p heterojunction is given as;

$$I = I_{OH} \left[\exp \left(\frac{qV_D}{KT} - 1 \right) \right] \qquad (6.87)$$

Where V_D is the voltage across the junction when the current becomes large and is given as:

$$V_D = V - 1\, r_D \qquad (6.88)$$

Here V is the voltage as in a p-n junction, r_D is the sum of the lead and internal diode series resistances, and I is the current. The saturation current I_{oh} is given as

$$I_{oh} = \frac{qD_e n_i^2}{L_e N_a} \quad X_T \qquad (6.89)$$

The factor X_T represents the carriers transmission from one material to another.

Generally under the operating conditions, the generation-recombination current is small compared to the diffusion current and is given as:

$$I_G = I'_G \ \mathrm{Sinh} \frac{qV}{2KT} \qquad (6.90)$$

Where I'_G depends on temperature, doping levels, and the characteristics of the traps in the semiconductor. For a single deep level recombination centre, I'_G can be written as:

$$I'_G = \frac{qn_i}{\tau} \quad \frac{KT}{qE_{max}}$$

$$= \cdot \frac{qn_i}{\tau} \quad \frac{KT}{q} \quad \frac{X_c}{V_B} \qquad (6.91)$$

Where E_{max} is the maximum depletion layer field strength, τ is the lifetime of minority carrier, and V_B is the built in potential given as:

$$V_B = \frac{KT}{q} \ln (n_e n_h / n_i^2) \qquad (6.92)$$

The current due to tunneling is quite large, and it is given as:

$$I_T = K_1 N_T [\ \exp (2h/3\pi) (m^*e/N)^{1/2}\ V_D] \qquad (6.93)$$

Where N is the impurity density; m* is effective mass; K_1 is constant depending on dielectric constant, effective mass, and built in potential; and N_t is constant depending on density of available states near the metallurgical junction.

6.6.3 Metal semiconductor junctions (Schottky junction)

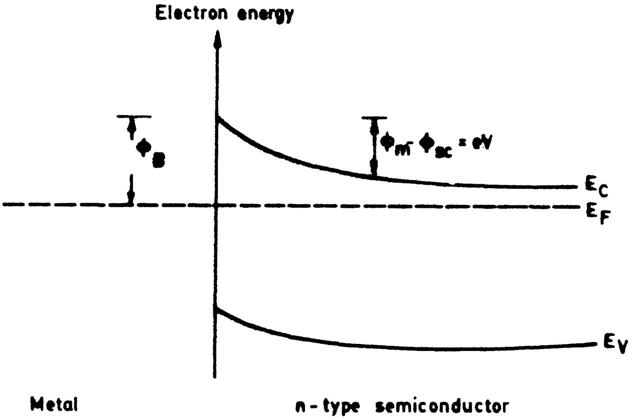


FIG.6.25.ENERGY BEND DIAGRAM OF A METAL-SEMICONDUCTOR HETEROJUNCTION (Schottky junction)

If a metal is brought in contact with a semiconductor, a potential drop takes place in the contact region to account for work function differences. Since there is a large difference in charge carriers in the metal and semiconductor, a potential drop on the semiconductor side of the junction is developed giving a depletion region at the interface similar to that in a p-n junction. Such junctions in a metal and semiconductor are known as Schottky junctions. A band diagram for the Schottky junction is shown in fig. 6.25. In this figure Φ_B is the barrier voltage and depends on the surface states at the interface. Due to the difference in the vacuum work functions in metal (Φ_m) and semiconductor (Φ_{sc}), the energy band in the semiconductor bends. The position of minority carriers in the semiconductor is the same as in the p-n junction, and for a n-type semiconductor the current due to minority carriers is given as:

$$I_{oh} = \frac{qD_h n_i^2}{L_h N_D} \left[\exp (qV/KT) - 1 \right] \qquad (6.94)$$

The height of the depletion-region potential barrier at the interface varies with the applied voltage. The emission of elections from the semiconductor in case of metal-on-n type barrier or emission of holes from the semiconductor in case of metal-on-p-type barriers is a function of thermionic emission and diffusion. The expression for current (thermionic emission) for metal on n-type semiconductor is given as:

$$I_{oe} = A^* T^2 \exp \left[- q \Phi_B/KT \right] \left[\exp(qV/KT) - 1 \right] \qquad (6.95)$$

Where A* is the effective Richardson constant and is given as

$$A^* = 120 \frac{m^*}{m} \qquad (6.96)$$

Where m is the free electron mass. As is seen from equation (6.95) the majority carrier current mainly depends on the height of the barrier Φ_B at the interface and is much larger than the minority carrier component of current[146]. Therefore the metal work function is selected such that it gives a large barrier height at the metal-semiconductor interface. But many semiconductors induce a barrier height which is independent of work function of metal. This can happen due to variety of reasons such as lattice mismatch or contamitants on the surface of semiconductor.

6.7 SILICON SOLAR CELLS

Silicon material is widely studied and its properties are widely known and silicon solar cells are perhaps the simplest and most widely used both for space and terristrial applications. As discussed earlier, silicon cell was first invented in 1953 at the Bell Laboratories. The first practical and technical success of silicon solar cell was the demonstration of a 9 W array powering a telephone repeater installed in Americus, Georgia, USA in 1955. The name 'silicon' comes from the latin silex, meaning flint and it is second most abundant element in the earth's crust, constituting about 20 percent of the earth's crust, occuring mainly in silicate rocks and also in the form of oxide SiO_2 based minerals in many attractive forms such as opal, flint, agate, jasper, quartzite, etc. The silicon was used in electronic industry in 1906 in point contact rectifiers and its use became significant in 1930s when it was used in microwave detectors. During world war II, silicon purification techniques were developed and in 1950, the first silicon diode was described. Teal and Buehler[147] were the first who in 1952 grown a single crystal of silicon using Czochralski method. For making a solar cell, high purity polycrystalline ingots with impurities less than 1 atom in 10^9 i.e. less than 10^{18} atoms per m^3 is required. The transformation of raw sand to very high purity silicon involves many steps as described below.

6.7.1. Purification of silicon

In the first step, the silicon dioxide(SiO_2) is reduced to silica(Si) with carbon(c) in a large arc furnace as shown in fig. 6.26.

$$SiO_2 + 2C \longrightarrow Si + 2CO$$

The silicon is further purified in the furnace by periodically pouring it and blown with oxygen or oxygen/chlorine mixture and finally it is solidified. The silicon so produced is about 98-99 percent pure with impurities like iron and aluminium and more than 1 million tons of silicon is produced every year which is largely used in steel and aluminium industries. This metallurgical grade silicon is to be further purified for its use is electronics industry in the semiconductor form.

There are many methods for purifying the metallurgical grade silicon to semiconductor form but the most preferred one is the Siemens process[148] in which the metallurgical grade silicon is converted into a volatile compound which is condensed and then refined by fractional distillation. In this process the metallurgical grade silicon is reacted in

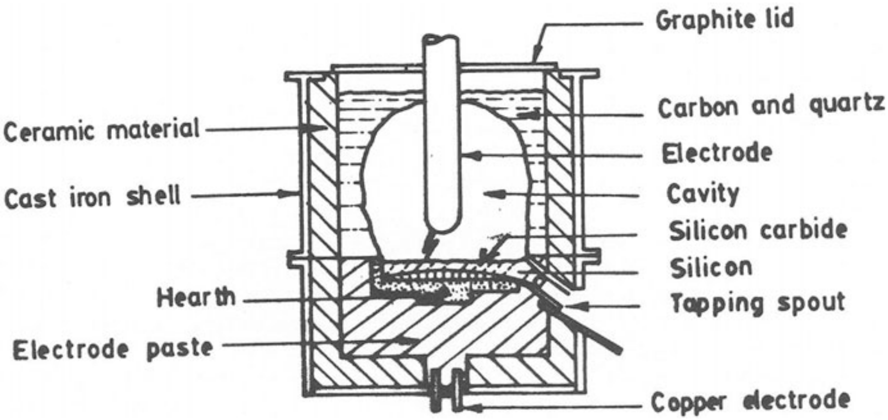


FIG.6.26.CROSS-SECTION OF AN ARC FURNACE USED TO PRODUCE METALLURGICAL GRADE SILICON

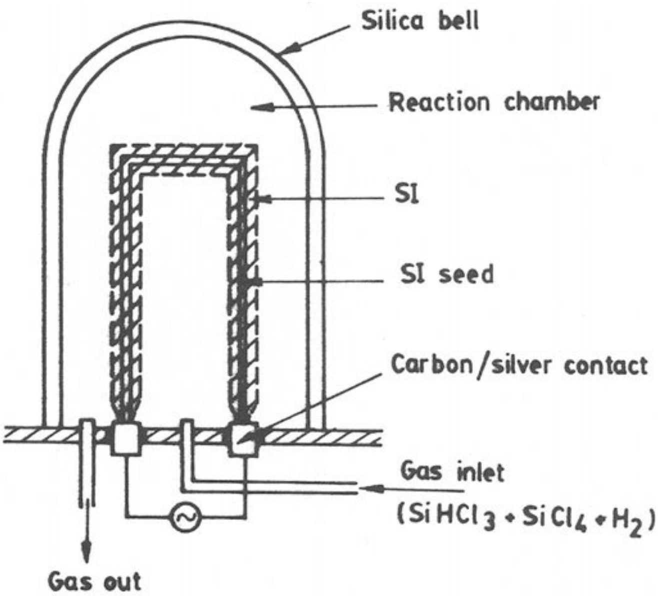


FIG.6.27. SIEMENS PROCESS OF CONVERTING METALLURGICAL GRADE SILICON TO SEMICONDUCTOR GRADE SILICON

the fluidized bed[149] reactor with dry HCl gas in the presence of Cu as catalyst (5 percent copper) at about 240°C and a mixture of trichlorosilicane ($SiHCl_3$) of 80 to 90 percent is obtained.

$$Si + 3\ HCl \longrightarrow SiHCl_3 + H_2$$

The gases are condensed and the resulting liquid is distilled and reduced by hydrogen, in which case the silicon in the fine polycrystalline form gets deposited on an r-f induction heated silicon rod at about 1100°C in the reacto as shown in fig. 6.27.

$$SiHCl_3 + H_2 \longrightarrow Si + 3\ HCl$$

This process is a high temperature, slow and batch process and the final product becomes expensive due to the use of very large amount of heat used. This polysilicon or

polycrystalline silicon which is pure (known as semiconductor grade polycrystalline silicon) is finally to be converted into the single crystal form for its use in solar cell.

6.7.2 Methods of growing crystal

There are several methods of growing single crystals of silicon involving growth from liquid, gas, or solution such as: Czochralski(CZ) technique, Heat exchanger method (HEM), shaped ribbon technology (EFG), the dentritic web method (WEB), silicon on ceramic (SOC) method, SEMIX method, etc. These methods will be described here briefly.

6.7.2.1 The Czochralski(CZ) Process

One of the most advanced, standard and used method for growing silicon crystal is the Czochralski(CZ) method in which a small amount of semiconductor grade polycrystalline silicon is put in a quartz crucible, which is put into a vacuum furnace and heating the same till the silicon melts, now adding traces of dopant which is boron in case of silicon cells to make the crystal p-type, and now putting a small single crystal 'seed' of solid silicon into the surface of the molten silicon, and now slowly rotating both the crucible and the seed in opposite directions while slowly pulling the seed in the upward direction. Generally the crystal is pulled at a rate of 10^{-4} to 10^{-2} cm/s and rotated at 10 to 40 rpm. In this way a single crystal of silicon in the form of rod generally 15 cm in diameter and 75 cm in length is grown. The CZ process is schematically shown in fig. 6.28. This large circular cylinder is removed from the furnace and later cut carefully using diamond saw to avoid wastages into thin wafers of about 0.2 to 0.5 mm thick. Generally the thickness of the saw blades used for slicing the crystal into thin wafers is of the same thickness to that of wafers and therefore 40 to 50 percent of the material gets wasted in this process[150]. Moreover, the damage caused to the surface of the wafers due to slicing is to be removed by acid etching. Sometimes the sides of these circular wafers are trimmed to get either a square or hexagonal shaped cell to have better packing density in a solar cell module. This high material loss for converting semiconductor grade silicon into single crystal silicon and then slicing it into wafers is very serious and serious work is in progress in this direction.

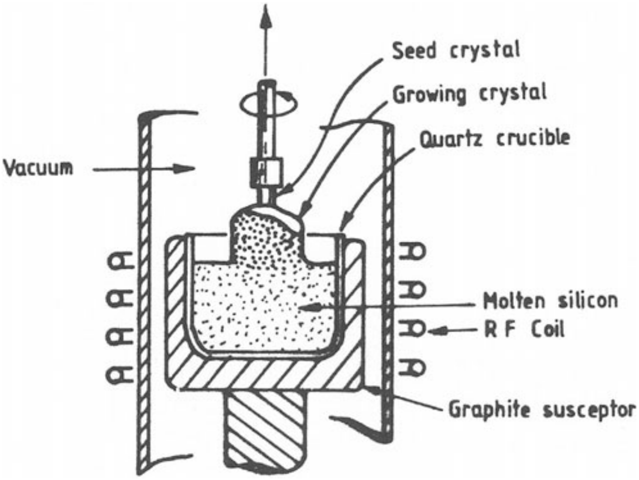


FIG.6.28.SCHEMATIC OF CZOCHRALSKI APPARATUS FOR GROWING SINGLE SILICON

6.7.2.2 Heat exchanger method (HEM)

The heat exchanger method (HEM) generally called as directional solidification casting method for producing low cost silicon is comparatively a newcomer and the process is still being perfected[151]. In this process the semiconductor grade polycrystalline silicon is placed on a square quartz fixed crucible placed in a constant temperature hot zone, the directional flow of heat from the hot ingot to the exterior being assumed by a gas cooled heat exchanger baseplate on which the crucible in placed. A single silicon crystal seed is used for crystal growth contained on the bottom of the crucible. The melting of the seed is avoided by a suitable control of heat transfer. A graded silica crucible is used to prevent heterogeneous nucleation at crucible walls. By this process square ingot of silicon with side 30 to 35 cm can be produced which is a single crystal except for around the edges. Finally the square wafers are cut from the square rod using standard methods. By slicing after the growth, the main advantage of large volume production rate gets lost through slicing. Generally the quartz crucible used in this method gets crack. Ciszek et al[152] at IBM have developed carbon crucibles which do not crack and used two techniques for directional solidification of silicon. In one technique, a carbon crucible of 5 cm diameter and 5 cm high containing liquid silicon was put in a temperature gradient of about 35°C/cm with maximum temperature at the crucible top and the solidification was achieved by reducing the system temperature at a rate of 4 to 5°C/min. In the second method a carbon crucible of 5 cm x 5 cm x 12 cm containing silicon is lowered through a fixed rf-coil at a rate of 5.5 mm/min. Solar cells made from HEM silicon have shown efficiencies in the range of 10-15 percent under AM-1 conditions.

6.7.2.3 Ribbon technology (EFG)

The edge defined film fed growth(EFG) ribbon technique in which ribbons of single crystal silicon of about 10 to 12 cm wide are produced avoids the expensive techniques and material wastages in slicing and polishing of wafers. The EFG technique as shown in fig. 6.29 was first applied to silocon by Ciszek[153] and has undergone through intense development[154]. In the EFG process a carbon capillary die which is partially immersed in the molten silicon is used through which silicon goes up and is pulled from the top of the die in a flat-ribbon form. The shape of the silicon ribbon can be controlled by the shape of the top of die, surface tension, temperature gradient, and the pulling rate. Ribbons of 0.05 cm thick and of 5 cm width can be grown at a rate of about 5 cm/min. Since the silicon ribbon is quite thin hence wafering is not required and even the surface is quite smooth and hence even polishing is not required. As many as 20 ribbons each upto 15 cm wide can be simultaneously grown from the same crucible and the molten silicon in the crucible can be replenished continually thereby ribbons as large as desired can be produced. Presently the ribbon technique is the least expensive technique for getting single crystal silicon. The silicon solar cells produced from EFG ribbon have shown efficiencies in the range of 10 to 15 percent.

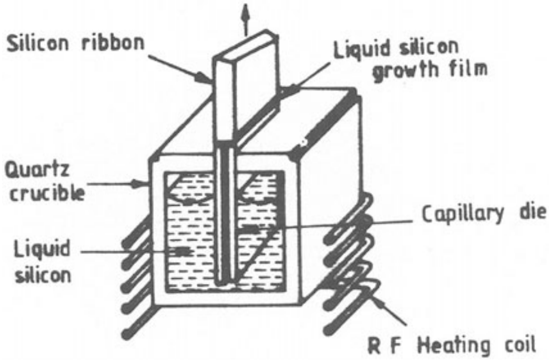


FIG.6.29.SCHEMATIC OF EDGE DEFINED FILM FED GROWTH(EFG) METHOD FOR PRODUCING RIBBONS OF SILICON

6.7.2.4 The dendritic Web method (WEB)

In the dendritic web growth method which is perfected by Westinghouse during 1966-67, a single crystal silicon ribbon of about 4 cm wide and 0.10 mm thick is obtained from the molten silicon without using a die material. In this process two parallel dendrites[155] are lowered into the liquid silicon and then slowly withdrawn and the capillary action forms a web between the two dendrites and on solidification leaving a single crystalline form of silicon. Precise temperature control is required in this process. silicon ribbon at a rate of 10 cm/min of about 4 cm wide and 0.10 mm thick with area output rates of 27cm^2/sec has been produced in this method. The crystal grown in WEB method is better and has <111> orientation compared to that grown by capillary method. The cells made with this WEB ribbon have shown efficiencies higher than 15 percent but the width of the ribbon which is 4.0 cm is the main limitation.

Both the WEB and EFG techniques of growing single crystal silicon ribbons have advantages and disadvantages and the same are compared by Schwuttke[156] in table 6.8

Table 6.8 Comparison of ribbon properties produced by WEB and EFG techniques (From Schwuttke[156])

Growth Characteristics	Web	Efg, Cast
Surface orientation	<111> Well controlled	Mainly <110>; Surface tilts of a few degress occur; also other orientations such as <112> , <114> can occur due to twinning.
Growth direction	<112> Well controlled	<112>
Thickness	As low as a few microns thick has been brown	Appears to be limited to 200 µm for practical reasons (buckling).
Width achieved	~40 mm	~125 mm
Handling ease	Strength through dendrites, dendirte removal can be a problem	Cab be a problem due to stress
Continuous growth	Yes(30 mm width)	Yes (75 mm width)
Twin planes	Parallel to surface; approx. in the middle of the web (can also be grown with twin planes only in denorites)	Intersect surface; Parallel or at an angle to growth direction

Table 6.8 Contd...

Twins	Simple twins; Influence on elec. properties not shown assumed to be small if any.	Higher order twins (non-coherent) present, shown to be weak or strong depending on dislocations in twin plane.
Dislocations	Parallel to<112>direction; close to twin planes, electrical activity not demonstarted (No SEM-EBIC). assumed to be low (High Eff.cells 15%AMI). density 10^4-10^6/cm^2	Dislocations show electrical activity and intersect surface. Either present homogeneously distributed(10^4 -10^6/CM^2) or piled up along twin or grain boundries. Main cause: Cooling stresses. Carbon if any?, In role of dislocation generation not known. Electrical activity of dislocations shown by EBIC.
Stacking faults	Large area of lower-cottrell type, electrical activity not known, assumed to be low, if any. No EBIC measurements have been made.	Intersect surface; Electrical activity varies from low to high depending on number of dislocations present. Activity shown in EBIC.
Grain boundaries	Normally not present if grown under controlled conditions. Too high a growth rate can lead to grain boundaries	Low angle and high angle boundaries present. Always inclined to surface (not perpendicular).

6.7.2.5 Silicon on Ceramic (SOC) method

Honewell Inc. has developed a technique known as silicon on ceramic process of growing large grained polycrystalline sheet of silicon in which a cermamic substrate is used to support the growth of silicon from the molten silicon. The process is schematically shown in fig. 6.30. In this process a mullite based ceramic which is coated with carbon on one side which makes it wettable with silicon is exposed to molten silicon and moved at constant rate leaving a thin (250μm) sheet of silicon. This mullite based substrate is slotted to provide electrical contact to the other side of the silicon. The present growth rate of crystal is about 300 cm^2/min with a film of thickness of less than 0.10 mm. The solar cells made from the silicon sheet produced by this method have shown an efficiency of around 11 percent at AM-1 conditions.

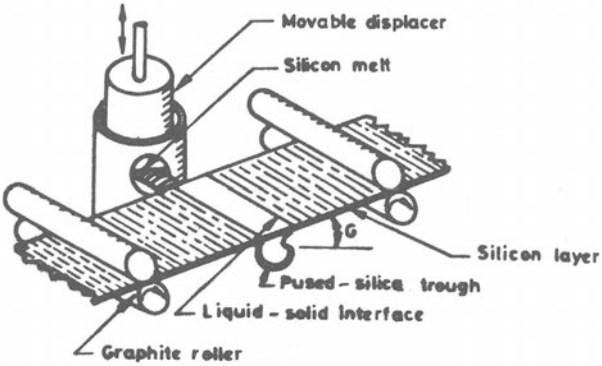


FIG.6.30. SCHEMATIC OF SILICON ON CERAMIC (SOC) METHOD OF GROWING SILICON SHEET

6.7.2.6 SEMIX METHOD

The Solarex Corporation of USA has established a new firm SEMIX to supply microcrystalline silicon to photovoltaic industries and the process by which the multicrystalline silicon is produced is now known as SEMIX method. In the semix method a low cost container in which the molten silicon is poured is used instead using a very expensive quartz crucible which gets crack also while cooling. In this process, the melt is maintained at a very uniform temperature allowing the growth of sufficiently large crystals throughout the material and showing better electrical properties. This material is finally sliced into large wafers. The cells made from this material have shown efficiencies of about 10 percent in sizes 10 cm x 10 cm under AM-1 conditions.

6.7.2.7 Zone refining process

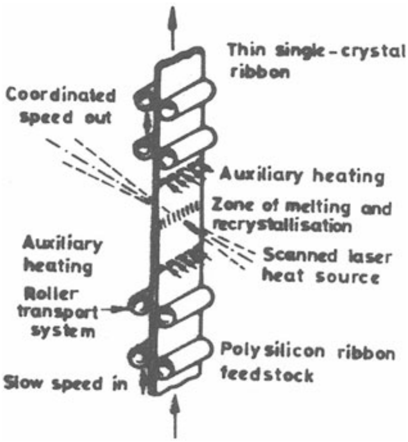


FIG.6.31. SCHEMATIC OF ZONE CRYSTALLIZATION OR LASER HEATING PROCESS

In this process the polycrystalline material is formed either in a rod or a ribbon as desired. This process is a crucible free, float-zone growth method as shown in fig.6.31 in which the polycrystalline ribbon or rod deposited by chemical vapor deposition (CVD) or cast is heated by radio frequency or with lasers. The liquid silicon is held in position due to surface tension and the shape (rod or sheet) of the final crystal depends on the shape of the feedstock. This process purifies the material and single crystals are obtained. There are tendencies of polycrystalline and dendritic growth and mechanical and thermal instability problems are experienced.

6.7.2.8 Other methods

Silicon can be grown from solutions at a lower temperature than its melting point using Sn or Ga as a solvent but in such cases the rate of growth is much low and are not in use for solar cells. The silicon film can be produced by vacuum evaporation using source temperature at about 1800°C and vacuum of the order of 10^{-7} torr. Vacuum deposition of silicon is rather difficult and not successful. However, cells using vacuum techniques have been produced which gave an efficiency of about 3 percent under AM-1conditions.

Chemical vapor deposition (CVD) technique is widely used for growing silicon films in which this film is grown using $SiCl_4$, SiH_4, $SiHCl_3$ or any other similar material at 600 to 1000°C. The silicon growth is diffusion limited at high temperatures and reaction rate limited at low temperatures and strongly depends on gas flow and pressure. The growth rate can be 10 to 15 µm/min. The advantage of CVD method is that the dopant concentration can be easily controlled by introducing gaseous dopants into the gas stream and by simply changing the dopant flow layers of p-type and n-type can be sequentially produced with ease.

6.7.3 Silicon Wafers to silicon solar cells

The fabrication of solar cells from the single crystal silicon wafers involves many steps such as surface preparation, dopants diffusion or junction formation, grid formation, antireflection coating, and module formation. A good review of all these steps is made by Van-Overstraeten[157] and from this review the following information is extracted.

6.7.3.1 Surface preparation

In some of the crystal growing techniques the surface of the crystal is not smooth and there may be a little damage at the surface. The clean and damage free wafers of silicon can be obtained by etching which also improves the cell durability. Etching can be done using acid or alkaline etchants. The acid etchants which are mostly used but expensive are 4 percent HNO_3, 20 percent CH_3COOH, 16 percent HF, and all give good results on both <100> and <111> surfaces. The alkaline etchent which is more common, less expensive, but orientation dependent and very good for <100> surfaces is 30 percent hot NaOH solution. Metallic contamination from the surface can be easily removed using dilute solution of HNO_3 or HCL.

6.7.3.2 Dopants diffusion

There are many dopants which can be used with silicon. The dopants selected should have suitable energy level, solubility and an acceptable diffusion constant. For both terristrial and space applications boron and phosphorus are the most widely used acceptor and donor dopants for silicon. Very high concentration of dopants in a semiconductor is to be avoided since it reduces the electronic mobility and decreases the minority carrier lifetime.

In most of the crystal growth techniques, the boron is always added in the molten silicon which results in p-type wafers. Then the n-layer on the p-type base can be obtained by diffusing a density of donors into the p-doped layer exceeding the density of acceptor there, by growing an additional n-doped layer. This n-doping is done in a variety of ways.

The most common method used making p-n junction is by diffusion[158]. In this process either P_2O_5 or $POCl_3$ is used as diffusion source, and carrier gas such as dry oxygen is used to transfer them to the silicon wafers stacked in a furnace. Thus an oxide layer containing phosphorus gets formed on the silicon wafers. Now at temperatures around 800-1000°C for about 30 minutes, the phosphorus diffuses from the oxide into the silicon and the phosphorus impurities becomes more than the boron impurities in thin regions on all the sides of the silicon wafers, making the silicon wafer a n-type on the surfaces. The time of diffusion can be varied from few minutes to an hour resulting in donor concentration of 3 to 4 x 10^{20} cm^3 with a junction depth of 0.2 to 1.0μm and sheet resistivities of around 40-100 ohms/cm^2. Later oxide layer is removed from the back and other sides except on the front side. Although this method is widely used but the disadvantages of the method are; it is a batch process, costly, energy wasteful, diffusion takes place on both the sides, uniformity may be a problem in very shallow junctions.

Another technique is ion implantation[159] which is recent and more controllable in both penetration depth and doping level than diffusion and the bombardment rate can be made quite high. The damage caused by bombardment can be removed using a thermal annealing, an electron beam, or a laser beam. Excellent results by ion implantation with thermal annealing are obtained with solar cell efficiencies in the range of 14-16 percent which is comparable to diffusion results. The only disadvantage of the process is the high cost of ion implanter.

Diffusion can also be achieved using a solid phase in which a dopant layer is deposited either by chemical vapor deposition(CVD), spin on, spray on, or screen printing technique which is followed by drive in of the dopant. In the CVD technique, uniform layers of phosphorus and boron doped oxides are deposited on either side of the silicon wafer at low temperature which may follow the drive in step resulting in much uniform profile and controlled dopant concentration. The advantage is that junction on the front side is made while the disadvantage is that highly pure and expensive gases are used.

6.7.3.3 Grid formation

Next step is to make the metallic contacts on the back and front side of the cell to collect the charge carriers. This should provide a good ohmic contact, low series resistance, good adherence and good solderability. Metals which are generally used with silicon materials, are Ni, Au, Ag, Ti, Pd and Al. Techniques which are generally adopted for providing the metallic contacts are vacuum evaporation, electroplating, and screen printing. The back metallic contact on the silicon p-type region is of aluminium which is deposited by vacuum evaporation on the entire back surface. The aluminium is heated in a vacuum so that it gets melted and vaporise and then deposited on the cooler side of the solar cell. Later a heat treatment at 500 to 800°C for about 20 minutes is given so that a part of Al diffuses in the p-layer and thus lowering the contact resistance.

The front contact is also made by vacuum evaporation. After deciding the grid shape and design, layers of titanium/palladium/silver are deposited one over the other by vacuum evaporation. First a thin layer of Ti is deposited on the n-layer silicon which provides a good adherence to silicon. After this a layer of Pd is deposited and then finally at the top a layer of Ag is deposited. The Pd layer between Ti and Ag layers is deposited to stop the electrochemical reaction causing corrosion in the presence of moisture between Ti and Ag. Later, the front contact is annealed at 500 to 600°C for 15 to 20 minutes which makes good adherence and low contact resistance. The series resistance can be reduced by making the Ag layer thick or a layer of Pb-Sn solder is deposited by dipping. Generally in a normal p-n junction cells, grid lines are about 0.3 cm apart and covers generally 5 to 10 percent of the cell area. This process is widely used, produces cells of high efficiency but is expensive since it is a batch process and also make use of expensive materials.

Screen printing is another technique by which the front and back contacts can be provided. In this technique generally Ag paste is used for front metallization and Al paste for the back surface metallization. Here the equipment used is inexpensive, easy to maintain, and production and material yield are high. Plating of nickel though a mask can also be done on the solar cell surface but generally due to the presence of oxide layer on the silicon surface the adherance becomes poor. The adherance can be improved by using a layer of Pd in between silicon and nickel and the resistivity is decreased using solder coating.

6.7.3.4 Antireflective Coating

Antifeflective coating (ARC) in an important part of a solar cell since the bare silicon has a reflection coefficient of 0.33 to 0.54 in the spectral range of 0.35 to 1.1 μm. The ARC not only reduces the reflection losses but also lowers the surface recombination velocity. A single optimal layer of ARC can reduce the reflection to 10 percent and two layers can reduce the reflection upto 3 percent in the desired range of wavelengths. Generally ARC's are produced on the solar cell by vacuum evaporation process only and the coatings which are tried are SiO_2, SiO, Al_2O_3, TiO_2, Ta_2O_5 and Si_3N_4. Other methods of deposition are sputtering, spin-on, spray-on, or screen printing. Only the vacuum evaporation and sputtering give good results but are expensive. The average reflection can be further reduced by using two antireflective coatings instead of one where the outside (exposed side) coating has an index of refraction of 1.3 to 1.6 and the second layer between silicon and the first layer has an index of refraction of 2.2 to 2.6. This two layer ARC gives a better impedance match between the index of silicon and the index of air.

6.7.3.5 Module design

The individual cells generally each of 10 cm^2 to 100 cm^2 are then interconnected in a series and parallel pattern and one module contains about 20 to 40 cells. Each module may have three to five columns of cells in series in such a way that one gets the desired output electrical characteristics. A typical module containing 30 cells each of 7.5 cm diameter may provide about 12 volts (nominal voltage), 1.2 amp. (nominal current), and peak power of 18 W which is sufficient to charge 12 V batteries. Since generally circular cells are produced hence packing density can not be high and about 15 to 20 percent of the module area remains uncovered. In case of square or hexagonal shaped cells better packing densities are obtained. Since these cells are thin, brittle, to be protected from weather, and the connections are light and soft, these cells are sandwiched or encapsulated with a transparent cover at the top. This encapsulation not only provides the mechanical strength to the cells but also protect the cells from damage due to dirt, dust, hail, birds, foreign materials, moisture penetration, and also it protects the metallic contacts, and interconnnections from weather and wind. The encapsulation also provides an electrical isolation of the voltages developed by the module. The material selected for the encapsulation should have life more than 20 years, should be UV stablised, should withstand the temperature extremes and thermal shocks, should have resistance to abrasion, the top cover should have high transparency for solar radiation, should not increase the temperature of cell, should be easily cleanable, and of course low in cost. Generally the cells are sandwitched in an inert filler between two clear glass sheets. Sometimes the front transparent material is a UV-stabilised plastic sheet and a plastic rigid plate on the back side. Silicones(sealant) are generally used as an adhesive and pottant layers since these are resilient in the operating temperature range, UV stabilised, and do not absorb much sun light. The sealing should be weathertight so that no water, dirt, etc. can go in. The rear plate should be strong so that it holds the total weight of the module.

6.7.4 Polycrystalline silicon cells

Single crystal silicon solar cells give quite high efficiency (> 16 percent under AM-1 conditions) and are quite reliable and stable both under terristrial and space conditions but their high production costs limit their application for terrestrial applications. In view of this, studies are conducted both on poly-crystalline and amorphous silicon materials as potential candidates for solar cells in

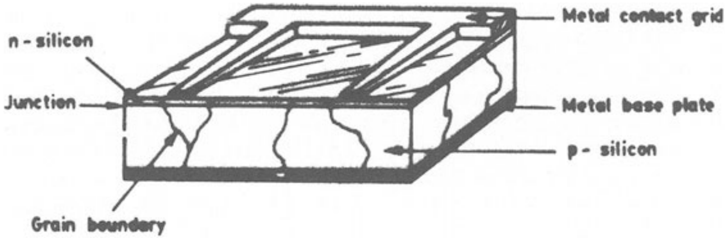


FIG.6.32. CROSS-SECTION OF POLYCRYSTALLINE SILICON SOLAR CELL

thin form. A good review of amorphous and polycrystalline silicon solar cells is made by Charles and Ariotedjo[71] and the present section is partly derived from their work. As discussed earlier the polysilicon can be obtained in the form of thin ribbon drawn from molten silicon bath, or allowing the silicon vapors to deposit on a cool flat-surface, or ingot, or solid block. If the molten silicon cools under normal conditons then the resulting ingot contains myriad of microscopic crystals. If the molten silicon is cooled very slowly, then crystallites of larger size are obtained. The polycrystalline silicone is in the form of granules and the size of crystallites mainly depends on the cooling conditions. The silicon solar cells made from polycrystalline silicon are low cost but are of low efficiency also ($\sim$5 to 10 percent). Considerable loss of photogenerated carriers occur at grain boundaries known as short circuiting as shown in fig. 6.32. Therefore the grains/crystallites should be large in order to get better performance.

There are three groups of solar cell structures which are prepared using polycrystalline silicon as discussed by Charles and Ariotedjo[71] and the same are shown[71] in fig. 6.33. These cells are p-n junction cells, metal-insulator-semiconductor (MIS) cells, and conducting oxide-insulator-semiconductor cells. In a p-n junction solar cell, the polycrystalline silicon film can be deposited by any one of the techniques like dipping, chemical vapor deposition, and vacuum evaporation on various substrates like graphite, glass, ceramic, sapphire, metallurgical-grade silicon, and metal. Chu et al[160-162] have done considerable work and deposited polycristalline silicon films on steel, graphite and metallurgical grade silicon using chemical vapor deposition technique. The characteristics of the best polycrystalline silicon cell obtained by him is shown in fig. 6.34 where the cell area is 9 cm^2 and the cell efficiency was of about 9.75 percent. The idea of a metal-semiconductor junction (Schottky junction) is quite attractive since it simplifies the manufacturing process and of low cost. These cells show a similar short circuit current I_{sc} and low open circuit voltage V_{oc} compared to p-n junction cells resulting in low cell efficiency. Considerable higher dark current takes place in these cells. By inserting a very thin insulating layer in between the metal and semiconductor, this problem can be solved and such cells are termed as metal-insulator-semiconductor (MIS) solar cells. By making the insulating layer very thin, the V_{oc} can be increased and can become almost equal to that of the p-n junction cell. Sometimes the oxide layer already present on the semiconductor material was used as an insulating material but this uncontrolled layer of oxide insulating layer has given overall poor performance, and therefore in more recent cells a controlled freshly prepared thin oxide layer is used which has given good performances[9]. Anderson et al[163] has developed a MIS cell in which the metal used is chromium, the oxide layer is SiO_2 of thickness 15 A^o and a p-type crystalline silicon is deposited on it. This cell has given I_{sc} 26 ma/cm^2, V_{oc} as 0.50 volts, and solar efficiency of about 8.1 percent under AM-1 conditions. One of their best cell has given an efficiency of 12.2 percent at AM-1 conditions when the cell area was 2 cm^2. Similarly Charlson and

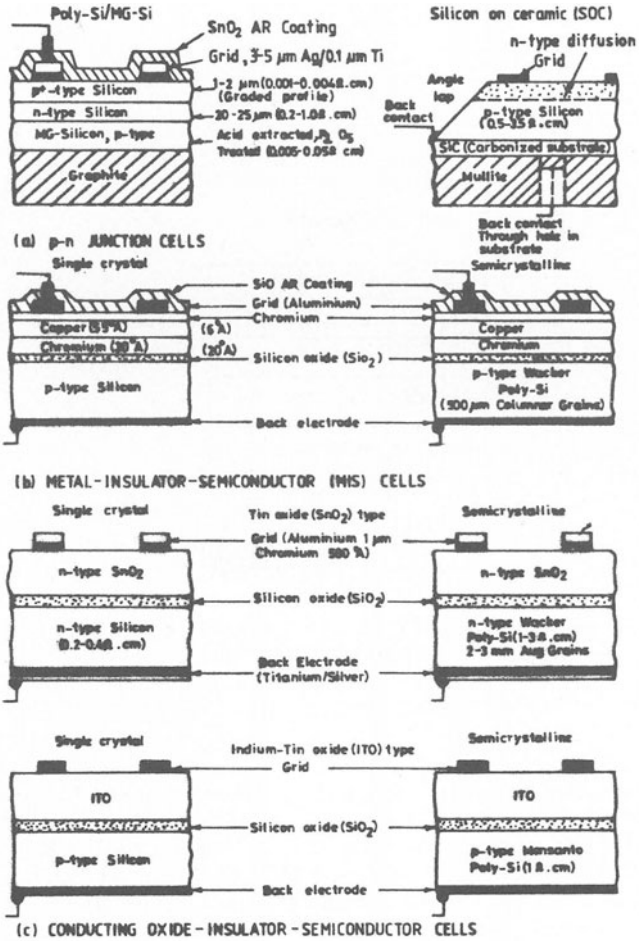


FIG.6.33. SCHEMATIC DIAGRAMS OF VARIOUS POLYCRYSTALLINE SILICON CELL STRUCTURES (From Charles and Ariotedjo[71])

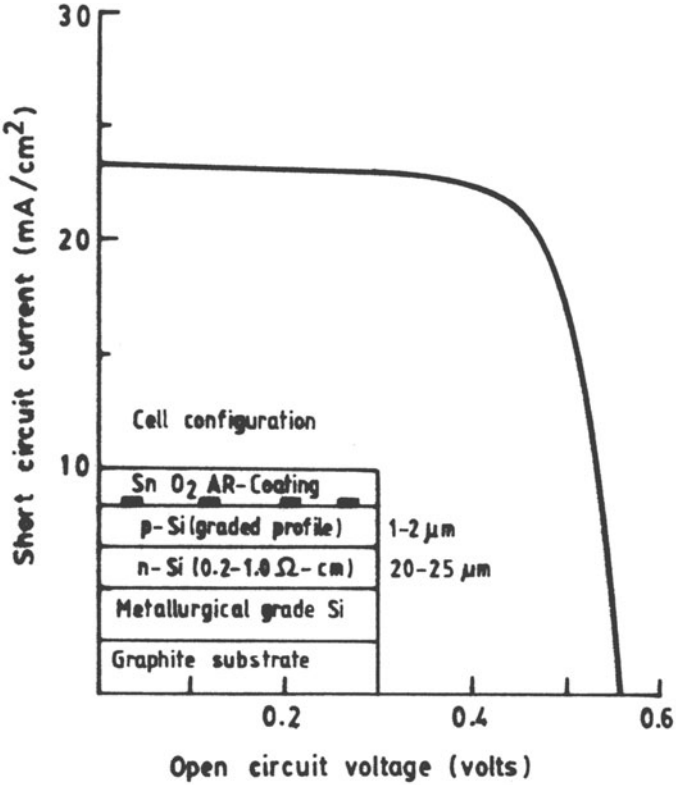


FIG.6.34. PERFORMANCE OF A THIN POLYCRYSTALLINE SOLAR CELL AS DESCRIBED BY CHU et al (CELL AREA IS 9 CM^2, FILL FACTOR IS 74.6 PERCENT AND CELL EFFICIENCY IS 9.75 PERCENT UNDER AM-1 CONDITIONS)

Lien[164] have used Aluminium as the metal, SiO_2 of 20-40 A^o thick layer as insulating layer and p-type crystalline silicon was deposited at the top. This cell has given I_{sc} as 26.5 mA/cm^2, V_{oc} as 0.55 volts, and solar cell efficiency of 8.0 percent under AM-1 conditions. The best cell fabricated with this combination has given an efficiency of 11 percent. Van Hallen et al[165] have used Titanium as the Schottky barrier metal because of its high optical transmittance value and this Ti-MIS cells using crystalline silicon has given an efficiency of 9.8 percent under AM-1 conditions. A new concept known as 'epitaxial solar cell' in which the active layer is a thin pure silicon layer which is deposited on a substrate which can be very impure have given encouraging results and cells of highest efficiencies, 9 to 12 percent, are expected to be obtained[166].

In the conducting oxide-insulator-semiconductor cells as shown in fig. 6.33(c), a window semiconductor is used over an active semiconductor substrate[71]. This thin film oxide window which has high transmittance for solar radiation and high electrical conductivity also acts as the antireflection coating. Several window materials such as SnO_2, In_2O_3 and ITO have been tried with different deposition techniques such as spray deposition, chemical vapor deposition, and electron beam deposition. SnO_2/sliced semicrystalline silicon substrate cell has given an efficiency[167] of 10.1 percent under AM-1 conditions.

6.7.5 Amorphous silicon cells

It is comparatively easy to produce amorphous silicon (also called alpha-silicon) compared to single crystal or polycrystalline silicon. Amorphous silicon is pure silicon which has no crystal properties and here the atoms in the solid are randomly distributed. For example glass is amorphous and not crystalline material. A film of silicon prepared by vacuum evaporation technique upto a substrate temperature of 600°C is amorphous. These films as such can not be used as optoelectronic devices since these contain large density of defects in the form of dangling bonds which act as recombination centres for photo-generated charge carriers. It was first shown in 1969 by Chittick, Alexander and Stirling[168] that when amorphous silicon (a-silicon) is produced by rf glow discharge decompositon of silane gas (SiH_4), then it shows considerable photo conductivity. It is believed that the so produced a-silicon films contained hydrogen which saturates dangling bonds on the internal microvoids of the film and at other defects in the structure reducing the density of states within the forbidden gap and allowing the material to be doped. By decomposition of mixture of silane (SiH_4) with phosphine (PH_3) and Diborane (B_2H_6) it is possible to produce n-and p-type hydrogenated amorphous silicon (a-Si:H). The discovery by Spear and LeComber[169] that the Fermi level in a glow discharge produced amorphous silicon (a-Si:H) can be moved up and down the band gap by doping like in a crystalline silicon opens up a potential application of amorphous semiconductors and fabrication of various devices including solar cells. Because these materials have high photoconductivity[170], high optical absorption of visible light (optical band gap of 1.55 eV), and large areas can be produced, therefore low cost solar cells can be produced using these films. Although there are variety of methods for producing amorphous silicon films like vacuum evaporation, electrolytic deposition, ion bombardment of single crystal silicon, cathode sputtering, and glow discharge decomposition of silane, but a film produced by glow discharge decomposition of silane is suitable for photovoltaic use.

Amongsts the various methods proposed for deposition of a-Si, the DC and RF flow discharge deposition methods are commonly employed for depositing a-Si films. A schematic diagram of a 4-electrode glow discharge deposition system wherein a DC electric field is superimposed onto an RF electric field is shown in fig. 6.35. Some of the deposition conditions are shown in table 6.9. In this apparatus as is seen from fig. 6.35, the plasma was excited by a 13.56 MHz rf oscillator through the electrodes. The thickness of the film can be controlled by flowrate, exposure time, and discharge power. By using different gas mixtures, different materials suitable for the fabrication of a -Si can be produced. Some of the materials are

Table 6.9. Conditions for deposition of a -Si:H film

RF Power	: 190 W
Frequency	: DC 13.56 MHz
Substrate temperature	: 260°C
Gas Pressure	: 2 - 3 torr
Flow rate	: 40 - 70 cc/min
SiH_4/H_2	: 10 percent
PH_3/H_2	: 500 ppm
B_2H_6/H_2	: 500 ppm
Deposition rate	: 1000 A/min.

$$SiH_4 + NH_3 \longrightarrow \text{a-SiN: H}$$
$$SiH_4 + B_2H_6 + CH_4 \longrightarrow \text{P type a- SiC : H}$$
$$SiH_4 + CH_4 \longrightarrow \text{a- SiC : H}$$

Dopants can be added to the SiH_4 vapor to dope the a-Si (e.g. Diborane (B_2H_6) for p-type and phosphine (PH_3) for n-type). A plasma-deposition furnace with consecutive seperated chambers in which the codiffusion and undesirable mixing of acceptor and donor impurities are completely removed is schematically shown in fig.6.36. A considerable improvement in the cell performance fabricated in multichamber was observed compared to single chamber.

The amorphous silicon cells can be fabricated basically with four structures, viz: (1) Heterojunction, (2) metal-

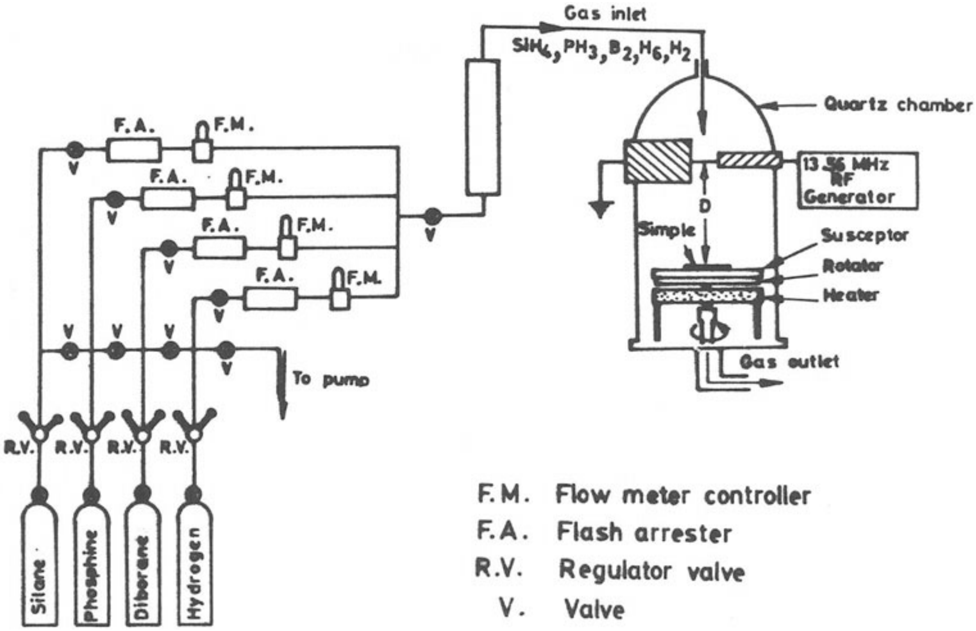


FIG.6.35. A SCHEMATIC OF GLOW DISCHRAGE APPARATUS FOR PREPARATION OF a-Si:H FILMS

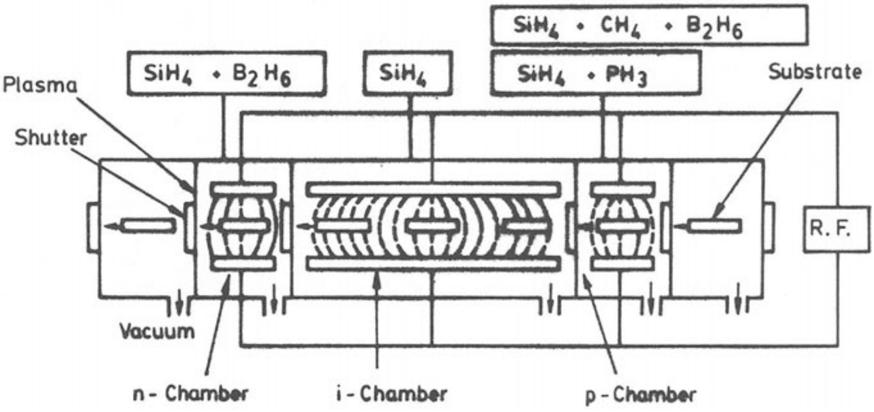
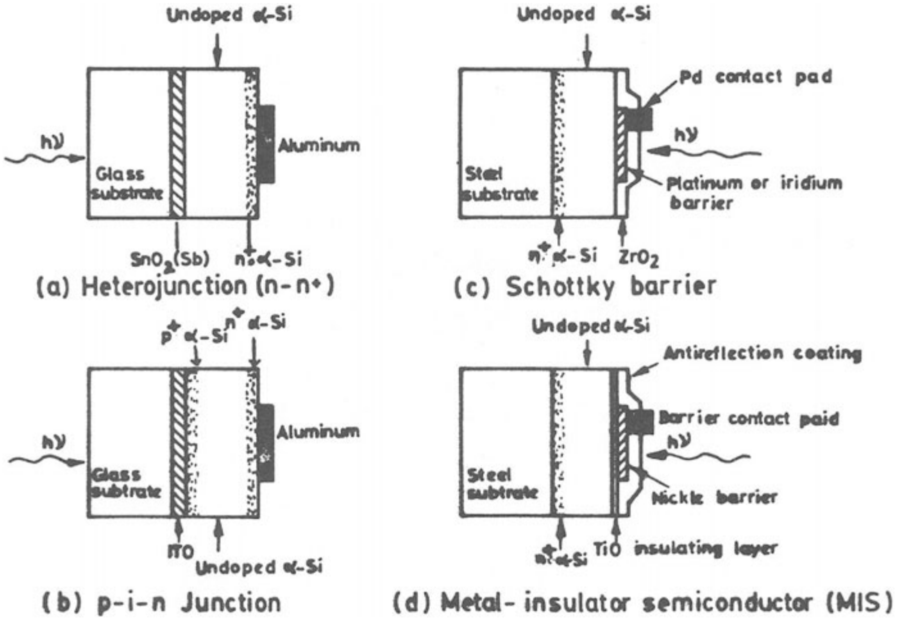


FIG.6.36. SCHEMATIC DIAGRAM OF A CONSECUTIVE SEPERATED REACTION CHAMBER FOR THE PREPARATION OF A-Si SOLAR CELL

insulator-semiconductor (MIS), (3) p-i-n devices, and (4) Schottky barriers. The structures of these four basic cells are shown[71] in fig. 6.37. In 1977, Carlson and Wronski[173] reported an a-Si:H Schottky barrier solar cell with a conversion efficiency of 5.5 which was the first amorphous solar cell. Later in 1978, a group of scientists at the Osaka University[174], Japan made a real dent in a-Si solar cell by producing a heterojunction solar cell with a construction of ITO/p-i-n/stainless steel with an efficiency of 4.5 percent. This type of solar cell structure is presently used because it can be produced on large areas with good reproducibility and the parameters responsible for the cell behaviour can be controlled.

The first heterojunction solar cell was produced by depositing amorphous silicon on glass coated with either tin-oxide doped with antimony or indium tin oxide (ITO). The best heterojunction solar cell was reported by Carlson [175] as shown in fig. 6.37(a) which was made by depositing a Si:H(undoped) on ITO or SnO_2:Sb-coated glass substrates,



(a) Heterojunction (n-n+)

(c) Schottky barrier

(b) p-i-n Junction

(d) Metal-insulator semiconductor (MIS)

FIG.6.37. SCHEMATIC DIAGRAMS OF VARIOUS AMORPHOUS SILICON CELL STRUCTURES (From Charles and Ariotedjo[71])

using a thin p-doped a-Si:H layer to make ohmic contact to an evaporated al contact. This cell has given a open circuit voltage of 0.43 volt, short circuit current of 10.0 mA/cm^2, a fill factor of 0.28, and a solar cell efficiency of 1.2 percent under AM-1 conditions. Recent studies are on amorphous silicon in conjuction with gallium nitride and amorphous silicon carbide.

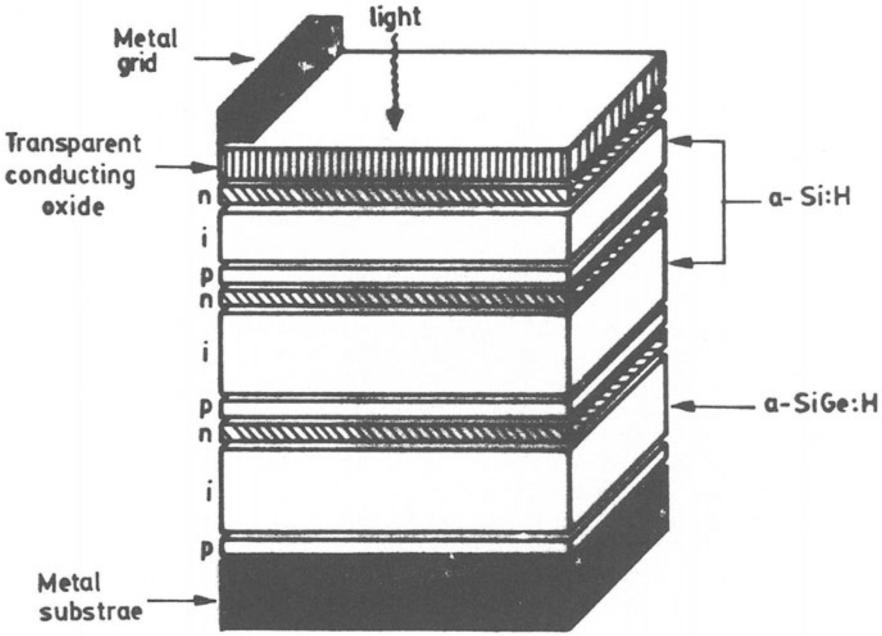


FIG.6.38. SCHEMATIC OF A STACKED a-Si:H CELL FOR HIGHER EFFICIENCY

The p-i-n junction a-Si solar cells are most suited for commercial production and give good performance. These can be produced in two types of structures (fig. 6.37(b)). In the first type, the substrate is of ITO (600 A^o coated glass and a cermet (Pt-SiO$_2$) (100 A^o), on which first a p-type a-Si:H layer (80-200 A^o), is deposited, then a layer of intrinsic a-Si:H layer (5000-7000 A^o) is deposited and finally a layer of n type a-Si:H layer (300-500 A^o) is deposited.

A Ti/Al (1000 A^o) metal layer is deposited on the back side of p-i-n structure as the collection electrode. This pt-SiO$_2$/p-i-n/a-Si solar cell has given [79] an open circuit voltage of 0.77 volt, short circuit current of 7.0 mA/cm^2, fill factor of 0.60, and solar cell efficiency of 3.30 under AM-1 conditions. Tawada et al.[176] fabricated n-a-Si: H/i-a-Si:H/p±solar cell on ITO coated glass with 2 mm diameter which gave an efficiency of 7.55 percent under AM-1 conditions. With some refinement in the cell design Catalano et al[177] reported a cell efficiency of 10.1 percent. In another type of p-i-n junction a-Si-solar cell, first a layer of boron doped a-Si :H(200 A^o) is deposited on steel, then a layer of undoped a-Si :H(5000 A^o) is deposited and over to it is deposited a layer of n-doped a-Si : H(80 A^o). Finally a 70 A^o thick layer of ITO is deposited on the n-type layer which acts as conducting electrode and as well as antireflective coating.

The Schottky barrier a-Si:H solar cells are easy to fabricate and as reported by Carlson[175], the same can be made (fig. 6.37(c)) a thin layer of p-doped n$^+$-a-Si on stainless steel structure, then a layer of undoped a-Si:H (1 μm), then a Schottky barrier metal (Pt) (50 A^o), then a Pd contact pad (1000 A^o) on one edge of Pt layer, and finally a 450 A^o thick layer of ZrO$_2$ which works as an antireflective coating. This cell has given an open circuit voltage of 0.80 volt, short circuit current of 12.0 mA/cm^2, fill factor of 0.58, and a solar cell efficiency of 5.5 percent under AM-1 conditions. This schottky structure solar cell has many advantages.

By introducing an insulating layer in the schottky barrier (the so called MIS cell) both the barrier height and the field region width get increased resulting the use of lower work function barrier metals which are less expensive than platinum or paladium. Wilson et al[178] and McGill et al[179] fabricated Ni/T$_i$O$_x$/a-Si:H cells with various thickness of T$_i$O$_x$ (here T$_i$O$_x$ is used as insulating layer). This cell has given an open circuit voltage of 0.68 volt, short circuit current of 7.90 mA/cm^2, fill factor of 0.51 and solar cell efficiency of 4.8 percent. A number of firms in Japan and USA have done tremendous work on a-Si:H solar cells and have produced cells with efficiencies upto 12.7 percent as can be seen from table 6.10.

Since in a single junction a-Si solar cell, the incident light with energy less than band gap is not utilized and is wasted as heat resulting in low cell efficiency. This idea of utilizing longwavelength photons by a highly reflective random surface was first proposed by Boer and VanStrijp[180] which was later proved by Exxon group[181]. The photons of longer wavelength can be absorbed using multijunction cell or stacked junctions in which semiconductors with different energy gaps is stacked on top of each

Table 6.10 Recent summary of developments in a-Silicon solar cells(Courtesy Prof. Y.Hamakawa)

Type	Configuration	Area (cm^2)	Eff. (%)	V_{oc} (V)	I_{sc} (mA/cm^2)	FF	Year	Institute
SJ	ITO/nipn a-Si/p poly Si/Al	0.082	12.7	1.380	14.18	0.65	1984	Sumitomo
SJ	ITO/nipn a-Si/p poly Si/Al	0.44	12.5	1.325	14.2	0.66	1982	Osaka Univ.
HJ	Ag/ni a-Si/P a-SiC/ text. TCO.glass	1.0	11.5	0.869	18.9	0.70	1984	Sanyo
HJ	Me/ni a-Si/p a-SiC/ text.SnO_2/ITO/glass	1.05	11.6	0.850	18.7	0.732	1985	TDK-SEL
TJ	ITO/nipnipn a-SiGe/ p a-Si/stainless steel	1.0	11.2	-	-		1985	ECD
HJ	Me/ni a-Si/p a-Sic/ TCO/glass	1.0	11.1	0.864	17.6	0.73	1984	Fuji
HJ	Ag/ni a-Si/p a-Sic/ text. SnO_2/glass	1.0	11.0	0.860	21.5	0.6	1985	Kanegafuchi
HJ	Me/ni a-Si/p a-Sic/ text. TCO/glass	0.32	10.7	0.840	18.8	0.68	1984	Komatsu
HJ	Ag/ITO/ni a-Si/p a-Sic/MTG	0.045	10.2	0.802	22.32	0.57	1984	ETL & Taiyo
HJ	Al/ni a-Si/p a-Sic/ text. SnO_2/glass	4.15	10.2	0.865	16.1	0.73	1984	ARCO
HJ	Ag/ni a-Si/p a-SiC/ SnO_2/glass	1.09	10.1	0.840	17.8	0.676	1982	RCA
HJ	Ag/p a-SiC/in a-Si/ SnO_2/glass	0.084	9.6	0.848	17.1	0.664	1984	TIT
SJ	ITO/nipn a-Si/ia-SiGe/pa-Si/Stainless steel	929	9.4	-	-	-	1985	ECD

Table 6.10 contd...

TJ	ITO/nipnipn a-Si/i a-SiGe/ p a-Si/stainless steel	0.09	8.5	2.200	6.74	0.57	1982	Mitsubishi
Mod	Me/ni a-Si/p a-SiC/TCO/ glass	100	8.1	11.96	15.6	0.61	1984	Sanyo
HJ	Me/ni a-Si/p a-SiC/TCO/ glass	100	8.0	0.850	14.4	0.654	1984	Fuji
SJ	Al/nipni a-Si/p a-SiC/ SnO_2/glass	4.15	7.7	1.710	6.23	0.71	1984	ARCO
HJ	Al/ni a-Si/p a-SiC/ SnO_2/glass	1.0	7.7	0.880	14.1	0.62	1982	Osaka Univ.
Mod	Al/ni a-Si/p a-SiC/ SnO_2/glass	400	7.5	47.8	114 mA	0.55	1985	Kanegafuchi
Mod	Me/ni a-Si/p a-SiC/ SnO_2/glass	600	7.0	16.0	12.5	0.63	1984	Sumitomo
Mod	Me/ni a-Si/p a-SiC/ SnO_2/glass	3200	6.7	48.7	890 mA	0.50	2985	Kanegafuchi

SJ: Double-stacked junction. HJ: Hetero-junction TJ: Triple-stacked junction Mod: Module other in decreasiang band gap order. Studies on stacked a-Si cells are in progress at SERI, USA[182] and the structure being studied is shown in fig.6.38. Generally three stacked cells (layers) using n-i-p configuration are considered ideal from practical consideration. The first two cells are standard a-Si:H acting as intrinsic layer while the third (Last) layer is an alloy of silicon, germanium, and hydrogen (a-SiGe:H). In this configuration the a-Si:H cells capture most of the blue-green end of the spectrum while the a-SiGe:H cell capture the red part of the spectrum. Theoretically this three layered structure with band gaps of 2.0, 1.7, and 1.45 eV respectively can result in an efficiency of 24 percent.

6.7.6 High efficiency silicon cells

The efficiency of a conventional p-n junction silicon solar cell is in the range of 11-14 percent. In these cells the diffused layer is of about 0.5 μm thick accompanied by the formation of a dead layer of about 0.1 μm thick. The surface electron concentration in the diffused region is in the range of 2 - 4 x $10^{20}cm^{-3}$ and dopant concentration of about $10^{21}cm^{-3}$ with a hole lifetime of about 10^{-10} sec. However, a cell known 'violet cell' was announced by Lindmayer and Allison[183] in 1972 where the response to blue-violet light in a p-n junction silicon cell is enhanced by reducing the thickness of the diffused n-type front layer to 0.2 - 0.3 μm and by lowering the doping level concentration resulting in reduction of dead layer effect and improvement in the short wavelength spectral response. This change boosted the cell efficiency to 15 percent under AM-1 conditions. An antireflection coating of Ta_2O_5 was used in place of SiOx or T_iOx coatings used earlier. Another improvement in the silicon solar cell was suggested by Arndt et al[184] where the front surface of the cell is textured forming a three-dimensional surface appearing like small pyramids 1-2 μm high. By texturing the front reflection losses get reduced due to multiple incidence and the light does not travel perpendicular to the junction interface. In this case the collection efficiency increased because the photogeneration takes place near the junction. The textured solar cell has given a photocurrent of 46 mA/cm^2 under AM-0 conditions which is about 10 to 15 percent more than the best violet cell.

Another improvement in the p-n junction silicon solar cell was the redesigning of the collection grid the so called high-low back junction[185] which offset the reduced conductivity of the thinned n-layer. This high-low junction develops an energy barrier for minority carriers, reduces the loss of these carriers to the back resulting in enhanced long wavelength response. Even it provides a low resistance ohmic contact for majority carriers. This effect has increased the open circuit voltage from 0.55 volt to 0.6 volt for 10 ohm cm substrate cell.

6.8 GALLIUM ARSENIDE SOLAR CELLS

The gallium arsenide (GaAs) is a direct band semiconductor and because of its ideal band gap of 1.43 eV which is optimum for solar energy conversion, holds good promise indicating a theoretical efficiency of 29 percent under AM-1 conditions. Because of its direct band gap and high optical absorption coefficient, more than 97 percent of the AM-1 photons are absorbed within a thickness of 2 μm only therefore reducing the material requirements. Because of its high energy band gap, it can be operated at temperatures upto 200°C and concentration ratio upto 500 without much degradation. The life time of the carriers and the diffusion lengths in a GaAs semiconductor are much smaller than silicon hence it is not effected with solar radiation. But because of the low resources of Ga, high cost, toxic nature of As, etc. these cells are not commercially produced.

The GaAs processes are not so well developed as that of silicon processes which is due to the fact that the processes involved for producing GaAs are complex compared to silicon. GaAs cells can be fabricated in either homojunctions or heterojunctions. Polycrystalline GaAs can be obtained after heating a very pure stoichiometric mixture of Ga and As in a closed vessel. Single crystals of GaAs is obtained from polycrystalline GaAs either by using Czochralski (CZ) technique, or horizontal Bridgman (HBG) freezing technique or chemical vapor deposition technique[186]. The arsenic losses in the CZ technique is prevented using a liquid encapsulant (generally B_2O_3) which floats on the GaAs melt and which suppresses the evaporation of arsenic. In order to balance the arsenic vapor pressure is used in the growth chamber. The single crystal is obtained by dipping a seed into the melt and then pulling it at a rate of 8 to 20 mm/hr range. This liquid encapsulated CZ technique is versatile and by using suitable seeds differently oriented ingots can be obtained. In the HBG technique which is simple and crystals of good crystalline quality is obtained, the GaAs is filled in a mold in a evacuated quartz chamber and then subjected to a controlled gradiant melt-freeze process converting GaAs into a single crystal ingot. The rods or ingots so obtained are then cut into thin wafers (250 μm thick) for final processing into solar cells. Dopants which can be used are S, Se, Sn, Si, Te, C and Ge as shallow donnors and Be, Zn, Mg, Si, Cd, Ge, and C as shallow acceptors.

The most studied GaAs solar cell uses a p-n homojunction using polished single crystal wafer on which n type material is doped to about $10^{17}cm^{-3}$. The p-n junction is formed by diffusing Zn or Cd acceptors to a depth of about 1 μm. Shallower depths have also been used. The high surface recombination velocity, poor diffusion length, and small minority carrier diffusion length result in low efficiency of cells. Rather than using a common diffusion technique of adding impurities in silicon solar cells, epitaxial layers which are chemically build up layers incorporating the required dopant densities are used in GaAs cells. These layers are obtained by heating the substrate in the presence of chemicals containing the materials to be deposited and which are in the liquid or vapor phase. The GaAs cell is formed by using a heavily doped p^+ substrate(GaAs), over to which is epitaxially grown a lightly doped P layer (GaAs) of few microns thick, and then over it a very thin heavily doped N^+ layer is grown. The recombination velocity is reduced using a thin N^+ layer and at its top a layer which is formed due to anodic oxidation. The MIT Lincoln Laboratory of USA suggested a thickness of 0.1 μm of the top N^+ layer to reduce the recombination velocity. Most of the sunlight gets transmitted through this thin N^+ layer and is absorbed in the p-type GaAs layer where most photogenerated carriers are created and thus surface recombination losses get reduced. The MIT has also suggested the use of silicon substrate upon which a thin layer of germanium is deposited. On this germanium film several layers of p-type (p^+) GaAs are epitaxially grown. Finally a thick P-GaAs layer of about 2 μm thick is epitaxially deposited to form a single crystal absorber layer. By using 20 thin P^+ layers it is possible to obtain a cell efficiency of about 20 percent.

In 1972, Woodall and Hovel[187] described a $Ga_{1-x}Al_xA_s$/P-GaAs/n-GaAs device in which layers are deposited by liquid phase epitaxy (IPE) technique and showed an efficiency of 15.3 percent at AM-1 and 19.1 percent at AM-2 conditions. A value of x equal to 0.8 for a layer will show a large indirect band gap. James and Moon[188] have shown that under a concentration ratio of 9.9 and at temperature of 30°C a cell of p-GaAlAs/p-GaAs/n-GaAs/n^+-GaAs will give an efficiency of 23 percent. Since the structure of GaAs and AlAs is almost similar, it is possible to prepare a exptaxial layer of $Ga_{1-x}Al_xAs$ on the surface of homojunction cell resulting in reduction of surface recombination losses. In this technique, a n-type substrate of GaAs is taken and on which a p-type $Ga_{1-x}Al_xAs$ layer from the liquid phase is epitaxially grown. A low resistance contact can be made either by etching the top layer and making the contact with the p-type GaAs or by making a contact on the heavily doped p-type GaAs layer made at the top in the contact area.

Research on GaAs solar cells are directed in two areas one developing low cost polycrystalline GaAs solar cells and second on high efficiency multiple junctions.

6.9 CdS/Cu$_2$S SOLAR CELLS

The photovoltaic effect in CdS/Cu$_2$S rectifiers was first discovered by Reynolds[189] et al. in 1954. A good history of CdS/Cu$_2$S solar cells is given by Deb[190] and Shirland[191]. The early pioneering work on single crystal CdS cells was conducted by Hammond and Shirland[192], Williams and Bube[193], and Boer[194], and several companies like Harshaw, RCA, ARL, Stanford, Clevite of USA, SAT of France, AEG-Telefunken of West Germany and IRD of UK were engaged in doing R&D work on CdS/Cu$_2$S cells. Recently a state of art report on ploycrystalline thin film solar cells and on Cu$_2$S/CdS solar cells is prepared by Pfisterer and Bloss [195-196]. Several review articles describing the design procedures, advantages, disadvantages, theory etc. of CdS/Cu$_2$S solar cells are recently published [85-93]. Several attempts are made in the past to make a commercial [195] CdS/Cu$_2$S solar cell.

Compared to silicon solar cell, the CdS/Cu$_2$S solar cell is much thinner and is made from polycrystalline material. There are several advantages of CdS/Cu$_2$S solar cell such as: (i) these can be easily and cheaply produced, (ii) these can be mass produced, (iii) large area cells can be made in rectangular shape reducing the spacial losses, and (iv) energy consumption in the cell production is low. Some of the disadvantages of CdS/Cu$_2$S cells are: (i) their efficiencies are low compared to silicon solar cells, (ii) these cells deteriorate when exposed to moisture and air, and (iii) cadmium is quite toxic is not abundanthy available.

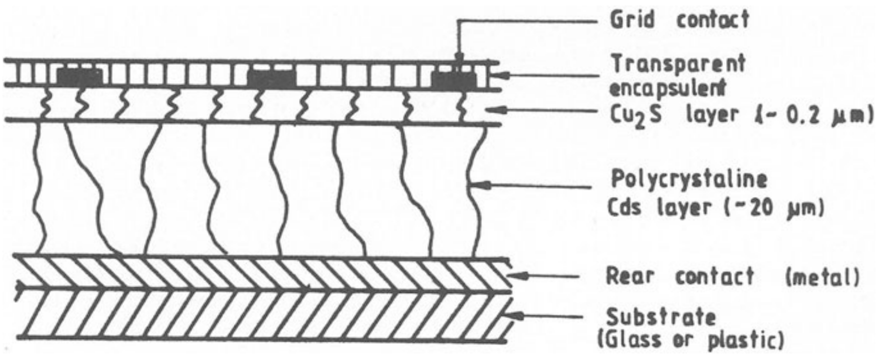


FIG.6.39. SCHEMATIC OF Cds/Cu$_2$S THIN FILM SOLAR CELL

A crossection of a typical polycrystalline CdS/Cu_2S solar cell is shown in fig 6.39. On a glass or plastic substrate a metal contact layer is deposited by evaporation and upon which a polycrystalline layer of CdS of thickness of about 20 µm is deposited either by vacuum evaporation or by spray pyrolysis. A heterojunction of Cu_2S/CdS at the top of this layer is formed by dipping the sheet in a hot solution of cuprous chloride (CuCl) at 80 to 100°C for 10 to 30 seconds which converts the top layer of CdS to Cu_2S. Finally after giving few treatments grid contact and encapsulation is done to finally completing the cell.

The CdS films are produced [196] mainly by three methods: (i) spray pyrolysis in which aqueous solutions of $SC(NH_2)_2$ (thiourea) and $CdCl_2$ are applied in a fog to a heated substrate, (ii) thermal evaporation of CdS powder on a heated substrate, and (iii) sintering of screen printed CdS pastes. The Cu_2S film on CdS layer is generally deposited with the method so called topotaxial formation process in which either Clevite wet process (dipping the CdS layer into a CuCl solution) or Philips dryprocess (vacuum deposition of CuCl and heat treatment) is used. The Clevite process is considerably improved and widely used. In the past three attempts have been made for commercial production of CdS/Cu_2S solar cells.

(1) The SES Inc., Newark, Delaware, USA used Clevite process in the production of CdS/Cu_2S solar cells and made sevral modifications. By 1980, this firm had sold 50 KW of CdS/Cu_2S cells. Efficiencies in the range of 4 to 5 percent are obtained in the production runs.

(2) The Photon Power, Inc., El Paso, Texas, USA used pyrolytic spraying technique for producing the CdS layer and the Clevite wet process (dipping) is used for producing Cu_2S layer. This firm had plans to produce CdS/Cu_2S cells with a capacity of 5-7 MW/year. Efficiencies of the order of 3 percent are obtained.

(3) Nukem, GmbH, Hanau, West Germany used a modified Clevite process developed at IPE, University of Stuttgart, West Germany for the manufacture of CdS/Cu_2S solar cells.

All the above three firms have stopped the manufacture of these cells largely due to degradation problems and low efficiency. There are several steps involved in the fabrication of CdS/Cu_2S solar cells. These steps as used by IPE, University of Stuttgart, West Germany and transferred to NUKEM, GmbH for commercial production of CdS/Cu_2S cells are depicted in fig 6.40. In this technique glass is used as a substrate material and glass is used for encapsulation. The Clevite process is used for producing CdS and Cu_2S layers. Silver is used as contact material for CdS and gold or graphite is used for Cu_2S layer.

The highest efficiency [87] reported for textured CdS/Cu_2S cell is 9.2 percent. The IEC has reported an efficiency of 10.2 percent for a (Cd, Zn) S/Cu$_2$S polycrystalline cell. The Zn/Cd ratio in the (Cd,Sn)S layer of 30 μm thick is 0.16 and Cu$_2$S layer of 0.3 μm is grown by ion exchange in the conventional manner.

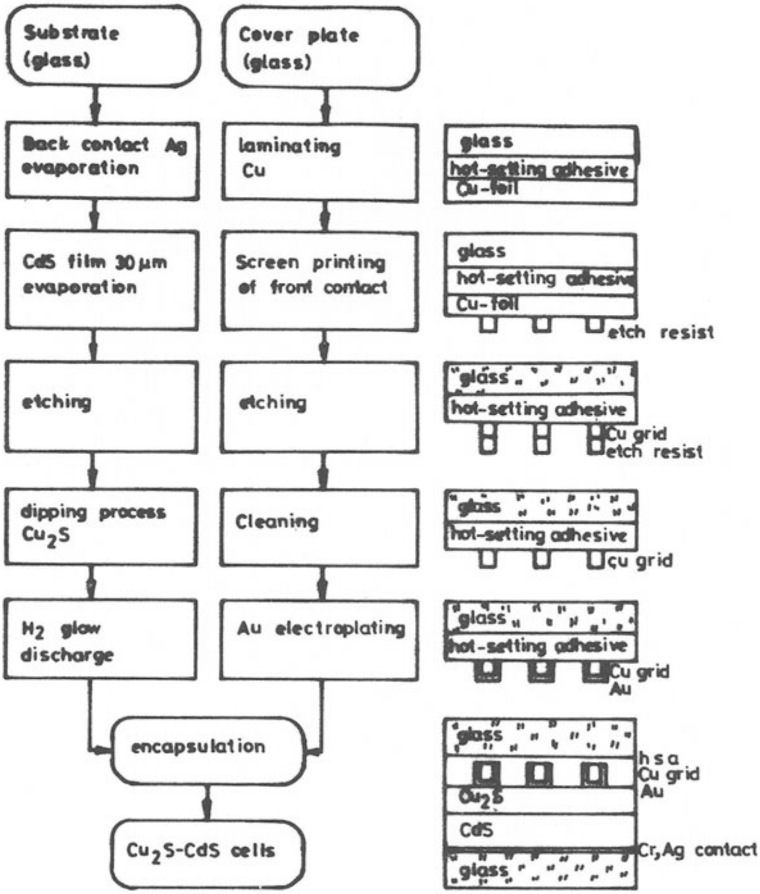


FIG.6.40. STEPS USED IN THE COMMERCIAL PRODUCTION OF CdS/Cu$_2$S SOLAR CELLS AT IPE UNIVERSITY OF STUTTGART WEST GERMANY (Courtesy W.H.Bloss and F.Pfisterer).

6.10 CADMIUM TELLURIDE (CdTe) SOLAR CELL

Cadmium telluride (Cd Te) shows several advantages for its use in thin film heterojunction devices:

- Its nearly direct optimum band gap of 1.47 eV matches with the sun's spectrum and is therefore a potentially high efficiency photvoltaic material.
- It is the only material which can be made highly conductive in both n-type and p-type.
- It has high absorption coefficient of about 10^{6}cm^{-1} and thus absorbing all the incident sunlight within a thickness of 1 µm.

Very little work [197] has been done on single crystal CdTe p/n homojunction cell. A couple of scientists have already reported an efficiency of 13 percent in case of single crystal homojunction cell which uses a p-type cadmium telluride which is grown epitaxially on n-type cadmium telluride. The most promising is the heterojunction structure which uses a wide band gap, high conductivity window layer. Here the base material is the single crystal or polycrystalline Cd Te Wafer[198] over which there is a thin film window layer of material like CdS, ITO, ZnO, ZnSe, SnO_2, CdO. Successful high efficiency CdTe solar cells are make by using single crystal CdTe over which various window materials are deposited by vacuum evaporation, spray pyrolysis, rf sputtering, or closed-spaced vapor transport vapor phase deposition. Presently there are six groups [196] who have claimed efficiencies more than 10 percent in case of heterojunction CdTe solar cells.

1. Matsushita, Japan has claimed an efficiency of 12.8 percent and used a screen printed and CdS-and sintered CdS-and CdTe layers.
2. The Stanford University, USA is using hot-wall vacuum evaporation technique to deposit CdTe film on a substrate.
3. The Southern Methodist University (SMU), USA is using a chemical vapor deposition technique to deposit CdTe film in which the cadmium, tellurium, and dopant glass are introduced via hydrogen carrier gases into a furnace where these are thermally decompose and gets deposited on the substrate. This group has developed a n-ITO/p-CdTe heterojunction cell with 8.2 percent efficiency.
4. The Solar Energy Research Institute of USA is looking to the possibilities of depositing CdTe film on a substrate using electro deposition technique. Monosolar company is also using electrodeposition technique and efficiencies as high as 9 percent have already been achieved on large area CdS-CdTe solar cells.
5. Kodak Company is using a closed-spaced sublimation (CSS) technique for producing CdS-CdTe solar cells.
6. ARCO of USA is also involved in the development of CdS-CeTe solar cells.

6.11 PHOTOVOLTAIC SUNLIGHT CONCENTRATORS

The cost of power produced from solar cell array per unit area can be reduced either by using high efficiency solar cells or by using concentrated sunlight on solar cells [199]. By using suitable type of solar energy concentrator, if the light intensity is increased by 100-fold, then electric power obtained from solar cell module will also increase by 100 times. Thus by using a little costlier cells, the electric power cost can be decreased by 100 times by using solar concentrators. However, the saving is cells cost should be enough to pay for the increased cost of solar cell concentrator, tracking mechanism, and associated control unit. Before deciding a type and size of concentrator following three points should also be carefully considered.

1. When the light intensity increases, the operating current increases, and therefore if the series resistance is of the order of 0.01 ohm. the power generated would be dissipated within the cell without much gain. Therefore the series resistance losses should be reduced to get the higher current.
2. When the light on the solar cell is intensified, the temperature of the solar cell is increased resulting in lowering in cell efficiency. Hence some kind of cooling device either passive or active is to be used to remove the thermal heat from the solar cell. If the light intensification is high more than 10 then active cooling device should be used.
3. The cells with lower band gap like silicon with band gap of 1.1 eV is not suitable for concentrated solar radiation, since the operating temperature of the cell depends on the band gap of the material. If the band gap is higher like that of GaAs which is 1.43 ev, the drop in efficiency will be smaller with the increase in temperature. For GaAs solar cell, the efficiency remain at 10 percent even at a temperature of 250°C.

Considerable work on GaAs solar cells with reference to its use under concentrated solar radiation, photovoltaic concentrators, effect of light intensity and temperature has been carried out [94-111]. As discussed earlier, at a fixed cell temperature, as the solar intensity on the cell increases, the short circuit current increases lineraly and the open circuit voltage increases logarithmically and therefore the fill factor also increases. The high eficiency can be observed only when the series resistance of the cell is low otherwise there will be large losses. The resistance of a cell can be lowered by many ways including: (i) the top contact should be made as fine (fingers) as possible to avoid resistive losses due to lateral current flows, (ii) thick metal contact layers should be used which will result in reducing resistive losses in fingers and busbars, (iii) the diffused top layer should be of low resistivity, and (iv) the substrate should be of low resistivity. The type of cell to be used under concentrated solar radiation depends on the cost of cell and the concentration ratio. If the concentration ratio is less than 100 then there is no point in using GaAs solar cell since the performance of silicon solar cell is also adequate. But if the concentration ratio is more than 100 i.e. around 1000 then Si solar cell should not be used and the only choice is of GaAs solar cell.

Solar energy concentrators which are generally recommended for solar cells re linear concentrators (parabolic trough, V-trough concentrator, linear fresnel lens), point focus concentrators (parabolic dish, point focus fresnel lens, parabolic conentrator, spherical concentrator), compound parabolic concentrators (stationary and seasonal adjusting type), and plane mirror boosters. Both the single axis, two axis tracking, and stationary concentrators have advantages and disadvantages. The concentration ratio in case of stationary concentrators is generally below 3 but these can be made easily. The concentrator with seasonal adjustment are simple and can give a concentration ratio upto 12. Both the symmetric and asymmetric stationary concentrators can be employed. If high concentration ratio is not required, then linear parabolic troughs with single axis tracking can be used. A number of firms are making point focus fresnel lenses made of acrylic sheets for their use with solar cells. A good review of solar energy concentrators is given by Garg[200].

Heat from the solar cell can be removed either by active or passive means. Active cooling device is quite effective and generally water or air is circulated behind the solar cells. The active cooling device is used where the concentration ratio is quite high resulting in cell temperatures more than 100°C. Where the concentration ratios are low and cell temperature is less than 100°C, passive cooling devices are quite effective. In passive cooling systems, some kind of fins are attached to the cell base which help in dissipating the heat to the surroundings. Recently a concept of combined photovoltaic/thermal (PV/T) concept is introduced where the photovoltaic module is fixed on a flat-base through which air or water is circulated and which gets heated and can be used for different applications. Some kind of concentrator generally CPC is also used in such units. Thus PV/T units appear to be more useful since both the electric power and thermal heat are obtained.

Several projects are funded by Department of Energy (DOE) and few firms of USA for the development of solar photovoltaic concentrator systems. The details of some of the projects are summarized in Table 6.11

Table 6.11 Typical photovoltaic concentrator designs

Component	Firms						
	Sandia	Spectrolab	Martin-Marietta	Argonne	Suntrack	General Electric	M.I.T.
Size	1 KW, 12.6 m^2	500W, 1.28x2.64 m troughs	9.2 KW,	100W, 1.5 m^2	50W, 0.77 m	22.3 m^2	0.29 m^2
Optics	135 fresnel lens each of 30cm dia. CR=60	parabolic trough CR=25	Circular fresnel lens(272 Nos.) each of 0.3x1.22 m, CR=34	Reflective CPC, CR=9.2	Reflective Cone, CR=9	Parabolitrough CR=34	paraboloidal dish CR=200
Tracking system	two axis tracking	two axis tracking	two axis tracking	seasonal adjustment	two axis tracking	two axis tracking	two axis tracking
Cell type	Silicon	Silicon	Silicon	Silicon	Silicon	Silicon	Silicon
Cooling	Passive	Passive	Actice	Passive	Passive	Active	Active

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APPENDICES

The following general information is given in the succeeding pages:

Appendix 1: Conversion factors.
Appendix 2: Physical properties of some solid materials.
Appendix 3: Physical properties of some building and insulating materials.
Appendix 4: Physical properties of some liquids.
Appendix 5: Physical properties of some liquid metals.
Appendix 6: Physical properties of saturated water.
Appendix 7: Physical properties of saturated steam.
Appendix 8: Physical properties of some gases.
Appendix 9: Physical properties of dry air at atmospheric pressure.
Appendix 10: Freezing points of aqueous solutions.
Appendix 11: Properties of typical refrigerants.
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APPENDIX 1

CONVERSION FACTORS

The following relations can be used for conversion of units fromone system to another (between Metric, British and SI).

(i) LENGTH (m)

1 in = 25.4 mm = 2.54 cm = 0.0254 m = 0.0833 ft = 0.0277 yd.
1 cm = 10 mm = 0.01m = 0.3937 in = 0.0328 ft = 0.0109 yd.
1 ft = 30.48 cm = 0.3048 m = 0.3333 yd.
1 yd = 3 ft = 36 in = 0.9144 m
1 m = 100 cm = 1000 mm = 3.2808 ft = 39.37 in = 1.0936 yd.
1 km = 0.62137 mile
1 mile = 1.60934 km
1 Angstrom = 10^{-8}cm
1 μm = 10^{-6}m = 10^{-4}cm = 10^{4} A°
1 mm = 1000 microns (μ)
1 Chain = 20.1168 m
1 Furlong = 201.168 m
1 mil = 2.54 x 10^{-3}cm
1 links = 0.2012 m
1 fathom = 1.8288 m

(ii) AREA (m^2)

1 ^{2} = 6.4516 cm^2 = 0.000645 m^2 = 0.0069 ft^2 = 0007716 yd^2.
1 cm^2 = $10^{-4}m^2$ = 10.764 x 10^{-4} ft^2 = 0.1550 in^2 = 10^{24} barns.
1 ft^2 = 0.0929 m^2 = 929.03 cm^2 = 144 in^2 = 0.111 yd^2
1 m^2 = 10.7693 ft^2 = 1.196 yd^2
1 yd^2 = 0.836 m^2
1 acre = 4046.86 m^2 = 0.404686 ha = 43560 ft^2
1 $mile^2$ = 2.58999 km^2 = 640 acres
1 ha = 10^4 m^2 = 2.47 acres

(iii) VOLUME (m^3)

1 in^3 = 16.387 cm^3 = 1.639 x 10^{-2}1
1 ft^3 = 0.02832 m^3 = 28.3168 1
1 yd^3 = 0.764555 m^3 = 7.646 x 10^2 1
1 1 = 1000 cm^3 = 61.024 in^3 = 0.21997 gallons (UK) = 0.2642 gallons (US)
1 m^3 = 10^6 cm^3 = 2.642 x 10^2 gallon (US) = 10^9 1
1 gallon (UK) = 4.54609 1 = 0.1605 ft^3 = 1.20108 gallon (US)

1 gallon (US) = 3.785 l = 0.83258 gallon (UK)
1 UK pint = 0.568261 l = 0.0568 m^3
1 bushel(bu) = 0.036369 m^3 = 8.000 gallon (UK)
1 barrel (US) = 42.000 gallon (US) = 0.1590 m^3
1 quart = 1.136 x 10^{-3} m^3
1 fluid ounce = 28.41 cm^3

(iv) MASS (kg)

1 g = 10^{-3} kg = 0.0938 tola = 0.5643 dram = 0.002205 lb = 15.432 grains
1 kg = 2.20462 lb = 0.068522 slug
1 lb = 16 OZ (Ounces) = 0.4536 kg
1 tola = 10.66 g
1 OZ = 28.3495 g
1 slug = 32.1739 lb = 14.59 kg
1 stone = 6.350293 kg
1 maund = 40 seers = 37.32 kg
1 quintal = 100 kg = 220.462 lb
1 grain = 0.0648 g
1 carat = 0.2 g
1 tons = 1016 kg
1 tonnes (t) = 1000 kg = 10 quintal = 2204.62 lb
1 dram = 1.772 g
1 hundred weight (wt) = 50.802345 kg

(v) DENSITY AND SPECIFIC VOLUME (kg/m^3, m^3/kg)

1 g/cm^3 = 10^3 kg/m^3 = 62.43 lb/ft^3
1 lb/ft^3 = 16.0185 kg/m^3 = 5.787 x 10^{-4} lb/in^3
1 kg/m^3 = 10^{-3} g/cm^3 = 0.06243 lb/ft^3
1 OZ/ft^3 = 1 kg/m^3
1 slug/ft^3 = 515.4 kg/m^3
1 cft (air) = 0.0809 lb = 36.5 gm at NTP
1 l (air) = 1.2982 g at NTP
1 gallon/lb = 0.010 cm^3/kg

(vi) DISCHARGE (m^3/s)

1 g.p.m.(gallons/minute) = 0.0785 x 10^{-3} cm^3/s
1 l/s = 10^{-3} m^3/s
1 lb/s = 0.4536 kg/s
1 tons/hr = 0.282 kg/s
1 cusecs (ft^3/s) = 0.02832 m^3/s
1 curnecs(m^3/s) = 1 m^3/s = 3.6 x 10^6 l/hr
1 ft^3/min = 0.4720 l/s = 4.179 x 10^{-4} m^3/s
1 yd^3/min = 12.74 l/s

(vii) ANGLE (rad.)

1 degree = 0.0174533 rad = 60 minute
1 minute = 0.000291 rad = 60 seconds
1 second = 4.84814 x 10^{-6} rad
2 rad = 360 degrees

(viii) TEMPERATURE (°C and K)

°F = (1.8 x °C) + 32
°C = (°F - 32) /1.8
°R = °F + 459.69, K = °R/1.8, °R = 1.8 K
k = °C + 273.16
Δt°C = Δt°F/1.8

(ix) PRESSURE (Pa)

1 bar = 0.98692 atm = 14.504 lbg/in^2 = 10^5 N/m^2 = 100 KPa = 1.00x10^6 dynes/cm^3 = 29.53 in Hg = 750.06 mm Hg = 401.85 m H_2O.

1 N/m^2 = 1 Pa = 10^{-5} bar = 7.5006 x 10^{-3} mmHg = 4.0185x10^3 in H_2O = 2.953 x 10^{-4} in Hg = 0.98692 x 10^{-5} atm. = 1.4504 x 10^{-4} lbf/in^2

1 atm = 1.013 x 10^5 N/m^2 = 760 mmHg = 101.325 KPa = 1.01325 bar

1 lb/in^2 = 702.7 kg/m^2 = 51.71 mmHg = 6.894757 KPa = 6.894757 x 10^3 N/m^2

1 Pa = 0.02088 lb/ft^2 = 10 dynes/cm^2 = 10^{-5} bar = 0.0075 Torr = 98.69 x 10^{-7} atm. = 0.00075 cmHg = 1 N/m^2

1 lb/ft^2 = 4.88 kg/m^2 = 47.88 Pa

1 torr = 0.1333 KPa

1 inch of Hg = 3.377 KPa = 0.489 lb/in^2 =33.4213 x 10^{-3} atm = 33.8582x10^{-3} bar = 33.8582x10^{-3} N/m^2

1 ft H_2O = 2.989 KPa

(x) VELOCITY (m/s)

1 ft/s = 0.3048 m/s
1 ft/min = 0.00508 m/s
1 mph = 0.44704 m/s = 1.4667 ft/s = 0.8690 knots
1 mph = 1.60934 km/hr
1 Knot = 0.5144 m/s = 1.6878 ft/s
Km/hr = 0.2778 m/s

(xi) FORCE(N)

1 N = 10^5 dyne = 0.1019 kgf = 0.2248 lbf = 7.233 poindal

1 Poundal = 0.138 255 N = 13.83 dynes

1 lbf = 4.448222 N = 444.8222 dynes

1 ton = 9.964 x 10^3N

1 Kgf = 9.8065 N = 2.205 lbf

1 dyne = 1.020 x10^{-6} kgf =2.2481x10^{-6} lbf = 7.2330x10^{-5} pondal = 10^{-5} N = 10 μn

1 kip = 4.44822 KN

(xii) VISCOSITY (Pa S, Ns/m^2)

1 g/cm s/(poise) = 100 cp (contipoise) = 360 kg/mhr = 1 dyne s/cm^2 = 10^{-1} kg/ms = 0.067197 lb/fts = 2.04191 x 10^2 lb/ft hr

1 lb/fts = 14.882 g/cm s = 148.82 cp = 3600 lb/ft hr

1 poise = 0.1 kg/ms = 0.1 NS/m^2 = 1.020x10^{-2} kgs/m^2 = 2.088x10^{-3} lbf s/ft^2

1 cp = 0.001 NS/m^2 = 10^{-3} kg/ms = 6.7197 x 10^{-4} lb/fts = 10^{-3} Pa s = 2.4191 lb/ft hr

1 centistokes (CSt.) = 10^{-6} m^2/s

1 NS/m^2 = 1000 cp = 0.1019 kgfs/m^2 = 0.947x10^{-3} lbfs/ft^2 = 0.658x10^{-5} lbf s/in^2

1 slug/ft s = 4.788 x 10 NS/m^2

(xiii) KINEMETIC VISCOSITY, DIFFUSIVITY α (m^2/s)

1 m^2/s = 3600 m^2/hr = 10^4 cm^2/s = 3.875 x 10^4 ft^2/hr = 10^6 cst = 10.76 ft^2/s = 15.50 in^2/s

1 m^2/hr = 2.7778 cm^2/s = 2.7778x10^{-4} m^2/s = 10764 ft^2/hr

1 cm^2/s(stoke) = 10^{-4} m^2/s = 3.875 ft^2/hr = 0.36 m^2/hr

1 ft^2/hr = 0.25807 cm^2/s = 2.5807x10^{-5} m^2/s = 0.09291 m^2/hr

(xiv) ENERGY (J)

1 J (Joule) = 2.390x10^{-4} kcal = 2.778x10^{-4} whr = 1 w-s = 10^7 erg = 0.73756 ft lb = 0.23901 cal = 9.4783x10^{-4} btu = 1 kgm^2 S^{-2}

1 cal = 4.184 J = 4.184x10^7 erg = 3.9657x10^{-8} btu = 1.5586x10^{-6} hphr = 1.1622x10^{-6} kwhr

1 Btu = 0.252 kcal = 2.93x10^{-4} kwh = 1.055x10^{3}J = 1.055x10^{10} erg = 0.39301 hphr

1 Kcal = 3.97 Btu = 12x10^{-4} kwh = 4.187x10^{3}J = 4.184x10^{10} erg

1 Kwh = 3.6x10^{6}J = 3.6x10^{13} erg = 860.42 Kcal= 3.4122x10^3 Btu = 1.341 hphr

1 erg = 10^{-7}J = 2.3901x10^{-8} cal = 9.4783x10^{-11} Btu = 3.7251x10^{-14} hphr = 2.7778x10^{-14} kwhr = 1gcm^2 S^{-2} = 1.0 x10^{-7} Nm = 1.0 dyne cm

1 watt = 1.0 J/s

1 hp = 632.34 kcal = 0.736 kwh = 2.685 MJ

1 therm = 1.055 x 10^{8}J = 105.51 MJ

1 chu = 1.9 x 10^{3}J

1 ft lbf = 1.3558 J = 0.32405 cal = 3558x10^7 erg = 1.2851x10^{-3} Btu = 5.0509x10^{-7} hphr = 3.7662x10^{-7} kwh

1 ev = 0.16021 aJ

(xv) POWER (W,J/S)

1 w = 1 J/S = 0.80 kcal/hr = 978x10^{-4}Btu/s = 1.341x10^{-3} hp = 0.7376 ft lb/s = 0.0143 kcal/m

1 hp (FPS) = 746 w = 596.8 kcal/hr = 1.015 hp (MKS) = 42.41 Btu/min = 550 ft lbf/s

1 hp (MKS) = 735.3 w = 0.17569 kcal/s = 75 m kg f/s

1 w/ft^2 = 10.76 w/m^2

(xvi) SPECIFIC HEAT, ENTROPY, LATENT HEAT (KJ/KgK)

1 Btu/lb = 0.5556 kcal/kg = 2.326 KJ/Kg = 0.5556 chu
1 Btu/lb°F = 1.0 Kcal/Kg°C = $4.187x10^{3}$J/Kg°C
1 Btu/lb°R = 4.187 KJ/Kg K

(xvii) THERMAL CONDUCTIVITY (w/m°C)

1 Btu/hrft°F = 1.488 kcal/hrm°C = 1.7307 w/mk
= $4.1365x10^{-3}$ cal/s cm k
1 Kcal/mhr°C = 0.6719 Btu/ft hr °F = 1.1631 w/m °C
= $2.778x10^{-3}$ cal/s cm k
1 w/m K = 0.5778 Btu/hrft°F = 8598 kcal/hr m °C
= $2.3901x10^{-3}$ cal/s m k
1 Btu in/ft^{2}hr°F = 0.124 kcal/m hr°C = 0.1442 w/m°C
1 Btu/in hr°F = 17.88 kcal/m hr°C
1 cal/s cm°F = 359.724 kcal/hrm°F = 241.75 Btu/hrft°F
= 418.4 w/mk

(xviii) HEAT TRANSFER COEFFICIENT (w/m^{2}°C)

1 Btu/ft^{2}hr°F = 4.883 kcal/m^{2}hr°C = 5.6782 w/m^{2}°C
= 1.3571 cal/m^{2}sk
1 Kcal/m^{2}hr°C = 1.163 w/m^{2} K = 0.2048 Btu/ft^{2} hr °F
= 2.78 x 10^{-5} cal/cm^{2}sk
1 w/m^{2}k = 10^{-4} w/cm^{2}k = 0.86 kcal/m^{2}hr°C = $1.7611x10^{-1}$
Btu/ft^{2}°F = $2.3901x10^{-5}$ cal/cm^{2} sk.
1 cal/cm^{2}sk = 4.184 w/cm^{2}k = 36000 kcal/m^{2}hr°C =
$7.3686x10^{3}$ Btu/ft^{2}hr°F
1 pcu/ft^{2}hr°C = 4.878 kcal/m^{2}hr°C

(xix) ENERGY FLOW RATE (W)

1 W=3.4143 Btn/hr=0.23901 Cal/S=0.86 K Cal/hr
1 Btu/hr=0.252 KCal/hr=0.29307W
1 KCal/hr=1.163W=3.968 Btu/hr=0.2778 Cal/S
1 Cal/S=4.184 W=14.285 Btu/hr=3600 Cal/hr
1 Ton (Ref.)=3.517 KW =50 KCal/min = 200 Btu/min

(xx) ENERGY FLUX (W/m^{2})

1 W/m^{2}= 0.137 Btn/hr ft^{2} =0.86 K cal/m^{2}hr=$2.3901x10^{-5}$
Cal/cm^{2}SK
1 Btu/ft^{2}hr= 3.1552 W/m^{2}=2.713 K cal/m^{2} hr
1 KCal/m^{2}=1.163 W/m^{2}=0.3690 Btu/ft^{2}hr=$27.78x1^{-6}$
Cal/Scm^{2}
1 pcu/ft^{2}hr=4.878 KCal/m^{2}hr
1 Cal/cm^{2}min=221.4 Btu/ft^{2}hr
1 Cal/cm^{2}s=30960w/m^{2}=14.285 Btu/ft^{2}=36000 KCal/m^{2}hr

(xxi) ENTHALPY (J/g)

1 Btu/lb.=2.321 J/g=0.5556 chu=0.5556 Cal/g

(xxii) HEAT LOSS (MJ/DD(°C)m^2)

1 Btu/DD(°F)ft^2=0.0204 41 MJ/DD(°C)m^2

(xxiii) ILLUMINATION

1 foot candle =10.7639 lx (lux)
1 lx = 1.000 lm (luman)/m^2
1 lm/m^2=1.000 foot candle
1 foot lamberts=3.426 candle/m^2

(xxiv) TIME (hr)

1 s (second) = 9.192631770 x 10^9 Hertz (Hz)
1 week = 7days = 168 hr = 10080 min = 604800 s
1 calender year = 365days = 8760 hr =5.256 x 10^5 minutes
1 mean solar day = 1440 minute = 86400 s
1 tropical mean solar year = 365.2422 days
1 sidereal year = 365.2564 days (mean solar)

APPENDIX 2

PHYSICAL PROPERTIES OF SOME SOLID MATERIALS

Material	Density Kg/m^3	Temperature ^oC	Thermal conductivity W/mk	Specific heat KJ/Kg^oC	Thermal diffusivity x10^3 m^2/hr
NON-METALS					
Alumina	3800	20	2.9	0.800	-
Aluminum Foil	20	50	0.047	-	-
Asbestos Fibre	470	50	0.110	0.816	1.04
Asphalt	2110	20	0.697	2.093	0.57
Brick, masonry	800 to 1500	20	0.23 to 0.29	-	-
Cellotex	215	20	0.047	-	-
Chalk	2000	50	0.093	0.879	1.91
Clinker	1400	30	0.163	1.675	0.41
Coal	1400	20	0.186	1.424	0.41
Concrete	2300	20	1.279	1.130	1.77
Cork, sheet	190	30	0.042	1.884	0.42
Firebrick	550	100	0.140	-	-
Glass	2500	20	0.744	0.670	1.60
Gravel	1840	20	0.360	-	-
Ice	920	0	2.249	0.261	3.89
Leather	1000	30	0.159	-	-
Marble	2700	90	1.302	0.419	4.15
Mica	290	-	0.581	0.879	8.20
Mineral wool	200	50	0.047	0.921	0.91
Paraffin	920	20	0.267	-	-
Plaster	1680	20	0.779	-	-
Perspex	1190	50	0.200	1.500	-
Rubber	1200	0	0.163	1.382	0.353
Sand Dry	1500	20	0.325	0.796	9.85

Appendix 2 Contd...

Sand, Wet	1650	20	1.127	2.093	1.77
Slate	2800	100	1.488	-	-
Snow	560	-	0.465	2.093	1.43
Soil dry	1500	-	0.138	-	-
Soil wet	1700	-	0.657	2.010	0.693
Teflon	2200	20	0.250	1.050	-
METALS					
Aluminum	2670	0	203.403	0.921	328.0
Brass	8600	0	85.429	0.877	95.0
Copper	8800	0	383.559	0.381	412.0
Iron	7220	20	62.764	0.502	62.5
Lead	11400	0	34.869	0.1298	85.0
Silver	10500	20	419.0	0.235	0.5
Solder(50Pb50Sn)	9000	-	-	0.176	-
Stainless steel (18 cr/8 Ni)	7930	20	150.0	0.510	-
Steel, mild	7860	-	63.0	0.420	-
Tin	7300	20	65.0	0.226	139
Zinc	7140	20	111.0	0.385	148

APPENDIX 3

PHYSICAL PROPERTIES OF SOME BUILDING AND INSULATING MATERIALS

Meterial	Temperature °C	Density Kg/m^3	Thermal Diffusivity x 10^3 m^2/hr	Thermal Conductivity x 10^3 W/m k	Specific heat KJ/Kg K
Alumina		3800	-	2900	-
Aluminium foil	50	20	-	46.5	-
Asbestos, fibre	50	470	1.04	110.5	0.816
Asbestos, sheet	30	770	0.71	116.3	0.816
Brick, Masonay	20	800-1500	-	233-291	0.840
Carborundum brick	-	1000	6.00	11281	0.678
Cardboard, corrugated	-	-	-	64.0	-
Chalk	50	2000	1.91	930.4	0.879
Clinker	30	1400	0.41	162.8	1.675
Coal	20	1400	0.37	186.1	1.306
Concrete	20	2300	1.77	1.279	1.130
Cork, granulated	20	45	-	38.4	-
Cork, sheet	30	190	0.42	41.9	1.884
Earth, dry	-	1500	-	138.4	-
Earth, wet	-	1700	0.69	657.1	2.010
Fibreplate	20	240	-	48.9	-
Glass	20	2500	1.60	744.3	0.67
Glass wool	20	200	1.00	37.2	0.67
Gravel	20	1840	-	360.5	-
Gypsum	-	1650	-	290.8	-
Leather	30	1000	-	159.5	-
Magnesia (85% powder)	100	216	-	67.5	-
Marble	90	2700	4.15	1303	4.187

Appendix 3 Contd...

Mica	-	200	8.20	581.5	8.792
Mineral wool	50	200	0.91	46.5	0.921
Paraffin	20	920	-	267.5	-
Perspex	-	1190	-	200	1.500
Plaster	20	1680	-	779.2	-
Polyethylene	-	920	-	-	2.300
Porcelein	95	2400	1.43	1035	1.089
Portland cement	30	1900	0.51	302.4	1.130
Quartz, across grain	0	2500-2800	12.00	7211	0.837
Refractory clay	450	1845	1.86	1035	1.089
Rubber	0	1200	0.35	162.8	1.382
Sand, dry	20	1500	9.85	325.6	0.796
Sand, wet	20	1650	1.77	1128	2.093
Sand, dust	20	200	-	69.8	-
Slag wool	100	250	-	69.8	-
Slate	100	2800	-	1489	-
Teflon (PTFE)	-	2200	-	250	1.050
Wool felt	30	330	-	52.3	-
Wood, Oak	-	700	-	150	-

APPENDIX 4

PHYSICAL PROPERTIES OF SOME LIQUIDS

Liquid	Formula	Density Kg/m^3	Viscosity x 10^3 Ns/m^2	Melting point K	Boiling point K	Thermal Conductivity W/mK	Specific heat J/KgK	latent heat x 10^4 J/Kg	Heat of Vapour-zation x 10^4 J/Kg	Coefficient of cubical expans-ion x 10^4 β/K
Acetic acid	$C_2H_4O_2$	1049	1.219	290	391	0.180	1960	18.1	39	10.7
Acetone	C_3H_6O	780	0.329	178	330	0.161	2210	8.2	52	14.3
Ammonia	NH_3	665	-	-	-	0.558	4606	-	-	- (at-20°C)
Benzene	C_6H_6	879	0.647	279	353	0.140	1700	12.7	40	12.2
Chloroform	$CHCl_3$	1489	0.569	210	334	0.121	960	7.9	2.5	12.7
Crude oil	...	860	1.379	...	...	0.155	...	...	...	10.8
Ethyl alcohol	C_2H_6O	789	1.197	156	352	0.177	2500	10.4	85	10.8
Glycerine	$C_3H_8O_3$	1262	1495	293	563	0.270	2400	19.9	83	4.7
Mercury	Hg	13546	1.552	234	630	7.6	140	1.17	29	1.82
Olive oil	...	920	85	...	570	0.17	1970	...	...	7.0
Paraffine Oil	...	800	1000	...	...	0.15	2130	...	...	...
Terpentine	...	870	1.49	263	429	0.136	1760	...	29	9.7
Sea-water	...	1020	1.02	264	377	...	3900	33.0	...	...
Water	H_2O	998	1.00	273	373	0.591	4190	33.4	226	2.1

APPENDIX 5

PHYSICAL PROPERTIES OF SOME LIQUID METALS

Metal	Melting Point ^oC	Temperature ^oC	Thermal Conduct-ivity w/m K	Density Kg/m^3	Specific heat KJ/Kg K	Viscosity Kg/m hr	Prandtl Number
Bismuth	271.1	300	16.505	10,020	0.144	5.95	0.0144
		500	15.575	9770	0.152	4.27	0.0116
		700	15.575	9530	0.162	3.35	0.0097
Lead	327.2	350	16.272	10,500	0.159	8.65	0.0235
		500	15.575	10,350	0.155	6.92	0.0190
		700	14.006	10,100	0.155	4.93	0.0150
Mercury	-38.3	15	8.136	13,550	0.138	5.73	0.0270
		150	11.623	13,200	0.138	3.95	0.0120
		300	14.064	12,800	0.134	3.11	0.0084
Potassium	63.9	150	44.981	810	0.796	1.34	0.0066
		400	39.518	740	0.754	0.64	0.0035
		700	33.126	670	0.754	0.46	0.0031
Sodium	97.8	100	86.591	930	1.382	2.51	0.0110
		350	72.295	858	1.298	1.04	0.0050
		700	59.626	780	1.256	0.64	0.0038
Alloy (25Na-75K)	-11.0	200	23.26	822	1.072	-	0.0171
		300	22.68	799	1.038	-	0.0134
		400	22.10	775	1.000	-	0.0108

Appendix 5 Contd...

Lithium	186	200	37.22	515	4.187	-	0.0643
		300	38.96	505	4.187	-	0.0503
		400	41.87	495	4.187	-	0.0404
		500	45.36	484	4.187	-	0.0328
Tin, Sn	231.9	250	34.08	6980	0.255	-	0.0141
		300	34.73	6940	0.255	-	0.0126
		400	33.15	6865	0.255	-	0.0106
		500	32.56	6790	0.255	-	0.0092

APPENDIX 6

PHYSICAL PROPERTIES OF SATURATED WATER

Temper- ature °C	Density Kg/m^3	Specific heat KJ/Kg °C	Thermal Conduct- ivity x10^2 W/mK	Thermal diffusi -iyity 10^4 m^2/hr	Viscosity 10^2 Kg/hr m	Kinematic viscosity x 10^6 m^2/Sec.	Prandtl Number
0	999.9	4.212	55.093	4.71	644.093	1.789	13.67
10	999.7	4.191	57.418	4.94	469.818	1.306	9.52
20	998.2	4.183	59.859	5.16	361.892	1.006	7.02
30	995.7	4.174	61.718	5.35	288.668	0.805	5.42
40	992.2	4.174	63.345	5.51	235.602	0.659	4.31
50	938.1	4.174	64.740	5.65	197.771	0.556	3.54
60	938.2	4.178	65.902	5.78	169.305	0.478	2.98
70	977.8	4.187	66.716	5.87	146.370	0.415	2.55
80	971.8	4.195	67.413	5.96	127.924	0.365	2.21
90	965.3	4.208	67.995	6.03	113.507	0.326	1.95
100	958.4	4.220	68.227	6.09	101.910	0.295	1.95
110	951.0	4.233	68.460	6.13	93.215	0.272	1.60
120	943.1	4.250	68.576	6.16	85.448	0.252	1.47
130	934.8	4.266	68.576	6.19	78.744	0.233	1.36
140	926.1	4.287	68.460	6.21	72.475	0.217	1.26
150	917.0	4.312	68.343	6.22	66.792	0.203	1.17
160	907.4	4.346	68.227	6.23	62.206	0.191	1.10
170	897.3	4.379	67.878	6.22	58.623	0.181	1.05
180	886.9	4.417	67.413	6.20	54.976	0.173	1.00
190	876.0	4.459	66.949	6.17	51.921	0.165	0.96
200	863.0	4.505	66.251	6.14	49.266	0.158	0.93

Appendix 6 Contd.....

220	840.3	4.614	64.508	5.99	44.823	0.148	0.89
240	813.6	4.756	62.764	5.84	41.356	0.141	0.87
260	784.3	4.949	60.440	5.61	38.274	0.135	0.87
280	750.7	5.229	57.418	5.27	35.596	0.131	0.90
300	712.5	5.736	53.931	4.75	32.835	0.129	0.97

APPENDIX 7

PHYSICAL PROPERTIES OF SATURATED STEAM

Temper -ature ^oC	Density Kg/m^3	Specific heat KJ/Kg^oC	Thermal conduct- ivity $x\ 10^2$ W/mK	Thermal diffusi -vity $x10^3\ m^2/hr$	Viscosity $x\ 10^2$ Kg/hr m	Kinematic viscosity $x\ 10^6\ m^2$ /sec.	Prandtl Number
100	0.598	2.135	2.371	67.9	4.320	20.02	1.08
110	0.826	2.177	2.487	49.8	4.487	15.07	1.09
120	1.121	2.206	2.592	37.8	4.613	11.46	1.09
130	1.496	2.257	2.685	28.7	4.757	8.85	1.11
140	1.966	2.315	2.790	22.07	4.861	6.89	1.12
150	2.572	2.395	2.883	17.02	5.030	5.47	1.16
160	3.258	2.479	3.010	13.40	5.162	4.39	1.18
170	4.122	2.583	3.127	10.58	5.276	3.57	1.21
180	5.157	2.709	3.266	8.42	5.430	2.93	1.25
190	6.394	2.855	3.417	6.74	5.604	2.44	1.30
200	7.862	3.023	3.545	5.37	5.745	2.03	1.36
210	9.488	3.199	3.179	4.37	5.906	1.71	1.41
220	11.62	3.408	3.894	3.54	6.050	1.45	1.47
230	13.99	3.634	4.091	2.90	6.245	1.24	1.54
240	16.76	3.881	4.289	2.37	6.409	1.06	1.61
250	19.98	4.158	4.510	1.96	6.564	0.913	1.68
260	23.72	4.467	4.800	1.63	6.774	0.794	1.75
270	28.09	4.815	5.103	1.36	6.948	0.688	1.82
280	33.19	5.234	5.486	1.14	7.174	0.600	1.90
290	39.15	5.694	5.823	0.941	7.404	0.526	2.01
300	46.21	6.280	6.265	0.778	7.654	0.461	2.13

320	64.72	8.206	7.509	0.509	8.240	0.353	2.50
340	92.76	12.351	9.763	0.252	9.539	0.272	3.35
360	144.00	23.027	12.785	0.139	10.460	0.202	5.23

APPENDIX 8

PHYSICAL PROPERTIES OF SOME GASES

Name	Formula	Melting temper -ature K	Boiling temper -ature K	Thermal conduct -ivity x 10^{-4} W/mK	Density (at S.T.P.) Kg/m^3	Viscosity x 10^{-6} Ns/m^2	Heat of Vapori-zation x 10^4 J/Kg	Specific heat (at 300 K) J/KgK	Ratio of specific heats
Acetylene	C_2H_2	192.4	189	189	1.175	9.35		1590	1.26
Air	(78.0 N_2 (20.95 O_2 (0.96 Misc		83	241	1.93	18.325 (300K)	21.4	993	1.402
Ammonia	NH_3	195.43	240	218	0.770	9.18	137.1	190	1.310
Carbon dioxide	CO_2	216	195	145	1.977	14	36.4	845	1.304
Carbon monoxide	CO	66	81	232	1.250	16.6	21.1	1040	1.404
Chlorine	Cl_2	171.7	238	72	3.214	12.9	28.1	478	1.355
Hydrogen	H_2	13.7	20.35	1684	0.090	8.35	45.3	14300	1.410
Methane	CH_4	190.64	109	302	0.717	10.3	51.1	2200	1.313
Nitrogen	N_2	62.7	77	243	1.250	16.7	20.9	1040	1.404
Oxygen	O_2	54	90	244	1.429	19.2	24.3	918	1.401
Water vapour (273K)	H_2O	273	373	158	0.800	8.7	226.1	1890 (at 373K)	...
Freon-12	CCl_2F_2	118.2	242.6	...	3.50	...	...	...	...
Freon-22	$CHClF_2$	113.2	229.5	...	4.20	...	...	...	...

APPENDIX 9

PHYSICAL PROPERTIES OF DRY AIR AT ATMOSPHERIC PRESSURE

Temper -ature °C	Density Kg/m^3	Specific heat KJ/KgK	Thermal conduct -ivity x 10^2 W/mK	Thermal diffus- ivity x 10^2 m^2/hr	Viscosity x 10^2 Kg/hr m	Kinematic Viscosity x 10^6 m^2/sec.	Prandtl Number
-50	1.584	1.013	2.034	4.57	5.264	9.23	0.728
-40	1.515	1.013	2.115	4.96	5.475	10.04	0.728
-30	1.453	1.013	2.197	5.37	5.645	10.80	0.723
-20	1.395	1.009	2.278	5.38	5.822	12.09	0.716
-10	1.342	1.009	2.360	6.28	5.996	12.43	0.712
0	1.293	1.005	2.441	6.77	6.188	13.28	0.707
10	1.247	1.005	2.511	7.22	6.346	14.16	0.705
20	1.205	1.005	2.592	7.71	6.533	15.06	0.703
30	1.165	1.005	2.673	8.23	6.717	16.00	0.701
40	1.128	1.005	2.755	8.75	6.904	16.96	0.699
50	1.093	1.005	2.824	9.29	7.067	17.95	0.698
60	1.060	1.005	2.894	9.79	7.221	18.97	0.696
70	1.029	1.009	2.964	10.28	7.344	20.02	0.694
80	1.000	1.009	3.045	10.87	7.523	21.09	0.692
90	0.972	1.009	3.127	11.48	7.701	22.10	0.690
100	0.946	1.009	3.208	12.11	7.880	23.13	0.688
120	0.898	1.009	3.336	13.26	8.170	25.45	0.686
140	0.854	1.013	3.487	14.52	8.479	27.80	0.684
160	0.815	1.017	.638	15.80	8.786	30.08	0.682
180	0.779	1.022	3.778	17.10	9.070	32.49	0.681
200	0.746	1.026	3.929	18.49	9.380	34.85	0.680
250	0.674	1.038	4.266	21.49	10.020	40.61	0.677

APPENDIX 10

FREEZING POINTS OF AQUEOUS SOLUTIONS

Alcohol		Glycerine		Ethylene glycol		Propylene glycol	
% by wt.	°C	% by wt.	°C	% by wt.	°C	% by wt.	°C
5	-2.2	10	-1.6	15	-5.3	5	-1.7
10	-4.7	20	-4.8	20	-8.8	10	-3.3
15	-6.8	30	-9.5	25	-12.2	15	-5.3
20	-10.4	40	-15.4	30	-15.8	20	-7.2
25	-14.7	50	-23.0	35	-29.0	25	-9.7
30	-19.2	60	-34.7	40	-24.7	30	-12.8
35	-25.1	70	-38.0	45	-30.0	35	-16.4
40	-29.4	80	-20.8	50	-35.8	40	-20.8
45	-33.0	90	-1.6			45	-26.1
50	-36.7	100	+17			50	-31.9
55	-40.3					55	-39.7
						59	-49.4

APPENDIX 11

PROPERTIES OF TYPICAL REFRIGERANTS

Refregerant	Boiling Point (°C)	Heat of vapour -ization at boiling point at atmospheric pressure (MJ/Kg)
Ammonia	-33.3	1.2900
Carbon dioxide	-79.2	0.2698
Ethyl chloride	13.1	0.4117
Freezol (isobutane)	-12.2	0.4036
Freon II (CCl_3F)	23.8	0.1820
Freon 12 (CCl_2F_2)	-29.8	0.1650
Freon 13 ($CClF_3$)	-81.4	0.1490
Freon 21 ($CHCl_2F$)	8.9	0.2424
Freon 22 ($CHClF_2$)	-40.8	0.2338
Freon 113 (CCl_2F, $CClF_2$)	47.6	0.1470
Freon 114 ($(CCl\ F_2)_2$)	3.6	0.1370
Freon 115 ($CCl\ F_2\ CF_3$)	-38.7	0.1260
Freon 502	-45.6	0.1780
Methyl Chloride	-23.7	0.2740
Sulphur dioxide	10.0	0.4008

APPENDIX 12

Extraterrestrial Solar Spectral Irradiance at Mean Sun-Earth Distance (WRC spectrum)

λ	$I_{on\lambda}$	$\sum_{0}^{\lambda} I_{on\lambda}$	$P_{o-\lambda}$	λ	$I_{on\lambda}$	$\sum_{0}^{\lambda} I_{on\lambda}$	$P_{o-\lambda}$
0.250	64.56	2.51	0.18	0.475	2016.25	247.45	18.10
0.255	91.25	2.84	0.21	0.480	2055.00	257.62	18.65
0.260	122.50	3.47	0.25	0.485	1901.26	267.64	19.58
0.265	253.75	4.29	0.31	0.490	1920.00	276.98	20.26
0.270	275.00	5.70	0.42	0.495	1965.00	286.59	20.97
0.275	212.50	6.87	0.50	0.500	1862.52	296.37	21.68
0.280	162.50	7.86	0.57	0.505	1943.75	305.80	22.37
0.285	286.25	9.12	0.67	0.510	1952.50	315.50	23.08
0.290	535.00	10.97	0.80	0.515	1635.01	325.05	23.78
0.295	560.00	13.31	1.02	0.520	1802.49	333.79	24.42
0.300	527.50	16.54	1.21	0.525	1894.99	343.33	25.12
0.305	557.50	19.26	1.41	0.530	1947.49	352.67	25.80
0.310	602.51	22.13	1.62	0.535	1926.24	362.34	26.51
0.315	705.00	25.51	1.87	0.540	1857.50	371.87	27.20
0.320	747.50	29.09	2.13	0.545	1895.01	361.22	27.89
0.325	782.50	32.70	2.39	0.550	1902.50	390.72	28.58
0.330	997.50	37.51	2.74	0.555	1885.00	400.17	29.27
0.335	906.25	42.34	3.10	0.560	1840.02	409.42	29.95
0.340	960.00	46.79	3.42	0.565	1850.00	418.71	30.63
0.345	877.50	51.45	3.76	0.570	1817.50	427.94	31.31
0.350	955.00	55.89	4.09	0.575	1848.76	437.11	31.98
0.355	1044.99	61.08	4.47	0.580	1840.00	446.22	32.64
0.360	940.00	65.72	4.81	0.585	1817.50	455.44	33.32
0.365	1125.01	71.01	5.20	0.590	1742.49	464.21	33.96
0.370	1165.00	76.92	5.63	0.595	1785.00	473.16	34.61
0.375	1081.25	82.15	6.01	0.600	1720.00	481.98	35.26
0.380	1210.00	88.32	6.46	0.605	1751.25	490.71	35.90
0.385	931.25	93.11	6.81	0.610	1715.00	499.35	36.53
0.390	1200.00	98.30	7.19	0.620	1715.00	516.51	37.79
0.395	1033.74	103.61	7.58	0.630	1637.50	533.22	39.01
0.400	1702.49	109.81	8.03	0.640	1622.50	549.73	40.22
0.405	1643.75	118.40	8.66	0.650	1597.50	565.79	41.39
0.410	1710.00	126.65	9.27	0.660	1555.00	581.10	42.51
0.415	1747.50	135.37	9.90	0.670	1505.00	596.65	43.65
0.420	1747.50	143.98	10.53	0.680	1472.50	611.50	44.73
0.425	1692.51	152.69	11.17	0.690	1415.02	625.86	45.78
0.430	1492.50	160.74	11.76	0.700	1427.50	640.28	46.84
0.435	1761.25	168.74	12.34	0.710	1402.50	654.28	47.86
0.440	1755.02	177.59	12.99	0.720	1355.00	668.10	48.87
0.445	1922.49	187.02	13.68	0.730	1355.00	681.84	49.88
0.450	2099.99	196.86	14.40	0.740	1300.00	695.28	50.86
0.455	2017.51	207.15	15.15	0.750	1272.52	708.17	51.81
0.460	2032.49	217.29	15.90	0.760	1222.50	720.62	52.72
0.465	2000.00	227.59	16.65	0.770	1187.50	732.70	53.60
0.470	1979.99	237.50	17.37	0.780	1195.00	744.52	54.47

0.790	1142.50	756.23	55.32	1.900	136.01	1273.42	93.16
0.800	1144.70	767.69	56.16	1.950	126.00	1280.08	93.64
0.810	1113.00	779.02	56.99	2.000	118.50	1286.30	94.10
0.820	1070.00	789.93	57.79	2.100	93.00	1296.72	94.86
0.830	1041.00	800.50	58.56	2.200	74.75	1305.00	95.47
0.840	1019.99	810.77	59.31	2.300	63.25	1312.05	95.98
0.850	994.00	820.96	60.06	2.400	56.50	1317.96	96.41
0.860	1002.00	830.85	60.78	2.500	48.25	1323.16	96.80
0.870	972.00	840.61	61.49	2.600	42.00	1327.66	97.12
0.880	966.00	850.39	62.21	2.700	36.50	1331.57	97.41
0.890	945.00	859.94	62.91	2.800	32.00	1334.98	97.66
0.900	913.00	869.26	63.59	2.900	28.00	1337.97	97.88
0.910	876.00	878.16	64.24	3.000	24.75	1340.60	98.07
0.920	841.00	886.81	64.87	3.100	21.75	1342.93	98.24
0.930	830.00	895.10	65.48	3.200	19.75	1344.99	98.39
0.940	801.00	903.27	66.08	3.300	17.25	1346.84	98.53
0.950	778.00	911.18	66.66	3.400	15.75	1348.48	98.65
0.960	771.00	918.90	67.22	3.500	14.00	1349.96	98.76
0.970	764.00	926.58	67.78	3.600	12.75	1351.30	98.85
0.980	769.00	934.21	68.34	3.700	11.50	1352.51	98.94
0.990	762.00	941.88	68.90	3.800	10.50	1353.60	99.02
1.000	743.99	949.41	69.45	3.900	9.50	1354.59	99.09
1.050	665.98	984.76	72.04	4.000	8.50	1355.49	99.16
1.100	606.04	1016.27	74.35	4.100	7.75	1356.31	99.22
1.150	551.04	1045.16	76.46	4.200	7.00	1357.05	99.27
1.200	497.99	1071.43	78.38	4.300	6.50	1357.72	99.32
1.250	469.99	1095.66	80.15	4.400	6.00	1358.33	99.37
1.300	436.99	1117.96	81.78	4.500	5.50	1358.89	99.41
1.350	389.03	1138.51	83.29	4.600	5.00	1359.49	99.45
1.400	354.03	1156.97	84.64	4.700	4.50	1359.86	99.48
1.450	318.99	1173.91	85.88	4.800	4.00	1360.29	99.51
1.500	296.99	1189.28	87.00	4.900	3.75	1360.69	99.54
1.550	273.99	1203.52	88.04	5.000	3.47	1361.04	99.57
1.600	247.02	1261.48	88.99	6.000	1.75	1363.50	99.75
1.650	234.02	1228.52	89.87	7.000	0.95	1364.79	99.84
1.700	215.00	1239.74	90.69	8.000	0.55	1365.52	99.89
1.750	187.00	1249.69	91.42	9.000	0.35	1365.96	99.93
1.800	170.00	1258.55	92.07	10.000	0.20	1366.24	99.95
1.850	149.01	1266.42	92.64	25.000	0.12	1366.97	100.00

λ = wavelength (μm)

Ionλ = Solar spectral irradiance (w/m2μm)

$\int_0^{\lambda}$ Ionλ = integrated solar irradiance in wavelength range 0- λ(w/m2)

Po-λ = Percentage of solar constant for wavelengths shorter than λ

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