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Performance Study Of A Double Basin Solar Still

By

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COMMITTEE DECISION

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Dedication

To
My
Parents
Brothers
Sisters
And
My Wife

ACKNOWLEDGEMENTS

I am greatly thankful for Dr. Mohammed A. Hamdan for his precious effort in helping and guiding me through the preparation of the present work.

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NOMENCLATURE

C_{pw}	Specific heat of water at constant pressure, (J/kg °C).
H_s	Incident solar radiation on a glass cover per unit area per unit time,(W/m^2).
h_b	Overall heat transfer coefficient from water to atmosphere through bottom and sides of stills, (W/m^2 °C).
h_{ba}	Heat transfer coefficient from absorbing surface to water, (W/m^2 °C).
h_{ca}	Convective heat transfer coefficient from glass cover to ambient, (W/m^2 °C).
h_{cw}	Convective heat transfer coefficient from water to glass cover, (W/m^2 °C).
h_{eff}	Evaporative heat transfer coefficient from water to glass cover, (W/m^2 °C).
h_{rw}	Radiative heat transfer coefficient from water to glass cover, (W/m^2 °C).
h_{sw}	Heat transfer coefficient from absorbing surface to water, (W/m^2 °C).
h_w	Latent heat of vaporization of water, (J/kg).
h_{1s}	Total heat transfer coefficient from water to glass cover (single basin), (W/m^2 °C).
h_{2s}	Total heat transfer coefficient from glass cover to ambient air (single basin), (W/m^2 °C).
h_{1d}	Total heat transfer coefficient from upper water to glass cover (double basin), (W/m^2 °C).
h_{2d}	Total heat transfer coefficient from glass cover to ambient air (double basin), (W/m^2 °C).
h_{3d}	Total heat transfer coefficient from lower glass to upper water (double basin), (W/m^2 °C).
h_{4d}	Total heat transfer coefficient from lower water to lower glass (double basin), (W/m^2 °C).
h_{1t}	Total heat transfer coefficient from upper water to glass cover (triple basin), (W/m^2 °C).
h_{2t}	Total heat transfer coefficient from glass cover to ambient air (triple basin), (W/m^2 °C).

h_{3t}	Total heat transfer coefficient from middle glass to upper water (triple basin), (W/m^2 °C).
h_{4t}	Total heat transfer coefficient from middle water to middle glass (triple basin), (W/m^2 °C).
h_{5t}	Total heat transfer coefficient from lower glass to middle water (triple basin), (W/m^2 °C).
h_{6t}	Total heat transfer coefficient from lower water to lower glass (triple basin), (W/m^2 °C).
K_i	Thermal conductivity of insulation, (W/m ° C).
L	Thickness of insulation, (m).
M_{gs}	Heat capacity of glass per unit area, (J/m^2 ° C).
M_{ws}	Heat capacity of water per unit area, (J/m^2 ° C).
M_{g1d}	Heat capacity of upper glass (double basin), (J/m^2 ° C).
M_{g2d}	Heat capacity of lower glass (double basin), (J/m^2 ° C).
M_{w1d}	Heat capacity of upper water (double basin), (J/m^2 ° C).
M_{w2d}	Heat capacity of lower water (double basin), (J/m^2 ° C).
M_{g1t}	Heat capacity of upper glass (triple basin), (J/m^2 ° C).
M_{g2t}	Heat capacity of middle glass (triple basin), (J/m^2 ° C).
M_{g3t}	Heat capacity of lower glass (triple basin), (J/m^2 ° C).
M_{w1t}	Heat capacity of upper water (triple basin), (J/m^2 ° C).
M_{w2t}	Heat capacity of middle water (triple basin), (J/m^2 ° C).
M_{w3t}	Heat capacity of lower water (triple basin), (J/m^2 ° C).
P	Partial vapor pressure at temperature T, (Pa).
P_{ws}	Partial pressure of water vapor at water temperature, (Pa).
P_{gs}	Partial pressure of water vapor at glass temperature, (Pa).
Q_{est}	Total amount of solar energy used for evaporation, (J/m^2 day).
Q_t	Total amount of solar radiation incident on the still cover, (J/m^2 day).
q_a	Total heat transfer per unit area per unit time from glass to ambient, (W/m^2).
q_{ca}	Heat transfer from glass cover to atmosphere by convection, (W/m^2).
q_{cw}	Heat transfer from water to glass by convection, (W/m^2).

q_{ew}	Heat transfer from water to glass by evaporation, (W/m^2).
q_{ins}	Heat transfer from basin liner to atmosphere by conduction through bottom insulation, (W/m^2).
q_{ra}	Heat transfer from glass cover to atmosphere by radiation, (W/m^2).
q_{rw}	Heat transfer from water to glass by radiation, (W/m^2).
q_w	Heat transfer from absorbing surface to water, (W/m^2).
R_1,R_2	Constants
T_a	Ambient temperature, (°C).
T_{gs}	Single basin glass temperature, (°C).
T_{ws}	Single basin water temperature, (°C).
T_{g1d}	Double basin upper glass temperature, (°C).
T_{g2d}	Double basin lower glass temperature, (°C).
T_{w1d}	Double basin upper water temperature, (°C).
T_{w2d}	Double basin lower water temperature, (°C).
T_{g1t}	Triple basin upper glass temperature, (°C).
T_{g2t}	Triple basin middle glass temperature, (°C).
T_{g3t}	Triple basin lower glass temperature, (°C).
T_{w1t}	Triple basin upper water temperature, (°C).
T_{w2t}	Triple basin middle water temperature, (°C).
T_{w3t}	Triple basin lower water temperature, (°C).
T_{skv}	Sky temperature, (°C).
U_b	Overall heat transfer coefficient from absorbing surface of the still to ambient, (W/m^2 °C).
V_w	Wind speed, (m/s)

GREEK SYMBOLS:

α_g	Absorption coefficient of glass
α_w	Absorption coefficient of water
ε_g	Emissivity of glass
ε_w	Emissivity of water
θ_{bas}	Temperature distribution, (°C).
η	Efficiency of still.
σ	Stefan - Boltzmann constant, 5.6697×10^{-8} , ($W/m^2\ {}^{\circ}K^4$).
α	Fraction of energy absorbed by glass or water.

ABBREVIATIONS

SBSS	Single Basin Solar Still
DBSS	Double Basin Solar Still
TBSS	Triple Basin Solar Still

ABSTRACT

" Performance Study of a Double Basin Solar Still "

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This thesis presented an experimental and theoretical investigation of three basin solar stills, namely ; single, double and, triple basins under Jordanian climatic conditions.

The three stills were constructed using 0.96 × 0.96 m^2 base area. The outer glass of the still was of pyramid shape and inclined at 45°. The middle and lower glass of the double and triple stills were inclined at 7°. Experiments on the system had been performed at different water depths in the lower basin. The temperatures of water, glass and ambient together with solar intensity, wind velocity and volume of distilled water were recorded on hourly basis during day time. The theoretical part carried out using a computer program written in FORTRAN language using iterative technique of Euler's equation.

The daily distilled water and efficiency were determined. The results showed that the distilled water output of triple basin solar still was 36 % higher than that of single basin and 7 % higher than the double basin , while the double basin was 26 % higher than single basin output. The maximum daily efficiency was about 44 % for the triple basin solar still followed by 41.8 % for double basin, while it was about 31.9 % for single basin solar still and there was no significant effect for water depth in the lower basin.

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

Solar distillation is strongly related to the general development in solar technology as a whole. However, the rapid industrial growth and population explosion all over the world has resulted in a large escalation of demand for fresh water, the developments in the use of solar energy have demonstrated that it is ideally suited in distillation when the demand for fresh water is not too large.

The wide variation of solar intensity, both daily and annually, requires that any device for using solar energy to distill water must be capable of operating at widely varying temperatures. The solar distillation process fluctuates with the solar energy intensity, its production varying from zero for most of the night to a maximum in the early afternoon of a sunny day.

The basin type is the only solar still which to date has been successfully applied to water distillation [1]. It is the application of the natural hydrologic cycle to a relatively small apparatus. The essential features of the natural hydrologic cycle are the production of water vapor above the ocean water's surface, the transportation of this vapor to cool regions by wind, and its subsequent condensation. The basin type solar still reproduces this sequence of events.

1.2 PRESENT WORK CONTRIBUTION

The present research investigates the performance of various types of basin solar stills under Jordan's climatic conditions, as well as some factors affecting the performance of such stills.

Experimental and theoretical tests were done to investigate stills performance. The experimental work includes the construction of three stills, single, double and triple basin. A computer program is used to simulate the stills performance and to compare the predicted results with the experimentally obtained results.

1.3 IMPORTANCE OF THE WORK

Many arid and semi-arid countries face shortages of potable water available from natural sources. The Arab World is a representative of such countries. To make matters worse, many aquifers in the Arab World are of high salinity or suffer from increasing deterioration of water quality as a result of increased water abstraction.

The water resources in the Arab World in 1985 were estimated to be about 172 billion m^3, while the water demand was estimated to be about 305 billion m^3, Asa'ad *et al.*[2].

Moreover, Dabbagh and Al-saqabi [3] noted that the development of water resources in Jordan will be far more difficult than in the other Arab Countries. Which makes the research in water field especially with a free source of energy of a considerable worth, so the solar distillation be in mind.

1.4 LAYOUT OF THE THESIS

The thesis is divided into six chapters, the first of which is this introduction. Literature review is presented in chapter two. Chapter three describes the experimental setup and procedure of construction solar stills. Chapter four presents the theoretical analysis of solar stills. The results obtained and their discussion are presented in chapter five. Finally, chapter six lists the general conclusions and recommendations reached by the present study.

CHAPTER TWO

LITERATURE SURVEY

Solar distillation has been in practice for a long time. The earliest documented work is that of the Arab alchemists in 1551 [4]. Many works have been reported about solar distillation after that using different types of solar stills, the present review is dealing with the basin type solar stills either experimental or theoretical tests.

Sodha *et al.* [5] analyzed the transient performance of a basin type mounted still. They obtained explicit expressions for hourly variation of the glass cover temperature and water temperature in the basin and a distillate output has been obtained. Their results were in good agreement with experiment.

Also, Sodha *et al.* [6] presented a periodic analysis of a double basin solar still (DBSS) mounted on a stand. The daily distillate production of such a still was on the average 36 % higher than that of a single basin solar still (SBSS).

Sodha *et al.* [7] developed a transient model of the performance of a DBSS and it was validated by experiments. On the other hand, they studied analytically the dependence of the daily output of the distillate on wind velocity, ambient temperature and daily irradiation. They found experimentally that the presence of a black dye in the lower basin increases the distillate output by 10-15 %.

Mahdi [13] studied the effect of number of basins on the daily productivity of the still. The results indicated that the daily output is increased by increasing the number of basins in the still.

Kumar *et al.* [14] presented a transient analysis of a double slope DBSS incorporating the effects of water mass on the upper and lower basin, the initial temperature in the lower basin, and heat transfer coefficient. A comparison was carried out between SBSS and DBSS. The DBSS gave better performance than single ones.

Tiwari *et al.* [15] derived an analytical expression for the daily yield as a function of the system and climatic parameters based on energy balances for different components of a DBSS under an active mode of operation (i.e. feeding of thermal energy into the basin from an external source) . They found that there may be an increase of about 30 % in daily efficiency by using double effect distillation if the flow rate is small.

Tiwari *et al.* [16] presented a transient analysis by incorporating the effect of attenuation of solar flux with depth of water in the basin. They also studied analytically the effects of concentrations of dye , water depth and absorptivity of basin on the performance of the solar still. They observed that for large water depth, no significant change is observed between their model and the theory presented by Sodha *et al.* [5].

Kumar *et al.* [17] studied analytically the performance of a DBSS integrated with a heat exchanger. They investigated the effects of water mass in the upper and lower basins, heat exchanger length, inlet temperature, mass flow rate, various heat transfer coefficients, as well as various meteorological parameters. They found that the use of heat exchanger increases the system efficiency significantly.

Venkatesh and Chatravedi [18] built a small single-slope solar still in the laboratory which was subjected to several tests on different days. The effects of various parameters such as depth of water in the basin, moisture in the insulation under the basin and the leakage through the sealant on the yield were experimentally studied.

Gupta *et al.* [19] presented a transient analysis of a DBSS incorporating the effect of intermittent flow of waste hot water into the lower basin at a constant rate during off sunshine hours. They found that the yield increases with flow rate if the inlet waste hot water temperature is above its optimum value. They also found that the yield decreases with an increase of water mass in the lower basin.

To summarize , the above literature review presented shows that the SBSS and DBSS were designed and successfully tested to increase the amount of distilled water. However, and to the best knowledge of the author the only available work on the triple basin solar still (TBSS) is that by Tiwari [11] which states that as the number of basins increase the amount of distilled water is expected to increase. In this work the performance of a TBSS will be studied theoretically and experimentally and will be compared to those of DBSS and TBSS.

CHAPTER THREE

EXPERIMENTAL SETUP AND PROCEDURE

3.1 INTRODUCTION

There are many types of basin solar stills. The square base pyramid one was used in this study for its simplicity in design and construction from the locally available materials which gives an acceptable performance.

Basin type solar still performance depends to a great extent, on the number of basins in the still. In this study, three stills, single, double and triple basin were designed and manufactured.

This chapter is devoted to describe the different components that were selected to construct the stills, and to describe the manufacturing processes that are followed to build them.

3.2 COMPONENTS OF BASIN TYPE SOLAR STILLS

The following are the main parameters considered for the design of solar stills :

3.2.1 Absorber plate:

The absorber plate is the major part of the solar still. It absorbs the coming insulation which is transmitted through the transparent cover. The absorber plate should be of maximum absorptivity, and is this why it painted with a special or ordinary non-reflective black painting. The absorber plates used in the present stills were made of black steel of 1.25 mm thickness with dimensions of (960×960) mm , this value of thickness was selected to stand arc welding .

3.2.2 Transparent Cover

Transparent covers may be of glass or plastic, arranged in single, double or multiple layers. The transparent cover should have high transmissivity and minimum absorptivity and reflectivity. Ordinary window glass of 4.0 mm thickness with an average transmissivity of 0.87 was used in this study, fig (3.1). Four glass sheets were used to form the shape of the pyramid. The transparent cover was sealed around the edges to prevent vapor loss and must be sloped at an angle sufficiently large to ensure that condensate formed on it will flow by gravity to the condensate troughs, rather than to drip back into the basin.

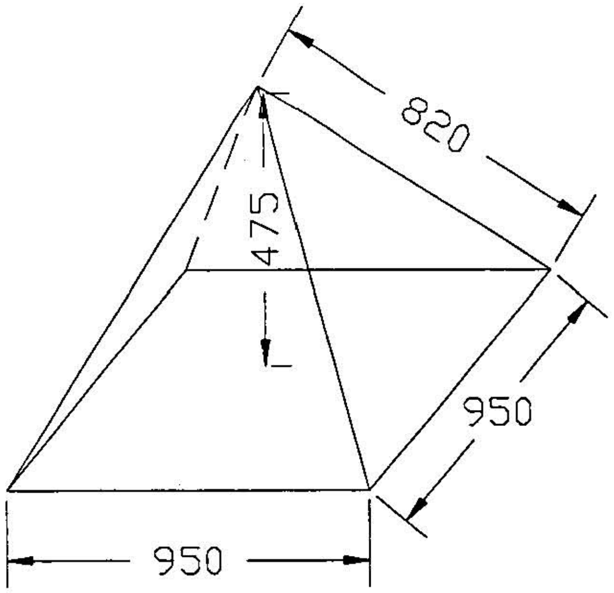


Fig (3.1) : Square base pyramid outer glass cover for the three stills.

3.2.3 Insulating Material

The reduction of heat losses from the solar stills, has a considerable effect on the overall efficiency of the solar still. So, the insulating material should be selected carefully. It should be of minimum cost, durable and non-toxic.

A rock wool of 30 mm and 0.0346 W/m °C thermal conductivity coefficient covered with aluminum foil of (7 - 9 microns) was used to insulate the lower plate and the outer sides of the three stills.

3.2.4 Condensate Troughs

The condensate troughs must be so arranged that they collect all of the condensate dripping from the lower edges and convey this condensate to the outside of the enclosure. In order to collect the distilled water a troughs of V-shape were designed with slope of 1.5 % from the black steel of 1.25 mm thickness.

3.3 MANUFACTURING PROCESS

The feasibility of the solar still depends to a great extent on the manufacturing process. The solar still components should be properly manufactured in order to meet the design requirements. In addition, the manufacturing process of the solar still must be easy, simple and relatively cheap. A large portion of building the stills was accomplished at the workshop of the industrial engineering department.

3.3.1 Building The Still

Building of the solar still is simple and relatively cheap, the following steps were followed in building the stills :

1- A steel box of dimensions (960x960x100) mm was constructed as shown in fig (3.2) . This box is used as the lower basin for the three types of stills. This box was bend from two sides and the other two sides was sealed by arc welding, and supplied by an outlet tube used for discharging the stills and for measuring water depth in the lower basin.

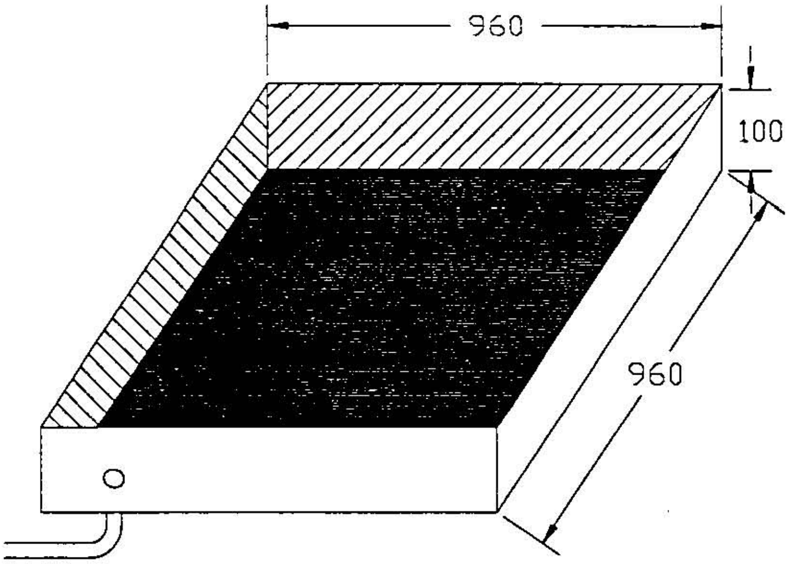


Fig (3.2) : The lower basin of the three stills

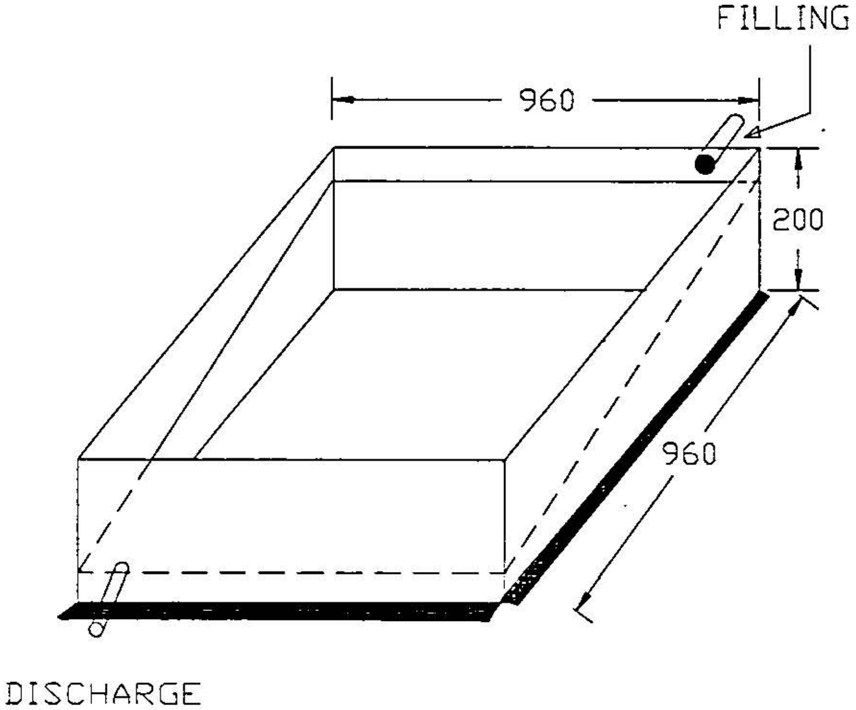


Fig (3.3) : a schematic diagram of the steel frame used to form the upper and middle basins in the DBSS and TBSS.

2- Three frame boxes were constructed, two for triple basin and the other one for double basin. These sides were made of the same steel sheet of 1.25 mm with dimensions of (960x960x200) mm. A V - shape flange is supplied in the lower edges of these sides to fix them on the lower box in the DBSS , and on the lower and middle basins in the TBSS. Also a V - shape trough was made to collect the distilled water from the inclined glass which was fixed on a steel frame. This frame was fixed with spot welding with an inclination of 7°. Filling and discharging tubes were supplied in each frame as shown in fig (3.3).

3- Three frames of a V - flange and a V - trough were constructed for each still used to support the upper square base pyramid glass cover and for collecting the distilled water from these covers. These frames were made from a steel sheet of 1.25 mm by using a bending machine. Each frame is supplied by a right angle tube for the upper basin output.

4- The surfaces of steel were cleaned and polished using emery paper and the surfaces were painted by red - oxide paint and then by an ordinary black paint.

5- The glass sheets were fixed using silicon paste in the lower and middle basins, while the upper glass covers were assembled to a square base pyramid using silicon paste and then fixed to the upper steel frame as shown in fig (3.4). A Cross-sectional view of the TBSS is shown in fig (3.5).

6- Finally, the lower and outer surfaces of the three stills were insulated by using a rock wool felts with 30 mm thickness having thermal conductivity of 0.0346 W/m °C to minimize the heat losses to the ambient.

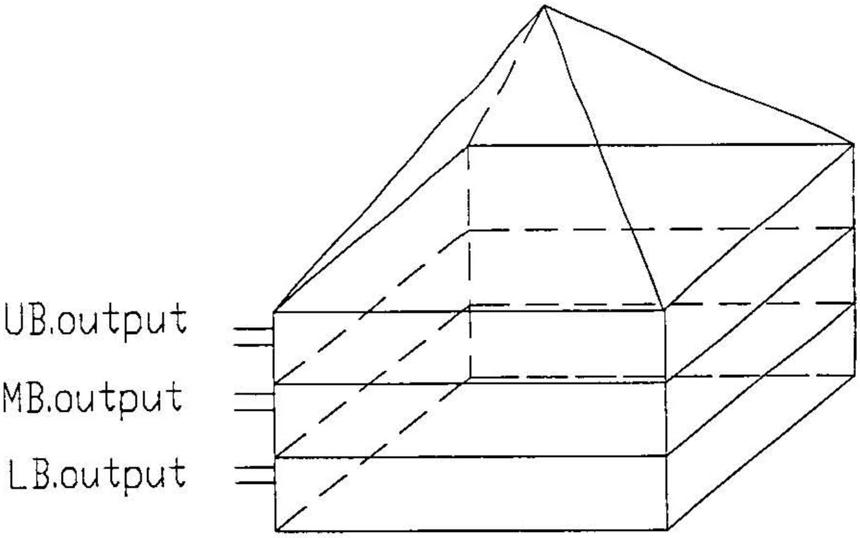
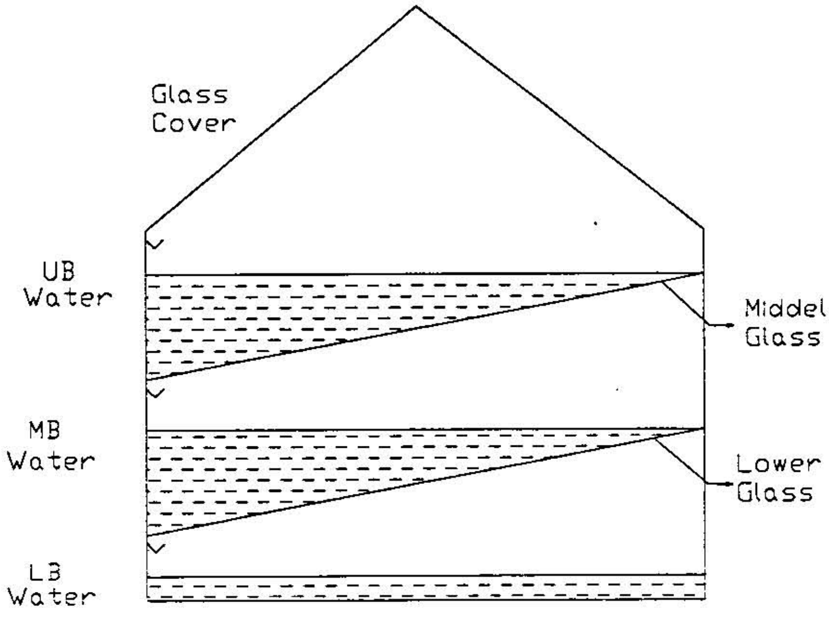


Fig (3.4) : schematic diagram of the TBSS.



Fig(3.5): Cross sectional view of TBSS

3.4 MEASURING INSTRUMENTS

3.4.1 Incident Solar Radiation Measurement

Incident solar radiation is measured by a Kipp and Zenon pyranometer (type CM5). It was fixed on a horizontal plane near the solar stills. A solar integrator (type CC11) is employed to record the incident solar radiation in Wh/m^2 . The incident solar radiation was measured on hourly bases.

3.4.2 Temperature Measurement

The temperatures at various locations within the stills were measured by means of Copper Constantan thermocouples. Thirty thermocouple wires were used to measure the plate, water and glass temperatures of each basin in the three stills. Ambient temperature was measured by a thermocouple positioned in the shaded region below the stills. All the thermocouple wires were connected to a data logger.

3.4.3 Wind Speed Measurement

The wind speed in front of the test stills was measured by a digital anemometer (type Edra 5). The wind speed was recorded every hour at a selected location near the stills at the same height of the still cover. These readings were used to estimate the heat transfer loss coefficient to ambient (h_{ca}).

3.5 EXPERIMENTAL PROCEDURE

The daily experimental test of the three stills was carried during the period between 9 a.m. and 6 p.m., while the distilled water collected over a 24 hour. The parameters measured are :

1- Plate, water and glass temperature for each basin in the three stills.
2- Ambient temperature (T_a).
3- Solar incident radiation on the horizontal surface (H_S).
4- Wind speed (V_W).
5- Distilled water from each basin.

The experimental procedure is summarized in the following points :

1- The thermocouple wires were connected to the data logger with thirty channels.
2- The lower basin of the three stills were filled with water to the required height, while the middle and the upper basins were filled until the inclined glass completely covered.
3- The water and glass temperatures together with the output distilled water, solar intensity and wind speed are measured and recorded on hourly basis.
4- The experiment continue with the same procedure until 6 p.m., after that the distilled water during night is collected at 9 a.m. next day for each basin in the three stills.

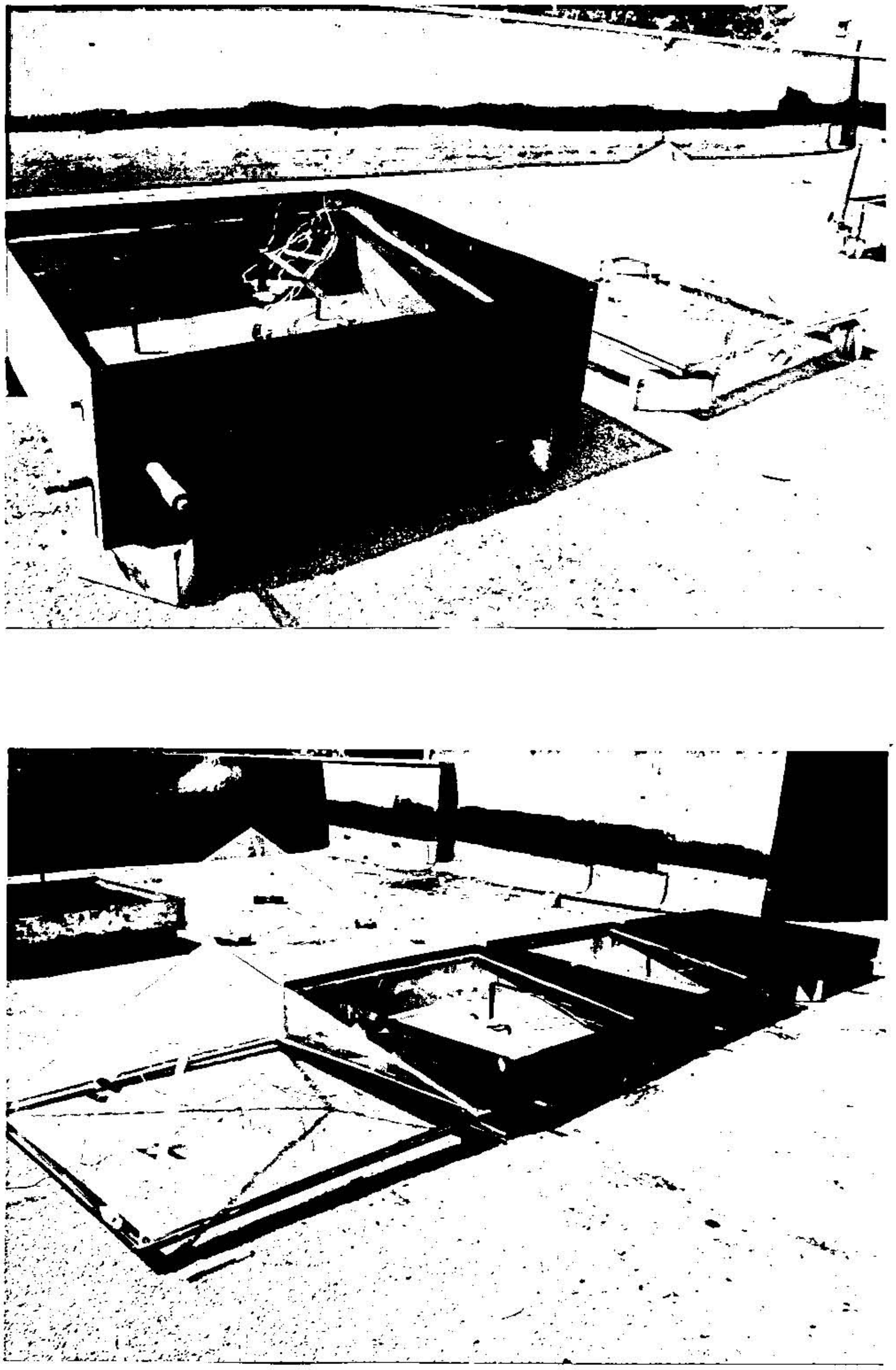


Fig. (3. 6) : Photographs of the main components of solar stills

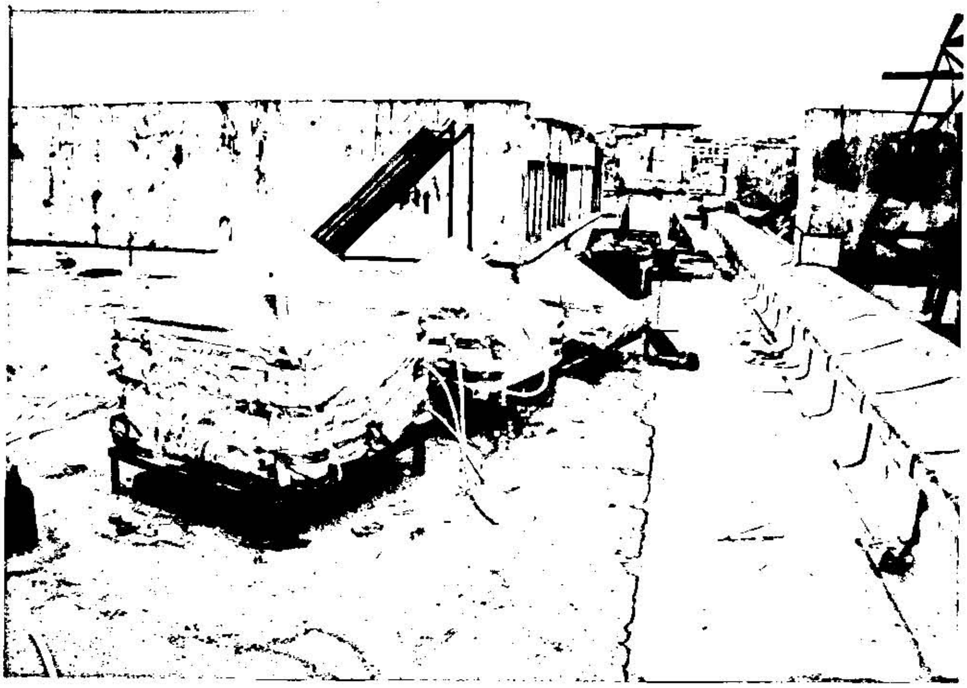


Fig (3.7) : Photographs for the experimental set up

CHAPTER FOUR:

THEORETICAL ANALYSIS

4.1 INTRODUCTION

The main objective of the present study is to test the three solar stills under Jordanian climatic conditions experimentally and compare them with theoretical results. In this chapter the theoretical analysis and the basic mathematical model is used to evaluate the performance parameters of these stills are outlined.

4.2 MODEL

The present analysis follows that of the model proposed by Sodha *et al.* [5], which assumes the following :

1- Evaporation have been assumed to be small compared to the basin water mass, so that the water mass may be assumed to be constant. For a large water depth this assumption is quite justified, or constant mass of water is maintained by continuos addition of water to keep a constant level in the basin, so that the rate of addition of water is the same as that of evaporation. It is further assumed that the heat required to heat the water from the ambient (before addition to the basin

) temperature to the temperature of water in the basin is negligible as compared to that required to evaporate the same mass i.e.:

$$C_p\,(T_w - T_a) \ll h_w$$

2- There is no vapor leakage in the still.

3- Temperature gradients along the glass cover thickness and water depth have been assumed to be absent.

4- The area of cover glass, still and surface area of water are considered to be equal.

4.3 ENERGY BALANCE

4.3.1 Single Basin

A schematic diagram of the basic configuration of a SBSS is shown in fig (4.1) . The figure also shows the basic heat flux components at various surfaces. The energy balance conditions at the top cover, the saline water surface and the absorbing surface may be written as:

$$M_{gs}\frac{dT_{gs}}{dt} = \alpha_{1s}H_s + (q_{rw} + q_{cw} + q_{ew}) - q_a \tag{4.1}$$

$$M_{ws}\frac{dT_{ws}}{dt} = \alpha_{2s}H_s + q_w - (q_{rw} + q_{cw} + q_{ew}) \tag{4.2}$$

$$\alpha_{3s}H_s = q_w + q_{ins} \tag{4.3}$$

The heat transfer rates, q_a, q_{cw}, q_{ew} and q_{rw} are defined by the following equations :

$$q_a = q_{ra} + q_{ca} \tag{4.4}$$

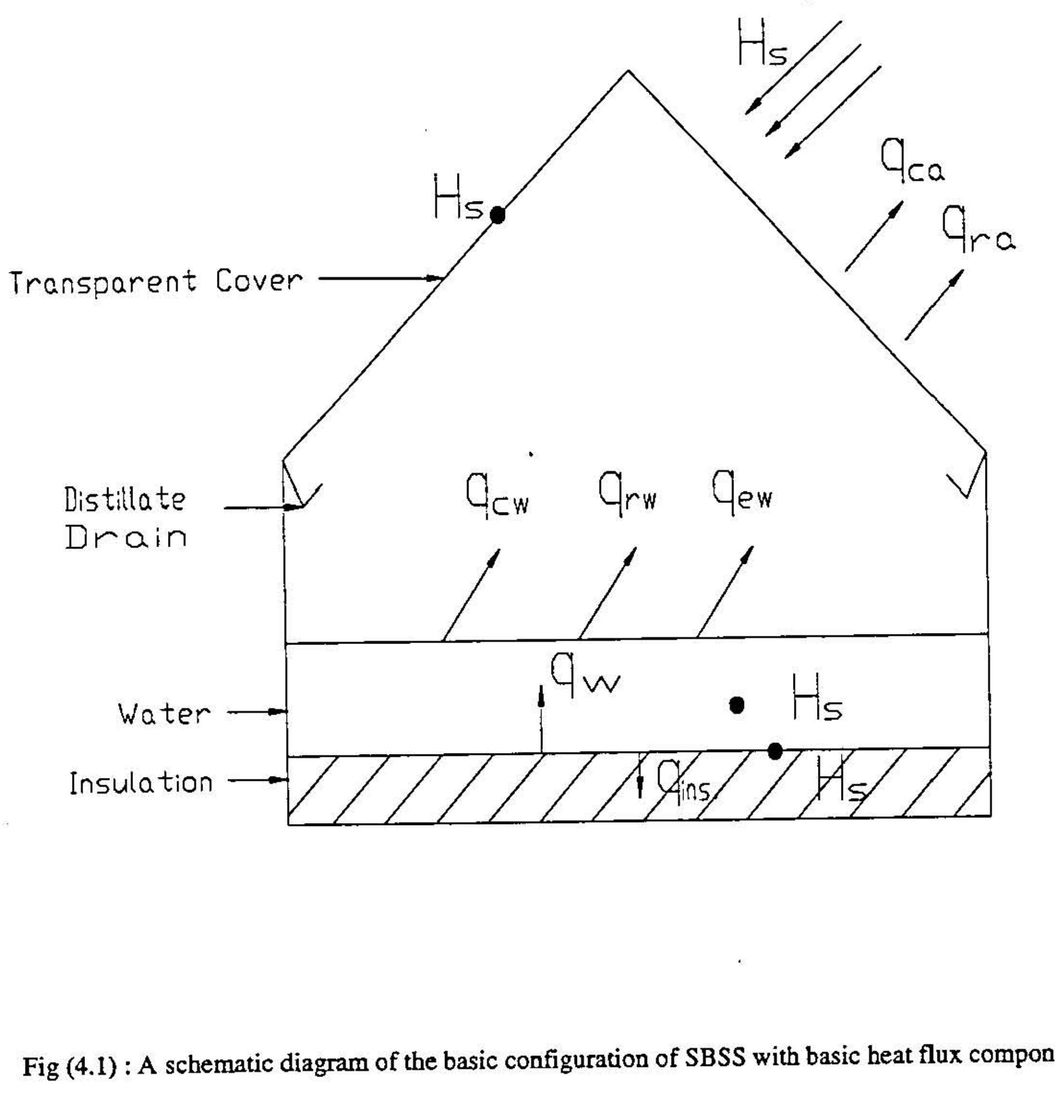


Fig (4.1) : A schematic diagram of the basic configuration of SBSS with basic heat flux components

the external radiation and convection losses from the glass cover to outside atmosphere can be expressed as :

$$q_{ra} = \in_g . \sigma \, [(T_{gs})^4 - (T_{sky})^4] \tag{4.5}$$

and

$$q_{ca} = h_{ca}(T_{gs} - T_a) \tag{4.6}$$

T_{sky} is the apparent sky temperature for long wave radiation exchange, assumed to be 12° C below ambient. The external convection coefficient h_{ca} is a function of wind velocity [20] and is given by :

$$h_{ca} = 5.7 + 3.8 V_w \tag{4.7}$$

so, the heat transfer rate outside the still may be written as:

$$q_a = h_2 (T_{gs} - T_a) \tag{4.8}$$

where

$$h_2 = h_{ca} + \varepsilon_g \sigma \frac{\left[(T_{gs})^4 - (T_a)^4\right]}{T_{gs} - T_a} \tag{4.9}$$

The convective and evaporative heat transfer rates are given by Dunkel's relation [21] :

$$q_{cw} = 0.884\left[T_{ws} - T_{gs} + \frac{(P_{ws} - P_{gs})(T_{ws})}{(268.9\times10^3 - P_{ws})}\right]^{1/3}(T_{ws} - T_{gs}) \tag{4.10}$$

$$q_{cw} = h_{cw}(T_{ws} - T_{gs}) \tag{4.11}$$

and

$$q_{ew} = 16.273\times10^{-3} h_{cw}(P_{ws} - P_{gs}) \tag{4.12}$$

the radiation heat transfer rate is given by :

$$q_{rw} = \frac{\sigma\left(T_{ws}^{4} - T_{gs}^{4}\right)}{\frac{1}{\varepsilon_{w}} + \frac{1}{\varepsilon_{g}} - 1} \qquad (4.13)$$

Under normal operating conditions the rise in temperature of the top cover and the saline water in the still is small and within this temperature range the vapor pressure inside the still may be approximately written as a linear function of temperature [22] :

$$P = R_1 T + R_2 \qquad (4.14)$$

where the constants R_1 and R_2 may be evaluated by fitting the saturation vapor pressure data in the temperature range of interest to a straight line. So, the heat transfer rates inside the still become :

$$q_{cw} = h_{cw}\left(T_{ws} - T_{gs}\right) \qquad (4.15)$$

$$q_{ew} = h_{eff}\left(T_{ws} - T_{gs}\right) \qquad (4.16)$$

$$q_{rw} = h_{rw}\left(T_{ws} - T_{gs}\right) \qquad (4.17)$$

where the heat transfer coefficients h_{cw}, h_{eff}, and h_{rw} are written as [4] :

$$h_{cw} = 0.884\left[T_{ws} - T_{gs} + \frac{R1\left(T_{ws} - T_{gs}\right)\left(T_{ws}\right)}{\left(268.9\times10^{3} - R2 - R1\left(T_{ws}\right)\right)}\right]^{1/3} \qquad (4.18)$$

$$h_{eff} = 16.273\times10^{-3} h_{cw} R1 \qquad (4.19)$$

$$h_{rw} = \frac{\varepsilon\sigma\left[\left(T_{ws}\right)^{4} - \left(T_{gs}\right)^{4}\right]}{\left(T_{ws} - T_{gs}\right)} \qquad (4.20)$$

and the total heat transfer coefficient is the sum of radiation, convection and evaporative coefficients which is given by :

$$h_l = h_{rw} + h_{cw} + h_{eff} \tag{4.21}$$

Energy transfer from the absorbing surface to the saline water can be written as :

$$q_w = h_{sw}\left(\theta_{bas} - T_{ws}\right) \tag{4.22}$$

the energy balance at the outer surface of the insulation separating the still from the atmosphere is given by :

$$-K\left(\frac{d\theta}{dx}\right)_{x=L} = h_b\left(\theta_{bas} - T_a\right) \tag{4.23}$$

substituting the above heat transfer rates in eq. (4.1) to (4.3), then these equations are reduced to :

$$M_{gs}\frac{dT_{gs}}{dt} = \alpha_{1s}H_s + h_{1s}(T_{ws} - T_{gs}) - h_{2s}(T_{gs} - T_a) \tag{4.24}$$

$$M_{ws}\frac{dT_{ws}}{dt} = \alpha_{2s}H_s - h_{1s}\left(T_{ws} - T_{gs}\right) + h_{sw}\left(\theta_{bas} - T_{ws}\right) \tag{4.25}$$

$$\alpha_{3s}H_s = h_{sw}\left(\theta_{bas} - T_{ws}\right) + h_b\left(\theta_{bas} - T_a\right) \tag{4.26}$$

where

$$h_b = \left[\frac{L}{K_i} + \frac{1}{h_{ba}}\right]^{-1} \tag{4.27}$$

substituting the values of θ_{bas} from eq. (4.26) into eq. (4.25) then:

$$M_{ws}\frac{dT_{ws}}{dt}=\alpha_s H_s-h_{1s}\left(T_{ws}-T_{gs}\right)-U_b\left(T_{ws}-T_a\right) \tag{4.28}$$

where

$$\alpha_s=\alpha_{2s}+U_b\left(\frac{L}{k_i}+\frac{1}{h_{ba}}\right)\alpha_{3s} \tag{4.29}$$

$$U_b=\left(\frac{1}{h_{sw}}+\frac{1}{h_b}\right)^{-1} \tag{4.30}$$

4.3.2 Double Basin

The energy balance at the top glass cover, the upper basin water, the lower glass cover, the lower basin water and the absorbing surface may be written as:

$$M_{g1d}\frac{dT_{g1d}}{dt}=\alpha_{1d}H_s+h_{1d}\left(T_{w1d}-T_{g1d}\right)-h_{2d}\left(T_{g1d}-T_a\right) \tag{4.31}$$

$$M_{w1d}\frac{dT_{w1d}}{dt}=\alpha_{2d}H_s+h_{3d}(T_{g2d}-T_{w1d})-h_{1d}(T_{w1d}-T_{g1d}) \tag{4.32}$$

$$M_{g2d}\frac{dT_{g2d}}{dt}=\alpha_{3d}H_s+h_{4d}(T_{w2d}-T_{g2d})-h_{3d}(T_{g2d}-T_{w1d}) \tag{4.33}$$

$$M_{w2d}\frac{dT_{w2d}}{dt}=\alpha_{4d}H_s+h_{sw}(\theta_{bas}-T_{w2d})-h_{4d}(T_{w2d}-T_{g2d}) \tag{4.34}$$

$$\alpha_{5d}H_s=h_{sw}(\theta_{bas}-T_{w2d})+h_b(\theta_{bas}-T_a) \tag{4.35}$$

substituting the value of θ_{bas} from eq. (4.35) , eq. (4.34) reduces to :

$$M_{w2d}\frac{dT_{w2d}}{dt} = \alpha_d H_s - U_b(T_{w2d} - T_a) - h_{4d}(T_{w2d} - T_{g2d}) \tag{4.36}$$

where

$$\alpha_d = \left(\alpha_{4d} + \frac{h_{sw}\alpha_{5d}}{h_{sw} + h_b}\right) \tag{4.37}$$

4.3.3 Triple Basin

Energy balance for the upper glass cover, the upper basin water, the middle glass cover, the middle basin water, the lower glass cover, the lower basin water and the absorbing surface, may be written as :

$$M_{g1t}\frac{dT_{g1t}}{dt} = \alpha_{1t}H_s + h_{1t}\left(T_{w1t} - T_{g1t}\right) - h_{2t}\left(T_{g1t} - T_a\right) \tag{4.38}$$

$$M_{w1t}\frac{dT_{w1t}}{dt} = \alpha_{2t}H_s - h_{1t}\left(T_{w1t} - T_{g1t}\right) + h_{3t}\left(T_{g2t} - T_{w1t}\right) \tag{4.39}$$

$$M_{g2t}\frac{dT_{g2t}}{dt} = \alpha_{3t}H_s + h_{4t}\left(T_{w2t} - T_{g2t}\right) - h_{3t}\left(T_{g2t} - T_{w1t}\right) \tag{4.40}$$

$$M_{w2t}\frac{dT_{w2t}}{dt} = \alpha_{4t}H_s - h_{4t}\left(T_{w2t} - T_{g2t}\right) + h_{5t}\left(T_{g3t} - T_{w2t}\right) \tag{4.41}$$

$$M_{g3t}\frac{dT_{g3t}}{dt} = \alpha_{5t}H_s + h_{6t}\left(T_{w3t} - T_{g3t}\right) - h_{5t}\left(T_{g3t} - T_{w2t}\right) \tag{4.42}$$

$$M_{w3t}\frac{dT_{w3t}}{dt} = \alpha_{6t}H_s - h_{6t}\left(T_{w3t} - T_{g3t}\right) + h_{sw}\left(\theta_{bas} - T_{w3t}\right) \tag{4.43}$$

$$\alpha_{7t}H_s = h_{sw}\left(\theta_{bas} - T_{w3t}\right) + h_b\left(\theta_{bas} - T_a\right) \tag{4.44}$$

substitute the value of θ_{bas} from eq. (4.44) ,eq. (4.43) reduces to :

$$M_{w3t}\frac{dT_{w3t}}{dt}=\alpha_t H_s-U_b\left(T_{w3t}-T_a\right)-h_{6t}\left(T_{w3t}-T_{g3t}\right) \tag{4.45}$$

where

$$\alpha_t=\left(\alpha_{6t}+\frac{h_{sw}\alpha_{7t}}{h_{sw}+h_b}\right) \tag{4.46}$$

4.4 HOURLY AND DAILY EFFICIENCY

As is clear from the above analysis , these differential equations are solved to calculate the water and glass temperatures for each basin in order to calculate the heat flux from the water to the cover, involved in the evaporation process for each still as given below:

For SBSS :

$$Q_{es}=h_{es}\left(T_{ws}-T_{gs}\right) \tag{4.47}$$

The amount of water distillate per unit time per unit basin area is given by:

$$m_{ws}=\frac{Q_{es}}{h_w}\times 3600 \qquad (\text{ kg/m}^2\text{ hr }) \tag{4.48}$$

The hourly efficiency of the SBSS is given by :

$$\eta_h=\frac{Q_{es}}{H_s}\times 100\% \tag{4.49}$$

The daily efficiency of the still is given by :

$$\eta_d = \frac{Q_{est}}{Q_t} \times 100\,\% \tag{4.50}$$

where Q_t (in J/m^2 day) is the amount of solar energy incident on the glass cover of the still and Q_{est} (in J/m^2 day) is the energy utilized in vaporizing water in the still.

The distilled water and efficiencies for the other basins in the DBSS and TBSS are calculated in the same way using the above equations with proper temperatures and evaporative heat coefficients.

4.5 COMPUTER PROGRAM

A computer program was written in order to compare the experimental results with the theoretical ones. The program was written in FORTRAN 77 using Euler's iterative method for solving ordinary differential equations. The program is presented in Appendix A

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CHAPTER FIVE

RESULT AND DISCUSSION

5.1 INTRODUCTION

Throughout the measurement made to establish the data presented in this work, care was taken to note possible sources of error and an error analysis based on the method of Kline and McClintock [23] was carried out. The error analysis indicated a ±1% in temperature, ±3% in condensate and ±3 in the efficiency of the stills. As previously mentioned the main objective of this work is to study the performance of three types of basin stills. This chapter is divided into two sections in which the present section is included. Section (5.2) deals with the results obtained in this study and their discussion .

5.2 RESULTS AND DISCUSSION

The experimental measured data and the theoretical results as calculated by using the performance equation introduced in section (4.3) are tabulated in Appendix B.

The hourly variation of experimental and theoretical plate temperature for the three stills at two different water depths are presented in figures (5.1 - 5.2). Experimental and theoretical variation of water and glass temperatures for each basin in the three stills were plotted in figures (5.3 - 5.5) and (5.6 - 5.10) respectively, for the two values of the selected water depth in the lower basin.

A comparison between experimental water and glass temperatures for the each still are plotted in figures (5.11 - 5.16). The experimental and theoretical condensate within the period from 9 a.m. to 6 p.m., for each still are plotted in figures (5.17 - 5.18). The total yield during the remaining interval of the day is shown in tables (5.1) and (5.2).

The hourly experimental and theoretical efficiencies are shown in figures (5.19 - 5.20) , while the daily experimental and theoretical efficiencies are shown in tables (5.3 - 5.4).

Figures (5.21 - 5.22) show hourly the experimental distilled water for the three stills with time. The experimental efficiencies of the three stills are plotted in figures (5.23 - 5.24). Finally the hourly ambient temperature and hourly solar intensity are plotted in figures (3.25 - 3.26).

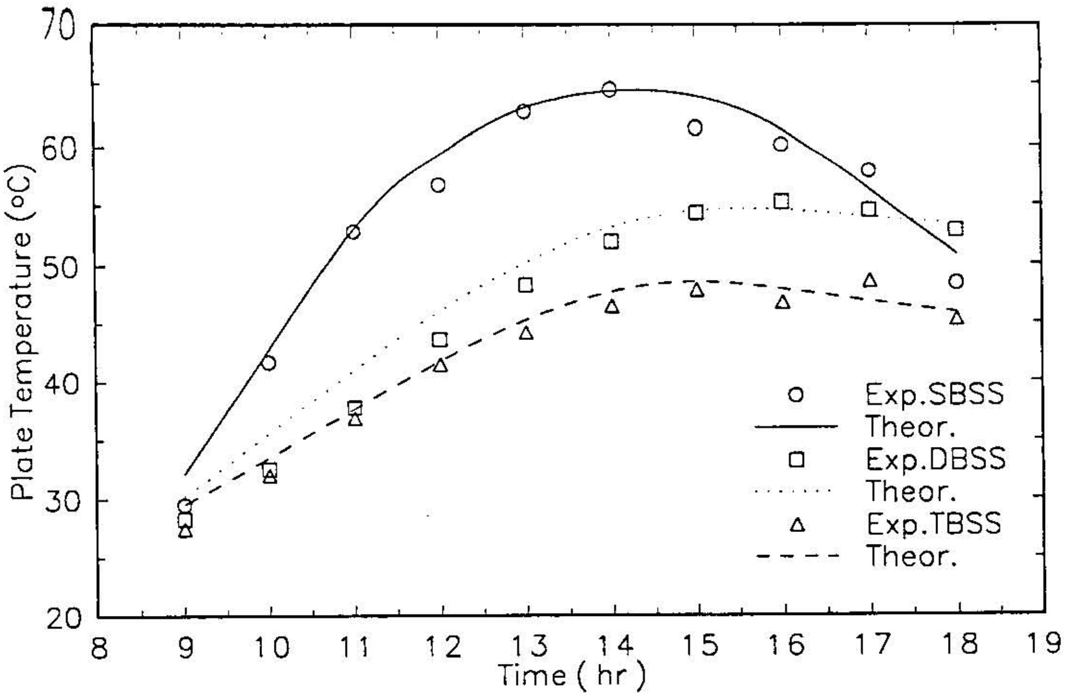


Fig (5.1) : Variation of both experimental and theoretical plate temperature for SBSS, DBSS and TBSS at 2 cm water depth with hours of the day

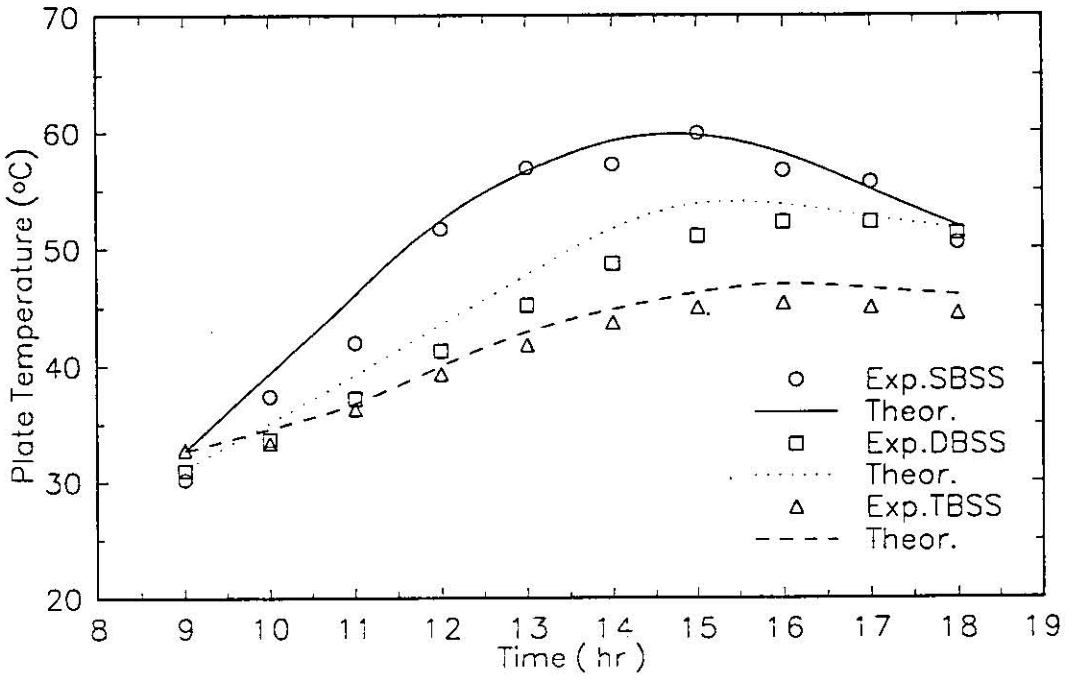


Fig (5.2) : Variation of both experimental and theoretical plate temperature for SBSS, DBSS and TBSS at 4 cm water depth with hours of the day

The variation of plate temperature for the three stills with time are shown in figures (5.1 - 5.2). In these figures the lower water temperature was taken the same as that of the plate temperature since it was assumed that there is no temperature gradient across the water layer. It is clear that the plate temperature increases with time until it reaches a maximum value after the solar time for the three stills, and beyond this value the plate temperature decreases with time. Also it is clear that the increase in SBSS plate temperature is higher than that of DBSS and TBSS , the maximum temperature for SBSS is 65 °C at 2 p.m., while the maximum temperature for DBSS is 55.2 °C at 4 p.m., and for TBSS it is about 49 °C at 5 p.m. This increase in plate temperature is due to the increase in solar intensity and the fraction of energy absorbed by the absorber plate. The difference between the stills plate temperatures is due to the variation of water and glass quantities for each still. The second part of these graphs shows that the decrease in SBSS plate temperature is higher than that of the other two stills since the upper and middle basins act as an insulation covers for the lower basin. From these figures, it may be noticed that both the experimental and theoretical are in good agreement.

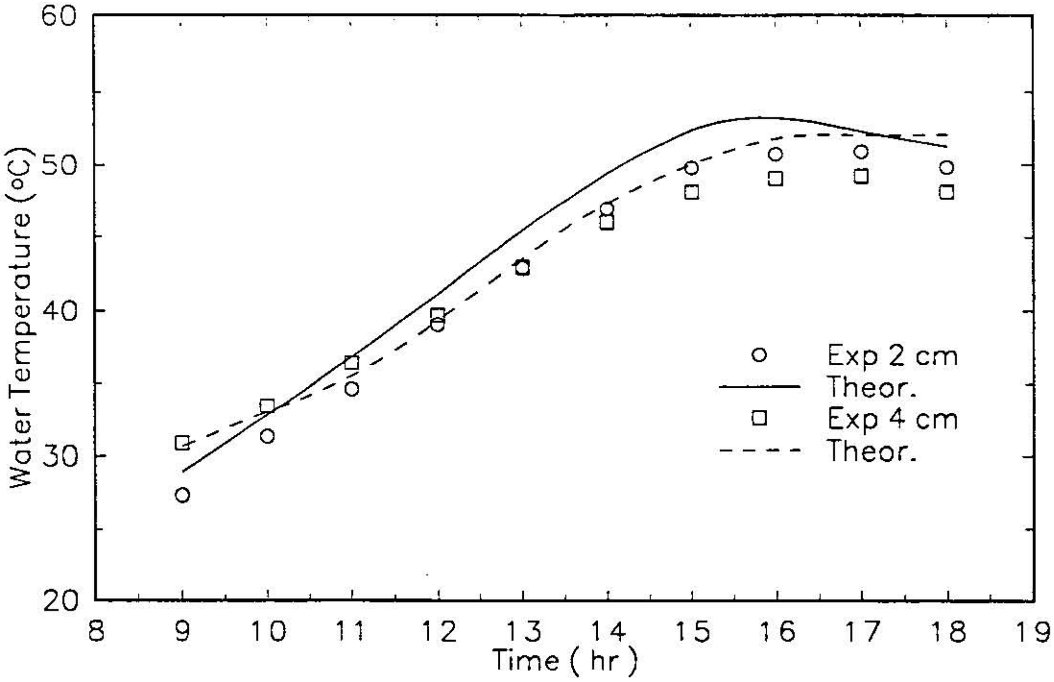


Fig (5.3) : Variation of experimental and theoretical water temperature for DBSS at 2 and 4 cm water depth in the lower basin with hours of the day

The hourly variation of water temperature for DBSS is shown in figure (5.3). It is to be noted that in SBSS the basin water and plate temperatures are assumed to be the same. It is clear that the water temperature increases with the intensity of solar radiation, however there is no immediate drop in water temperature when solar radiation starts to decrease due to the energy absorbed in the still's water.

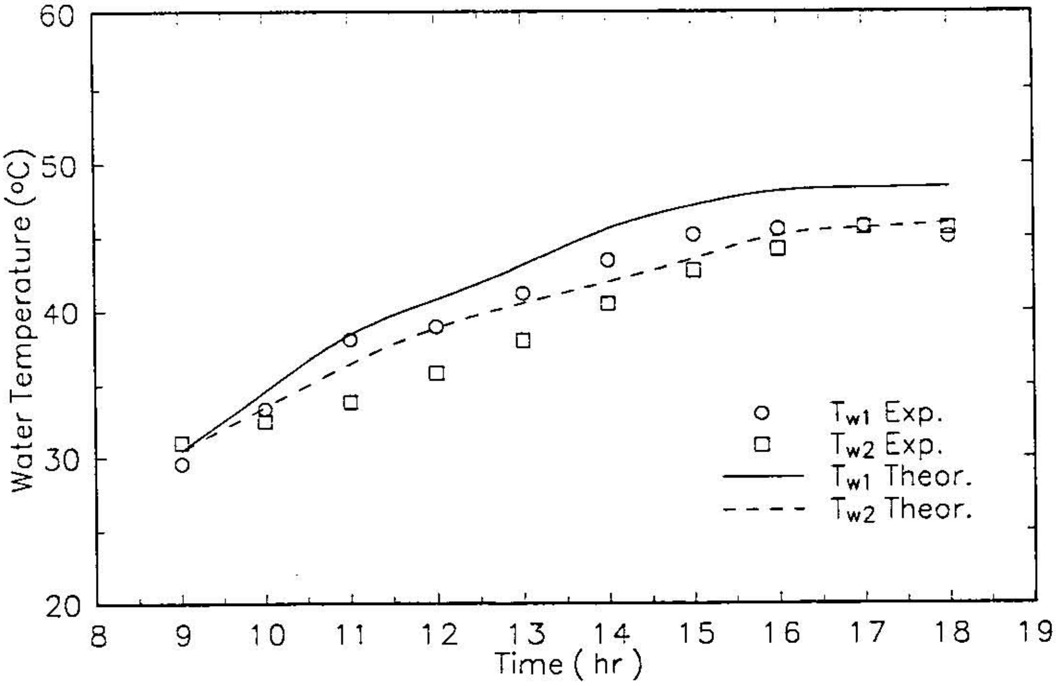


Fig (5.4) : Variation of water temperature of TBSS at 2 cm water depth in the lower basin with hours of the day

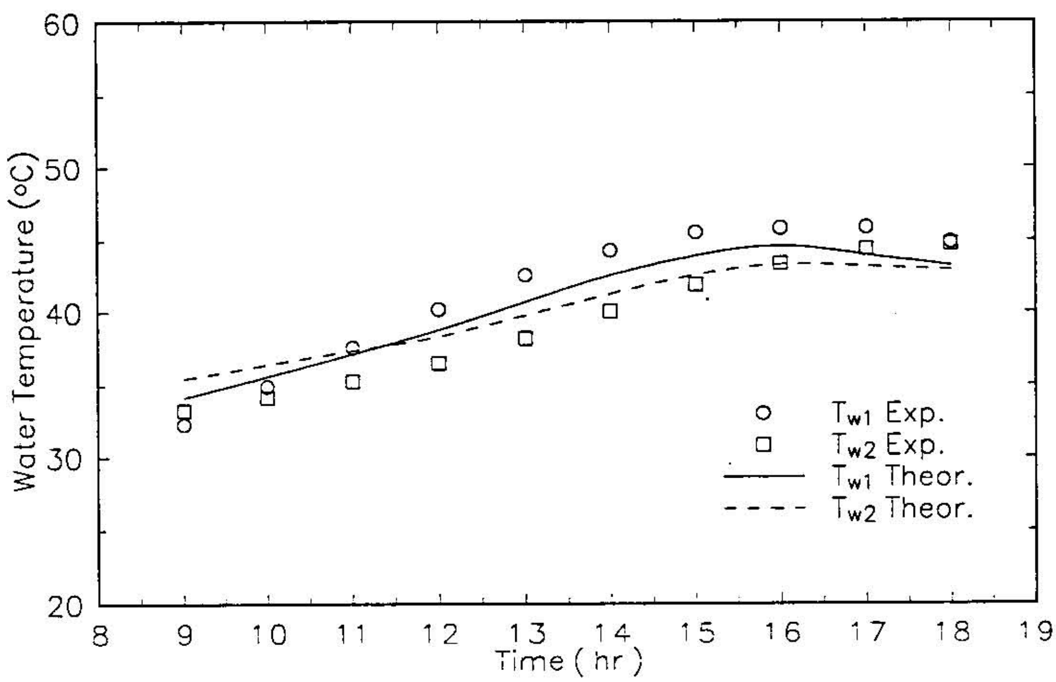


Fig (5.5) : Variation of water temperature of TBSS at 4 cm water depth in the lower basin with hours of the day

Figures (5.4 - 5.5) show the hourly variation in water temperature of the TBSS. As it may be seen, the upper basin water temperature is slightly higher than that of the middle basin one especially within the interval near the solar time. This behavior is explained by the fact that the upper and middle basins contain the same amount of water and have the same absorptivity, but the fraction of energy that reaches the middle basin is lower than that of the upper basin. As shown in figures (5.3 - 5.5) there is a good agreement between experimental and theoretical temperatures.

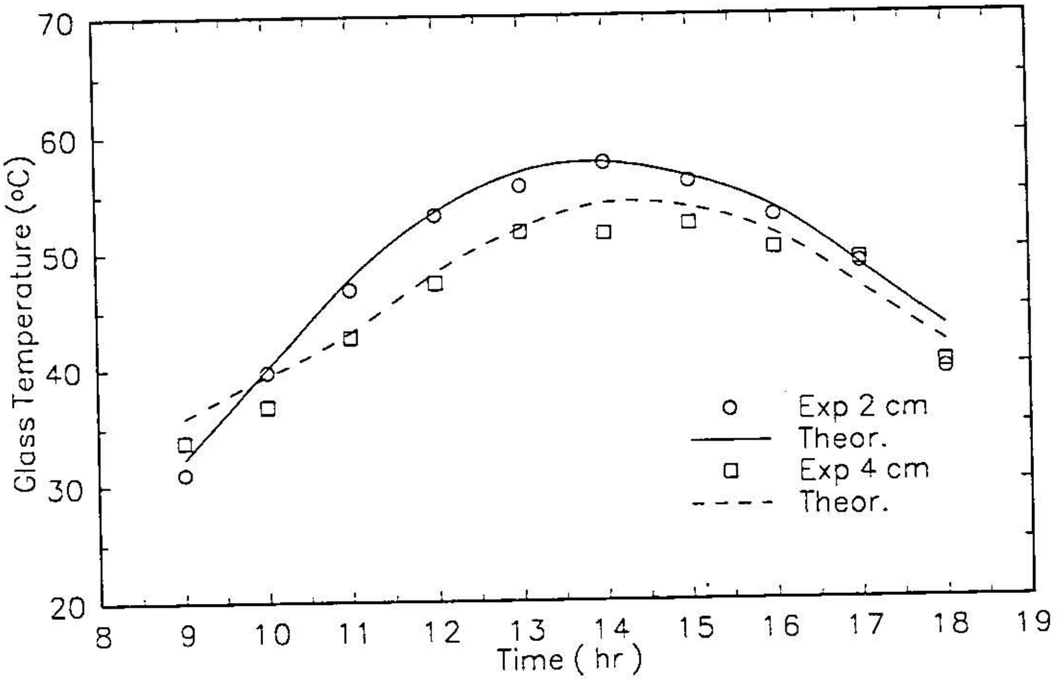


Fig (5.6) : Variation of both experimental and theoretical glass temperature of SBSS at 2 and 4 cm water depth in the lower basin with hours of the day

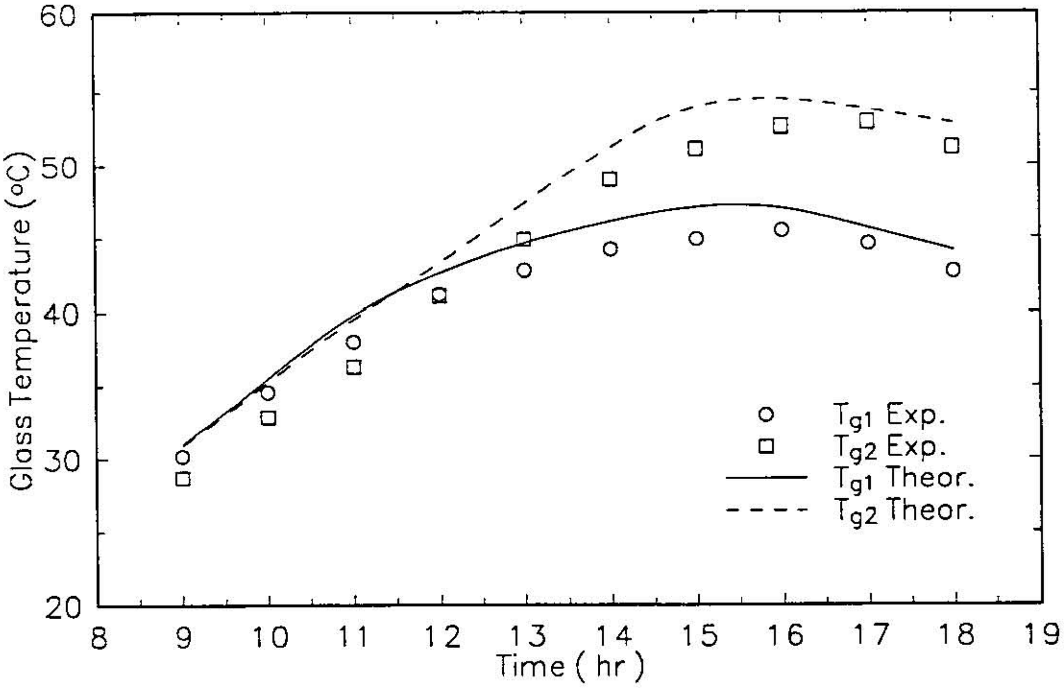


Fig (5.7) : Variation of glass temperature of DBSS at 2 cm water depth in the lower basin with hours of the day

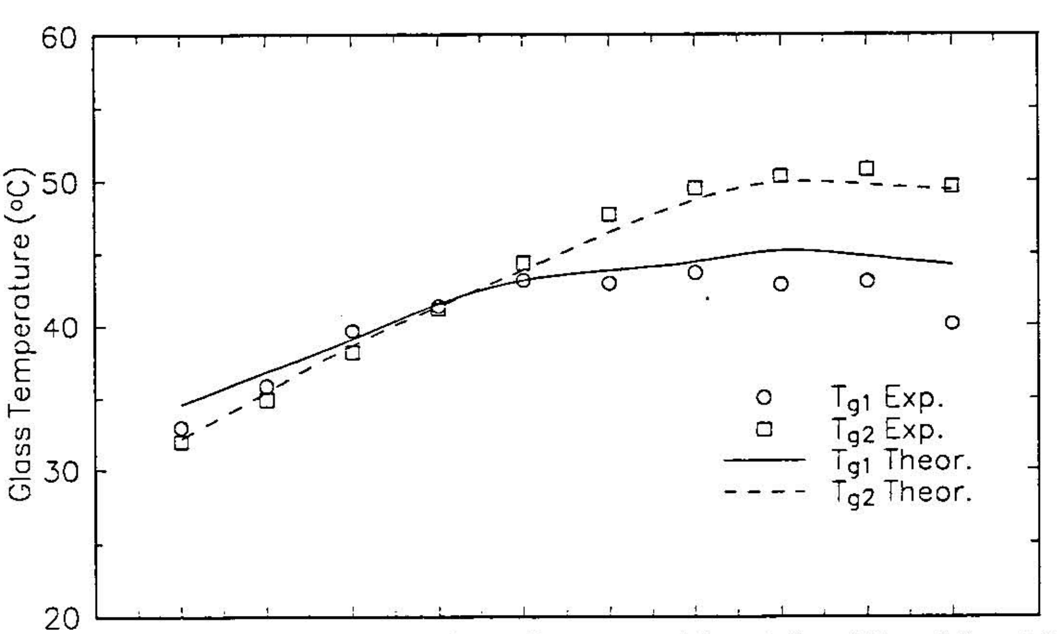
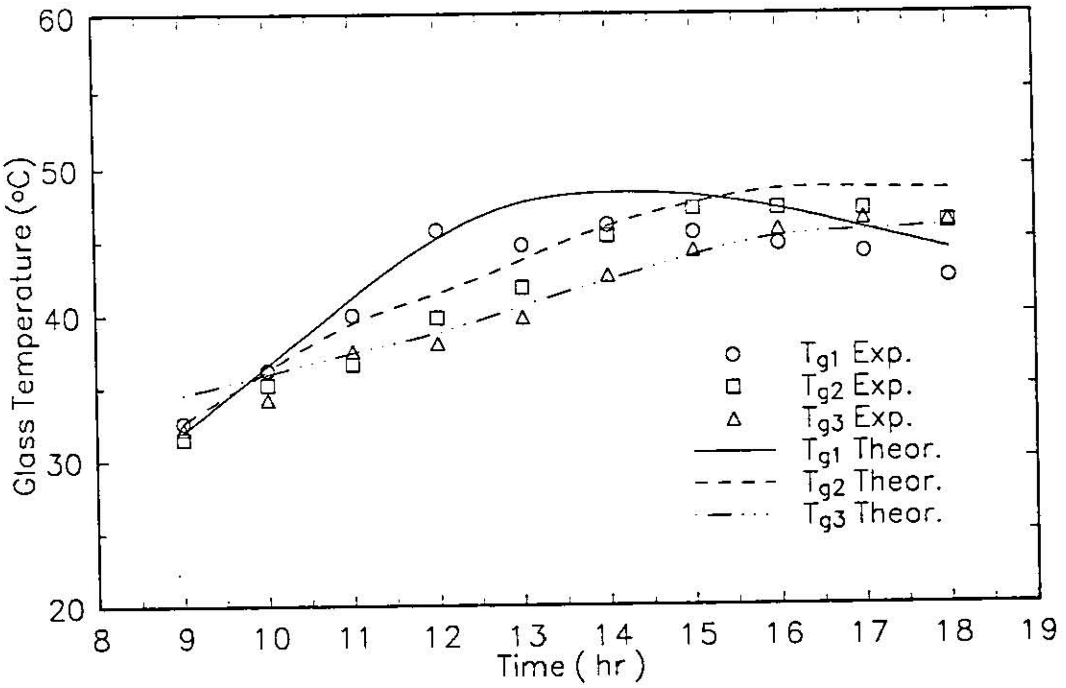
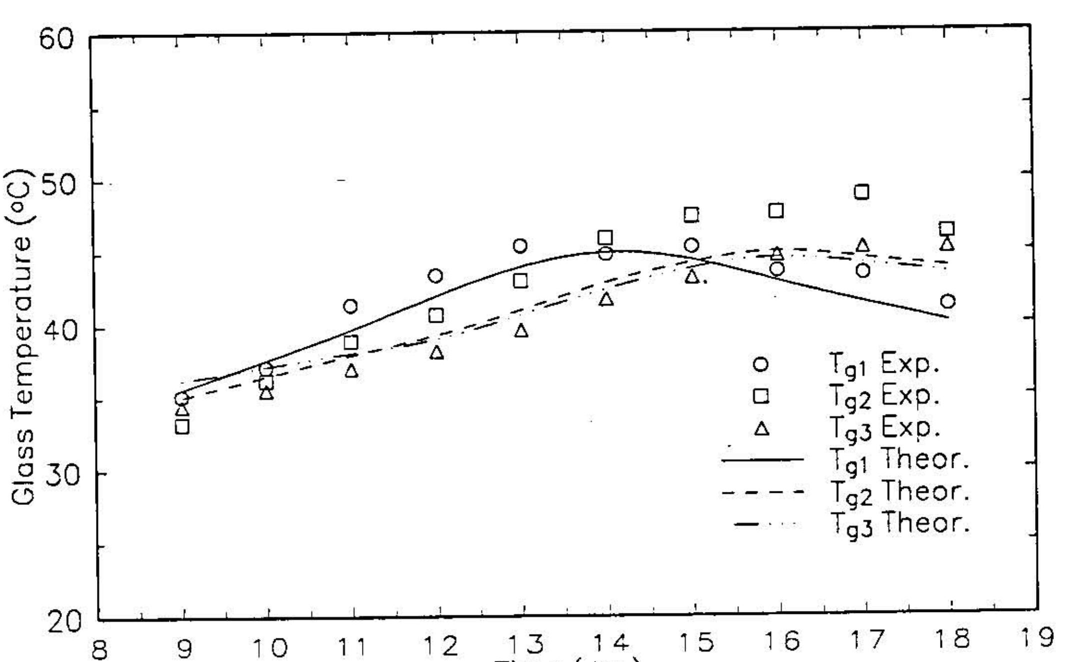


Fig (5.8) : Variation of glass temperature of DBSS at 4 cm water depth in the lower basin with hours of the day

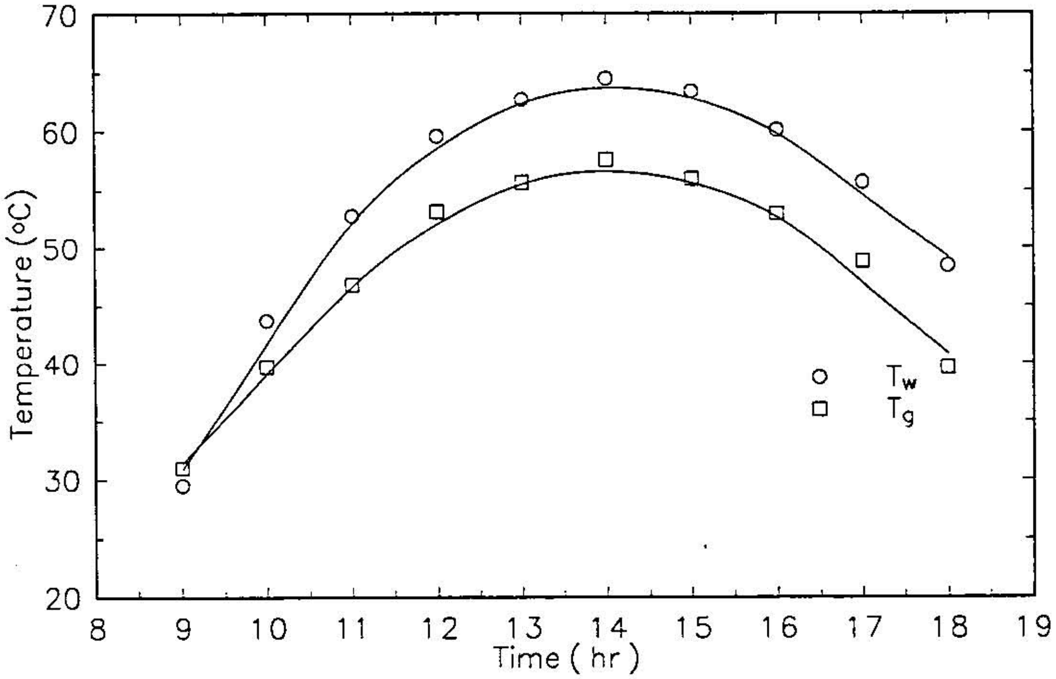


Fig(5.9) : Variation of glass temperature of TBSS at 2 cm water depth in the lower basin with hours of the day

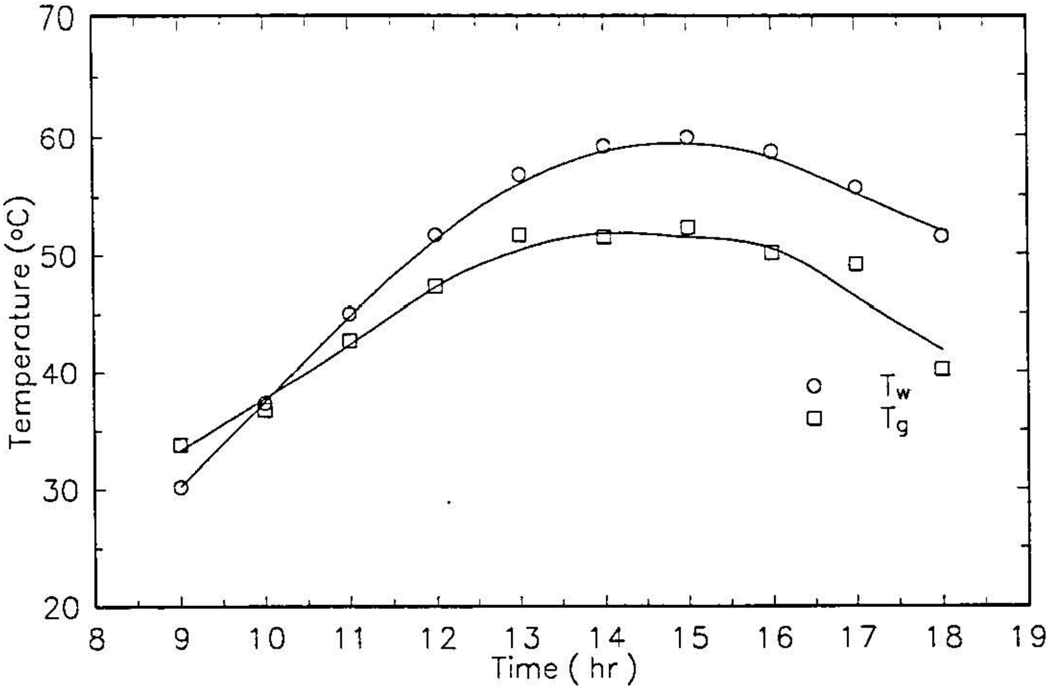


Fig(5.10) : Variation of glass temperature of TBSS at 4 cm water depth in the lower basin with hours of the day

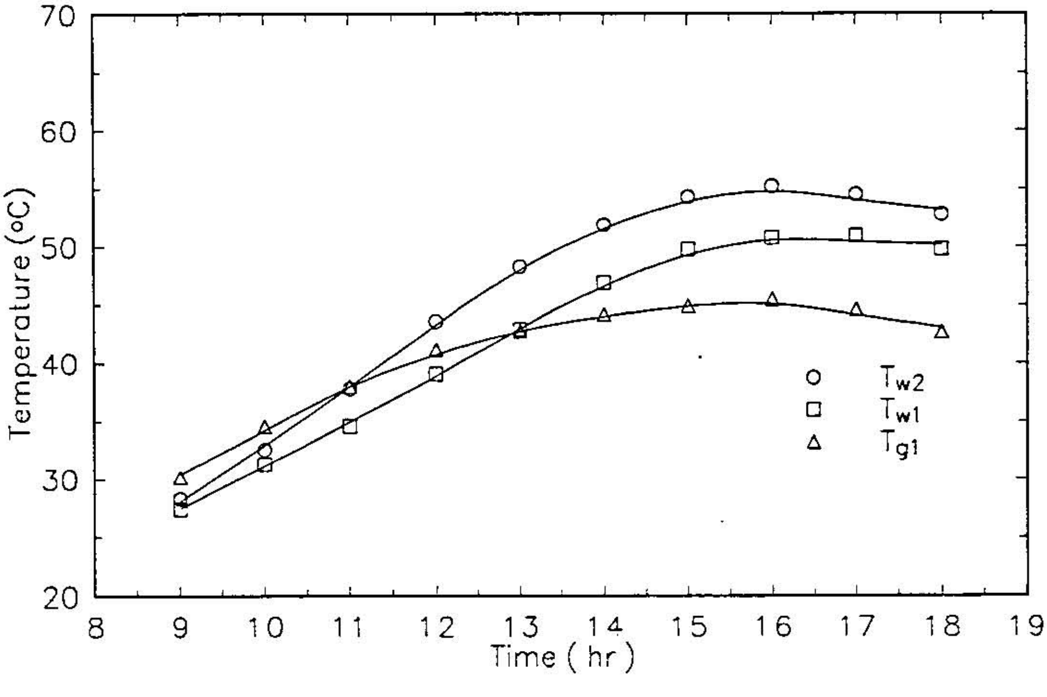
Experimental and theoretical variation of the hourly glass temperature for the three stills are shown in figures (5.6 - 5.10). It is noticed that the upper glass temperature in the three stills increase and then decrease with time, in the same trend as that of solar intensity and ambient temperature, since it is exposed to ambient directly, while for the DBSS it is observed that initially the lower and upper glass temperature is slightly the same, however the lower glass cover temperature begin to increase since it is in contact with water of the upper basin. In the TBSS the middle and lower glass temperatures are close to each other, since they are nearly under the same conditions.



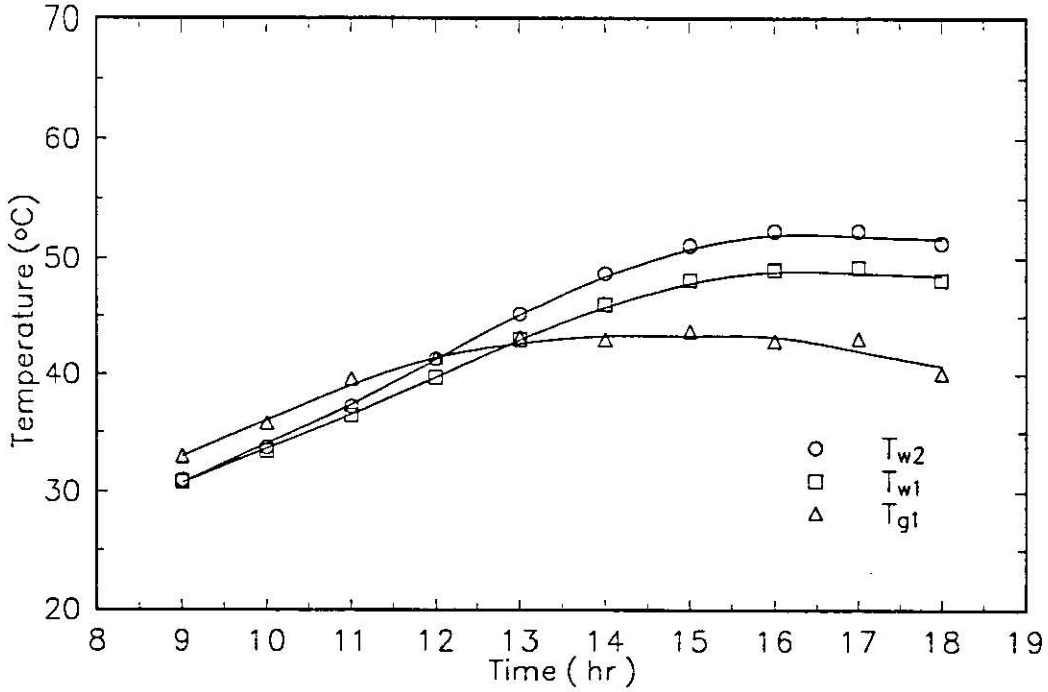
Fig(5.11) : Variation of water and glass temperatures of SBSS at 2 cm water depth with hours of the day



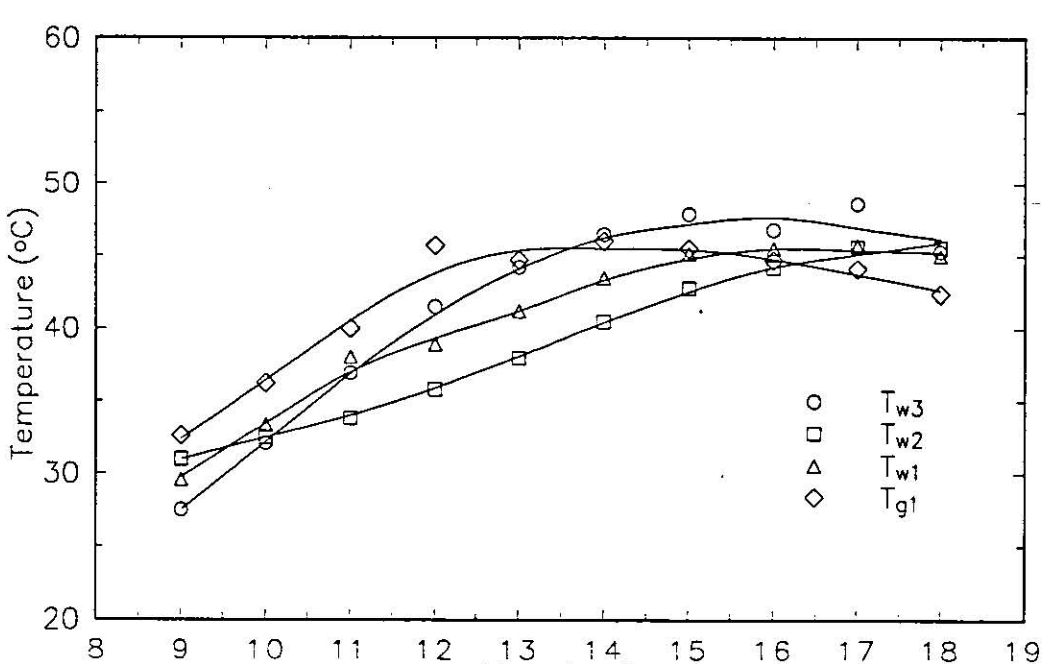
Fig(5.12) : Variation of water and glass temperatures of SBSS at 4 cm water depth with hours of the day



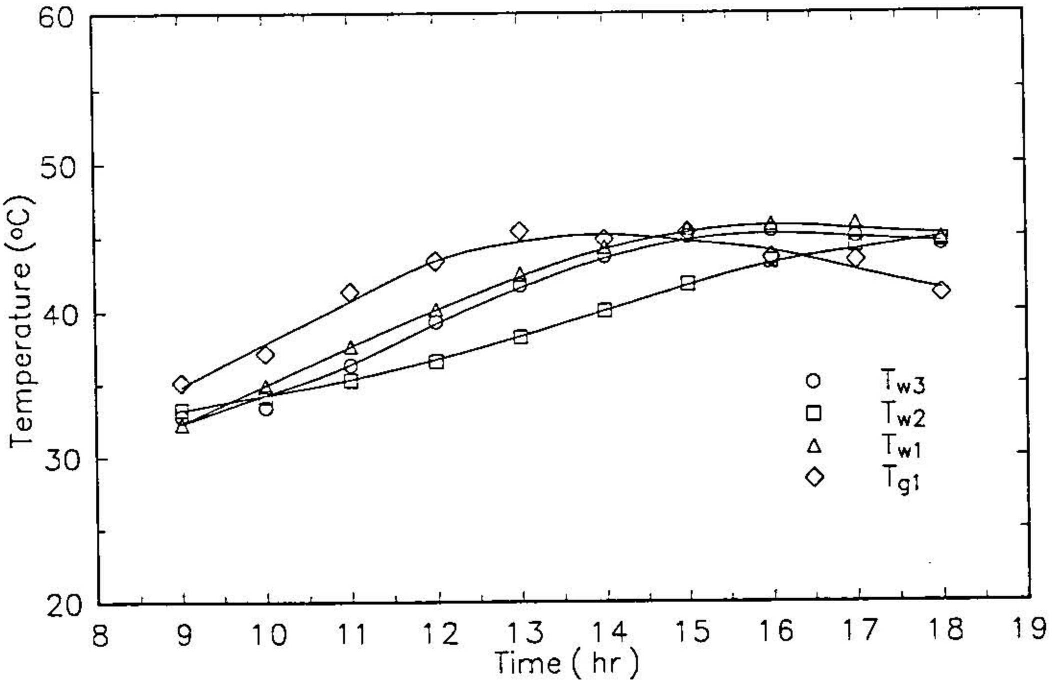
Fig(5.13) : Variation of water and glass temperatures of DBSS at 2 cm water depth in the lower basin with hours of the day



Fig(5.14) : Variation of water and glass temperatures of DBSS at 4 cm water depth in the lower basin with hours of the day

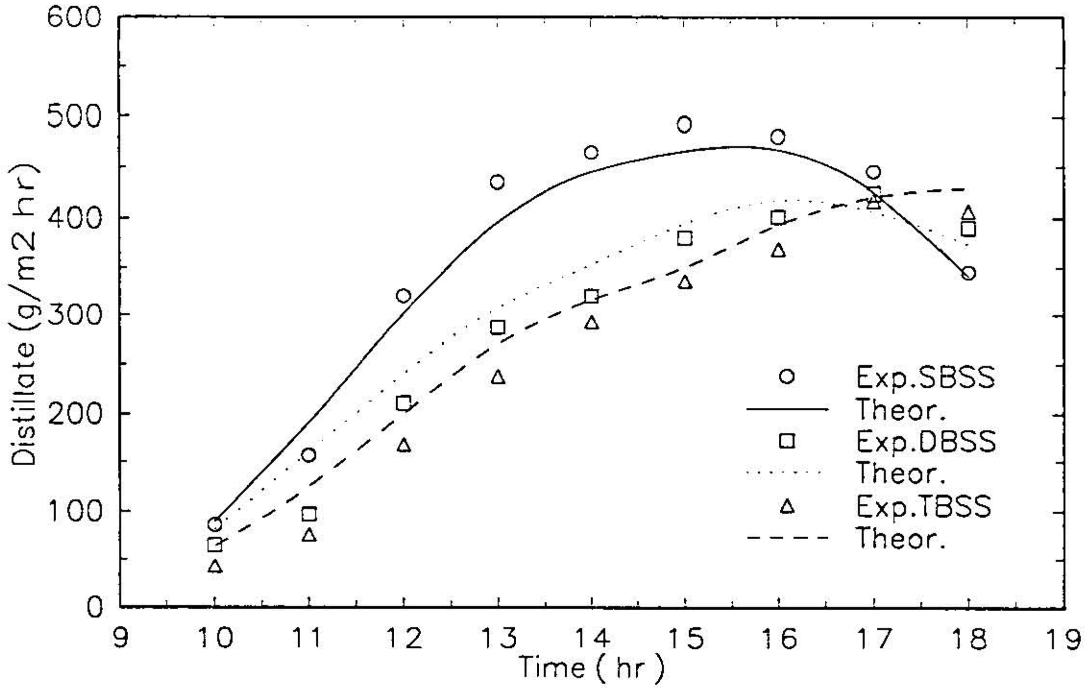


Fig(5.15) : Variation of water and glass temperatures of TBSS at 2 cm water depth in the lower basin with hours of the day

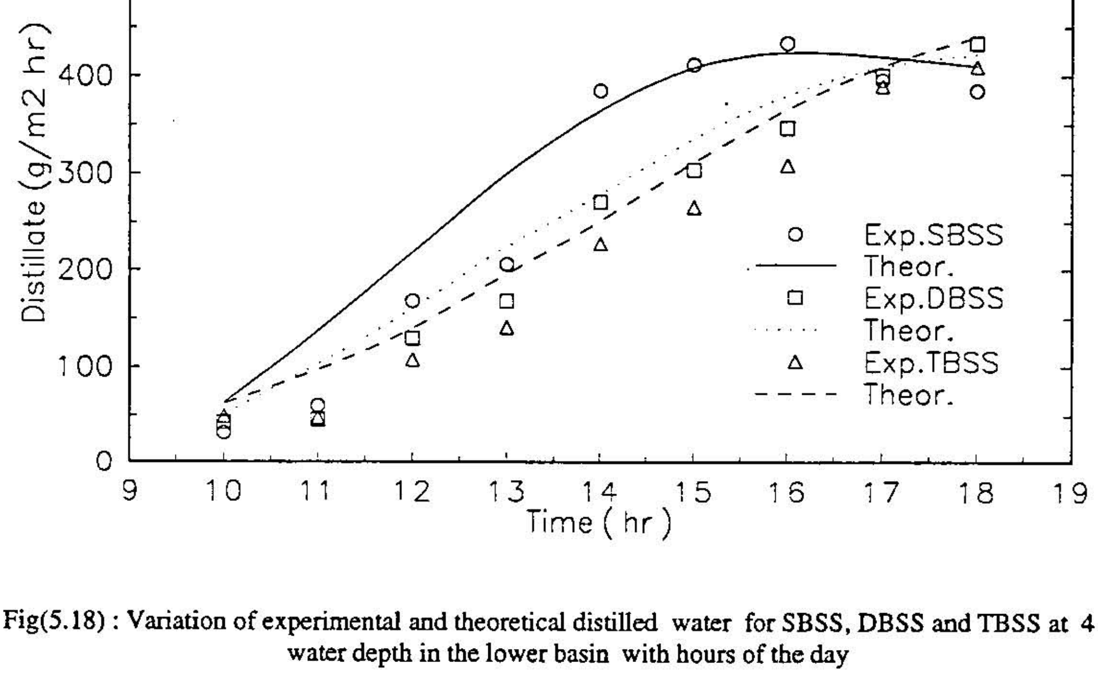


Fig(5.16) : Variation of water and glass temperatures of TBSS at 4 cm water depth in the lower basin with hours of the day

A comparison between the hourly water and glass temperature for each basin in the three stills is presented in figures (5.11 - 5.16). It is clear from these figures that the water temperature is higher than the glass temperature for the measuring period except within the first hour for SBSS, and within the first three hours for DBSS and the first four hours for the TBSS where the glass temperature is slightly higher. Since the heat capacity of glass is lower than of water so it's temperature increases rapidly in the first hours. The difference between water and glass temperature is the driving force for evaporation of water. This difference is increasing gradually starting from morning until it reaches a maximum value for SBSS at 3 p.m., while for the DBSS and TBSS it is maximum at the end of experimentation period, resulting in a higher distilled water output.



Fig(5.17) : Variation of experimental and theoretical distilled water for SBSS, DBSS and TBSS at 2 cm water depth in the lower basin with hours of the day



Fig(5.18) : Variation of experimental and theoretical distilled water for SBSS, DBSS and TBSS at 4 cm water depth in the lower basin with hours of the day

The theoretical and experimental quantities of distilled water from the three stills are shown in tables (5.1) and (5.2) for two water depths. Also the variation of output yield with time of the day are plotted in figures (5.17 - 5.18). These figures represents the hourly output during the working period, while the output of other period of the day is shown in tables (5.1) and (5.2).

Table (5.1) : Experimental and theoretical distilled water output for 2 cm water depth for the three solar stills

Time	Experimental			Theoretical		
	SBSS (g/m^2)	DBSS (g/m^2)	TBSS (g/m^2)	SBSS (g/m^2)	DBSS (g/m^2)	TBSS (g/m^2)
10:00	86	65	43	100	90	70
11:00	157	97	76	165	140	110
12:00	320	211	168	320	280	200
13:00	434	287	238	410	310	290
14:00	466	320	293	450	350	310
15:00	493	380	336	470	400	350
16:00	482	401	369	480	430	390
17:00	445	423	417	450	415	440
18:00	345	390	407	330	370	420
18:00-9:00	613	2224	2799	740	2350	2900
Total	**3836**	**4798**	**5146**	**3915**	**5135**	**5480**

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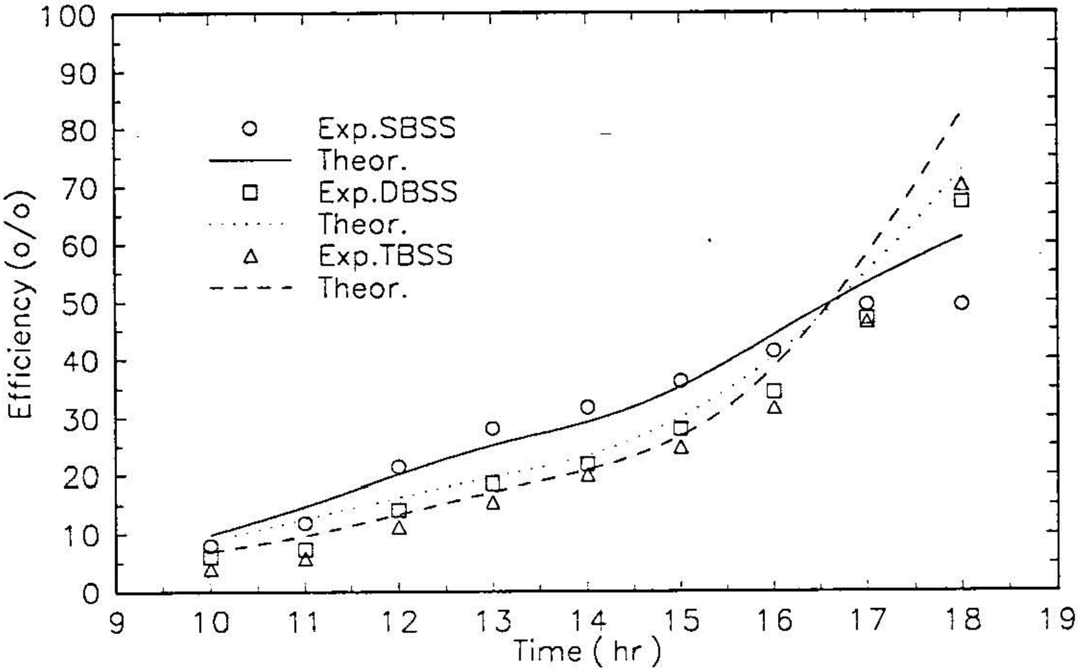
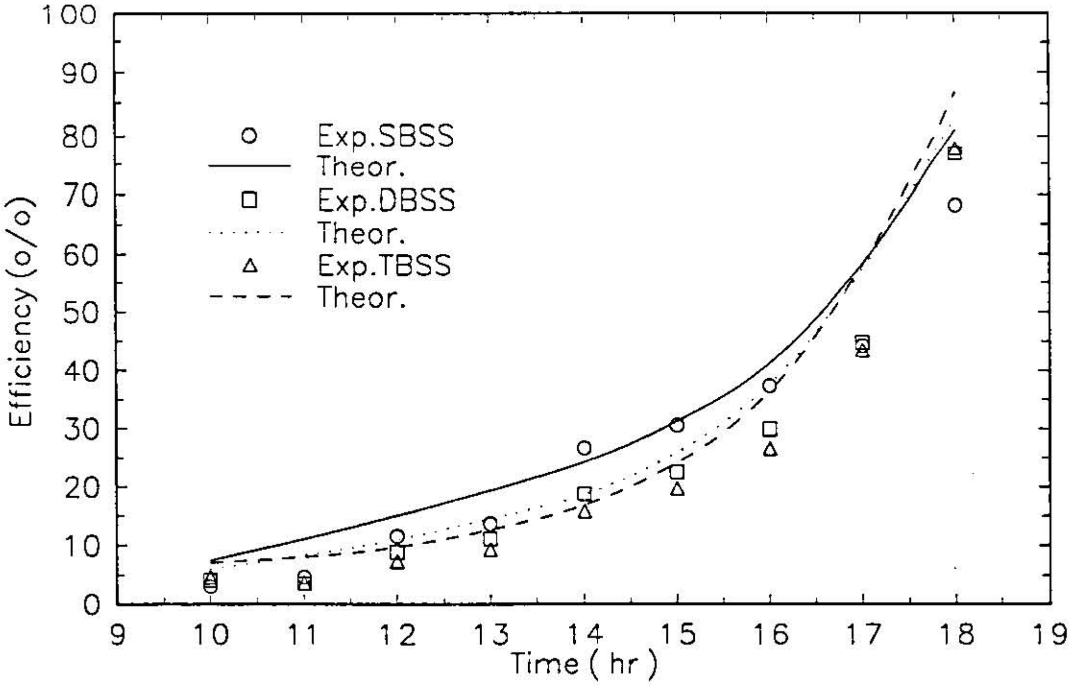
Table (5.4) : Experimental and theoretical hourly and total efficiencies for 4 cm water depth for the three solar stills

Time	Experimental			Theoretical		
	SBSS %	DBSS %	TBSS %	SBSS %	DBSS %	TBSS %
10:00	3.1	4.14	4.71	7.89	6.77	7.33
11:00	4.67	3.6	3.73	10.02	6.68	7.52
12:00	11.54	8.93	7.42	15.82	12.38	9.63
13:00	13.69	11.16	9.37	18.91	13.24	11.97
14:00	26.68	18.78	15.8	23.65	18.64	16.71
15:00	30.53	22.53	19.7	30.62	24.06	21.87
16:00	37.42	29.92	26.64	39.57	35.89	34.97
17:00	44.2	44.76	43.53	54.28	53.63	52.99
18:00	68.22	76.9	77.79	82.79	84.81	88.86
Total	**31.23**	**38.98**	**41.4**	**31.5**	**40.4**	**44.2**



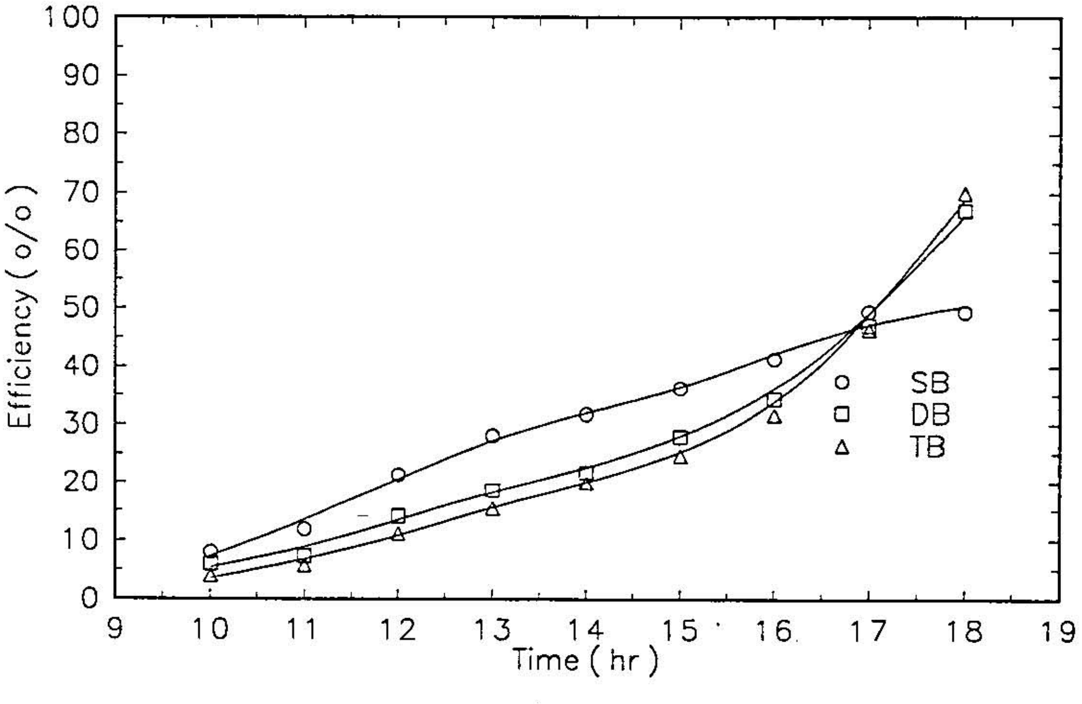
Fig(5.19) : Variation of hourly efficiency both experimental and theoretical for SBSS, DBSS and TBSS at 2 cm water depth in the lower basin with hours of the day



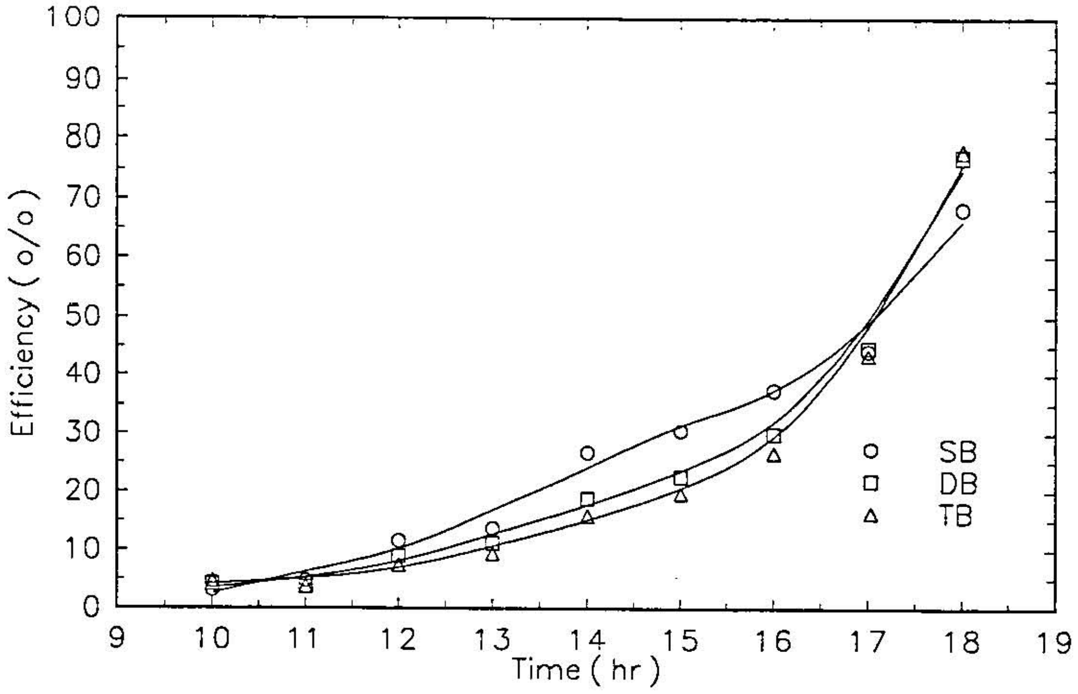
Fig(5.20) : Variation of hourly efficiency both experimental and theoretical for SBSS, DBSS and TBSS at 4 cm water depth in the lower basin with hours of the day

For all types of stills the distilled water increases with time until it reaches a maximum value and then decreases. In SBSS the maximum output was about 490 (g/m^2.hr) during the interval from 14:00 to 15:00 with a total daily output of about 3.8 (kg/m^2 day) . In DBSS the maximum yield was about 420 (g/m^2.hr) during the interval from 16:00 to 17:00 with a total daily output of about 4.8 (kg/m^2 day). And for TBSS the maximum yield was about 420 (g/m^2.hr) during the interval from 16:00 to 17:00 with a total daily output of about 5.15 (kg/m^2 day). From these figures it is noticed that the output of TBSS is higher than SBSS by about 36 % , and higher than that of the DBSS by about 7 % , while the DBSS yield is about 26 % higher than that of the SBSS. Also these figures show that there is a reasonable agreement between experimental and theoretical results, but in general the performance of theoretical ones is higher than that of experimental due to the assumptions introduced in the theoretical analysis.

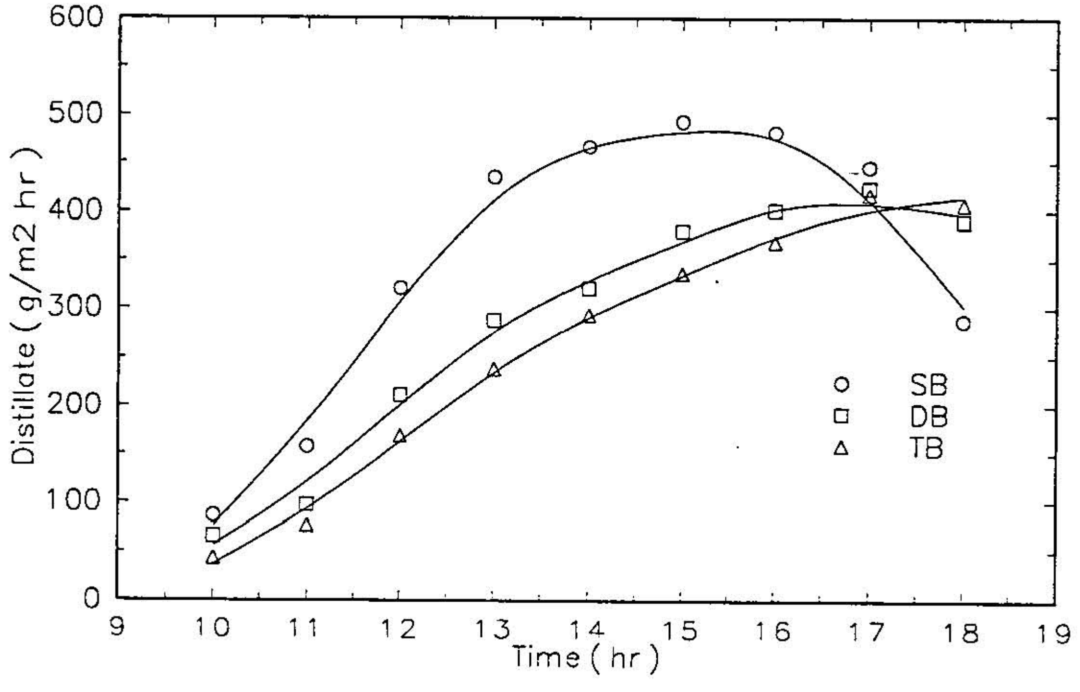
The variation of hourly efficiency for the each still is plotted in figures (5.19 - 5.20), while the daily efficiency which is calculated by using eq. (4.50) is shown in tables (5.3) and (5.4), also the hourly efficiency of the three stills compared with each other are plotted in figures (5.21 - 5.22) . From these figures , it is clear that the hourly efficiency is very small in the first two or three hours, and it increase at a lower rate before solar time, since most of the energy received was used to heat up the basin water in the three stills, then it increase at higher rate as shown.



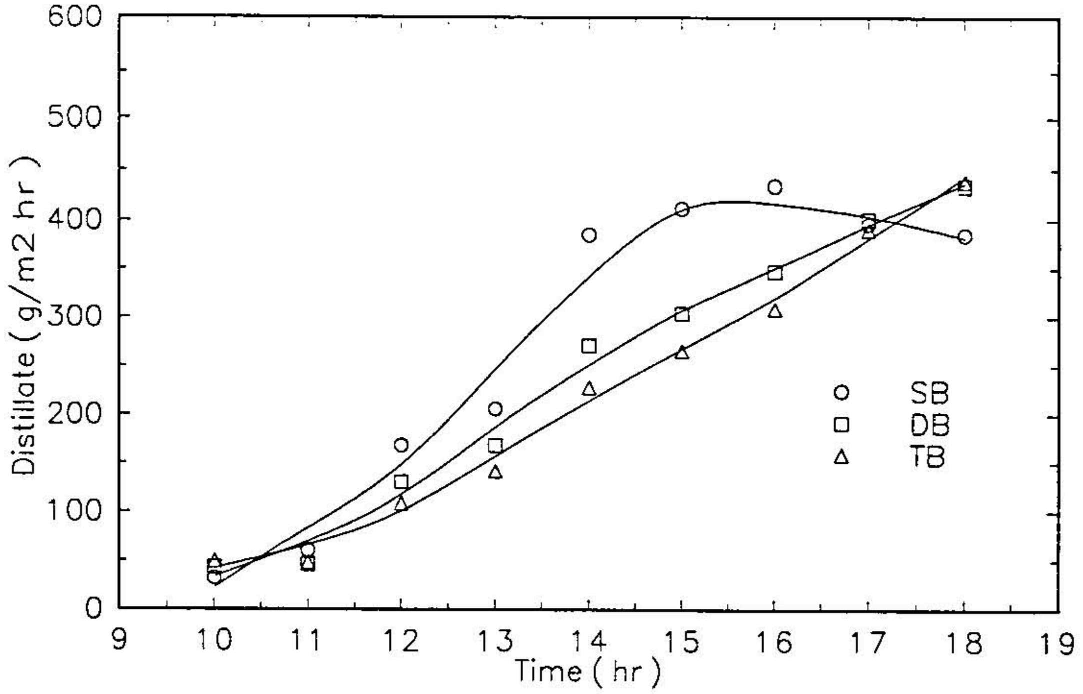
Fig(5.21) : Variation of hourly efficiency (experimentally) for SBSS, DBSS and TBSS at 2 cm water depth in the lower basin with hours of the day



Fig(5.22) : Variation of hourly efficiency (experimentally) for SBSS, DBSS and TBSS at 4 cm water depth in the lower basin with hours of the day



Fig(5.23) : Variation of hourly distilled water for SBSS, DBSS and TBSS at 2 cm water depth in the lower basin with hours of the day



Fig(5.24) : Variation of hourly distilled water for SBSS, DBSS and TBSS at 4 cm water depth in the lower basin with hours of the day

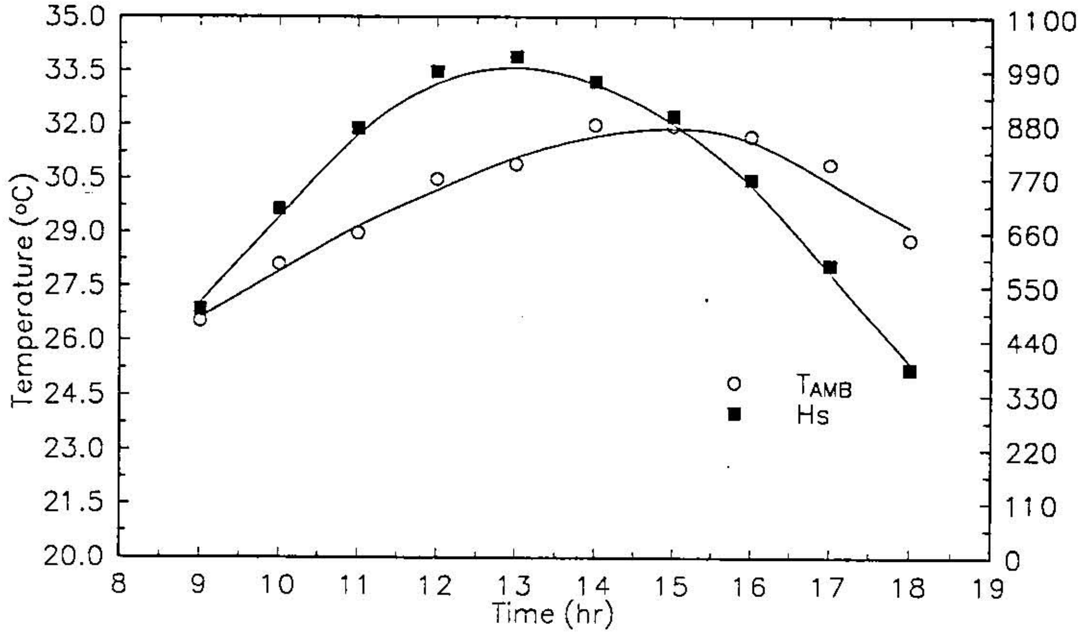


Fig (5.25) : Variation of hourly ambient temperature and solar intensity for 2 cm water depth in the lower basin.

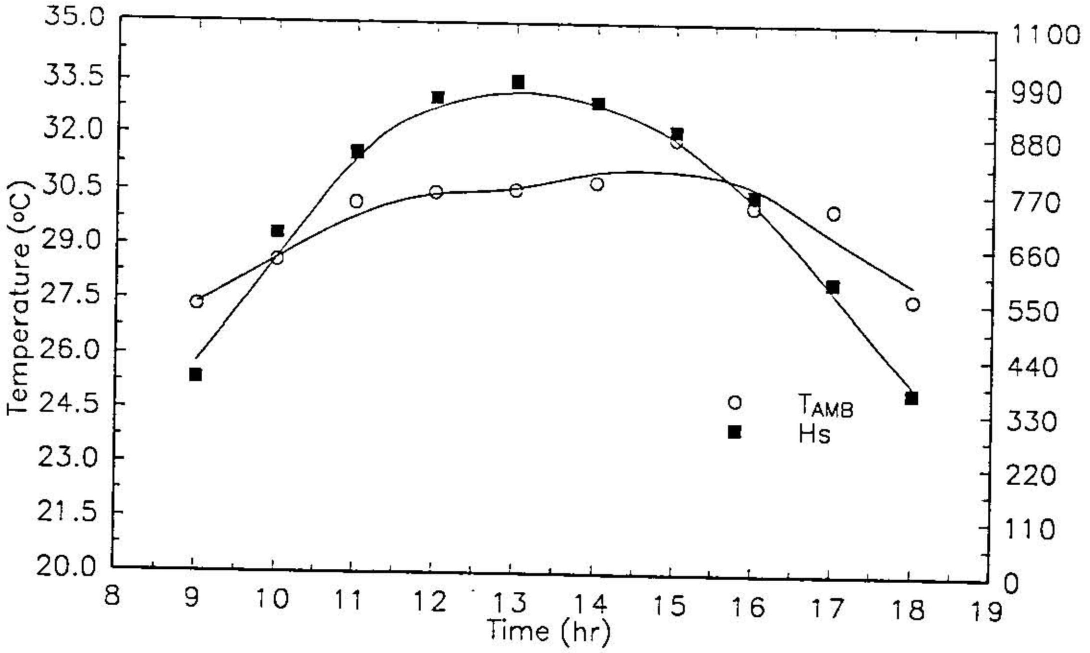


Fig (5.26) : Variation of hourly ambient temperature and solar intensity for 4 cm water depth in the lower basin.

The performance of the three stills were compared to each other as shown in figures (5.23 - 5.24), in these figures the distilled water of the three stills are plotted against time. From these figures it is clear that the SBSS is the most efficient one during most of the day, however late in the afternoon it becomes the least efficient one. This is due to low masses in SBSS compared with the other two stills, since the same amount of solar energy was received by the three still.

For SBSS the hourly efficiency varies between 3.1 % at 10 a.m. to 68.2 % at 6:00 p.m., while for DBSS it has a maximum value of 76.9 % at 6:00 p.m., while for TBSS it is about 88 % at 6:00 p.m. This increase in hourly efficiency is due to the stored energy in the basin water.

The daily efficiency which is the ratio between the amount of energy used to evaporate water to the total incident solar intensity on the horizontal absorber plate , are shown in tables (5.3) and (5.4). As shown in the tables the daily efficiency of each solar still is independent of the water depth in the basin.

Further the TBSS was found to be the most efficient still followed by the DBSS and the SBSS which was the least efficient one. Finally and as shown in the figures there is a good agreement between the theoretical and experimental efficiencies of the three types of stills.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

From the results of this study, the following conclusions may be stated :

1- The daily distillate production of a TBSS is 36 % higher than that of a SBSS and 7 % higher than that of a DBSS, while the productivity of DBSS is 26 % higher than that of a SBSS.

2- There is a good agreement between the theoretical and experimental efficiency of the three stills.

3- 26 % increase in the productivity was obtained when the number of basins increased from one to two , while a 7 % increase in it when the number of basins increased from two to three.

4- During sunrise hours the productivity of SBSS is higher than the other two stills, while it is lower during night.

5- The daily distillate yield is almost independent of the water height in the lower basin.

6.2 RECOMMENDATIONS

The following recommendations can be made based on this study which require further investigation :

1- The effect of reducing the slope angle of the glass cover on the still output.
2- The effect of continuous supplying of saline water on the still output.
3- The effect of sides shading, by changing the ratio of side length to the basin area.
4- The outer glass cover cooling.
5- Integrating this system with buildings.
6- Temperature gradient through glass and water layers should be taken into consideration.
7- The effect of adding some volatile materials to increase the evaporation rate.
8- Use of waste water in the lower basin.

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الصفحة غير موجودة من أصل المصدر

```
C       SINGLE1 BASIN
        CHARACTER*10 AFILE
        REAL L,K,MW,MG,MDW,MDWO,MDWT
        DATA RG,AG,AW,AB/.02,.05,.02,.86/
        PRINT*,'ENTER OUTPUT FILE NAME'
        READ*,AFILE
        OPEN(UNIT=2,FILE=AFILE,STATUS='NEW')

        PRINT*,'ENTER STARTING TIME, PERIOD (HOURS)'
        READ*,FTIME,PERIOD
        PRINT*,'ENTER TIME STEP, TIME PRINT (SECONDS)'
        READ*,DT,IDT
        PRINT*,'ENTER INITIAL VALUES TGO,TWO'
        READ*,TGO,TWO
        PRINT*,'ENTER WATER DEPTH IN CM'
        READ*,WD
        NITER=INT(PERIOD*3600./DT)


C THESE ARE TEMPORARY CONSTANTS

        H1=16.07
        H2=40.88

C     THESE ARE CONSTANTS
        MW=41870.*WD
        MG=7500.
        HI=22.7
        L=.03
        K=.04
        H3=137.
        H4=22.7
        HE=8.55
        HW=2372520

C       TAU1=(1.-RG)*AG
C       TAU2=(1.-RG)*(1.-AG)*AW
C       TAU3=(1.-RG)*(1.-AG)*(1.-AW)*AB
C       PRINT*,'TAU1,2,3=(.1,0,.7)',TAU1,TAU2,TAU3
        TAU1=0.1
        TAU2=0.0
        TAU3=0.7
        EMIS=.2
        EMISG=.3
        SIG=5.67E-8
        R1=293.3
        R2=-84026.4
        V=1.5

        HB=1./((1./HI)+(L/K))
        UB=1./((1./H3)+(1./HB))
        TAU4P=TAU2+UB*((L/K)+(1./H4))*TAU3
C       PRINT*,'UB=',UB,'HB=',HB,'TAU4P=',TAU4P

C       PRINT*,'NITER=',NITER
        MDWO=0.
```

```
      DO 10 I=1,NITER

      PTIME=REAL(I)*DT/3600.
      TIME=FTIME+PTIME
      HS=HSF(TIME)
      TA=TAF(TIME)

C***  THE AMOUNT OF DISTILLATE WATER PER UNIT TIME PER UNIT AREA
      MDW=(HE*(TWO-TGO)/HW)*3600

      TEMP=TWO-TGO+(R1*(TWO-TGO)*(TWO+273.))/(2.689E3-R2-R1*
     + (TWO+273.))
C     PRINT*,'TEMP=',TEMP
      IF(TEMP.LT.0)THEN
      TEMP=TEMP*(-1)
      ENDIF
      HCW=0.884*TEMP**(.33333333)

C     PRINT*,'HCW',HCW
      HEFF=16.276E-3*HCW*R1
      HRW=EMIS*SIG*((TWO+273.)**4-(TGO+273)**4)/(TWO-TGO)

      HCA=5.7+3.8*V
C     PRINT*,'H1,H2',H1,H2
      H1=HRW+HCW+HEFF
      H2=HCA+EMISG*SIG*((TGO+273)**4-(TA+273)**4)/(TGO-TA)



      IF (MOD(INT(PTIME*3600.),IDT).EQ.0) THEN

C     PRINT*,'I=',I
C     PRINT*,'PTIME(HOURS)=',PTIME
      PRINT*,'-------------------------------------'
      PRINT*,'PTIME(SECONDS)=',PTIME*3600.
      PRINT*,'TIME=',INT(TIME),':',(TIME-REAL(INT(TIME)))*60.
      PRINT*,'TA=',TA,'HS=',HS
      PRINT*,'TGN=',TGN,'TWN=',TWN
      PRINT*,'MDW (KG/M2.HR)=',MDW
      MDWT=MDWO+MDW
      PRINT*,'MDWT=',MDWT

      WRITE(2,*)'-------------------------------------'
      WRITE(2,*)'PTIME(SECONDS)=',PTIME*3600.
      WRITE(2,*)'TIME=',INT(TIME),':',(TIME-REAL(INT(TIME)))*60.
      WRITE(2,*)'TA=',TA,'HS=',HS
      WRITE(2,*)'TGN=',TGN,'TWN=',TWN
      WRITE(2,*)'MDW (KG/M2.HR)=',MDW
      MDWT=MDWO+MDW
      WRITE(2,*)'MDWT=',MDWT

      ENDIF

      TGN=TGO+(DT/MG)*(TAU1*HS+H1*(TWO-TGO)-H2*(TGO-TA))
      TWN=TWO+(DT/MW)*(TAU4P*HS-H1*(TWO-TGO)-UB*(TWO-TA))

      TGO=TGN
      TWO=TWN
      MDWO=MDWT
```

```
10    CONTINUE

      STOP
      END

      REAL FUNCTION HSF(TIME)

C TIME IS IN HOURS

C INITIAL VALUES AT TIME=8:00AM

      TIME=(TIME/24.-REAL(INT(TIME/24.)))*24.

C     HSF=757.828*EXP(-0.5*((TIME-11.677)/2.366)**2)

C     SAT 23/7/1994  R=0.9816
C     HSF=1060.85*EXP(-0.5*((TIME-12.185)/3.10933)**2)

C     SUN 24/7/1994  R=0.98
C     HSF=1072.36*EXP(-0.5*((TIME-12.2213)/3.12107)**2)

C     MON 25/7/1994  R=0.982
C     HSF=1072.64*EXP(-0.5*((TIME-13.2434)/3.10278)**2)

C     TUE 26/7/1994  R=0.9825
      HSF=1051.02*EXP(-0.5*((TIME-13.3182)/3.06114)**2)

C     WED 27/7/1994  R=0.9849
C     HSF=1055.68*EXP(-0.5*((TIME-13.197)/3.0651)**2)

C     PRINT*,'HSF=',HSF
      RETURN
      END

      REAL FUNCTION TAF(TIME)

C TIME IS IN HOURS
C INITIAL VALUES AT TIME=8:00AM

      TIME=(TIME/24.-REAL(INT(TIME/24.)))*24.

C    TAF=22.192-3.6337*TIME+0.7986*TIME**2-.048541*TIME**3
C   + +.00089405*TIME**4

C     SAT 23/7/1994  R=0.89
C    TAF=26.629-3.9023*TIME+0.71962*TIME**2-.040361*TIME**3
C   + +.00069779*TIME**4

C     SUN 24/7/1994  R=0.93
C    TAF=27.369-5.3271*TIME+1.0242*TIME**2-.059544*TIME**3
C   + +.0010735*TIME**4

C     MON 25/7/1994  R=0.9553
C    TAF=27.81-3.9639*TIME+0.74641*TIME**2-.042617*TIME**3
C   + +.00075229*TIME**4

C     TUE 26/7/1994  R=0.93
     TAF=25.803-6.263*TIME+1.2511*TIME**2-.074415*TIME**3
    + +.0013649*TIME**4
```

```
C       WED 27/7/1994  R=0.9151
C     TAF=25.564-4.8904*TIME+0.86331*TIME**2-.047922*TIME**3
C    + +.00083406*TIME**4

C       PRINT*,'TAF=',TAF
        RETURN
        END

C       DOUBLE1 BASIN

        REAL L,K,MW1,MG1,MW2,MG2,MDWU,MDWL,MDWUO,MDWUT,MDWLO,MDWLT

        CHARACTER*10 AFILE
        PRINT*,'ENTER OUTPUT FILE NAME'
        READ*,AFILE
        OPEN(UNIT=2,FILE=AFILE,STATUS='NEW')

        PRINT*,'ENTER STARTING TIME, PERIOD (HOURS)'
        READ*,FTIME,PERIOD
        PRINT*,'ENTER TIME STEP, TIME PRINT (SECONDS)'
        READ*,DT,IDT
        PRINT*,'ENTER INITIAL VALUES TG1O,TW1O,TG2O,TW2O'
        READ*,TG1O,TW1O,TG2O,TW2O
        PRINT*,'ENTER WATER DEPTH IN CM'
        READ*,WD
        NITER=INT(PERIOD*3600./DT)

C THESE ARE TEMPORARY CONSTANTS

        H1=16.17
        H2=70.47
        H4=15.97

C     THESE ARE CONSTANTS

        MW1=251220.
        MW2=41870.*WD
        MG1=7500.
        MG2=7500.
        HI=22.7
        HEU=8.64
        HEL=8.12
        HW=2372520
        L=.03
        K=.04
        H3=94.14
        H5=111.9
        DATA RG,AG,AW,AB/.02,.05,.02,.86/
        TAU1=(1.-RG)*AG
        TAU2=(1.-RG)*(1.-AG)*AW
        TAU3=(1.-RG)*(1.-AG)*(1.-AW)*AG
        TAU4=(1.-RG)*(1.-AG)**2*(1.-AW)*AW
        TAU5=(1.-RG)*(1.-AG)**2*(1.-AW)**2*AB

C       TAU1=0.1
C       TAU2=0.0
C       TAU3=0.1
```

```
C     TAU4=0.
C     TAU5=0.5
      EMIS=.2
      EMISG=.3
      SIG=5.67E-8
      R1=293.3
      R2=-84026.4
      V=3

      HB=1./((1./HI)+(L/K))
      UB=1./((1./HB)+(1./H5))
      TAU=(TAU4+(H5*TAU5)/(H5+HB))
C     PRINT*,'UB=',UB,'HB=',HB,'TAU4P=',TAU4P

C     PRINT*,'NITER=',NITER
      MDWUO=0.
      MDWLO=0.
      DO 10 I=1,NITER


      PTIME=REAL(I)*DT/3600.
      TIME=FTIME+PTIME
      HS=HSF(TIME)
      TA=TAF(TIME)

C***  THE AMOUNT OF DISTILLATE WATER PER UNIT TIME PER UNIT AREA
      MDWU=(HEU*(TW1O-TG1O)/HW)*3600
      MDWL=(HEL*(TW2O-TG2O)/HW)*3600

      TG1N=TG1O+(DT/MG1)*(TAU1*HS+H1*(TW1O-TG1O)-H2*(TG1O-TA))
      TW1N=TW1O+(DT/MW1)*(TAU2*HS+H3*(TG2O-TW1O)-H1*(TW1O-TG1O))
      TG2N=TG2O+(DT/MG2)*(TAU3*HS+H4*(TW2O-TG2O)-H3*(TG2O-TW1O))
      TW2N=TW2O+(DT/MW2)*(TAU*HS-UB*(TW2O-TA)-H4*(TW2O-TG2O))

      IF (MOD(INT(PTIME*3600.),IDT).EQ.0) THEN

C     PRINT*,'I=',I
C     PRINT*,'PTIME(HOURS)=',PTIME
      PRINT*,'------------------------------------'
      PRINT*,'PTIME(SECONDS)=',PTIME*3600.
      PRINT*,'TIME=',INT(TIME),':',(TIME-REAL(INT(TIME)))*60.
      PRINT*,'TA=',TA,'HS=',HS
      PRINT*,'TG1N=',TG1N,'TW1N=',TW1N
      PRINT*,'TG2N=',TG2N,'TW2N=',TW2N
      PRINT*,'MDWU (KG/M2.HR)=',MDWU
      PRINT*,'MDWL (KG/M2.HR)=',MDWL
      MDWUT=MDWUO+MDWU
      MDWLT=MDWLO+MDWL
      PRINT*,'MDWUT=',MDWUT
      PRINT*,'MDWLT=',MDWLT

      WRITE(2,*)'------------------------------------'
      WRITE(2,*)'PTIME(SECONDS)=',PTIME*3600.
      WRITE(2,*)'TIME=',INT(TIME),':',(TIME-REAL(INT(TIME)))*60.
      WRITE(2,*)'TA=',TA,'HS=',HS
      WRITE(2,*)'TG1N=',TG1N,'TW1N=',TW1N
      WRITE(2,*)'TG2N=',TG2N,'TW2N=',TW2N
      WRITE(2,*)'MDWU (KG/M2.HR)=',MDWU
      WRITE(2,*)'MDWL (KG/M2.HR)=',MDWL
```

```
      MDWUT=MDWUO+MDWU
      MDWLT=MDWLO+MDWL
      WRITE(2,*)'MDWUT=',MDWUT
      WRITE(2,*)'MDWLT=',MDWLT

      ENDIF

      TG1O=TG1N
      TG2O=TG2N
      TW1O=TW1N
      TW2O=TW2N
      MDWUO=MDWUT
      MDWLO=MDWLT
10    CONTINUE

      STOP
      END

      REAL FUNCTION HSF(TIME)

C TIME IS IN HOURS

C INITIAL VALUES AT TIME=8:00AM

      TIME=(TIME/24.-REAL(INT(TIME/24.)))*24.

C     HSF=757.828*EXP(-0.5*((TIME-11.677)/2.366)**2)

C     SAT 23/7/1994  R=0.9816
C     HSF=1060.85*EXP(-0.5*((TIME-12.185)/3.10933)**2)

C     SUN 24/7/1994  R=0.98
C     HSF=1072.36*EXP(-0.5*((TIME-12.2213)/3.12107)**2)

C     MON 25/7/1994  R=0.982
C     HSF=1072.64*EXP(-0.5*((TIME-13.2434)/3.10278)**2)

C     TUE 26/7/1994  R=0.9825
C     HSF=1051.02*EXP(-0.5*((TIME-13.3182)/3.06114)**2)

C     WED 27/7/1994  R=0.9849
      HSF=1055.68*EXP(-0.5*((TIME-13.197)/3.0651)**2)

C     PRINT*,'HSF=',HSF
      RETURN
      END

      REAL FUNCTION TAF(TIME)

C TIME IS IN HOURS
C INITIAL VALUES AT TIME=8:00AM

      TIME=(TIME/24.-REAL(INT(TIME/24.)))*24.

C    TAF=22.192-3.6337*TIME+0.7986*TIME**2-.048541*TIME**3
C   + +.00089405*TIME**4

C     SAT 23/7/1994  R=0.89
C    TAF=26.629-3.9023*TIME+0.71962*TIME**2-.040361*TIME**3
```

```
C     + +.00069779*TIME**4

C        SUN 24/7/1994  R=0.93
C      TAF=27.369-5.3271*TIME+1.0242*TIME**2-.059544*TIME**3
C     + +.0010735*TIME**4

C        MON 25/7/1994  R=0.9553
C      TAF=27.81-3.9639*TIME+0.74641*TIME**2-.042617*TIME**3
C     + +.00075229*TIME**4

C        TUE 26/7/1994  R=0.93
C      TAF=25.803-6.263*TIME+1.2511*TIME**2-.074415*TIME**3
C     + +.0013649*TIME**4

C        WED 27/7/1994  R=0.9151
      TAF=25.564-4.8904*TIME+0.86331*TIME**2-.047922*TIME**3
     + +.00083406*TIME**4

C        PRINT*,'TAF=',TAF
         RETURN
         END
C        TRIPLE1 BASIN

         REAL L,K,MW1,MG1,MW2,MG2,MW3,MG3,MDWU,MDWM,MDWL,MDWUO,MDWUT,
     + MDWMO,MDWMT,MDWLO,MDWLT

         CHARACTER*10 AFILE
         PRINT*,'ENTER OUTPUT FILE NAME'
         READ*,AFILE
         OPEN(UNIT=2,FILE=AFILE,STATUS='NEW')

         PRINT*,'ENTER STARTING TIME, PERIOD (HOURS)'
         READ*,FTIME,PERIOD
         PRINT*,'ENTER TIME STEP, TIME PRINT (SECONDS)'
         READ*,DT,IDT
         PRINT*,'ENTER INITIAL VALUES TG1O,TW1O,TG2O,TW2O,TG3O,TW3O'
         READ*,TG1O,TW1O,TG2O,TW2O,TG3O,TW3O
         PRINT*,'ENTER WATER DEPTH IN CM'
         READ*,WD
         NITER=INT(PERIOD*3600./DT)


C THESE ARE TEMPORARY CONSTANTS

         H1=16.17
         H2=70.47
         H4=15.97

C     THESE ARE CONSTANTS

         MW1=251220.
         MW2=251220.
         MW3=41870.*WD
         MG1=7500.
         MG2=7500.
         MG3=7500.
         HI=22.7
         HEU=8.64
         HEL=8.12
```

```
      HW=2372520
      L=.03
      K=.04
      H3=94.14
      H5=94.14
      H6=15.97
      H7=94.14

      DATA RG,AG,AW,AB/.0,.05,.0,.86/
      TAU1=(1.-RG)*AG
      TAU2=(1.-RG)*(1.-AG)*AW
      TAU3=(1.-RG)*(1.-AG)*(1.-AW)*AG
      TAU4=(1.-RG)*(1.-AG)**2*(1.-AW)*AW
      TAU5=(1.-RG)*(1.-AG)**2*(1.-AW)**2*AG
      TAU6=(1.-RG)*(1.-AG)**3*(1.-AW)**2*AW
      TAU7=(1.-RG)*(1.-AG)**3*(1.-AW)**3*AB
      PRINT*,'T1-7',TAU1,TAU1,TAU3,TAU4,TAU5,TAU6,TAU7
C     TAU1=0.1
C     TAU2=0.0
C     TAU3=0.1
C     TAU4=0.
C     TAU5=0.3
C     TAU6=0.
C     TAU7=0.5
      EMIS=.2
      EMISG=.3
      SIG=5.67E-8
      R1=293.3
      R2=-84026.4
      V=3

      HB=1./((1./HI)+(L/K))
      UB=1./((1./HB)+(1./H7))
      TAU=(TAU6+(H7*TAU7)/(H7+HB))
C     PRINT*,'UB=',UB,'HB=',HB,'TAU4P=',TAU4P

C     PRINT*,'NITER=',NITER
      MDWUO=0.
      MDWMO=0.
      MDWLO=0.

      DO 10 I=1,NITER


      PTIME=REAL(I)*DT/3600.
      TIME=FTIME+PTIME
      HS=HSF(TIME)
      TA=TAF(TIME)
C***  THE AMOUNT OF DISTILLATE WATER PER UNIT TIME PER UNIT AREA
      MDWU=(HEU*(TW1O-TG1O)/HW)*3600
      MDWM=(HEL*(TW2O-TG2O)/HW)*3600
    MDWL=(HEL*(TW3O-TG3O)/HW)*3600

      TG1N=TG1O+(DT/MG1)*(TAU1*HS+H1*(TW1O-TG1O)-H2*(TG1O-TA))
      TW1N=TW1O+(DT/MW1)*(TAU2*HS+H3*(TG2O-TW1O)-H1*(TW1O-TG1O))
      TG2N=TG2O+(DT/MG2)*(TAU3*HS+H4*(TW2O-TG2O)-H3*(TG2O-TW1O))
      TW2N=TW2O+(DT/MW2)*(TAU4*HS+H5*(TG3O-TW2O)-H4*(TW2O-TG2O))
      TG3N=TG3O+(DT/MG3)*(TAU5*HS+H6*(TW3O-TG3O)-H5*(TG3O-TW2O))
      TW3N=TW3O+(DT/MW3)*(TAU*HS-UB*(TW3O-TA)-H6*(TW3O-TG3O))
```

```
      IF (MOD(INT(PTIME*3600.),IDT).EQ.0) THEN

C     PRINT*,'I=',I
C     PRINT*,'PTIME(HOURS)=',PTIME
      PRINT*,'-----------------------------------'
      PRINT*,'PTIME(SECONDS)=',PTIME*3600.
      PRINT*,'TIME=',INT(TIME),':',(TIME-REAL(INT(TIME)))*60.
      PRINT*,'TA=',TA,'HS=',HS
      PRINT*,'TG1N=',TG1N,'TW1N=',TW1N
      PRINT*,'TG2N=',TG2N,'TW2N=',TW2N
      PRINT*,'TG3N=',TG3N,'TW3N=',TW3N
      PRINT*,'MDWU (KG/M2.HR)=',MDWU
      PRINT*,'MDWM (KG/M2.HR)=',MDWM
      PRINT*,'MDWL (KG/M2.HR)=',MDWL
      MDWUT=MDWUO+MDWU
      MDWMT=MDWMO+MDWM
      MDWLT=MDWLO+MDWL
      PRINT*,'MDWUT=',MDWUT
      PRINT*,'MDWMT=',MDWMT
      PRINT*,'MDWLT=',MDWLT

      WRITE(2,*)'-----------------------------------'
      WRITE(2,*)'PTIME(SECONDS)=',PTIME*3600.
      WRITE(2,*)'TIME=',INT(TIME),':',(TIME-REAL(INT(TIME)))*60.
      WRITE(2,*)'TA=',TA,'HS=',HS
      WRITE(2,*)'TG1N=',TG1N,'TW1N=',TW1N
      WRITE(2,*)'TG2N=',TG2N,'TW2N=',TW2N
      WRITE(2,*)'TG3N=',TG3N,'TW3N=',TW3N
      WRITE(2,*)'MDWU (KG/M2.HR)=',MDWU
      WRITE(2,*)'MDWM (KG/M2.HR)=',MDWM
      WRITE(2,*)'MDWL (KG/M2.HR)=',MDWL
      WRITE(2,*)'MDWUT=',MDWUT
      WRITE(2,*)'MDWMT=',MDWMT
      WRITE(2,*)'MDWLT=',MDWLT
      ENDIF

      TG1O=TG1N
      TG2O=TG2N
      TG3O=TG3N
      TW1O=TW1N
      TW2O=TW2N
      TW3O=TW3N
      MDWUO=MDWUT
      MDWMO=MDWMT
      MDWLO=MDWLT
10    CONTINUE

      STOP
      END
      REAL FUNCTION HSF(TIME)

C TIME IS IN HOURS
C INITIAL VALUES AT TIME=8:00AM

      TIME=(TIME/24.-REAL(INT(TIME/24.)))*24.

C     HSF=757.828*EXP(-0.5*((TIME-11.677)/2.366)**2)
```

```
C     SAT 23/7/1994  R=0.9816  1 CM
C     HSF=1060.85*EXP(-0.5*((TIME-12.185)/3.10933)**2)

C     SUN 24/7/1994  R=0.98    2 CM
C     HSF=1072.36*EXP(-0.5*((TIME-12.2213)/3.12107)**2)

C     MON 25/7/1994  R=0.982   3 CM
C     HSF=1072.64*EXP(-0.5*((TIME-13.2434)/3.10278)**2)

C     TUE 26/7/1994  R=0.9825  4 CM
C     HSF=1051.02*EXP(-0.5*((TIME-13.3182)/3.06114)**2)

C     WED 27/7/1994  R=0.9849  5 CM
      HSF=1055.68*EXP(-0.5*((TIME-13.197)/3.0651)**2)

C     PRINT*,'HSF=',HSF
      RETURN
      END

      REAL FUNCTION TAF(TIME)

C TIME IS IN HOURS
C INITIAL VALUES AT TIME=8:00AM

      TIME=(TIME/24.-REAL(INT(TIME/24.)))*24.
C    TAF=22.192-3.6337*TIME+0.7986*TIME**2-.048541*TIME**3
C   + +.00089405*TIME**4

C     SAT 23/7/1994  R=0.89      1 CM
C    TAF=26.629-3.9023*TIME+0.71962*TIME**2-.040361*TIME**3
C   + +.00069779*TIME**4

C     SUN 24/7/1994  R=0.93      2 CM
C    TAF=27.369-5.3271*TIME+1.0242*TIME**2-.059544*TIME**3
C   + +.0010735*TIME**4

C     MON 25/7/1994  R=0.9553    3 CM
C    TAF=27.81-3.9639*TIME+0.74641*TIME**2-.042617*TIME**3
C   + +.00075229*TIME**4
C     TUE 26/7/1994  R=0.93      4 CM
C    TAF=25.803-6.263*TIME+1.2511*TIME**2-.074415*TIME**3
C   + +.0013649*TIME**4

C     WED 27/7/1994  R=0.9151    5 CM
     TAF=25.564-4.8904*TIME+0.86331*TIME**2-.047922*TIME**3
    + +.00083406*TIME**4
C     PRINT*,'TAF=',TAF
      RETURN
      END
```

APPENDIX B

DATA AND RESULTS

Table A.1 Measured data for the three stills as performed on 23/7/1994. Water depth = 1 cm

1 cm	TBSS						DBSS				SB		23/7/1994	
Time	Tp3	Tg3	Tw2	Tg2	Tw1	Tg1	Tp2	Tg2	Tw1	Tg1	Tp1	Tg1	Tamb	Hs
9.00	20.70	28.50	25.07	27.80	23.31	30.30	26.60	29.30	26.70	30.40	31.20	28.50	22.84	506.80
10.00	34.00	33.50	32.20	34.80	32.90	35.30	35.70	34.40	32.86	34.50	48.60	43.00	24.34	705.90
11.00	38.10	35.80	33.60	36.50	35.12	39.50	39.50	37.00	35.50	38.00	56.50	50.50	28.44	865.90
12.00	45.50	40.00	39.19	41.20	40.58	44.40	50.50	46.20	43.97	43.00	66.50	58.90	28.60	973.20
13.00	47.00	41.00	38.50	41.80	40.84	44.20	51.00	46.90	44.52	42.90	66.00	59.80	28.84	1007.4
14.00	47.30	42.10	40.50	45.50	42.32	44.80	53.70	50.60	47.92	44.60	64.00	57.40	29.57	959.90
15.00	47.80	44.50	42.80	46.20	43.85	45.00	55.50	52.50	50.15	45.50	61.80	54.60	29.34	891.80
16.00	47.60	46.00	44.32	46.70	44.56	43.60	56.10	53.30	51.41	45.50	57.80	50.80	30.50	749.00
17.00	45.90	46.50	45.11	47.20	44.85	43.60	54.60	52.70	51.32	44.80	52.10	46.20	29.45	570.00
18.00	45.05	45.50	45.39	45.80	44.32	41.70	52.40	51.20	49.89	42.50	44.20	37.00	27.91	364.00

Table. A.2 Measured data for the three stills as performed on 24/7/1994. Water depth = 2 cm

2 cm	TBSS						DBSS				SBSS		24/7/1994	
Time	Tp3	Tg3	Tw2	Tg2	Tw1	Tg1	Tp2	Tg2	Tw1	Tg1	Tp1	Tg1	Tamb	Hs
9.00	27.50	32.20	31.00	31.50	29.60	32.60	28.30	28.70	27.40	30.20	29.50	31.00	26.54	503.60
10.0	32.10	34.20	32.49	35.20	33.37	36.20	32.60	32.90	31.33	34.60	41.70	39.70	28.11	708.00
11.0	36.90	37.50	33.83	36.60	38.04	40.00	37.80	36.30	34.62	38.02	52.80	46.80	28.98	872.10
12.00	41.50	38.00	35.80	39.80	38.92	45.70	43.60	41.10	39.07	41.20	56.60	53.20	30.48	988.20
13.00	44.20	39.80	37.98	41.80	41.23	44.70	48.30	44.90	42.93	42.80	62.70	55.70	30.90	1019.2
14.00	46.48	42.60	40.50	45.30	43.47	46.00	51.90	49.00	46.93	44.20	64.50	57.60	32.00	969.00
15.0	47.87	44.30	42.77	47.10	45.15	45.50	54.30	51.10	49.80	44.90	61.40	56.00	31.97	897.30
16.00	46.80	45.70	44.18	47.10	45.53	44.70	55.20	52.50	50.77	45.50	60.10	53.00	31.68	768.20
17.00	48.60	46.40	45.65	47.00	45.73	44.10	54.50	52.80	50.95	44.60	57.70	48.80	30.90	593.20
18.00	45.30	46.20	45.60	46.10	45.02	42.40	52.80	51.20	49.82	42.70	48.40	39.60	28.80	382.90

Table A.3 Measured data for the three stills as performed on 25/7/1994. Water depth = 3 cm

3 cm	TBSS						DBSS				SBSS		25/7/1994	
Time	Tp3	Tg3	Tw2	Tg2	Tw1	Tg1	Tp2	Tg2	Tw1	Tg1	Tp1	Tg1	Tabm	Hs
9.00	28.30	32.40	31.09	30.90	29.60	32.60	28.10	28.70	27.48	30.10	28.60	31.10	25.00	479.50
10.00	32.70	34.50	32.89	35.20	33.68	36.00	32.50	33.20	31.48	34.10	39.80	37.10	27.42	707.00
11.00	35.90	36.00	34.02	37.60	36.07	39.80	36.50	36.20	34.51	37.70	47.30	43.20	28.43	869.00
12.00	39.70	37.30	35.60	39.50	38.82	42.90	41.10	39.80	38.18	40.80	54.60	49.60	29.62	980.90
13.00	42.70	39.30	37.56	41.80	41.37	44.50	45.70	43.60	41.92	42.10	59.70	53.00	31.06	1012.0
14.00	44.50	41.50	39.54	45.00	43.26	44.70	49.30	47.40	45.48	42.80	61.70	54.00	30.78	976.70
15.00	45.00	42.90	41.40	46.50	44.56	44.90	51.80	49.80	47.83	43.50	61.40	53.70	30.72	900.20
16.00	46.00	44.90	43.50	47.20	45.60	43.80	53.10	51.40	49.35	43.30	59.90	51.50	31.13	777.20
17.00	45.60	45.50	44.72	47.70	45.78	43.70	52.90	51.30	49.67	43.50	56.20	49.20	30.17	594.30
18.00	45.00	45.60	45.20	46.30	45.09	42.30	51.80	50.20	48.92	41.90	50.70	41.40	29.04	371.50

Table A.4 Measured data for the three stills as performed on 26/7/1994. Water depth = 4cm

4 cm	TBSS						DBSS				SBSS		26/7/1994	
Time	Tp3	Tg3	Tw2	Tg2	Tw1	Tg1	Tp2	Tg2	Tw1	Tg1	Tp1	Tg1	Tamb	Hs
9.00	32.80	34.40	33.24	33.20	32.27	35.10	31.00	32.00	30.90	33.00	30.20	33.80	27.34	392.10
10.00	33.40	35.50	34.14	36.20	34.91	37.10	33.70	34.90	33.44	35.80	37.40	36.80	28.58	684.40
11.00	36.30	37.00	35.27	38.90	37.59	41.40	37.20	38.10	36.42	39.60	42.00	42.70	30.20	846.20
12.00	39.30	38.20	36.54	40.70	40.18	43.40	41.30	41.20	39.71	41.40	51.70	47.30	30.47	959.70
13.00	41.80	39.60	38.22	43.00	42.53	45.40	45.20	44.40	42.99	43.20	56.90	51.70	30.55	991.80
14.00	43.70	41.70	40.04	45.90	44.29	44.80	48.70	47.70	46.01	43.00	57.20	51.50	30.77	951.00
15.00	45.00	43.20	41.85	47.40	45.55	45.30	51.10	49.50	48.12	43.70	59.90	52.30	31.92	889.20
16.00	45.40	44.70	43.37	47.60	45.82	43.60	52.30	50.30	49.05	42.90	56.70	50.10	30.13	764.40
17.00	45.00	45.20	44.39	48.80	45.88	43.40	52.30	50.80	49.22	43.10	55.70	49.10	30.08	590.40
18.00	44.50	45.20	44.74	46.20	44.87	41.20	51.30	49.60	48.13	40.10	50.50	40.20	27.62	371.90

Table A.5 Measured data for the three stills as performed on 27/7/1994. Water depth = 5cm

5 cm	TBSS						DBSS				SBSS		27/7/1994	
Time	Tp3	Tg3	Tw2	Tg2	Tw1	Tg1	Tp2	Tg2	Tw1	Tg1	Tp1	Tg1	Tamb	Hs
9.00	30.00	30.50	30.98	29.95	28.62	27.80	28.30	28.60	27.68	25.90	24.90	25.10	20.43	446.90
10.00	30.90	33.30	31.57	32.60	30.76	32.00	30.30	31.10	29.73	30.50	30.30	29.70	22.36	661.70
11.00	33.30	34.30	32.63	35.30	33.53	36.10	33.40	34.30	32.64	34.10	37.10	34.90	24.44	863.20
12.00	35.70	35.20	33.81	37.20	36.28	39.50	36.80	37.30	35.86	37.00	43.50	40.10	25.65	968.90
13.00	38.10	36.50	35.25	39.50	38.88	41.10	40.20	40.28	38.87	38.50	49.10	43.80	28.43	994.10
14.00	39.80	38.70	36.82	42.50	40.83	42.10	43.40	43.40	41.90	39.70	52.90	46.50	27.30	960.50
15.00	41.00	39.70	38.33	44.10	42.36	43.20	45.80	45.80	44.20	40.90	54.80	48.30	28.51	892.90
16.00	41.50	40.90	39.77	44.60	43.28	41.60	47.30	46.70	45.44	40.00	55.20	47.70	28.41	758.20
17.00	41.40	41.60	40.76	45.00	43.28	41.60	47.80	47.10	45.60	40.10	53.50	46.30	26.94	541.00
18.00	41.00	41.70	41.22	43.30	42.31	38.80	47.30	45.90	44.69	37.90	49.80	39.70	25.55	333.60

Table A6 : Theoretical temperatures for the three stills as calculated for 2 cm water depth in the lower basin

2 cm	TBSS						DBSS				SBSS	
Time	Tp3	Tg3	Tw2	Tg2	Tw1	Tg1	Tp2	Tg2	Tw1	Tg1	Tp1	Tg1
9.00	29.50	34.10	30.50	32.00	30.00	32.30	30.30	30.70	29.40	30.70	31.00	32.00
10.00	33.69	36.90	33.20	37.00	35.00	36.00	35.30	35.50	32.10	35.90	44.50	40.70
11.00	37.20	36.50	37.10	40.10	39.50	41.00	41.20	39.70	36.50	40.20	53.50	47.30
12.00	42.30	39.10	38.50	40.90	40.00	46.50	46.30	43.20	42.10	43.10	60.70	55.20
13.00	45.50	40.50	41.00	43.50	43.30	47.30	50.60	47.00	44.50	44.30	63.00	57.10
14.00	48.00	42.10	41.90	46.70	46.10	49.00	53.40	52.10	50.20	46.70	65.30	58.20
15.00	49.50	44.30	43.20	47.20	47.00	48.00	55.20	54.00	53.00	47.10	64.40	57.30
16.00	47.60	45.20	45.70	48.50	48.30	47.00	54.50	55.10	53.50	47.50	62.00	53.20
17.00	46.80	46.10	46.10	49.50	49.00	46.20	54.00	53.70	52.70	46.20	57.00	50.70
18.00	46.00	45.50	45.50	47.70	48.00	44.00	53.30	52.50	51.00	43.70	50.20	42.20

Table A7 : Theoretical temperatures for the three stills as calculated for 4 cm water depth in the lower basin

4 cm	TBSS						DBSS				SBSS	
Time	Tp3	Tg3	Tw2	Tg2	Tw1	Tg1	Tp2	Tg2	Tw1	Tg1	Tp1	tg1
9.00	33.20	36.00	35.30	35.00	34.20	35.50	31.50	32.30	31.00	35.00	33.50	36.90
10.00	33.90	37.50	36.70	36.50	35.50	37.90	34.50	35.10	32.50	36.00	37.70	37.50
11.00	36.20	38.00	37.30	38.00	37.00	39.00	39.30	39.00	35.20	39.00	47.20	43.50
12.00	40.50	38.70	38.10	39.20	39.00	42.50	43.70	41.30	39.00	42.00	52.70	48.10
13.00	43.00	40.50	39.70	40.70	40.20	44.20	47.50	43.90	44.00	43.50	57.30	53.00
14.00	45.20	42.90	41.50	43.20	43.00	45.00	52.10	46.50	47.50	43.90	59.50	54.30
15.00	46.10	43.50	42.20	44.50	44.10	45.50	55.30	48.90	50.30	44.20	60.70	55.00
16.00	47.50	45.20	44.00	44.80	44.50	42.10	53.50	50.50	52.10	45.30	58.50	51.20
17.00	47.00	44.50	43.20	45.60	45.10	41.50	52.70	50.00	53.00	46.00	55.00	48.10
18.00	45.70	43.10	42.70	43.20	42.50	40.20	51.80	49.10	51.50	43.50	51.90	41.20

Table. A8 : Experimental distilled water and hourly efficiency at water depth = 2 cm

24/7/1994	Distilled water (g/m2 hr)			Efficiency (%)		
Time	SBSS	DBSS	TBSS	SBSS	DBSS	TBSS
10.00	86.00	65.00	43.00	8.00	6.05	4.00
11.00	157.00	97.00	76.00	11.86	7.33	5.74
12.00	320.00	211.00	168.00	21.34	14.07	11.20
13.00	434.00	287.00	238.00	28.06	18.56	15.39
14.00	466.00	320.00	293.00	31.69	21.76	19.93
15.00	493.00	380.00	336.00	36.20	27.91	24.68
16.00	482.00	401.00	369.00	41.35	34.40	31.66
17.00	445.00	423.00	417.00	49.44	46.99	46.33
18.00	345.00	390.00	407.00	49.39	67.12	70.05

Table. A9 : Experimental distilled water and hourly efficiency at water depth = 4 cm

26/7/1994	Distilled water (g/m2 hr)			Efficiency (%)		
Time	SBSS	DBSS	TBSS	SBSS	DBSS	TBSS
10.00	32.00	43.00	49.00	3.10	4.14	4.71
11.00	60.00	46.00	48.00	4.67	3.60	3.73
12.00	168.00	130.00	108.00	11.54	8.93	7.42
13.00	206.00	168.00	141.00	13.69	11.16	9.37
14.00	385.00	271.00	228.00	26.68	18.78	15.80
15.00	412.00	304.00	266.00	30.53	22.53	19.70
16.00	434.00	347.00	309.00	37.42	29.92	26.64
17.00	396.00	401.00	390.00	44.20	44.76	43.53
18.00	385.00	434.00	410.00	68.22	76.90	77.79

Table. A10 : Theoretical distilled water and hourly efficiency at water depth = 2 cm

24/7/1994	Distilled water (g/m2 hr)			Efficiency (%)		
Time	SBSS	DBSS	TBSS	SBSS	DBSS	TBSS
10.00	100.00	90.00	70.00	10.47	9.40	7.32
11.00	165.00	140.00	110.00	13.06	11.08	8.71
12.00	320.00	260.00	200.00	21.23	17.60	13.27
13.00	410.00	310.00	290.00	25.26	19.10	17.86
14.00	450.00	350.00	310.00	28.53	22.19	19.65
15.00	470.00	400.00	350.00	33.97	28.92	25.30
16.00	480.00	430.00	390.00	43.84	39.27	35.62
17.00	450.00	415.00	440.00	54.55	53.30	56.27
18.00	330.00	370.00	420.00	60.48	73.42	83.33

Table. A11 : Experimental distilled water and hourly efficiency at water depth = 4 cm

26/7/1994	Distilled water (g/m2 hr)			Efficiency (%)		
Time	SBSS	DBSS	TBSS	SBSS	DBSS	TBSS
10.00	70.00	60.00	65.00	7.89	6.77	7.33
11.00	120.00	80.00	90.00	10.02	6.68	7.52
12.00	230.00	180.00	140.00	15.82	12.38	9.63
13.00	300.00	210.00	190.00	18.91	13.24	11.97
14.00	370.00	290.00	260.00	23.65	18.64	16.71
15.00	420.00	330.00	300.00	30.62	24.06	21.87
16.00	430.00	390.00	380.00	39.57	35.89	34.97
17.00	420.00	415.00	410.00	54.28	53.63	52.99
18.00	410.00	420.00	440.00	82.79	84.81	88.86

ملخص

" دراسة أداء مُقطِّر شمسي ثنائي القاعدة "

إعداد
أكرم محمود موسى
إشراف
د. محمد أحمد حمدان

تعرض هذة الاطروحة دراسة تجريبية ونظرية لثلاثة أنواع من المـُقَطِّرات الشمسية ذات القاعدة، وهي أُحادي وثنائي وثلاثي القاعدة؛ تحت الظروف المناخية الأردنية.

صُنعت المـُقَطِّرات الثلاثة بقواعد قياسها ٩٦,. × ٩٦,. م٢ . وقد كان الزجاج الخارجي على شكل هرم بزاوية ميل ٤٥ ° ، و الزجاج الأوسط والسفلي بزاوية ميل ٥٧° . وأجريت التجارب على قياسات مختلفة لارتفاع الماء في القاعدة السفلية، وقيست درجات الحرارة للماء والزجاج والهواء الخارجي؛ إِضافة الى الإشعاع الشمسي وسرعة الريح وحجم الماء المقطَّر، لكل ساعة من ساعات النهار.

وطُوِّر برنامج حاسوب لمحاكاة أداء المـُقَطِّرات الشمسية معتمداً على: عدد القواعد للمُقَطِّرات، وإرتفاع الماء في القاعدة السفلية كمدخلات رئيسية، حيث يحسب البرنامج حجم الماء المقطَّر الناتج، وتوزيع درجات الحرارة لكل من الماء والزجاج والكفاءة اليومية. وبني البرنامج بالاعتماد على طريقة أويلر لحل المعادلات التفاضلية ذات القيمة الابتدائية باعتماد لغة الفورتران للبرمجة.

وتبين النتائج المتحصل عليها أن حجم الماء المقطَّر من المقطَّر ثلاثي القاعدة أعلى منه في أُحادي القاعدة بنسبة ٣٦٪ ويزيد على نظيره ثنائي القاعدة بنسبة ٧٪. ومقارنة بأُحادي القاعدة فإن ثنائي القاعدة يزيد عليه بنسبة ٢٦٪. وحسبت قيمة الكفاءة اليومية للمـُقَطِّرات الثلاث؛ وكانت أعلى كفاءة للمقطَّر ثلاثي القاعدة بنسبة مقدارها ٤٤٪. ولم يلاحظ تأثير واضح لاختلاف ارتفاع الماء في القاعدة السفلية.