Faculty of Graduate Studies

University of Jordan



# PERFORMANCE OF SOLAR AIR HEATER THAT UTILIZES LOCALLY AVAILABLE CORRUGATED GALVANIZED IRON SHEETS AS AN ABSORBER PLATE



by

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Submitted in partial fulfillment of the requirement

for the degree of Master of Science in

Mechanical Engineering

Faculty of Graduate Studies

University of Jordan

March, 1996

# COMMITTEE DECISION

This thesis was defended successfully on 25, March, 1996.

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# ACKNOWLEDGEMENTS

I am greatly thankful for prof. Mohammed Al - Saad who provided me by incomparable suggestions and comments and helped me to accomplish this study in the proper way.

My thanks to the staff working at the Industrial Engineering Workshop and at the Laboratories of Mechanical Engineering Department at the University of Jordan. Also, my thanks to the staff working at the Faculty of Engineering and Technology Computer Center.

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# NOMENCLATURE

| | |
|---|---|
| $A$ | Absorber plate area; ( $m^2$ ). |
| $C_p$ | Specific heat; ( kJ / kg .°C). |
| $D_H$ | Hydraulic diameter; (m). |
| $F'$ | Collector efficiency factor. |
| $F_{12}$ | The view factor. |
| $F_R$ | Collector heat removal factor. |
| $g$ | Gravitational constant; ($m/s^2$) |
| $h_a$ | Connective heat transfer coefficient for air flow rate inside the collector; ($W/m^2.°C$). |
| $h_{con}$ | Convective heat transfer coefficient between the cover and absorber plate; ($W/m^2.°C$). |
| $h_{r,sk}$ | Radiative heat transfer coeff. between the sky and the cover; ($W/m^2.°C$). |
| $h_{rc}$ | Radiative heat transfer between the cover and the absorber plate; ( $W/m^2.°C$). |
| $h_w$ | Wind convective transfer coefficient; ($W/m^2.°C$). |
| $I$ | Insident solar radiation on tilted surfaces; ( $Wh/m^2$ ). |
| $K$ | Thermal conductivity; (W/m.°C) |
| $m$ | Air mass flow rate; (kg/s). |
| $Nu$ | Nusselt number. |
| $Q_u$ | Useful heat gain from the collector; (kJ). |
| $Ra$ | Rayleigh number . |
| $Re$ | Renold number . |
| $t$ | Time in seconds of the time interval; (seconds). |
| $T_a$ | Ambient temperature; (°C). |
| $T_c$ | Cover temperature; (°C). |
| $t_c$ | Time constant; (minute). |
| $T_i$ | Inlet air temperature; (°C). |
| $T_{ic}$ | The averaged inlet air temperatures to the collector for time interval; (°C). |
| $T_m$ | Temperature of air at the middle of collector; (°C). |
| $T_o$ | Outlet air temperature; (°C). |
| $T_{oc}$ | The averaged outlet air temperatures to the collector for time interval; ( °C). |
| $T_{oc,i}$ | Outlet air temperature from the collector, when the solar radiation is interrupted; (°C). |
| $T_{oc,tc}$ | Outlet air temperature from the collector at time constant $t_c$; (°C ). |
| $T_s$ | Surface temperature of absorber plate; (°C). |

| | |
|---|---|
| $T_{sk}$ | Sky temperature; (°C). |
| $U_e$ | Effective overall heat loss coefficient; (W/m$^2$.°C). |
| $U_L$ | Overall heat loss coefficient from the collector; (W/m$^2$.°C). |
| V | Velocity of air inside the collector; (m/s) . |
| $V_w$ | Wind speed; (m/s). |

**Greek Symbols**

| | |
|---|---|
| $\alpha$ | Absorptance or thermal diffusity. |
| $\eta$ | Collector efficiency. |
| $\eta_i$ | Collector instantaneous efficiency. |
| $\eta_d$ | Daily collector efficiency. |
| $\rho_a$ | Air density. |
| $\rho_w$ | Water density. |
| $\tau$ | Transmittance. |
| $(\tau\alpha)_e$ | Effective transmittance - absorbtance product. |
| $\beta$ | Collector tilt angle; (degree). |
| $\gamma$ | Azimuth angle; ( degree ). |
| $\phi$ | Latitude angle; (degree ). |
| $\varepsilon$ | Emisivity. |
| $\sigma$ | Stefan - Boltzmann constant. |
| $\beta'$ | Volumetric coeff. of expansion for fluid ( air ). |
| $\nu$ | Kinematics viscosity . |
| $\Omega$ | Parameter defined in equation (3.14). |

**Subscripts**

| | |
|---|---|
| a | ambient. |
| av | average. |
| b | black. |
| c | collector. |
| e | effective. |
| i | inlet. |
| L | loss or lower. |
| m | mid. |
| o | outlet. |
| s | surface. |
| t | top. |

# ABSTRACT

**Performance of Solar Air Heater that Utilizes Locally Available Corrugated Galvanized Iron Sheets as an Absorber Plate.**

by

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prof. Mohammed Al-saad.

This thesis presents an experimental investigation of two solar air heaters model, one of which uses locally available corrugated galvanized iron sheets as an absorber plate and the other one uses locally available flat-plate steel sheets as an absorber plate.

The collectors used in this study were tested in outdoor and open loop circulated flows. Tests which were performed on both collectors are forced circulation test with load conditions, stagnation test and time constant test.

Both collectors were tested under Jordan's climatic conditions. The tests were performed in August and September, 1995, where the working fluid was air. The investigated flow rates were 0.0215, 0.0166, 0.0138, and 0.0098 kg/s. The period test was selected from 8:00 to 17:00.

The experimental tests for both collectors were performed by the aid of an instrumentation system consisting of a pyranometer and solar

integrator, eighteen copper-constantan thermocouple wires, digital microprocessor, digital anemometer and pitot tube.

The results show that the efficiency of corrugated type is higher than the efficiency of conventional design at the same flow rates. The efficiency of both collectors increases as the flow rate increases.

several conclusions and recommendations are suggested in order to improve the system efficiency of both collectors are drawn.

## 1.2 Types of solar air collectors

Air collector designs may be classified according to the type of absorbing surface. The air flow may be either above or below or both above and below the absorbing surface. The classification is as follows[2]:

### 1.2.1 Simple flat plate collector(Conventional type)

In this type, the area of the absorber plate is equal the area of the glass cover. This type is considered simple and most commonly used. It has no element that causes air turbulence, so heat transfer and efficiency are low.

Flat-plate collectors are mechanically simpler than concentrating collectors. The criteria used in their design are minimum cost, ease of manufacture and maintenance free operation. The major application of these units are in solar air heating, building heating and some industrial process such as crop drying. The importance of flat plate collector in thermal processes is such that their thermal performance is treated in considerable detail.

### 1.2.2 Corrugated plate collector

The corrugation include increase the surface area facing the sun, this increases the amount of solar radiation outward. In this research we are utilized locally available corrugated galvanized iron sheets as an absorber plate. The criteria are used in their design are minimum cost, ease of manufacturing. The major applications of these units are same applications of the conventional type.

### 1.2.3 Finned plate collector

Same as conventional type , but rear fins are added to improve heat transfer characteristics which increase the efficiency of the collector.

### 1.2.4 Overlapped transparent plate type collector

This type is composed of a staggered array of transparent plates which are partially blackened. Air flows on both sides of each plate. In addition, the clear portion of each plate captures solar radiation from the plate below it, reducing heat loss.

### 1.2.5 Matrix type of collector

In this type, an absorbing matrix is placed in the air flow path between the glazing and an absorbing back plate, providing large amount of turbulence which improves heat transfer.

From the above mentioned types, the simple type and the corrugated plate type are selected for the present study.

## 1.3 Literature survey

Performance of flat plate air solar collectors have received a lot of investigations, while the performance of corrugated type has received a little attention.

Research and development in solar air heaters commenced in the 1940s and have been subjected to many analytical and experimental studies.

Biondi, et al.[3] have theoretically analyzed the performance of solar air heaters of conventional designs. They discussed a theoretical and numerical analysis of the performances of solar air heaters of the simplest design and the easiest construction.

Oreszcyn and Jons [4] have showed that a transient test method can be applied for air heating collectors. They have found that transient test method yields an efficiency curve of air heater collectors.

Hamdan and Jubran [5] obtained the performance of three types(bare-plate, covered plate, and finned plate) of solar air collectors tested under Jordanian climate, where three flat-plate collectors are evaluated for use in air heating.

Parker [6] presented a theoretical expression for the efficiency and loss factors of several solar air heaters. The main aim of this paper was to discuss the efficiency factor which measures the effectiveness of a collector absorber plate in transferring heat to the fluid. The loss factor for air type collectors, were mathematically derived.

Parker et al. [7] investigated the sensitivity of the thermal efficiency, the collector efficiency factor, and the collector loss coefficient, to design parameter changes(top loss, bottom loss, convective and radiative heat transfer in the collector) and presented the results graphically.

Klien et al. [8] presented a simulation model for the estimation of the long term performance of solar heating systems. They produced a simple graphical method that requires monthly average meteorological data, which can be used to design economical solar heating systems.

Zhao and leonard [9] presented a computer model derived from the basic laws governing thermal energy exchanges between surfaces for the transient simulation of flat-plate collectors. The model was validated with measured data and a good agreement was found.

To reduce the cost of a solar system, Bansal and Unlemann [10] developed and tested solar air heater utilizing plastic films for the absorber and glazing. A comparison of the developed collector with the available conventional collectors shows that the present conventional type has better economic potential even if one assigns a short life time for it.

Lee, et al. [11] presented an experimental and theoretical study on the corrugated water- trickle collectors, which included detailed calculation of overall heat transfer coefficient from the corrugated surface to the ambient. They performed analytical analysis for corrugated geometry, then analytical mathematical equations for corrugated collector were derived.

Bhargava et al. [12] compared the performance of two solar air collectors of conventional design, where two metal plates and one glazing are used. The first collector with forced flow in the lower channel and stagnant air between the plate and glazing, and the second with thermosyphon flow in the upper channel and forced flow in the lower one. The important conclusions of this paper, is the first type has a better performance when compared to the second type.

Bernini and Gowan [13] extends the current techniques in the prediction of flat plate solar collector performance for use in the analysis of non metallic collectors. An analytical model was developed to study the characteristics of these solar collectors which eliminate the need for metals, glass, and special coatings. Using this model, plate efficiency factors are presented for various common non-metallic absorber plate configurations.

Loveday [14] have studied thermal performance of air heating solar collectors with thick, poorly conducting absorber plates. This work included the derivation of useful energy equation and overall heat transfer coefficient expressions. Expressions are derived for the efficiency and loss factors of the coverless, air heating solar collector in which it is possible to assign finite values for the thickness and thermal conductivity of the absorber plate. In the geometry treated air flow is beneath a flat absorber and heat transfer is both steady state and one dimensional.

Choundhury et al. [15] theoretically analyzed the parameters of a one-pass, corrugated, bare-plate solar air heater. In this research, the performance of each system have discussed.

Francey and Papaioannou [16] have analyzed the performance of a flat-plate collector. This study represents by wind related heat losses of flat plate collector for free and forced convection. The heat loss from a flat-plate solar collector is measured over a range of inlet temperatures , tilt angles and wind velocities while operating in a wind tunnel. The measurements were compared with recent empirical relations for calculating top losses. while there is good a agreement for zero or low wind velocities.

Maroulis and Sarvacos [17] had showed the solar heating of air for drying a agricultural products. The capacity and the efficiency of the system were analyzed using computer simulation method. The results obtained with computer simulation of a solar air heating system are useful in evaluating the feasibility of solar drying.

Gama et al.[18] have analyzed the theoretical study of an air heating solar collector. Solar energy is collected in an absorbing triangularly corrugated plate with a selective surface. The collector also has a selective glass cover. Solar energy passing through the glass is incident on the selectively absorbing surface of the v-groove plate. The absorbed energy raises the temperature of the plate and heats air that is pumped through the triangular passages of the collector. The efficiency that can be obtained with the collector is determined as a function of a number of parameters of the problem.

Cole-Apple and Haberstroh [19] theoretically examined the flow paths for a single flat plate employing two glass covers. They used simple linear model to compare the thermal performance of five flat plate solar air heater designs.

From the previous presentation, it is obvious that the question of relative thermal performance of the conventional and corrugated types is yet open to question.

## 1.4 Objectives of the present work

The objective of the present work is to compare the performance of two solar air collectors representing the conventional (flat-plate)and corrugated types. Both types are constructed and tested under Jordan climatic conditions. Both collectors have the same length and size. All the construction parameters are made for both types, then study and discuss the analysis of these collector. Mathematical models are developed for corrugated galvanized iron sheets. These model are capable of predicting its performance.



In this research the relative performance between the conventional type and the corrugated type collectors are studied and analyzed experimentally and theoretically under the same experimental conditions.

# CHAPTER 2

# MANUFACTURING AND SPECIFICATIONS OF AIR HEATERS

## 2.1 Introduction

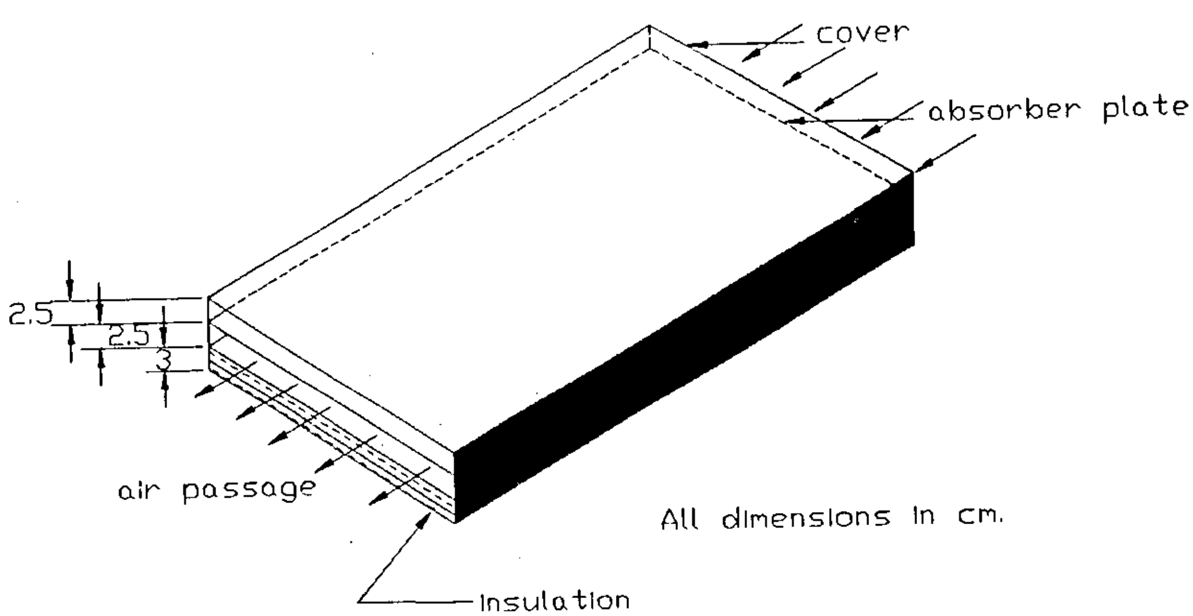
Many types of solar air heaters are commercially available. They differ in design and performance and in price. They have to meet demands in operation configuration and metelorgical conditions. In Jordan, no solar air collectors are available in the commercial market. The different types of solar air collectors have different designs, performance and cost. Any type of solar air collector must be efficient, so the collector must absorb as much of the incident radiation as possible, minimize heat loss to the environment and transfer the heat collected to the heat transfer fluid flowing through it effectively.

In this study, construction of two solar air heater collectors, one of which uses locally available corrugated galvanized iron sheets and the other uses flat plate sheets (conventional type). Both collectors were built in the workshops of Industrial Engineering Department at the University of Jordan.

In this chapter, the different components that were selected to form the body mass of both collectors will be described together with the manufacturing process of them. The following sections describes the individual components and considerations that together make up an efficient solar air heating system.

## 2.2 Collector specifications

The two types of collector consist of: absorber plate, transparent cover, insulation material and frame. The important components of the two types collector are shown in figures(2.1) and(2.2); respectively.




Figure(2.1) Flat plate collector(conventional type).

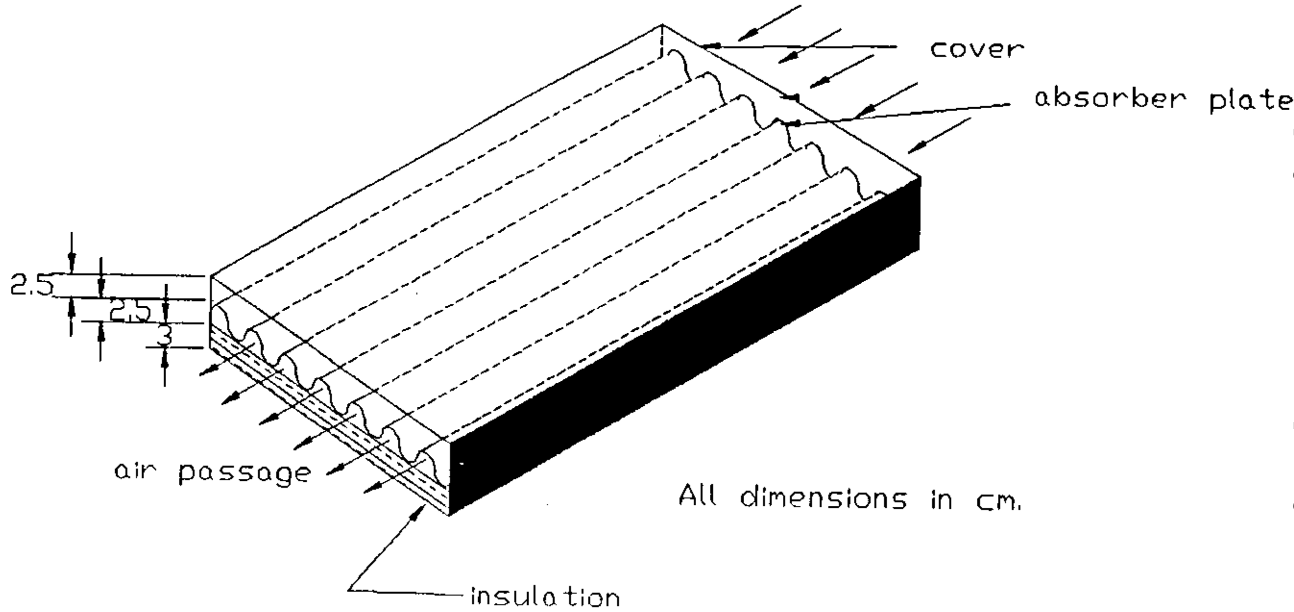



Figure (2.2) Corrugated plate collector.

## 2.2.1 Absorber plate

Absorber plate is the main element for the collectors. It affects both collector efficiency and total system efficiency. The radiation characteristics of the absorber plate are of great importance to the efficiency with which the light striking the collectors can be collected as useful heat. So, the absorber plate should have maximum absorbtivity. Absorber plate must absorb sunlight and transfers as much heat as possible to the heat transfer fluid (air).

Many materials can be used as absorber plates, such as copper, aluminum, steel and selective surfaces. The use of these metals is limited by cost and availability. But heat conduction is considered of great importance.

The absorber plates are used in this research are: one of that uses locally available corrugated galvanized iron sheets painted with an ordinary black paint and the other of conventional type( flat-plate collector) which uses a black steel plate with an ordinary black paint.

The black steel and locally available corrugated galvanized iron sheets are of 0.9 mm thickness. The sizes and materials of each collector are shown in table (2.1)

Table (2.1) Sizes and materials for each absorber plate collector

| Collector type | Dimension (mm) | Material |
|---|---|---|
| corrugated type | 2000x830x0.9<br>Pitch= 60 mm<br>Amplitude= 25mm | galvanized iron |
| plate type | 2000x830x0.9 | steel |

### 2.2.2 Transparent cover

A material must have high transmissivity, low absorbtivity and low reflectivity to be used as a cover, which can reduce convective and radiative losses. Glass can be used for these purposes. Single, double, or multiple covers may be used.

In the present work, single ordinary window glass of 4 mm thick with 830 x 2000 mm dimensions, of an average transmissivity 0.89 was used. The top heat transfer coefficient of the collectors is dependent on the spacing between the absorber plate and the transparent cover, where the top heat transfer coefficient is not substantially affected by spacing more than 25mm [20]. So, a single glass cover with 20 mm spacing was used for both collectors.

### 2.2.3 Insulation material

Insulation material was used to reduce heat losses of the collectors, and thus increase the efficiency of each collector. In selecting the insulation material, many factors must be taken into consideration like cost, durability, toxicity, fabrication, and free of organic binder, because high collector temperatures. The types of insulation material available for solar collectors are fiber glass or rock wool. Rock wool insulation is locally available and cheap, whose thermal conductivity is 0.036 W/m.°C. It is used for insulating

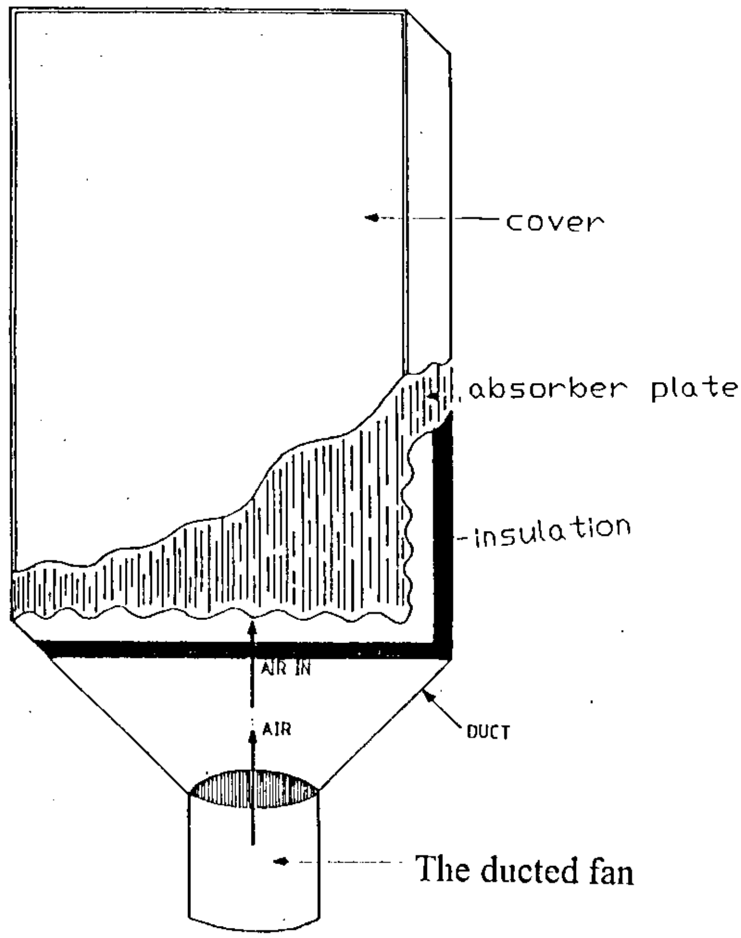



Figure (2.3) The ducted fan

## 2.4 Manufacturing process

The steps which were followed to build the two collectors are summarized as follows:

1. Two plates, one of which uses locally available corrugated galvanized iron sheet of dimensions 2000 mm long x 830 mm wide and the other one uses steel sheets to manufacture the absorber plates. Five

galvanized steel sheet of dimensions 2000 mm long x 1000 mm wide are also used. Two of them were used to reconstruct each collector frame, and two of them were put over the material insulation to have a smooth of air flow. The fifth sheet was used to manufacture the fan duct.

2. Eighteen thermocouple wires where used to measure the various temperatures needed to study the thermal performance of both collectors. The location of these thermocouples are as shown in figure (2.4).

These thermocouple wires were installed as following:

a) Three thermocouple wires were installed at the inlet and three thermocouple wires were installed at the outlet of each collector, as shown in figure (2.4), where the wire numbers 1 and 3 measures the inlet air temperatures, and the wire numbers 7 and 9 measures the outlet air temperatures. The thermocouple wire numbers 2 and 8 used to measure the surface collector temperatures of absorber plate at the inlet and outlet, respectively.

b) Three thermocouples are installed at the center of each collector, as shown in figure (2.4). The thermocouple wire number 5 is used to measure the surface collector temperature and the wires number 4 and 6 are used to measure the temperature of air flow at the center of each collector.

# CHAPTER 3

# EXPERIMENTAL SET UP, PROCEDURE AND ANALYSIS

## 3.1 Introduction

The two collectors of this experimental study were tested outdoor under Jordan's climatic conditions.

This chapter describes the experimental set up in section (3.2). While section (3.3) is devoted to describe the measuring instruments. Then the section (3.4) discusses the experimental test conditions. In section (3.5) the experimental tests and procedures are introduced. The last section is devoted to discuss the mathematical analysis of each collectors.

## 3.2 Experimental set up

The experimental set up for each collector consists of the solar collector and ducted fan. The two solar air heater collectors were mounted on a metal frame with tilt angle of 30°. Each collector was oriented to face south. Ducted fan was used to supply air flow, where the air flow rate was controlled by adjustable power supply that is fixed on the frame of the fan. Figure (3.1) shows schematic diagram of the experimental set up.

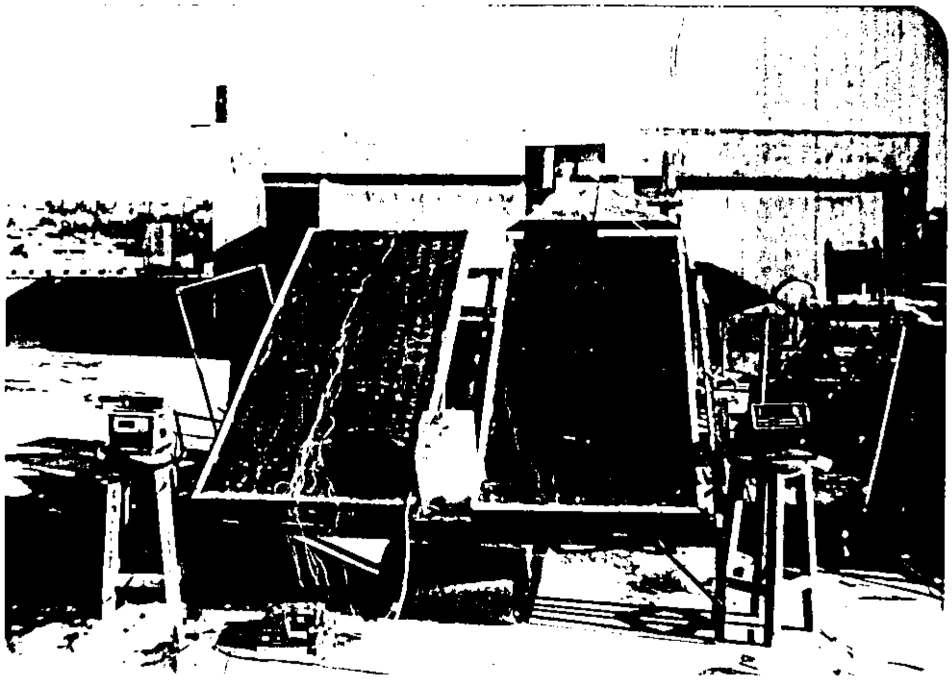


Figure (3.1) Photographs for the experimental set up.

## 3.3 Measuring instruments

The following measuring instruments were used during the test of the two air heater collectors:

1. Incident Solar Radiation Measurement

Incident solar radiation was measured by using pyranometer (Kipp and Zonen Pyranometer, type CM5) and a solar integrator (type CC11) to record the incident radiation in $Wh/m^2$. The intensity of the incident solar radiation was measured at regular intervals each of 30 minutes.

2. Temperature Measurements

Copper constantan thermocouple wires were used to measure the temperature at different locations in the collectors. The thermocouple wires were connected to two multi-point digital thermometer (microprocessor thermometer 6200). Eighteen thermocouple wires were used to measure the temperatures of the two air heaters collector, nine of which were used for conventional type model and the remaining nine for the corrugated model.

3. Flow Rate Measurements

Air mass flow rates was calculated from the air velocity measured by means of a pitot tube. The difference in the stagnation pressure and static pressure was read out from the manometer ($h$), The air velocity, V, is calculated by using the following relation:

$$V = \sqrt{2g\left(\frac{\rho_{\omega}}{\rho_a} - 1\right)h} \qquad (3.1)$$

where:

g : gravitational constant

$\rho_{\omega}$: water density

$\rho_a$: air density

$h$: pressure head in mm water.

Then, the mass flow rate, $m^{\bullet}$, is given by:

$$m^{\bullet} = \rho_a V A \qquad (3.2)$$

Where A is the cross sectional area.

4. Wind Velocity Measurement

Digital anemometer (type Edra 5) was used to measure the wind velocity. The velocity range that can be measured by this device is from 0 to 30m/s. The wind velocity was recorded every 30 minutes over two selected locations around the collectors. These readings were used to estimate the average wind velocities, which were used to estimate the daily wind velocity, $V_w$.

### 3.4 Experimental test conditions

The collectors of this study were mounted on the roof of the Mechanical Engineering Laboratories Department, University of Jordan, Amman (latitude =32°, longitude =36° and hight =980 m above sea level), Jordan.

The relative performance comparison of the two collectors were studied under the following experimental test conditions :

1. Same collector size.
2. Same transparent cover material and thickness.
3. Same insulation material and thickness (thickness=30.0 mm)
4. Same collector tilt angle ($\beta$ = 30° )
5. Same surface azmith angle ($\gamma$ = 0°)
6. Same working fluid flow ( Air).
7. Same coating material ( ordinary black paint)

### 3.5 Experimental tests and procedures

The two collectors were tested outdoors with open loop circulated flow. The tests were carried out during the months of July, August and September, 1995. Each collector was allowed to operate at various mass flow rates. All tests were carried out between 8.00 Am. and 5.0 P.m, where the reading recorded every 30 minutes. In each experimental day, the glass cover of both collectors were cleaned before starting the test, then the pyranometer was properly installed on the collectors plane at same tilt angle ( $\beta$ = 30°). Both collectors must be brought to the same identical conditions, but in the present work, the test for each collector was performed on different days, because we have only one ducted fan which was use for the two collectors. The recorded measurements are:

1. Inlet ($T_{i1}$, $T_{i2}$) and outlet ($T_{o1}$,$T_{o2}$) air temperatures.

2. The temperatures of air on the middle for each collector ( $T_{m1}$, $T_{m2}$).

3. The surface temperatures for absorber plate for each collector: at the inlet ($T_{s1}$), at the middle ($T_{s2}$) and at the outlet ($T_{s3}$).

4. Ambient temperature ($T_a$).

5. Solar incident radiation on the collector plane (I).

6. Air mass flow rates ($\dot{m}$).

7. Wind speed ( $V_w$).

The following tests were conducted for both collectors:

### 3.5.1 Forced circulation test with load conditions

The objectives of this test is to calculate the efficiency of both collectors at different mass flow rates.

This test was performed in August and September, The test was carried out for 4 days during the month of August at two air mass flow rates of 0.0215 kg/s and 0.0166 kg/s. Also the test was carried out for 4 days during the September at mass flow rates of 0.0138 and 0.0098 kg/s for both collectors.

The measured data are tabulated in tables (A.1 to A.16) in appendix A.

### 3.5.2 Stagnation test

The stagnation conditions occur when the heat loss from the absorber plate is equal to the absorbed solar irradiance. This condition occurs when the useful heat gain from the collector equals to zero. So,

$$A_C F_R\left[I(\tau\alpha)_e - U_L(T_i - T_a)\right] = 0.0 \qquad (3.3)$$

Where:

$F_R$ : heat removal factor

$A_C$ : The collector area

I : The incident solar radiation on the collector plane.

$(\tau\alpha)_e$ : The effective transmittance-absorbtance product of the cover system.

$U_L$ : Over all heat transfer coefficient.

$T_i$ : Inlet fluid temperature

$T_a$ : The ambient temperature

Equation(3.3) yields:

$$U_L = \frac{I(\tau\alpha)_e}{T_i - T_a} \qquad (3.4)$$

from which $U_L$ can be determined.

The objective of this test is to evaluate the collector overall heat loss coefficient ($U_L$).

Experimentally, it is difficult to reach the stagnation conditions, especially, during hot summer days. Many experimental tests were performed until the stagnation conditions are attained on September 24th, 1995, where the flow rate was 0.0098 kg/s for corrugated collector and on September 25th, 1995, at the same flow rate for plate collector.

The measured data are tabulated in tables (A.19 and A.22) in appendix A.

### 3.5.3 Time constant test

Time constant test is used to measure the rapidity of a collectors response to transient solar conditions. It is defined as the time required for the fluid leaving a collector to attain change through 0.632 of the total change from its initial to its ultimate steady value after a step change in incident radiation or inlet fluid temperature [1].

The corrugated type collector was operated on September 10th, 1995, to evaluate its time constant. This test was performed with an inlet air temperature of 32.4°C at 12:15 . The time constant test for the flat plate type was conducted on September 11th, 1995 . This test was performed with an inlet air temperature of 31.75°C at 12:15. The solar radiation for both collectors is abruptly shut off by shading the tested collectors, then the outlet temperature of each collector is recorded every minute until the equality of the following equation is attained [1]:

$$\frac{T_{oc,tc} - T_{ic}}{T_{oc,i} - T_{ic}} = 0.368 \qquad (3.5)$$

where:

$T_{oc,tc}$ : The air outlet temperature at time constant ($tc$).

$T_{oc,i}$ : The outlet temperature when solar radiation is interrupted.

$T_{ic}$ : The inlet air temperature during the test.

The measured data for this test are shown in tables (A.17) and (A.18) in appendix A.

$$(\tau\alpha)_e = 1.02\,\tau\alpha \tag{3.7}$$

The useful heat gain is also given by [1] :

$$Q_u = \dot{m}\, C_p\, (T_o - T_i)t \tag{3.8}$$

where: $T_o$, is the collector outlet fluid temperature, $T_i$, is the collector inlet fluid temperature, and t is time in seconds of the test interval.

### 3.6.2 Heat removal factor

The heat removal factor ( $F_R$ ) is given by [1]

$$F_R = \frac{\dot{m} c_p}{A_C U_L}\left[1 - \exp\left(-A_C U_L F' \big/ \dot{m} c_p\right)\right] \tag{3.9}$$

where:

$\dot{m}$ : Mass flow rate of air (kg/s.)

$c_p$ : Specific heat of air (kJ/kg.°C)

$F'$ : The collector efficiency factor.

The collector efficiency factor for the two collectors is given by[1]:

$$F' = \frac{1}{1 + U_L \Big/ \left[h_a + 1 \Big/ \left(\frac{1}{h_a} + \frac{1}{h_{rc}}\right)\right]} \tag{3.10}$$

Where $h_a$ : Convecctive heat transfer coefficient for air flow rate inside the collector, it is given by:

$$h_a = \frac{N_u K_a}{D_H} \qquad (3.11)$$

where $N_u$, is the Nusselt number whose value depend on the flow characteristics (laminar or turbulent), the Nusselt number is equal 0.0158(Renold number)$^{0.8}$ since the flow incide each collector is turblent (Renold number>2100) at each mass flow rate and at each time intervals. $K_a$, is the thermal conductivity of air flow. $D_H$, hydraulic diameter is given by:

$$D_H = \frac{4 * (Flow\ Area)}{Wetted\ Perimeter} \qquad (3.12)$$

The basic equation for the radiative heat transfer between the cover and the absorber plate $h_{rc}$,

a) for the corrugated type is given by [11]:

$$h_{rc} = \frac{\sigma\left(T_2^2 + T_1^2\right)\left(T_2 + T_1\right)}{\frac{1-\varepsilon_1}{\varepsilon_1 + 1} + \frac{1}{F_{12}} + \frac{\left(1-\varepsilon_2\right)A_1}{\varepsilon_2 A_2}} \qquad (3.13)$$

Where $\sigma$, is the Stefan-Boltzmann constant (5.67 x$10^{-8}$ W/m$^2$ K$^4$), $\varepsilon_1$ is the transparent cover emisivity, $\varepsilon_2$ is the absorber plate emissivity, $A_1$ and $A_2$ are the surface area of collector and absorber plate respectively, $T_1$ is the temperature of the glass cover, $T_2$ is the temperature of the surface of absorber plate and $F_{12}$ is the view factor which can be expressed as [11]

$$F_{12} = \sin(\Omega/2) \tag{3.14}$$

where Ω, is the parameter defined by figure (3.2).

b) The radiation heat transfer, $h_{rc}$, for the conventional type (flat-plate) is given by [1]:

$$h_{rc} = \frac{\sigma\left(T_2^{\,2} + T_1^{\,2}\right)\left(T_2 + T_1\right)}{\dfrac{1}{\varepsilon_1} + \dfrac{1}{\varepsilon_2} - 1} \tag{3.15}$$

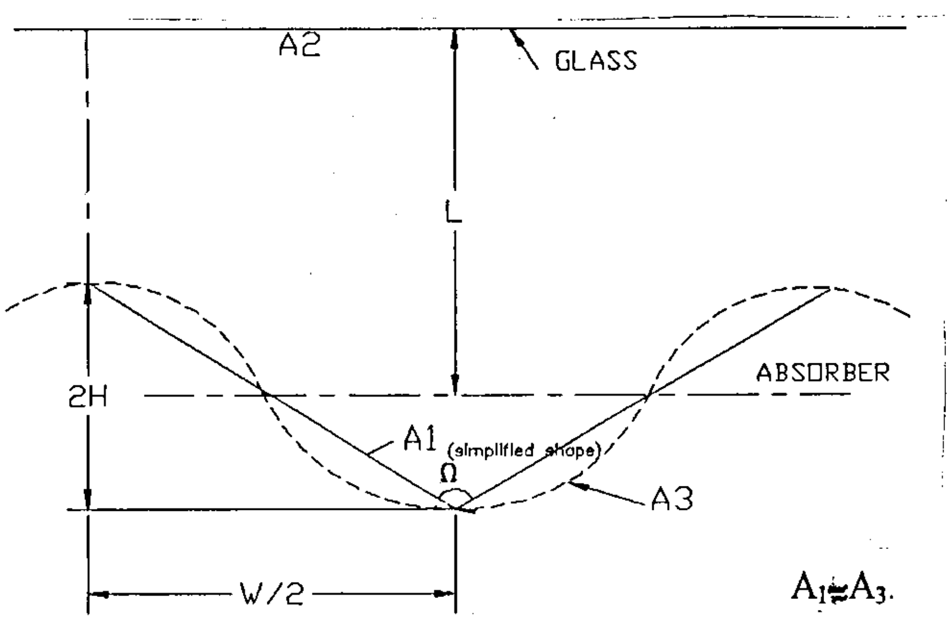



Figure (3.2) Calculation of view factor.

### 3.6.3 Overall heat transfer coefficient

The overall heat transfer coefficient, $U_L$, is given by[11]:

$$U_L = U_t + U_B \tag{3.16}$$

Where $U_t$, is the top heat transfer coefficient, and is given by:

$$U_t = \frac{1}{\frac{1}{h_{rc} + h_{con}} + \frac{1}{h_{r,sk} + h_w}} \tag{3.17}$$

Where $h_{con}$, is the convective heat transfer coefficient between the cover and the absorber plate, $h_{r,sk}$, is the radiative heat transfer coefficient between the sky and the cover, $h_w$, is the wind convective transfer coefficient and $U_B$, is the back loss coefficient, given by:

$$U_B = \frac{K_B}{d_B} \tag{3.18}$$

Where $K_B$, is the conductivity of the insulation material, and $d_B$ back side insulation depth.

The convective heat transfer coefficient between the cover and absorber plate, $h_{con}$ (flat-plate or corrugated plate) can be expressed as:

$$h_{con} = \frac{N_{u,k}}{L} \tag{3.19}$$

Where $N_{u,k}$, is the Nusselt Number and L is the distance between the cover and the absorber plate.

The Nusselt number, $N_{u,k}$ can be expressed as reported by hollands et al. [21]

$$N_{u,k} = 1 + 1.44\left[1 - \frac{1708}{R_a \cos\beta}\right]^{+}\left[1 - \frac{1708(\sin 1.8\beta)^{1.6}}{R_a \cos\beta}\right] + \left[\left(\frac{R_a \cos\beta}{5830}\right)^{1/3} - 1\right]^{+}$$

(3.20)

The (+) exponent means that the positive values of the terms in the square brackets are to be used (i.e, use zero if the term is negative). The Rayleigh number, $R_a$ , is defined as :

$$R_a = \frac{g\beta' \Delta T L^3}{\upsilon\alpha} \qquad (3.21)$$

Where g; gravitational constant, $\beta'$; volumetrtric coefficient of expansion for fluid (air), $\Delta T$; temperature difference between plates, L; mean distance between absorber plate, $\upsilon$; kinematics viscosity, and $\alpha$; thermal diffusely.

The wind convection transfer coefficient $h_w$, can be expressed as [1]:

$$h_w = 5.7 + 3.8 V_w \qquad (3.22)$$

or

$$h_w = 2.8 + 3.0 V_w \qquad (3.23)$$

where $V_w$, is the wind velocity

In this research , $h_w$ was computed from the modern equation (3.23).

The radiative heat transfer coefficient between the sky and the cover, $h_{r,sk}$ is expressed as [11]:

$$h_{r,sk} = \sigma\varepsilon_2\left(T_{sk}^{\ 2} + T_c^{\ 2}\right)\left(T_{sk} + T_C\right) \tag{3.24}$$

Where the sky temperature $T_{sk}$ is given by

$$T_{sk} = 0.0552 T_a^{\ 1.5} \tag{3.25}$$

Where $T_a$, is the ambient temperature.

In the present work the over all heat loss coefficient is given by:

$$U_L = U_B + U_t + U_e \tag{3.26}$$

Where $U_e$, is the effective overall heat loss coefficient.

### 3.6.4 The instantaneous and daily efficiencies

The Instantaneous efficiency, $\eta_i$ is given by :

$$\eta_i = \frac{Q_u}{A_c I} 100\% \tag{3.27}$$

The daily efficiency, $\eta_d$ of the collector is the ratio of the useful energy gain obtained during the test day to the total radiation incident on the collector during that day. It is expressed as:

$$\eta_d = \frac{Q_u(total)}{A_c \Sigma I} 100\% \tag{3.28}$$

# CHAPTER 4

# RESULTS AND DISCUSSION

## 4.1 Introduction

The performance comparison between the corrugated and the conventional types of solar air heaters is carried out by performing three tests, as outlined in chapter three. The systems performance is studied with detailed analysis. This study is based on experimental results obtained from the performed tests.

This chapter is divided into three sections: introduction, performance calculations and results. The last section deals with the discussion and analysis of the results obtained.

## 4.2 Calculations and results

Most of the calculations of this study were performed by using the equations introduced in section (3.6) of the previous chapter. The data collected during all tests are tabulated in Appendix A. For all tests, all measured temperatures during a given interval were averaged by using the values at the beginning and at the end of each time period. The results of these calculations are tabulated in Appendix B. Figures of this study are prepared by using the AXUM computer program.

Theoretical calculations of this study were performed by using a FORTRAN computer program as presented in Appendix C.

The results and the sample calculations of all tests are presented in the following sub-sections:

### 4.2.1 Results of forced circulation test with load conditions

This test was performed at the following mass flow rates: 0.0215, 0.0166, 0.0138 and 0.0098 Kg/s. The data collected during the test are tabulated in Appendix A. The results of testing are included here to find out the amount of useful energy collected by each collector and to calculate the efficiency of each collector . These results are tabulated in tables (B.1 - B.16) in Appendix B for both collectors .

The averaged inlet, outlet and the ambient temperatures at different mass flow rates are plotted against time of day for two types of collectors as shown in figures (4.1- 4.10).

The useful heat gain and the incident radiation are plotted against time of day as shown in figures (4.13-4.16). The useful heat gain at different mass flow rates is plotted against incident solar radiation for each collector as shown in figures (4.17) and (4.18). Then the useful heat gain is plotted against incident solar radiation for both collectors as shown in figures (4.19-4.22).

The instantaneous efficiency was calculated using equation (3.27) and plotted against $[(T_i-T_a)/I]$ as shown in figures (4.23 - 4.26). From the coefficient of the linear fit we obtained the parameters $F_R(\tau\alpha)_e$ which is the intercept with the y-axis and $-F_RU_L$ which is the slope. The obtained efficiency equations for each collector at different mass flow rates are given in table(B.17). Heat removal factor and overall heat loss coefficient are plotted against mass flow rate for both collectors as shown in figures (4.30) and (4.31) respectively. The daily efficiency are plotted against mass flow rates as shown in figure (4.27). The average air temperature at the mid of each collector $(T_m)$ are plotted against time of day for different mass flow rates as shown in figures (4.11) and (4.12).

**Sample calculations**

To illustrate the calculation procedure followed, the calculation will be carried out for the test day of August, 15th, 1995 (for corrugated collector type) at a mass flow rate 0.0215 Kg/sec and at time interval 10:00-10:30. Referring to table (A.1), the measured data for the selected interval are :

| Time | $T_{i1}$ | $T_{i2}$ | $T_{o1}$ | $T_{o2}$ | $T_{amb}$ |
|---|---|---|---|---|---|
| 10:00 | 27.1 | 28.5 | 51.9 | 52.4 | 22.0 |
| 10:30 | 28.2 | 29.6 | 54.5 | 55.1 | 22.5 |

And from table (A.2) the measured data for this time interval are :

| Time (hr) | I(Wh/m$^2$) | $V_w$ (m/s) |
|---|---|---|
| 10:00-10:30 | 436.4 | 1.6 |

The averaged inlet and outlet temperatures calculation are tabulated in table (B.1), the calculated data at time 10:00 and 10:30 are :

| Time(hr) | $T_{iav}$ | $T_{oav}$ |
|---|---|---|
| 10:00 | 27.8 | 52.15 |
| 10:30 | 28.9 | 54.80 |

where:

$T_{iav} = \frac{T_{i1} + T_{i2}}{2}$ and $T_{oav} = \frac{T_{o1} + T_{o2}}{2}$ then, the averaged inlet and outlet temperatures calculations at this time inlerval are:

$$T_{ic} = \frac{T_{iav/at\ 10:00} + T_{iav/at\ 10:30}}{2}$$

$$= \frac{27.8 + 28.9}{2} = 28.35\ C^o$$

Also

$$T_{oc} = \frac{T_{oav/at\ 10:00} + T_{oav/at\ 10:30}}{2}$$

$$= 53.48\ C^o$$

The averaged ambient temperature, $T_{a,av}$=22.25 $C^o$

3.8)

$$Q_{uc} = \dot{m}.C_p(T_{oc} - T_{ic})t$$

$$= (0.0215)(1.0065)(53.48 - 28.35)1800$$

$$= 978.85\ KJ$$

The intensity of solar radiation I in $KJ/m^2$ is calculated as follows :

$$I = \frac{(436.4)(3600)}{1000} = 1571.04\ KJ/m^2$$

The instantaneous efficiency of the collector during this interval is evaluated using equation (3.27):

$$\eta_i = \frac{Q_u}{A_c I} 100\%$$

where A is the absorber plate area which is equal to :

- For corrugated type $A_c$ =1.0×1.9=1.9 $m^2$

- For convent type $A_c$ =0.79×1.9=1.5 $m^2$

Then:

$$\eta_i = \frac{978.85}{(1.9)(1571.04)}100\% = 32.79\%$$

The term ($T_{ic}$ - $T_a$ )/I for the same time interval is obtained as follows :

$$\frac{T_{ic} - T_a}{I} * 100 = \frac{28.35 - 22.25}{436.4} * 100$$
$$= 1.40\left(\frac{m^2 {}^{o}C}{Wh}\right)$$

The values of the above parameters for all time intervals are obtained following similar procedure for both collectors. The results of these calculations for all tests are shown in tables (B.1-B.16) in Appendix B.

The daily efficiency, $\eta_d$ , is calculated using equation 3.28 for each mass flow rate (0.0215, 0.0166, 0.0138 and 0.0098 Kg/sec). Table (4.2) presents the daily efficiencies for both collectors at each mass flow rate.

Table (4.1) Daily efficiency of the tested solar collectors.

| $\dot{m}$ (Kg/sec) | $\eta_d$ (%) for corrugated type | $\eta_d$ (%)for conventional type |
|---|---|---|
| 0.0215 | 32.81 | 29.57 |
| 0.0166 | 29.46 | 26.93 |
| 0.0138 | 25.34 | 23.07 |
| 0.0098 | 21.40 | 20.12 |

To illustrate the calculation procedure of the daily efficiency, the useful energy gain for corrugated type are considered at mass flow rate 0.0125 Kg/s. The values of the useful heat gain and incident solar radiation are obtained from table (B.2) as :

$$\sum Q = 16109.6\ KJ$$
$$\sum I = 25845.43\left(\frac{KJ}{m^2}\right)$$

The collector daily efficiency is calculated using equation (3.28) :

$$\eta_d = \frac{\Sigma Q}{A_c \Sigma I} 100\%$$

$$= \frac{16109.6}{(1.9)(25845.43)} 100\% = 32.81\%$$

### 4.2.2 Results of stagnation test

The data collected during this test are tabulated in tables (A.19-A.22) in Appendix A. The overall heat loss coefficients for both collectors were determined as follows :

As presented in Table A.20 the stagnation conditions are attained during the time interval 15:50-16:00 for the conventional type the averaged measured data during this interval are as follows :

$$T_{ic} = T_{oc} = 46.90\ ^{o}\mathrm{C}$$
$$T_a = 24.5\ ^{o}\mathrm{C}$$
$$I = 308.4\ W/m^2$$

Then, the overall heat loss coefficient for the conventional type can be calculated by using equation (3.4) which yields :

$$U_L = \frac{(308.4)(0.81)}{46.90 - 24.5} = 11.15\ \mathrm{W/m^{2o}}C$$

Similarly for the corrugated type : as presented in table (A.22) the stagnation conditions are attained during the time interval 15:30-15:40. The averaged measured data during this interval are as follows :

$$T_{ic} = T_{oc} = 50.18\ ^{\circ}\mathrm{C}$$
$$T_a = 24.75\ ^{\circ}\mathrm{C}$$
$$I = 378.6 W/m^2$$

Then, the over all heat loss coefficient for corrugated type is:

$$U_L = \frac{(378.6)(0.81)}{50.18 - 24.75} = 12.06\ \mathrm{W/m^{2\circ}}C$$

### 4.2.3 Results of time constant test

The averaged measured data during the test are tabulated in tables A.17 and A.18 in Appendix A. The outlet temperature for each model is plotted against time of day as shown in figures (4.28) and (4.29). Using these figures and equation (3.5) the time constant is calculated as follows:

A) For corrugated type:

From the table (A.17), the averaged inlet air temperature, $T_{ic}$=30.17°C, the outlet air temperature when the solar radiation is suddenly interrupted, $T_{oc}$=49.20 °C and the ambient temperature, $T_a$=29.0 °C. From equation (3.5) the average outlet air temperature, $T_{oc,tc}$ at the time constant, tc, is:

$$\begin{aligned} T_{oc,tc} &= 0.368\left(T_{oc,i} - T_{ic}\right) + T_{ic} \\ &= 0.368(49.20 - 30.17) + 30.17 \\ &= 37.17\ ^\circ C \end{aligned}$$

B) For conventional type:

From the table (A.18), the averaged inlet air temperature, $T_{ic}$=30.44°C, the outlet air temperature when the solar radiation is suddenly interrupted $T_{oc}$=47.8°C and the ambient temperature $T_a$=29.5°C. From equation (3.5) (simillary as corrugated type):

$$\begin{aligned} T_{oc,tc} &= 0.368(47.80 - 30.44) + 30.44 \\ &= 36.83\ ^\circ C \end{aligned}$$

Referring to tables (A.17) and (A.18) or figures (4.26) and (4.27), correspond to time constant of 7.26 minute and 8.31 minute for corrugated type and conventional type respectively. Table (4.3) summarizes the results of the time constant test for both collectors.

Table 4.2: Results and conditions of the time constant test.

| Collector | $T_{ic}$ (°C) | $T_a$ (°C) | $T_{oc}$ (°C) | $T_{oc,tc}$ (°C) | tc (min.) |
|---|---|---|---|---|---|
| corrugated | 30.17 | 29.0 | 49.20 | 37.17 | 7.26 |
| conventional | 30.44 | 29.5 | 47.80 | 36.83 | 8.31 |

### 4.2.4 Theoretical results

The theoretical calculation presented in this study were performed by using the FORTRAN computer program in Appendix C.(i.e program 1 for the corrugated type and program 2 for the conventional type). The results collected during the two programs presented in tables (C.1) and (C.2). The theoretical calculation results are presented at mass flowrate 0.0215 kg/s. Figures (4.32-4.41) show that the comparison between theoretical and experimental results for each model. All equations are used in computer programs for performance calculations of conventional and corrugated type are shown in section (3.6). While, the equations of the incident solar radiation calculations (IT) are expressed as in computer programs.

## 4.3 Discussion of results:

The Performance of both collectors are studied at various flow rates, while all other design parameters are kept fixed. The discussion of the performance parameters is outlined in the following subsections:

### 4.3.1 Temperature distribution of air inside collectors

The measured temperature for all tests are presented in tables (A.1, A.3, A.5, A.7, A.9, A.11, A.13, and A.15). The averaged inlet, outlet, and ambient temperatures are shown in figure (4.1-4.10). These figures show that the temperatures difference across the corrugated collector is higher than that across the conventional collector for all tests because the corrugated type has better performance when compared to the conventional type. The maximum temperature was attained during the time interval 12:00-13:00 for both collectors. For the time interval 16:00-17:00 both collectors have nearly the same outlet temperatures, so the shading effect of the corrugated type is higher than of the conventional type. The difference between outlet temperatures of both collectors is increased gradually from the early morning till it reaches a maximum value at the mid of day. Then the difference drops gradually till it reaches a minimum value at the end of the test day, because the solar incident radiation reaches a maximum value at the mid of day. The maximum outlet temperature of corrugated type was

69.95°C and it is higher than that of maximum temperature for the conventional type by about 8.0°C. The performance temperatures of air at the middle of both collectors for different mass flow rate as shown in figures (4.11) and (4.12). These figures show that the comparison of performance temperatures between the two solar collectors.

### 4.3.2 Useful heat gain

The useful heat gain for each type was calculated using equation (3.8). The variation of the useful heat gain and solar radiation are plotted against time of day as shown in figures (4.13-4.16). The useful heat gain increases as the intensity of solar radiation increases. Also, the useful heat gain increases as the mass flow rate increases as shown in figures (4.17) and (4.18) for both collectors.

All tests show that the useful heat gain of the corrugated type is higher than that of the conventional type for all time intervals and flow rates investigated, so the surface area facing to the sun and heat removal factor of the corrugated type is higher than that of the conventional type. The useful heat gain of both collectors, increases gradually from the beginning of the test, till it attains a maximum value at the mid of the day, there after, it drops gradually. This is due to the decreasing rate of the incident solar flux during the afternoon hours.

The difference between the useful heat gain of both collectors increases gradually from the beginning of the day test, till it reaches a maximum value of the time interval 12:00-13:30, then the difference drops gradually till it reaches a minimum value at the end of the test day, due to shading effect, so the heat losses of the corrugated type was increased. When both collectors were operated under forced circulation mode, the inlet air was provided for each model near the ambient temperature to minimize the heat losses from the collectors. For this test and under low flow rate 0.0098 kg/s the maximum heat gain was attained at the time interval 12:00-13:00 for both models. For this time interval the useful heat gain of the corrugated type is greater by about 24.4% than that of the conventional type. As the flow rate is increased (0.0215 kg/s), the maximum useful heat gain of the corrugated type is higher by about 34.3% than that of the conventional type, so the increased of mass flow rate improvement the heat gain of corrugated type higher than that of the conventional type.

### 4.3.3 Instantaneous and daily efficiencies

The instantaneous efficiency; $\eta_i$, for each type was calculated using equation (3.27). The variation of the instantaneous efficiency with ( Ti - Ta ) / I for both collectors are presented in figures (4.23-4.26) for the forced flow tests. The instantaneous efficiency of the corrugated type is higher than that of the conventional type for all the time intervals and flow rates investigated because the heat gain of the corrugated type is higher than that of the conventional type. As the flow rate is increased the difference between the instantaneous efficiency of both collectors is increased, so the difference between the heat gain of two collectors is increased. At the last two hours of the test day, the decreasing rate of the instantaneous efficiency of the corrugated type is higher than that of the conventional type due to the shading effect. For each model, the efficiency is higher for lower values of the parameter (Tic-Ta)/I, since under such conditions the inlet air temperature value is near that of ambient, hence the minimum heat loss to the environment is occurred.

The daily efficiency of each collector model at each flow rate was evaluated from equation (3.28)using the corresponding averaged measured data. The daily efficiency was based on the summation of the incident solar energy and the useful heat gain for all time intervals during the test day. The daily efficiencies are shown in table (4.2) for each collector at each mass flow rate. This table shows that the increase in the daily efficiency is due to the increase in the air flow rate. For example, as the air flow rate is increased from 0.0166 to 0.0215 kg/s, the improvement in daily efficiency of the corrugated type is 9.8%. The corresponding improvement for the conventional type is 9.1%.

### 4.3.4 Heat removal factors and overall heat loss coefficients

Based on figures (4.23 - 4.26), Table (4.1) presents the instantaneous efficiency expressions for the forced test with load conditions. These expressions show that the heat removal factor of the corrugated type, $F_{RC}$, is higher than that of the conventional type for all the investigated flow rates. The variation of the these heat removal factors with mass flow rate are presented in figure (4.30). The maximum value of the $F_R$ was attained at the mass flow rate of 0.0215 kg/s equals to 0.451. It is also clear from the results that the overall heat loss coefficient of both collectors is higher at lower air mass flow rate, as shown in figure (4.31).

Results show that the overall heat loss coefficient of the corrugated type is higher than that of the conventional type for all the investigated air flow rate. For example, for air flow rate of 0.0215 kg/sec, the overall heat loss coefficient of the corrugated type is higher than that of the conventional type by about 13%. The maximum value of the $U_l$ is 11.89 $W/m^2.°C$, at air flow rate 0.0098 kg/s for the corrugated collector type.

### 4.3.5 Stagnation test

From the stagnation test results, the overall heat loss coefficient for both collectors were found to be 12.06, and 11.15 $w/m^2.°C$ for corrugated and conventional type respectively.

Stagnation test show that the overall heat loss coefficient of the conventional type is less than that of the corrugated type by 7.5 % . The overall heat loss coefficient of the corrugated type is higher than that of the conventional type, so the absorber plate area for the corrugated type is higher than that of the conventional type.

#### 4.3.6 Time constant test

The time constant for each model is evaluated according to equation (3.5). Tables (A.17) and (A.18) present the results of this test. The variation of the outlet temperatures of both collectors with time , after the sudden interruption of the solar radiation on the collectors is shown in figures (4.28) and (4.29).

Results of this test show that the time constant of the corrugated type is 7.26 minute, and 8.31 minute for the conventional type. The reason for this time constant variation between both collectors is that air temperature rise in the corrugated type collector is higher than that in the conventional collector.

#### 4.3.7 Theoretical results

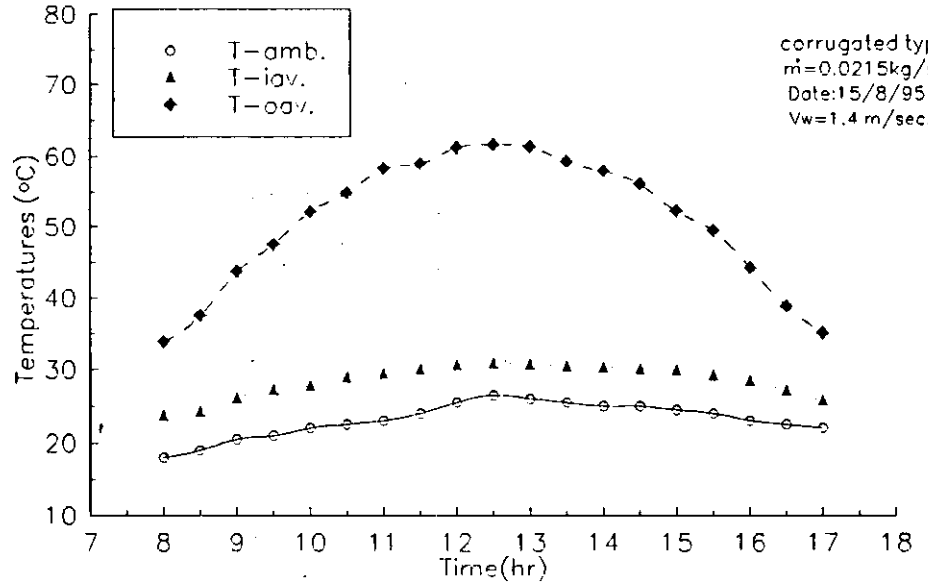
Most of theoretical calculations of this study were performed by using a FORTRAN computer programs as presented in Appendix (C) . The results of these calculations are tabulated in tables (C.1) and (C.2) or figures (4.32 -

4.41) show that the differences between the theoretical results and experimental results came from: the equations used in the programs to give the theoretical results have depended on some approximations and assumptions, uncertainty of the measuring instruments and personal errors of experimental tests.

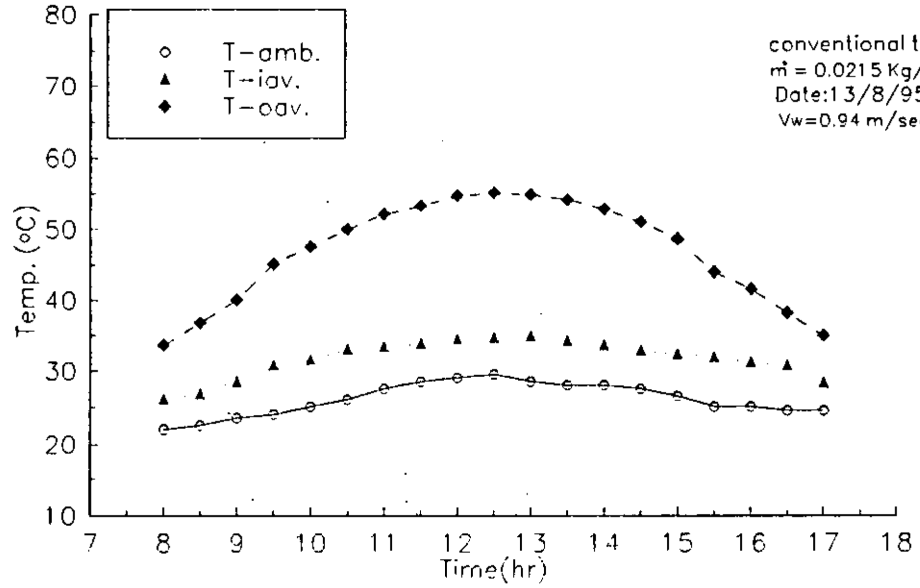
For example, the overall heat loss coefficient at air flow rate of 0.0215 kg/s for the corrugated type is about 9.34 W/m$^2$.°C, but from experimental test the overall heat loss coefficient is about 8.75. The error is about 6.6%.

### 4.4 Error analysis

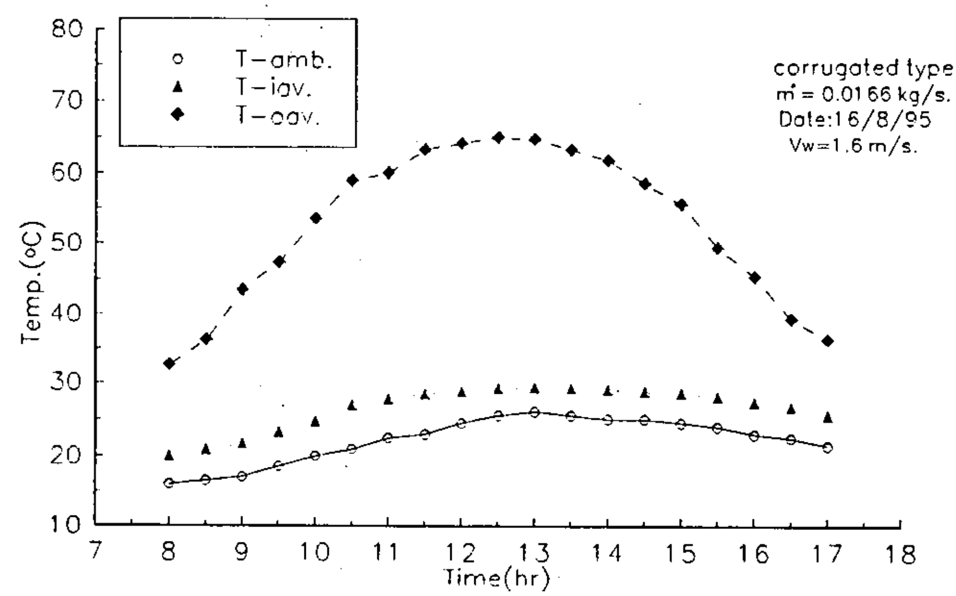
We have already noted that is in somewhat more explicit to speak of experimental uncertainty rather than experimental error. We shall be interested in knowing the uncertainty in the final result due to the uncertainties in the primary measurements. This may be done by a commonsense analysis of the data which may be take many forms. The analysis would combine all the errors in the most detrimental way in order to determine the maximum error in the final results[22]. The maximum associated error in calculating $Q_u$ was 5.7%, while the maximum error in calculating of instantaneous efficiency and daily efficiency are 0.3% and 1.4%, respectively, as shown in appendix D.



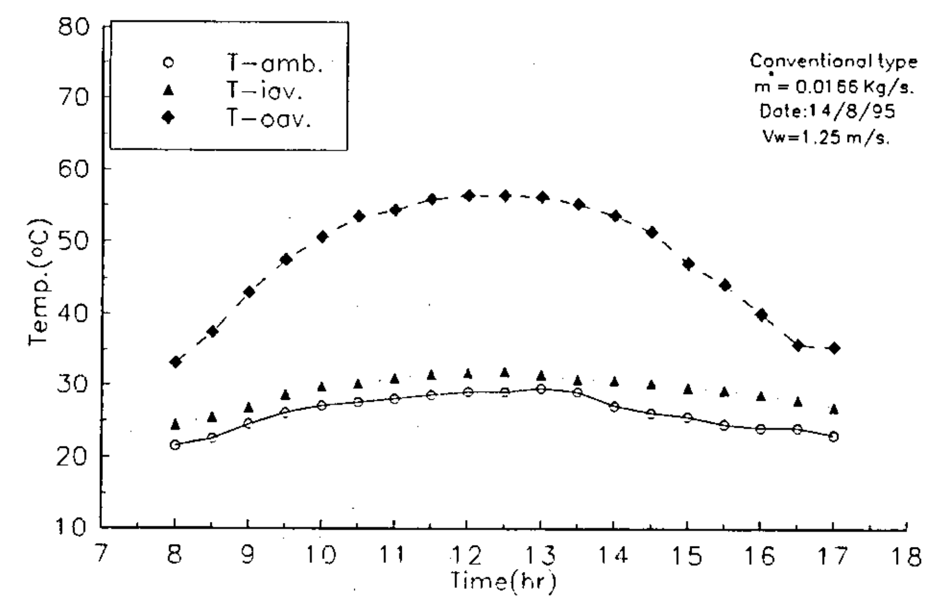

Figure(4.1)Variation of inlet, outlet, and ambient tempratures with time of day for the corrugated solar collector.



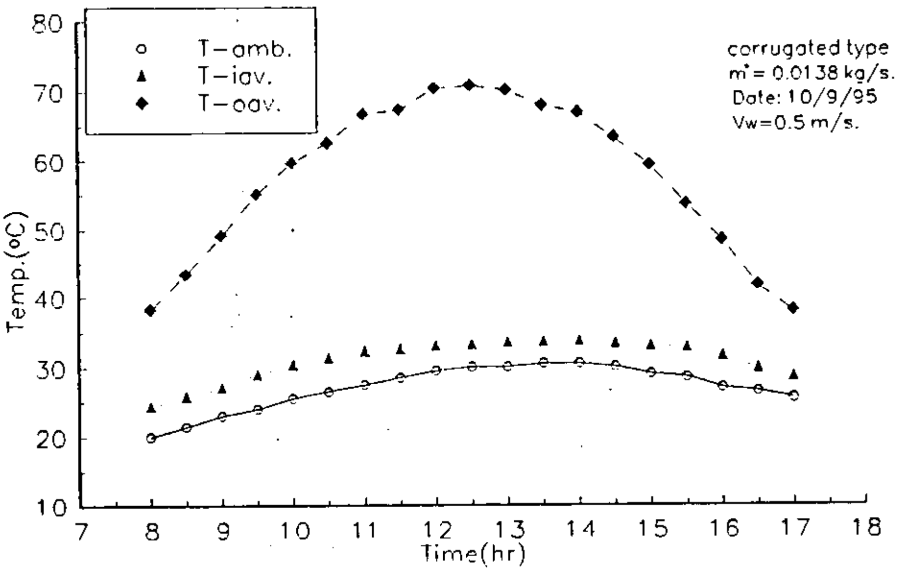

Figure(4.2)Variation of inlet, outlet, and ambient temperatures with time of day for the conventional solar collector.



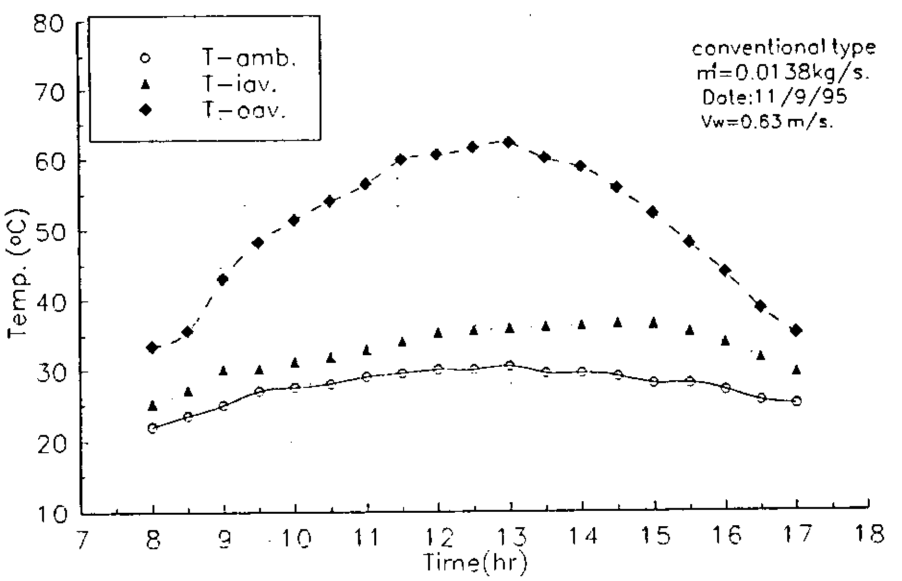

Figure(4.3) The variation of inlet, outlet, and ambient temperatures with time of day for the corrugated solar collector.



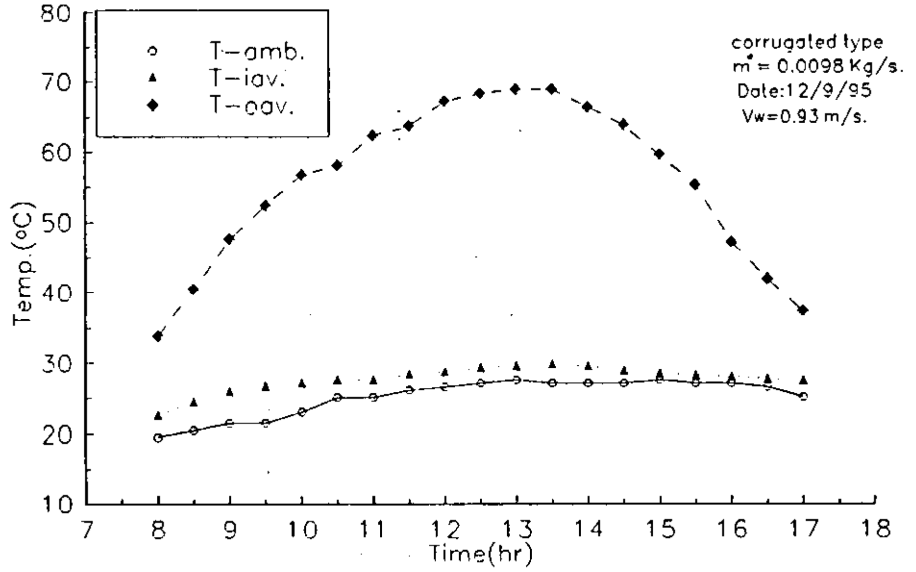

Figure(4.4) The variation of inlet, outlet, and ambient temperatures with time of day for the conventional solar collector.



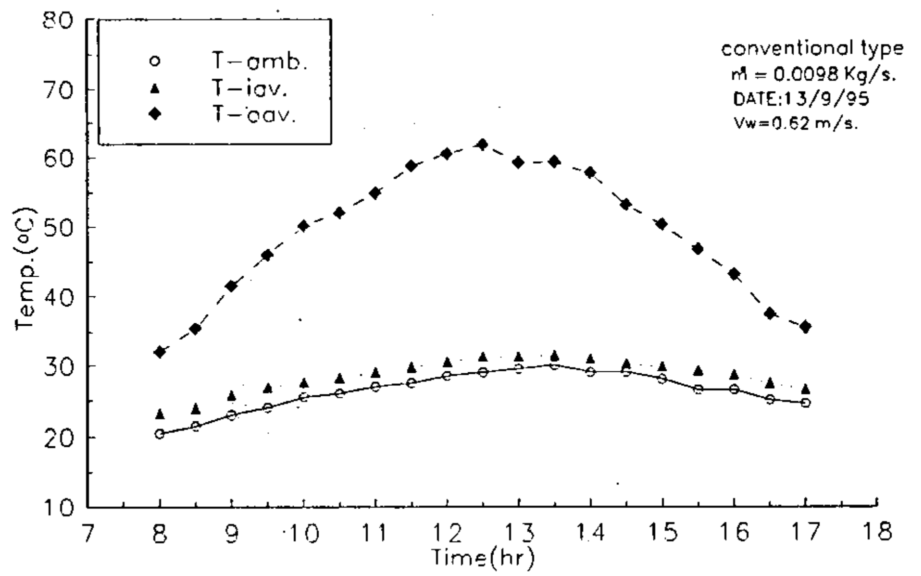

Figure(4.5) The variation of inlet, outlet, and ambient temperatures with time of day for the corrugated solar collector.



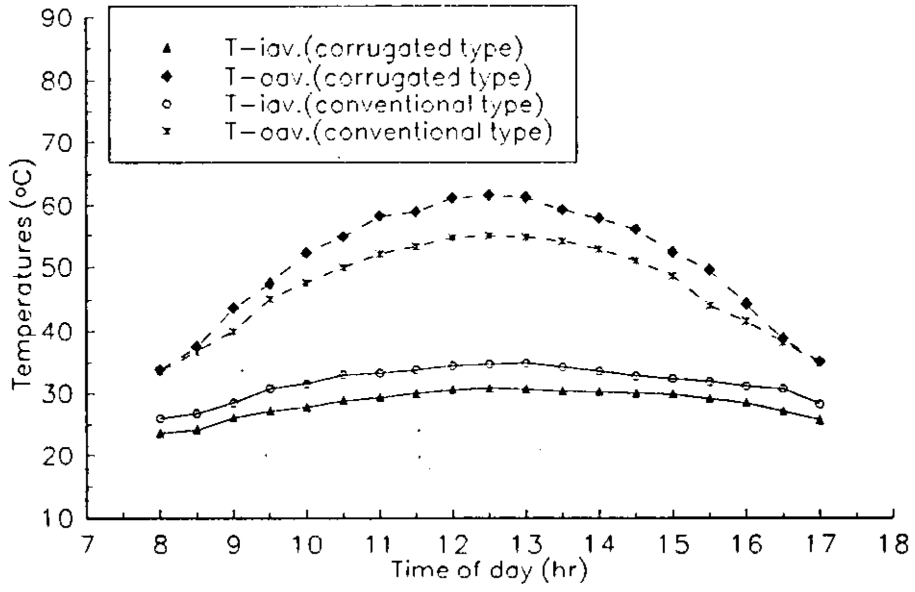

Figure(4.6) The variation of inlet, outlet, and ambient temperatures with time of day for the conventional solar collector.



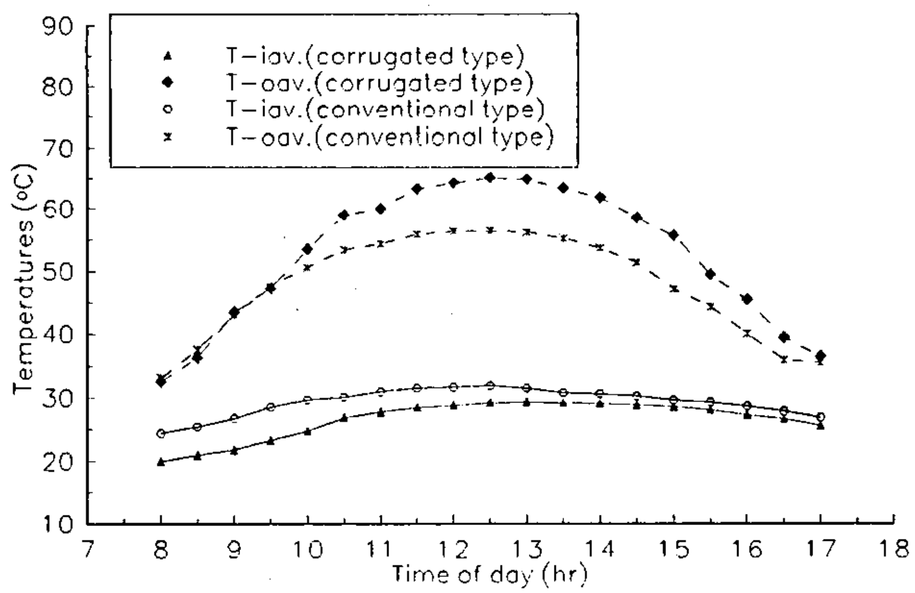

Figure(4.7) The variation of inlet, outlet, and ambient temperatures with time of day for the corrugated solar collector.



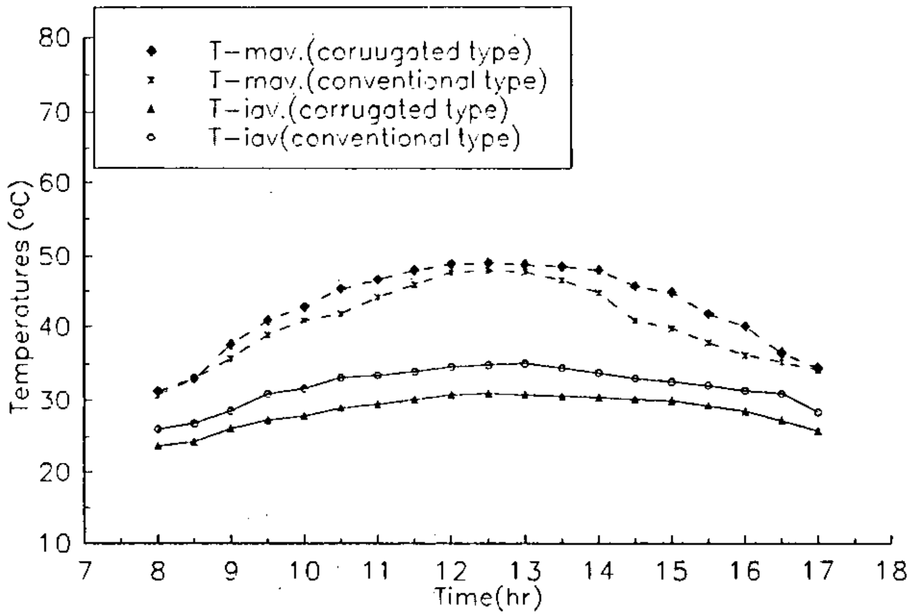

Figure(4.8) The variation of inlet, outlet, and ambient temperatures with time of day for the conventional solar collector.



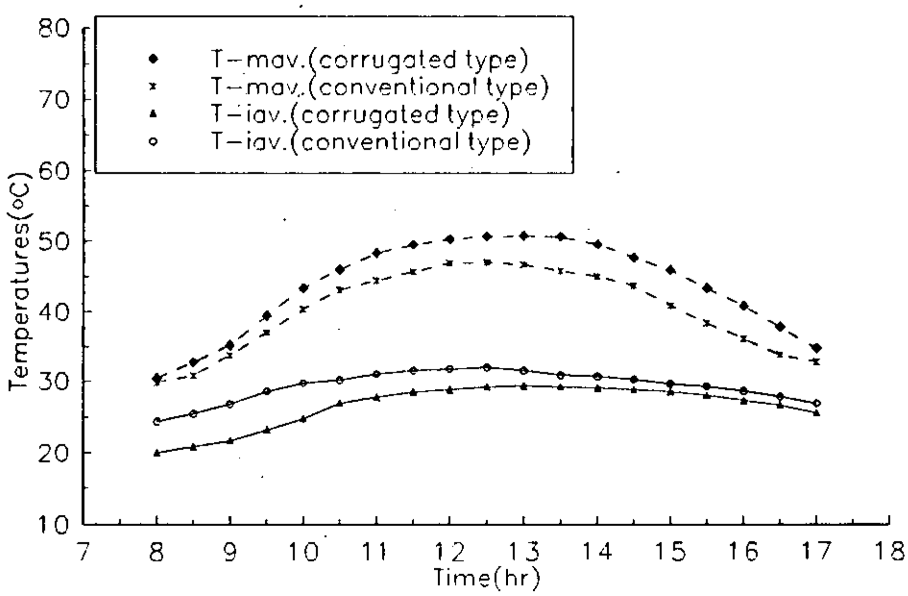

Figure(4.9) Variation of inlet and outlet temperatures with time of day for the corrugated and conventional solar collectors. $\dot{m}$=0.0215 kg/s.



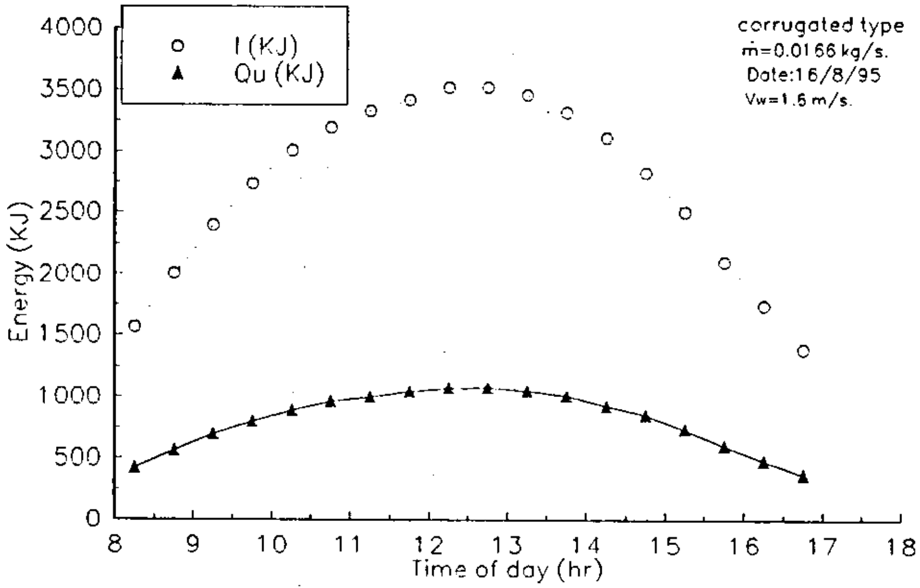

Figure(4.10) Variation of inlet and outlet temperatures with time of day for the corrugated and conventional solar collectors. $\dot{m}$=0.0166 kg/s.



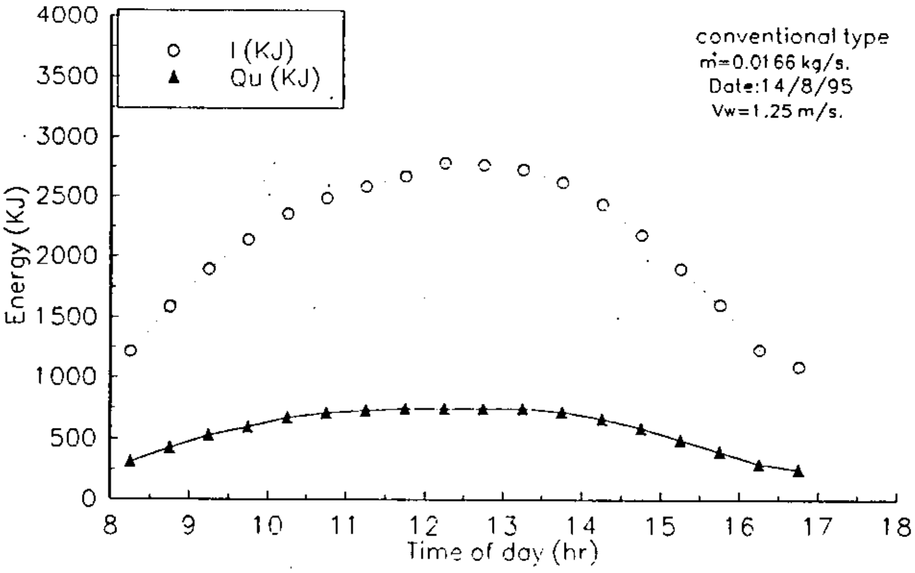

Figure(4.11)Variation of inlet temperatures and temperatures of air at the middle(T−mav.) for both collectors with time of day.ṁ=0.0215 kg/s.



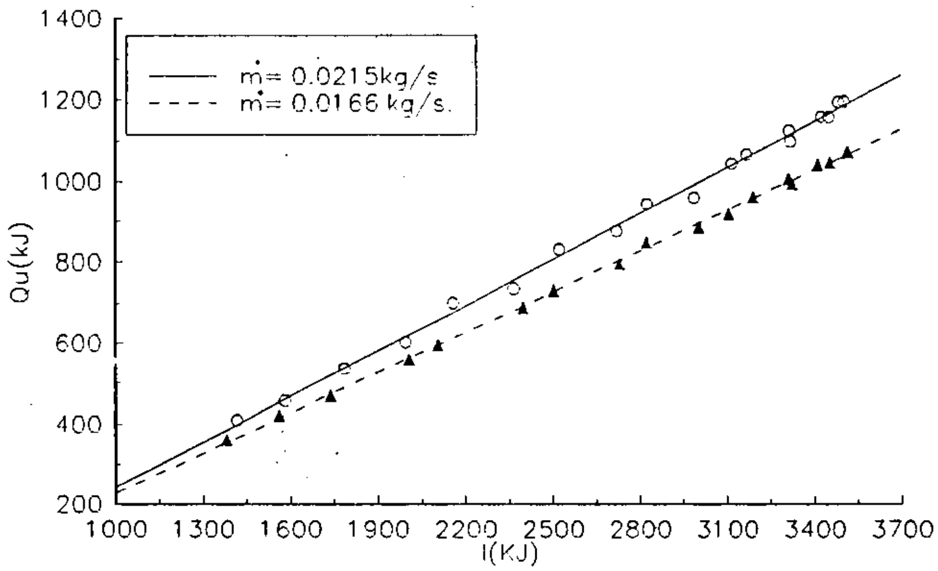

Figure(4.12)Variation of inlet temperatures and temperatures of air at the middle(T−mav.) for both collectors with time of day. ṁ=0.0166 kg/s.



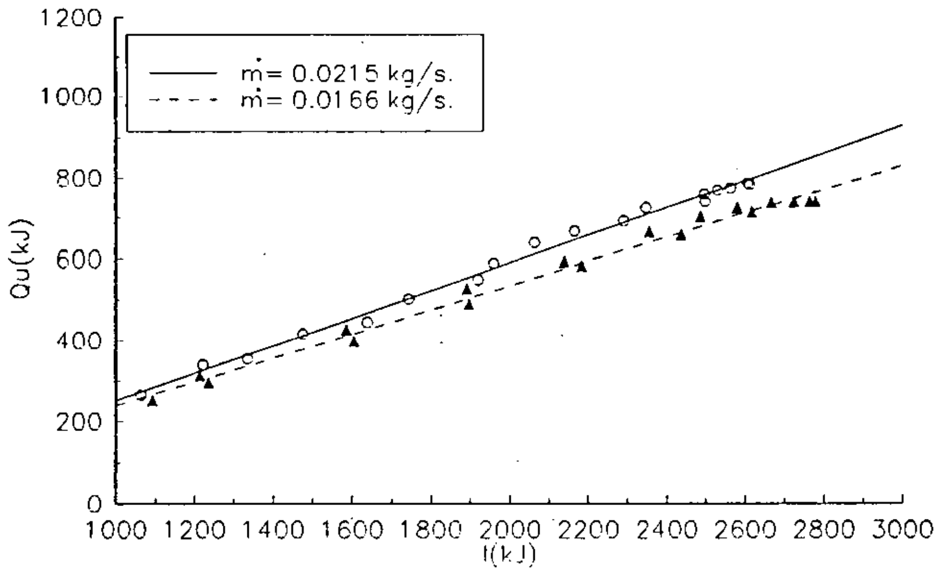

Figure(4.15) Variation of incident solar radiation and useful energy gain with time of day for the corrugated solar collector.



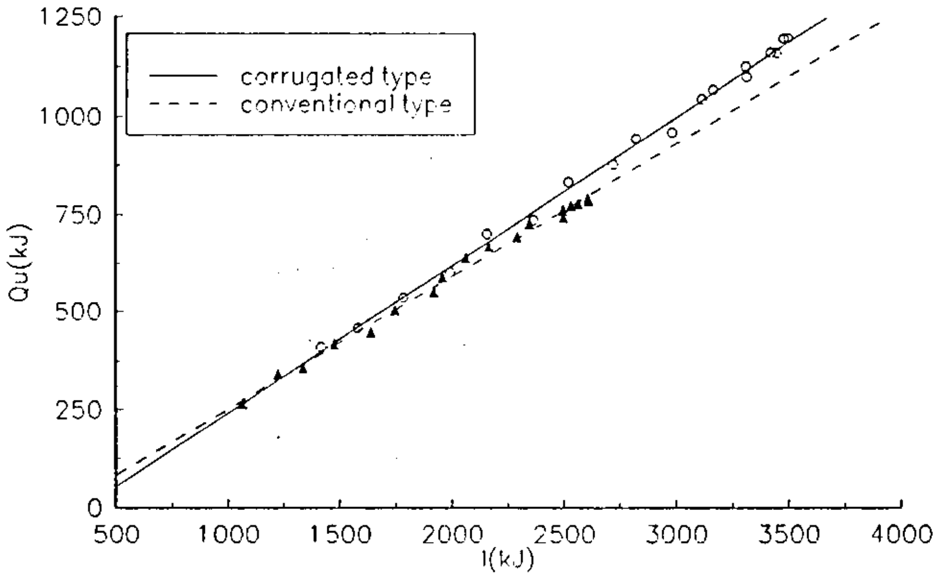

Figure(4.16) Variation of incident solar radiation and useful energy gain with time of day for the conventional solar collector.



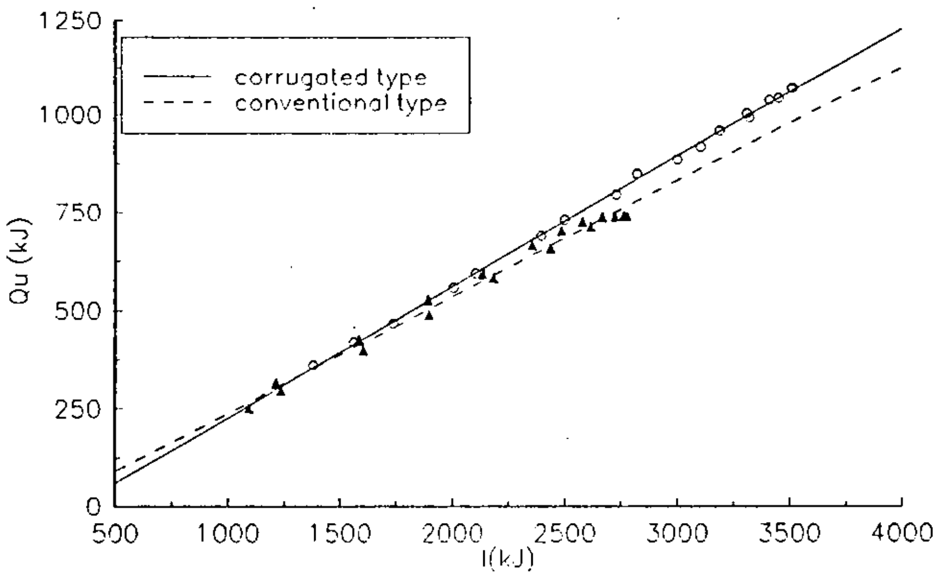

Figure(4.17) Useful heat gain(Qu) .vs. incident solar radiation(I) for the corrugated solar collector.



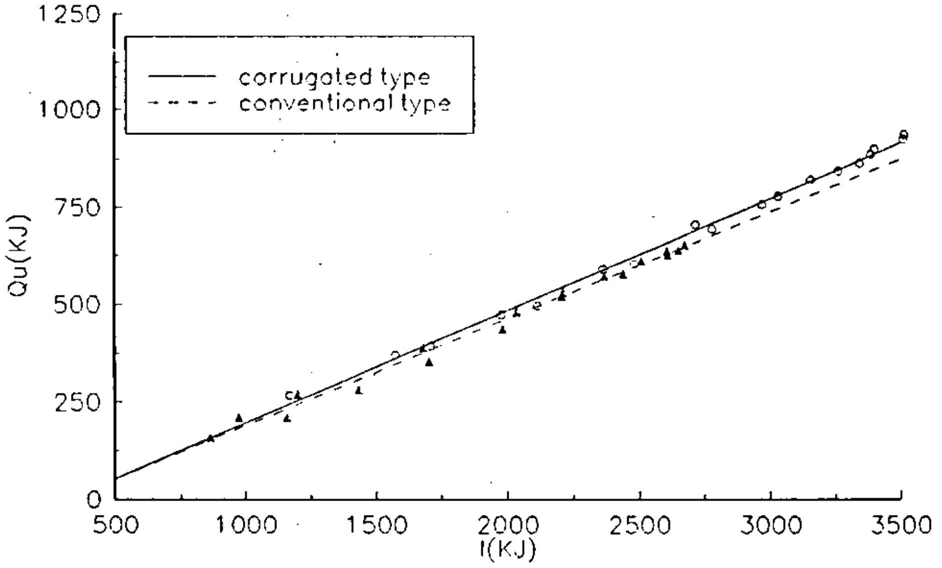

Figure(4.18) Useful heat gain (Qu) vs. incident solar radiation (I) for the conventional solar collector.



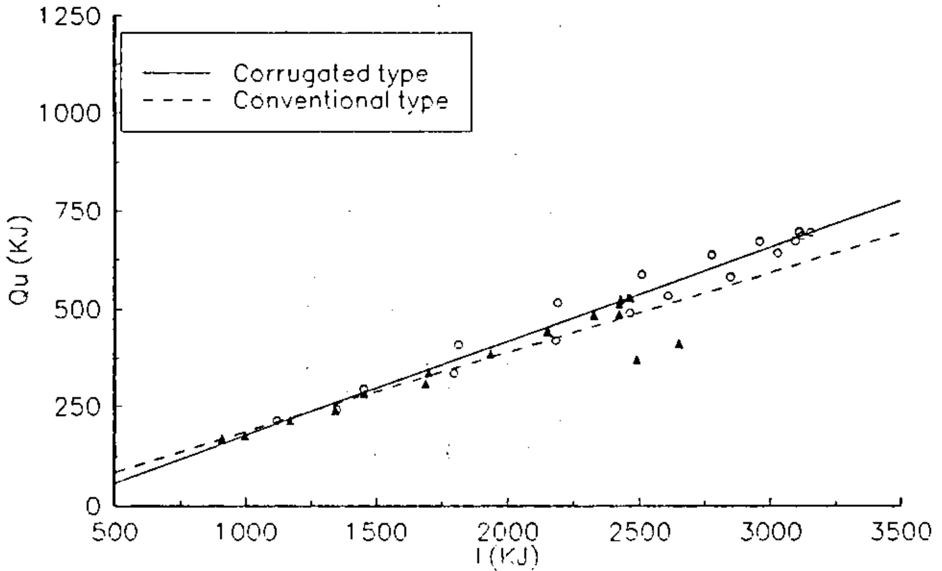

Figure(4.19) Useful heat gain (Qu) vs. Inciden solar radiation (I) for the corrugated and conventional solar collectors.ṁ=0.0215 kg/s.



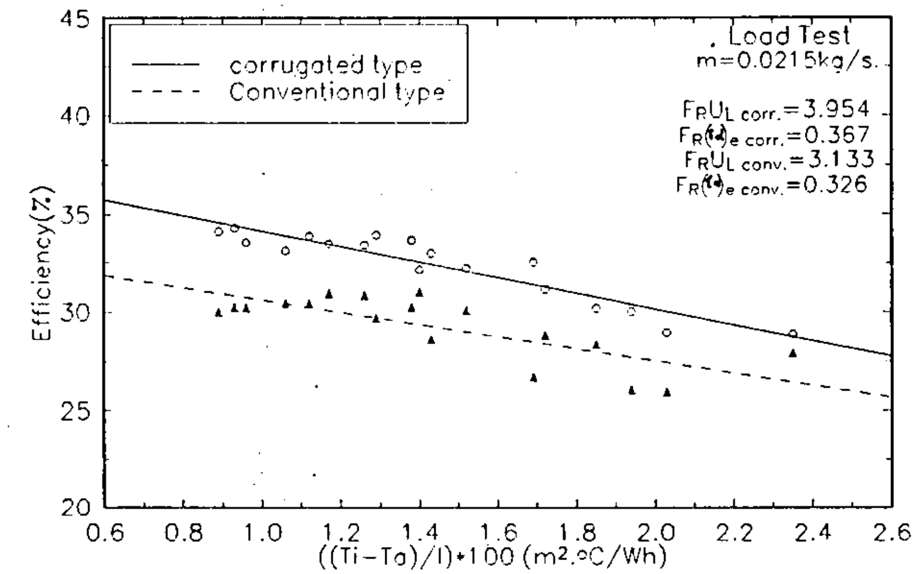

Figure(4.20) Useful heat gain vs. Incident solar radiation (I) for the corrugated and conventional solar collectores.ṁ=0.0166 kg/s.



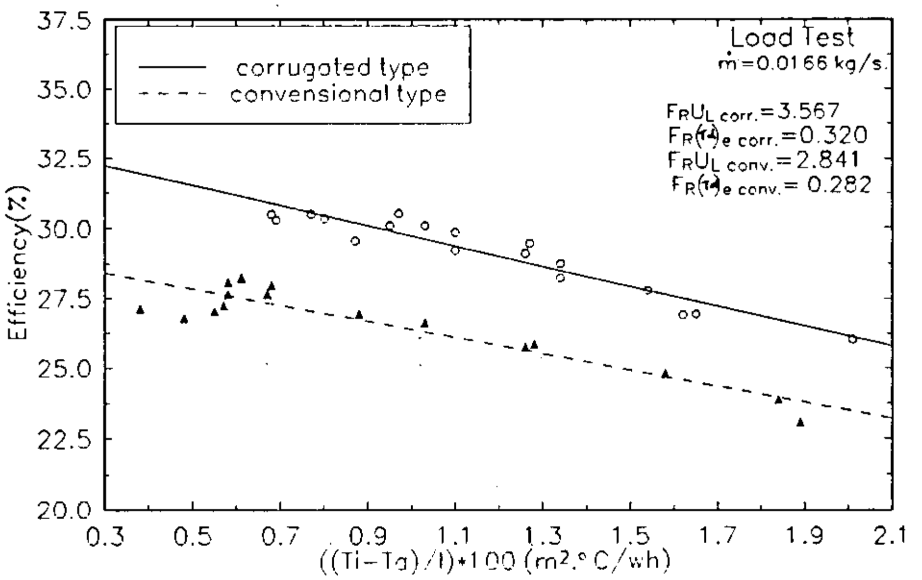

Figure(4.21) Useful heat gain (Qu) vs. Incident solar radiation (I) for the corrugated and conventional solar collectors. $\dot{m}$=0.0138 kg/s.



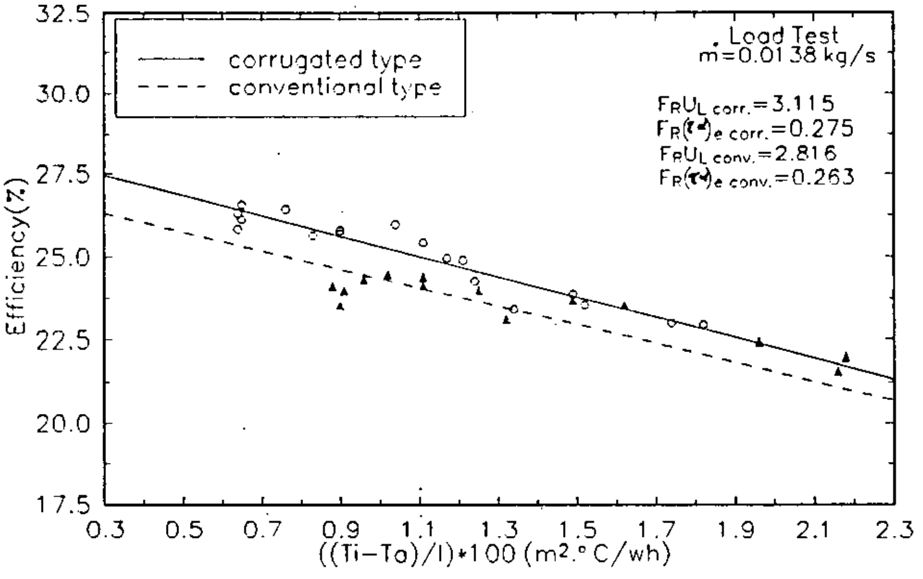

Figure(4.22) Useful heat gain (Qu) vs. incident solar radiation for the corrugated and conventional solar collectors. $\dot{m}$=0.0098 kg/s.



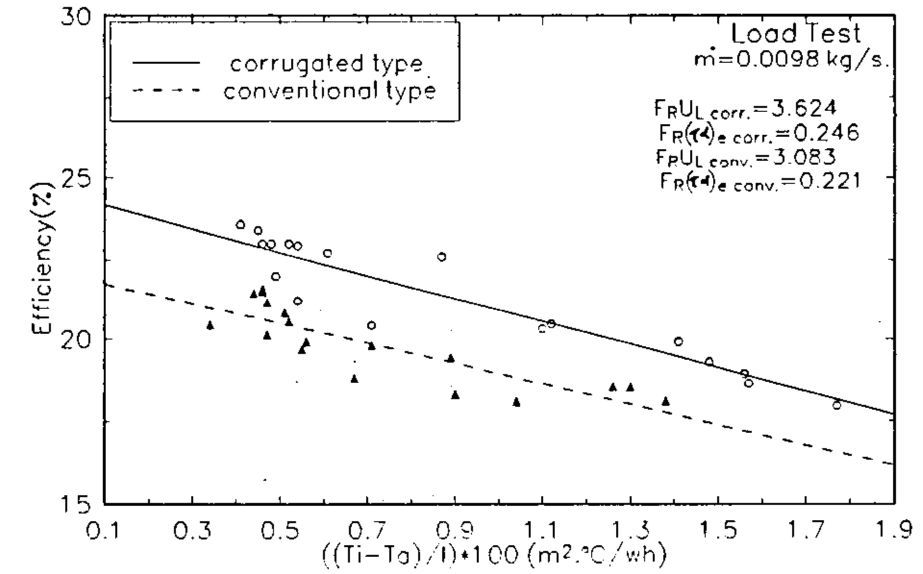

Figure(4.23) Variation of instantaneous efficiency against (Ti-Ta)/I for each collector.



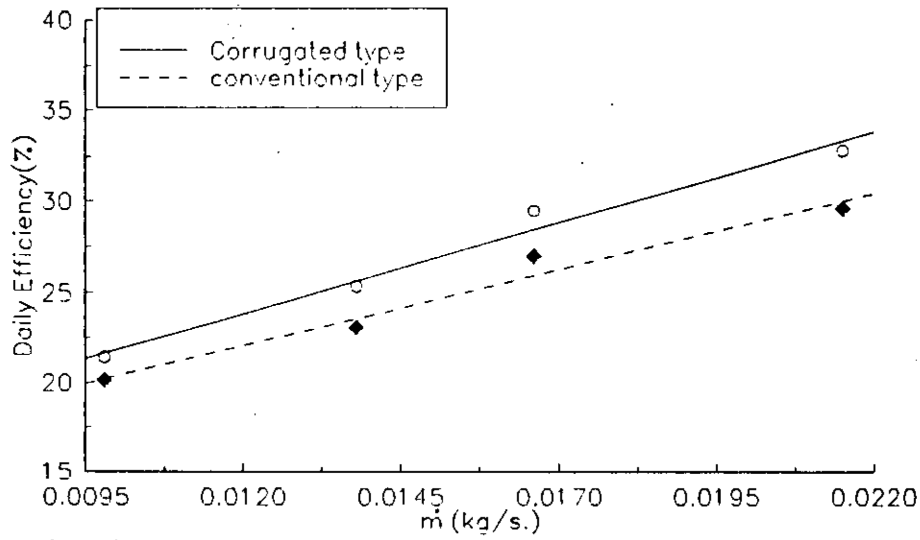

Figure(4.24) Variation of instantaneous efficiency gainst (Ti-Ta)/I for each collector.



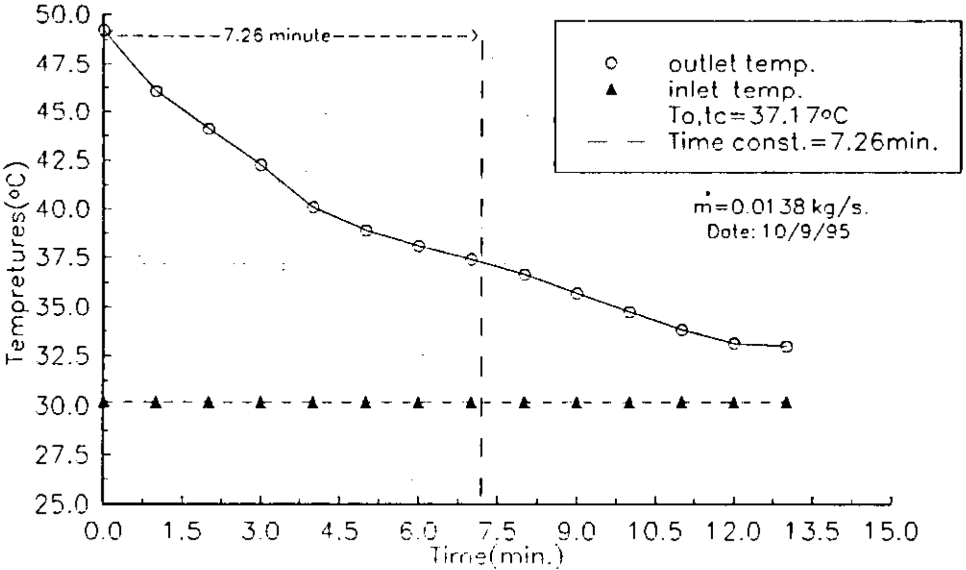

Figure(4.25) Variation of instantaneous efficiency against (Ti-To)/I for each collector.



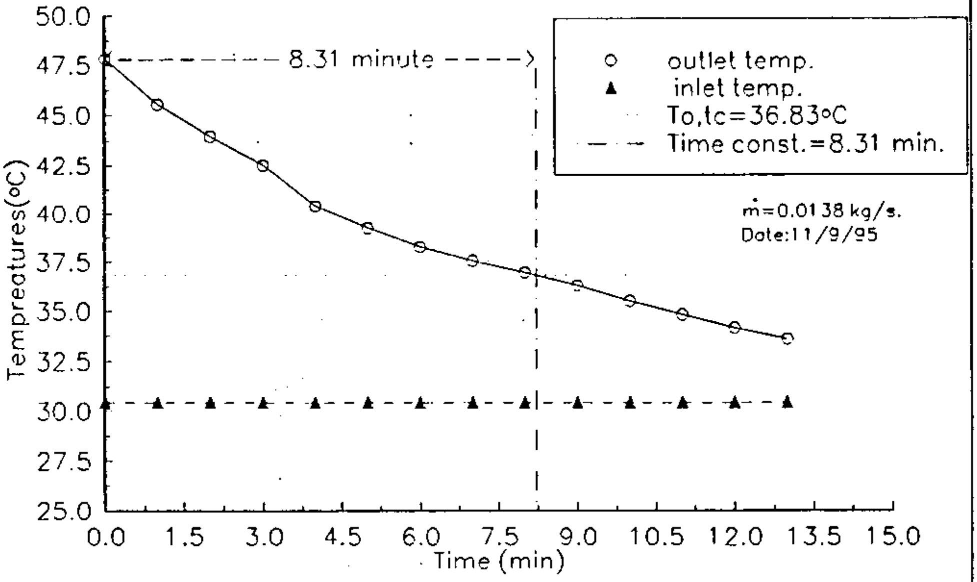

Figure(4.26) Variation of instantaneous efficiency against (Ti-To)/I for each collector.



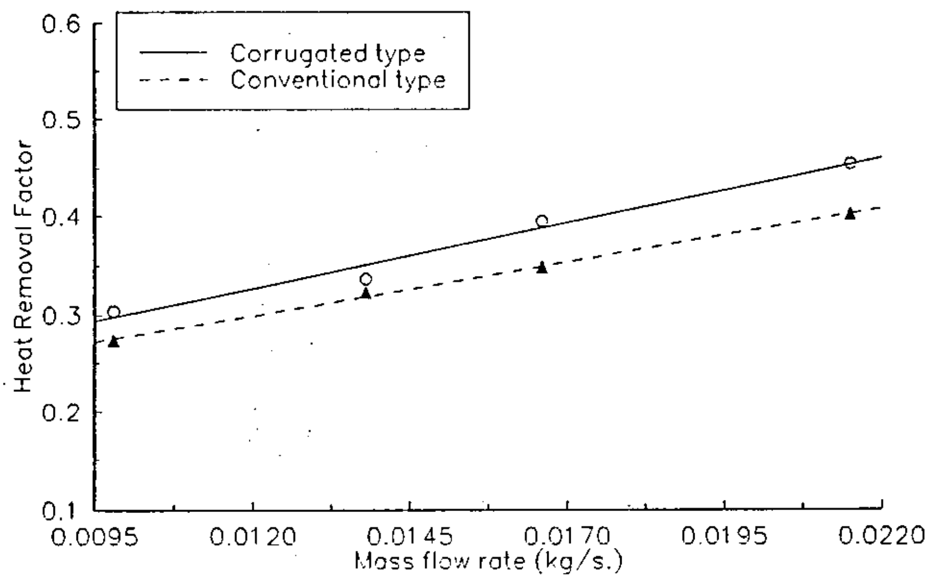

Figure(4.27) The daily efficiency .vs. mass flow rates for the corrugated and conventional solar collectors.



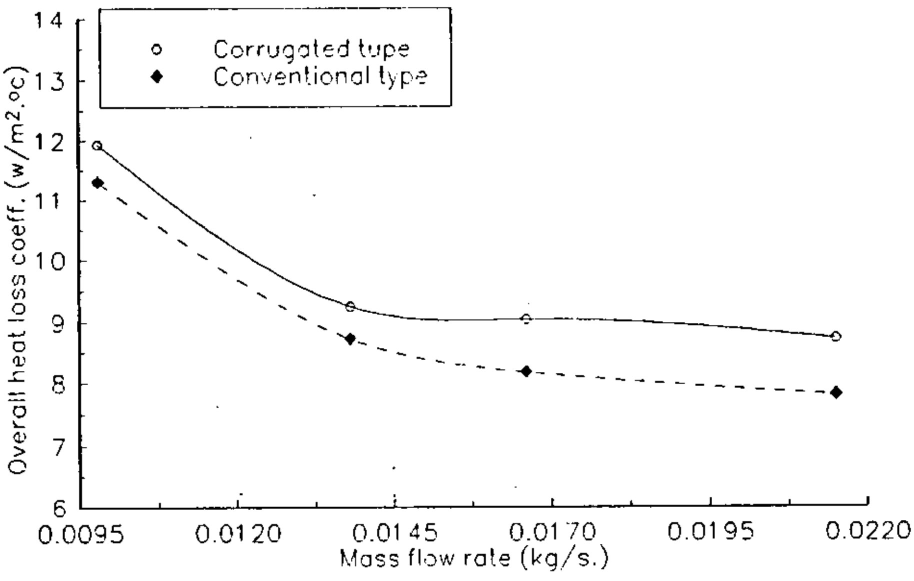

Figure(4.28) A time temperature plot for the collector showing temperature drop on sudden interruption of the solar radiation on the corrugated type



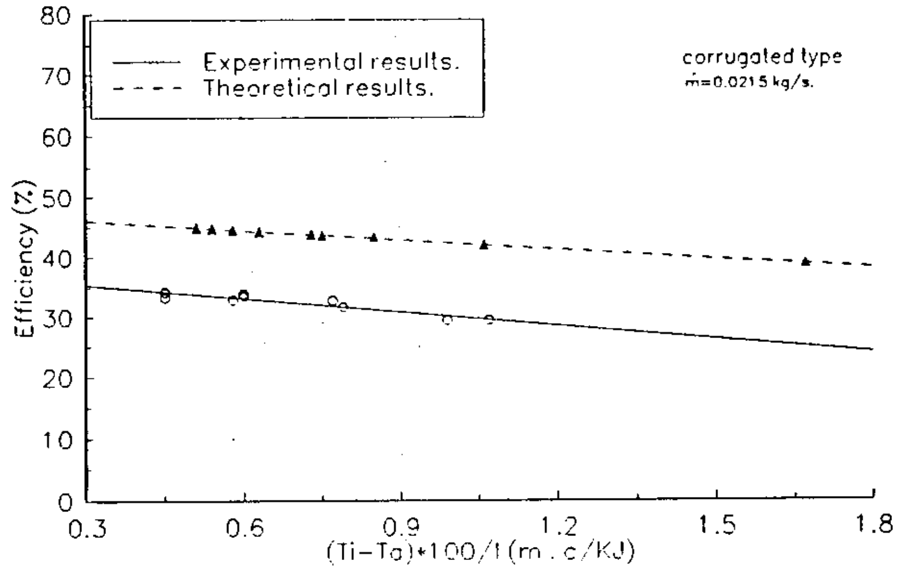

Figure(4.29) Atime temperature plot for the collector showing temperature drop on sudden interruption of the solar radiation on conventional type.



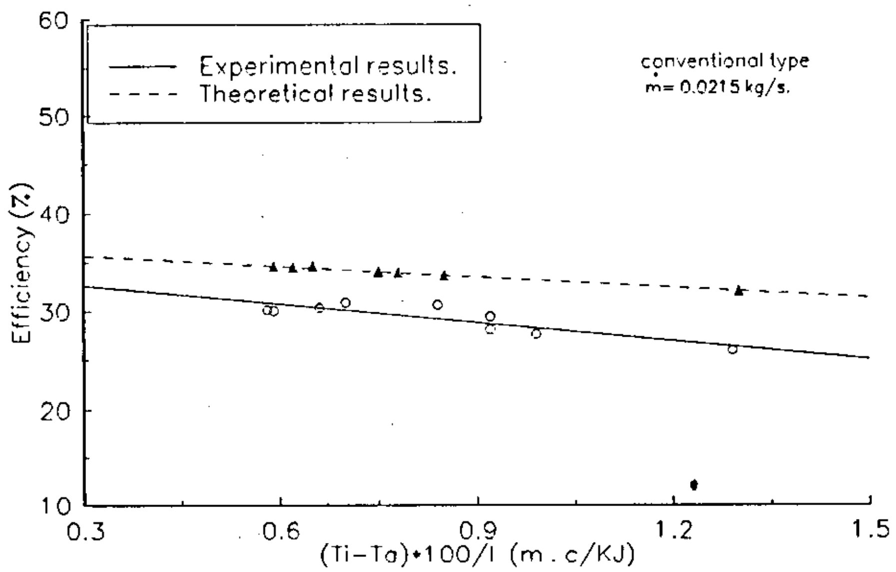

Figure(4.30)Heat removal factor .vs. mass flow rate for the corrugated and conventional solar collectors.



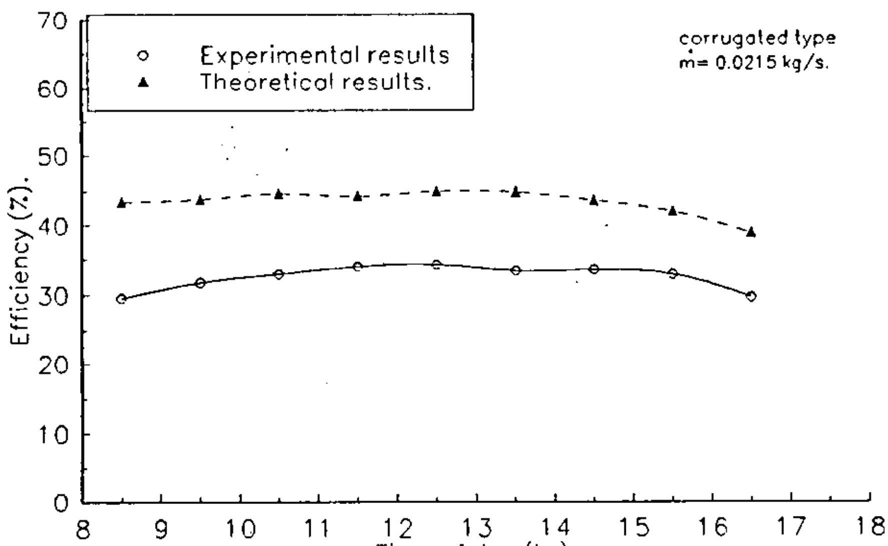

Figure(4.31)Overall heat loss coefficient .vs. mass flow rate for the corrugated and conventional solar collectors.



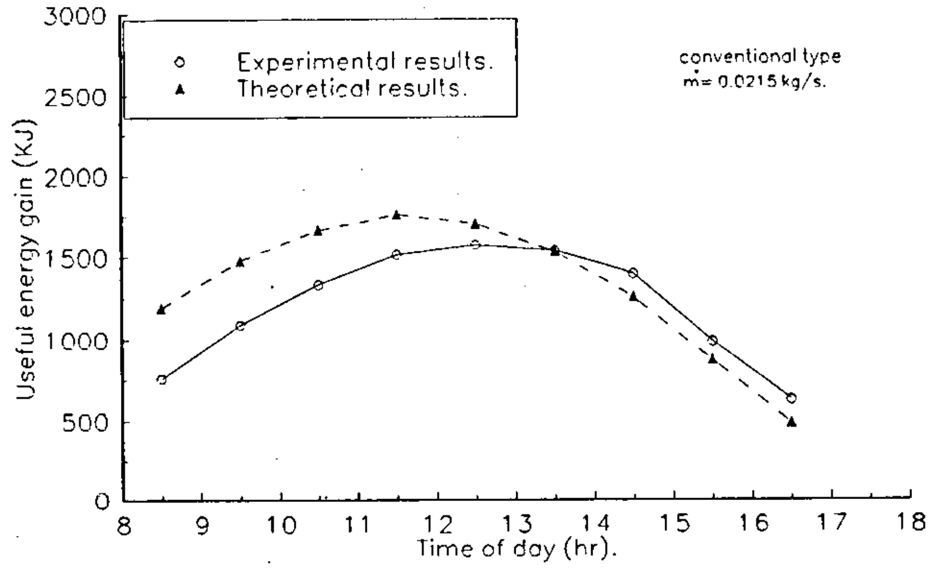

Figure(4.32) Efficiency vs. (Ti–Ta)/I. Theoritical and experimental results for the corrugated solar collector.



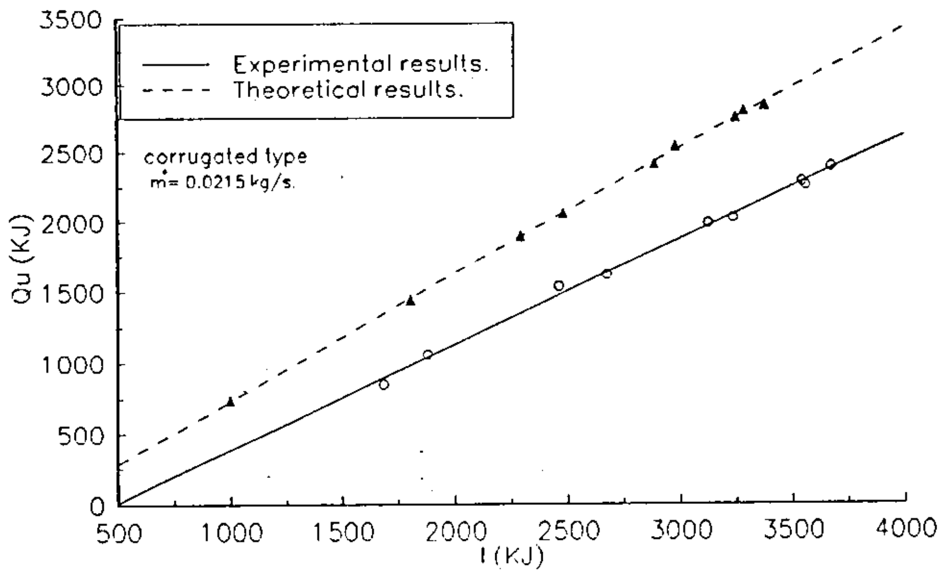

Figure(4.33) Variation of efficiency (exp. and theo.) vs. (Ti−Ta)/I for the conventional solar collector.



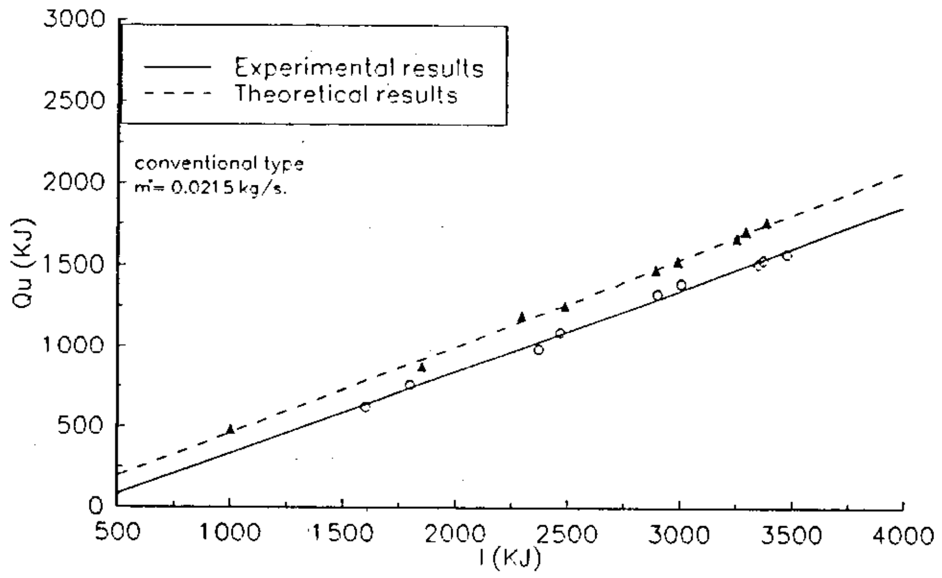

Figure(4.34) Variation of efficiency(exp. and theo.) against time of day for the corrugated type.



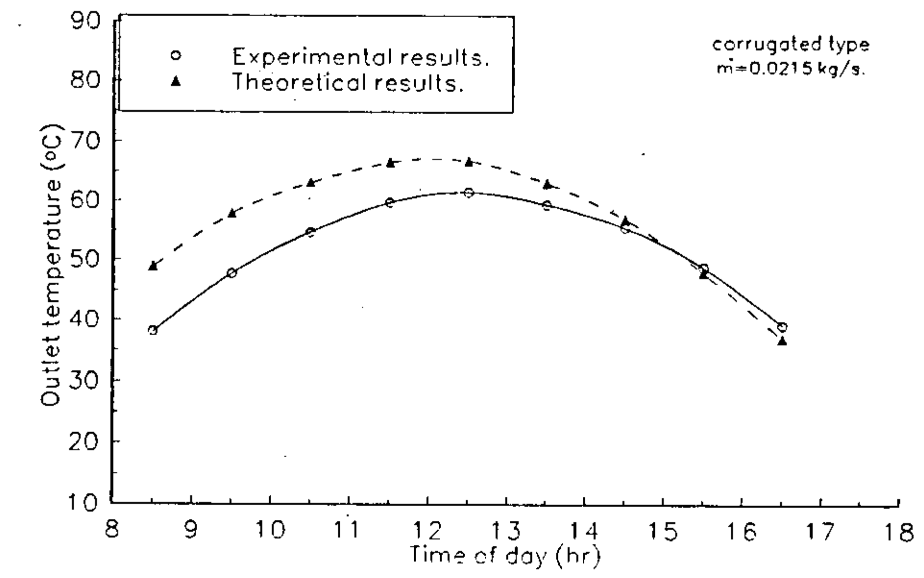

Figure(4.37) Variation of useful energy gain (exp. and theo.) with time of day for the conventional solar collector.



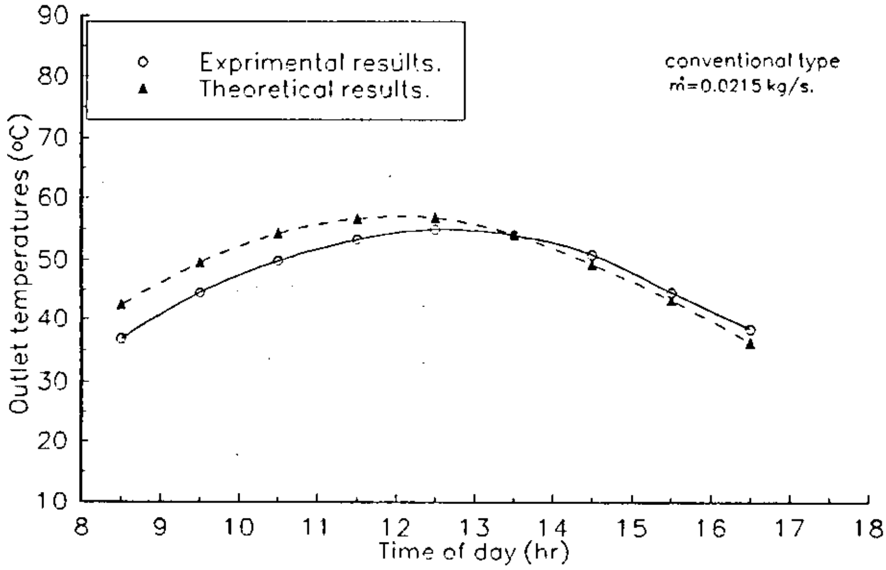

Figure(4.38) Useful heat gain vs. incident solar radiation(I) for the corrugated solar collector.(exp. and theo. results).




Figure(4.39) Useful heat gain vs. incident solar radiation (I) for the conventional type. (exp. and theo. results).




Figure(4.40) Variation of outlet temperature(exp. and theo.)against time of day for the corrugated type.




figure(4.41) Variation of outlet temperature (exp. and theo.) against time of day for the conventional type

# CHAPTER 5

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

In this study, two collectors were tested under nearly the same experimental conditions. From the results of this study, the following conclusions may be stated :

1. Under forced circulation test, the corrugated type has better performance when compared to the conventional type, especially during the time interval 9:30-15:30.

2. As the solar intensity is increased, the ability of the corrugated type in converting the solar irradiance into useful heat gain becomes more significant than that of the conventional type.

3. After the time interval 15:00-15:30, as the time passes then the performance of both collectors comes near to each other. By the end of the test day both collectors have, nearly, the same performance. This behavior becomes more and more evident under low flow rates.

4. As the flow rate is increased, then the performance of the corrugated type is better than that of the conventional type.

5. Results of the stagnation test show that the overall heat loss coefficients of the corrugated types is higher than that of the conventional by 0.91 $W/m^2.^{\circ}C$.

6. The influence of the shading effect of the corrugated type is higher than that on the conventional type. This effect is decreased as the flow is increased.

7. The time constant of the corrugated type is lower than that of the conventional type by about 12.5 % . The time constant of the corrugated and the conventional types are 7.26 and 8.31 minutes, respectively.

8. The daily efficiency of each collector under forced test with load conditions increases with the increase of the mass flow rate.

## 5.2 Recommendations

The following recommendation came out from the study :

The effect of using varies sizes of the collectors, different depth spacing, different tilt angles, and different types of absorber plate, on the performance of both collectors can be investigated and studied experimentally and theoretically.

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# APPENDIX A.
# MEASURED DATA

**TABLE A.1:** Measured data for air heater collector with corrugated galvanized iron sheets test under Jordanian climate conditions perfomed on 15/8/95. Mass flow rate =0.0215 Kg /sec. All temperatures in (°C).

| Time Of Day(hr) | $T_{i1}$ | $T_{s1}$ | $T_{i2}$ | $T_{m1}$ | $T_{s2}$ | $T_{m2}$ | $T_{o1}$ | $T_{s3}$ | $T_{o2}$ | $T_a$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 8.00 | 23.5 | 29.1 | 23.8 | 31.1 | 36.7 | 31.3 | 33.4 | 34.8 | 34.2 | 18.0 |
| 8.30 | 23.9 | 31.1 | 24.5 | 34.7 | 43.3 | 35.1 | 37.2 | 41.9 | 37.8 | 19.0 |
| 9.00 | 25.8 | 34.9 | 26.4 | 38.2 | 49.6 | 38.9 | 43.5 | 48.2 | 43.9 | 20.5 |
| 9.30 | 26.7 | 36.4 | 27.8 | 40.4 | 54.8 | 41.2 | 47.2 | 53.3 | 47.7 | 21.0 |
| 10.00 | 27.1 | 38.3 | 28.5 | 42.4 | 59.7 | 43.1 | 51.9 | 57.6 | 52.4 | 22.0 |
| 10.30 | 28.2 | 40.5 | 29.6 | 44.9 | 63.9 | 45.6 | 54.5 | 61.7 | 55.1 | 22.5 |
| 11.00 | 28.6 | 41.8 | 30.2 | 46.1 | 66.5 | 47.1 | 57.9 | 64.5 | 58.6 | 23.0 |
| 11.30 | 29.3 | 42.9 | 30.8 | 47.3 | 69.4 | 48.6 | 58.5 | 67.1 | 59.4 | 24.0 |
| 12.00 | 29.8 | 43.5 | 31.5 | 48.3 | 70.8 | 49.4 | 60.6 | 68.8 | 61.8 | 25.5 |
| 12.30 | 30.1 | 43.8 | 31.6 | 48.5 | 71.1 | 49.5 | 60.8 | 69.0 | 62.4 | 26.5 |
| 13.00 | 30.0 | 43.7 | 31.4 | 48.2 | 70.2 | 49.3 | 60.5 | 68.1 | 62.1 | 26.0 |
| 13.30 | 29.8 | 43.1 | 31.1 | 47.9 | 68.9 | 48.8 | 58.6 | 67.1 | 59.9 | 25.5 |
| 14.00 | 29.7 | 42.0 | 30.9 | 47.0 | 65.6 | 47.9 | 57.2 | 64.2 | 58.6 | 25.0 |
| 14.30 | 29.5 | 40.8 | 30.6 | 45.5 | 62.4 | 45.9 | 55.6 | 61.1 | 56.5 | 25.0 |
| 15.00 | 29.4 | 39.1 | 30.3 | 44.6 | 59.0 | 45.0 | 51.8 | 57.4 | 52.8 | 24.5 |
| 15.30 | 28.9 | 36.6 | 29.5 | 41.6 | 53.2 | 41.9 | 49.0 | 51.3 | 49.9 | 24.0 |
| 16.00 | 28.1 | 34.2 | 28.8 | 39.7 | 49.4 | 40.3 | 43.7 | 47.7 | 44.8 | 23.0 |
| 16.30 | 26.7 | 31.7 | 27.6 | 35.9 | 42.6 | 36.7 | 38.2 | 41.1 | 39.4 | 22.5 |
| 17.00 | 25.2 | 29.5 | 26.3 | 34.0 | 38.8 | 34.5 | 34.9 | 37.3 | 35.4 | 22.0 |

**TABLE A.2** : Mesured data for air heater collector with corrugated galvanized iron sheets test under Jordanian climate conditions on 15/8 /1995.
Mass flow rate= 0.0215 Kg/sec.

| Time (hr) | I (wh/$m^2$) | Vw(m/sec) |
|---|---|---|
| 08:00-08:30 | 231.3 | 1.2 |
| 08:30-09:00 | 291.3 | 1.4 |
| 9:00-9:300 | 345.5 | 1.1 |
| 9:30-10:000 | 397.6 | 1.3 |
| 10:00-10:30 | 436.4 | 1.6 |
| 10:30-11:00 | 463.0 | 1.4 |
| 11:00-11:30 | 484.3 | 1.2 |
| 11:30-12:00 | 500.4 | 1.1 |
| 12:00-12:30 | 508.9 | 1.0 |
| 12:30-13:00 | 511.9 | 0.9 |
| 13:00-13:30 | 504.3 | 0.8 |
| 13:30-14:00 | 484.9 | 1.3 |
| 14:00-14:30 | 455.6 | 1.6 |
| 14:30-15:00 | 412.8 | 1.5 |
| 15:00-15:30 | 368.4 | 1.8 |
| 15:30-16:00 | 315.2 | 1.8 |
| 16:00-16:30 | 260.7 | 1.9 |
| 16:30-17:00 | 207.0 | 2.1 |

**TABLE A.3** : Measured data for air heater with corrugated galvanized iron sheets test under Jordanian climate conditions performed on 16/8/95 . Mass flow rate =0.0166 kg/sec. All temperatures in (°C).

| Time(hr) | $T_{i1}$ | $T_{S1}$ | $T_{i2}$ | $T_{m1}$ | $T_{S2}$ | $T_{m2}$ | $T_{o1}$ | $T_{S3}$ | $T_{o2}$ | $T_a$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 8.00 | 19.8 | 28.0 | 20.1 | 28.0 | 39.8 | 28.7 | 31.9 | 38.8 | 32.9 | 16.0 |
| 8.30 | 20.5 | 29.1 | 21.2 | 30.3 | 42.5 | 30.9 | 36.0 | 39.7 | 36.4 | 16.5 |
| 9.00 | 21.4 | 31.3 | 22.0 | 32.9 | 49.0 | 33.4 | 42.9 | 46.4 | 44.0 | 17.0 |
| 9.30 | 22.6 | 34.8 | 23.8 | 36.8 | 56.2 | 38.1 | 46.8 | 52.9 | 47.7 | 18.5 |
| 10.00 | 25.0 | 38.2 | 25.7 | 40.6 | 62.4 | 42.1 | 52.9 | 59.0 | 54.1 | 20.0 |
| 10.30 | 26.6 | 40.1 | 27.1 | 43.1 | 66.2 | 44.8 | 55.8 | 63.6 | 57.0 | 21.0 |
| 11.00 | 27.5 | 41.9 | 28.3 | 45.3 | 70.1 | 47.2 | 59.3 | 67.1 | 60.6 | 22.5 |
| 11.30 | 28.0 | 43.0 | 28.9 | 47.0 | 73.4 | 47.9 | 61.6 | 69.8 | 62.8 | 23.0 |
| 12.00 | 28.3 | 43.3 | 29.7 | 47.8 | 75.3 | 48.7 | 63.7 | 71.8 | 64.6 | 24.5 |
| 12.30 | 28.8 | 43.8 | 29.2 | 48.1 | 75.4 | 49.2 | 64.6 | 71.9 | 65.4 | 25.5 |
| 13.00 | 28.9 | 43.7 | 29.6 | 48.1 | 75.1 | 49.4 | 64.3 | 71.7 | 65.2 | 26.0 |
| 13.30 | 28.7 | 43.3 | 29.7 | 47.9 | 74.3 | 49.3 | 62.8 | 71.1 | 64.7 | 25.5 |
| 14.00 | 28.6 | 43.1 | 29.5 | 46.8 | 73.1 | 48.2 | 61.2 | 69.0 | 62.4 | 25.0 |
| 14.30 | 28.3 | 42.8 | 29.3 | 44.9 | 67.9 | 46.4 | 57.4 | 64.4 | 58.8 | 25.0 |
| 15.00 | 27.9 | 40.7 | 29.1 | 43.3 | 62.6 | 44.4 | 55.1 | 59.9 | 56.2 | 24.5 |
| 15.30 | 27.2 | 38.2 | 28.8 | 40.9 | 56.3 | 41.8 | 49.0 | 54.8 | 49.9 | 24.0 |
| 16.00 | 26.6 | 35.5 | 27.9 | 38.4 | 50.9 | 39.3 | 45.1 | 49.2 | 45.6 | 23.0 |
| 16.30 | 26.0 | 33.1 | 27.2 | 35.2 | 45.5 | 36.4 | 39.3 | 43.4 | 39.9 | 22.5 |
| 17.00 | 25.1 | 30.4 | 25.9 | 32.6 | 39.6 | 32.9 | 36.0 | 37.7 | 36.8 | 21.5 |

**TABLE A.4 :** Mesured data for air heater collector with corrugated galvanized iron sheets test under Jordanian climate conditions on 15/8 1995.
Mass flow rate = 0.0166 Kg/sec.

| Time (hr) | I ($wh/m^2$) | Vw(m/sec) |
|---|---|---|
| 08:00-08:30 | 228.3 | 1.0 |
| 08:30-09:00 | 293.2 | 1.2 |
| 9:00-09:300 | 350.2 | 1.1 |
| 9:30-10:000 | 399.1 | 1.7 |
| 10:00-10:30 | 438.9 | 1.4 |
| 10:30-11:00 | 466.2 | 1.3 |
| 11:00-11:30 | 485.8 | 1.6 |
| 11:30-12:00 | 498.5 | 1.5 |
| 12:00-12:30 | 513.3 | 1.1 |
| 12:30-13:00 | 513.8 | 1.3 |
| 13:00-13:30 | 504.6 | 1.4 |
| 13:30-14:00 | 484.1 | 1.6 |
| 14:00-14:30 | 454.0 | 1.8 |
| 14:30-15:00 | 412.7 | 1.7 |
| 15:00-15:30 | 363.9 | 2.3 |
| 15:30-16:00 | 307.6 | 2.6 |
| 16:00-16:30 | 253.8 | 2.2 |
| 16:30-17:00 | 201.9 | 2.3 |

**TABLE A.5**: Measured data for air heater with plate sheets test under Jordanian climate conditions performed on 13/8/95. Mass flow rate =0.0215 Kg/sec. All temperatures in (°C).

| Time(hr) | $T_{i1}$ | $T_{S1}$ | $T_{i2}$ | $T_{m1}$ | $T_{S2}$ | $T_{m2}$ | $T_{o1}$ | $T_{S3}$ | $T_{o2}$ | $T_a$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 8.00 | 25.7 | 34.4 | 26.4 | 30.5 | 42.5 | 30.7 | 33.2 | 40.0 | 34.0 | 22.0 |
| 8.30 | 26.5 | 36.1 | 27.1 | 32.6 | 46.1 | 33.2 | 36.3 | 44.2 | 37.2 | 22.5 |
| 9.00 | 28.1 | 39.6 | 28.9 | 34.7 | 55.6 | 36.6 | 39.4 | 51.7 | 40.6 | 23.5 |
| 9.30 | 30.4 | 41.1 | 31.2 | 38.3 | 63.8 | 39.4 | 44.2 | 58.0 | 46.0 | 24.0 |
| 10.00 | 31.1 | 43.6 | 32.0 | 39.8 | 66.7 | 41.9 | 46.4 | 62.5 | 48.4 | 25.0 |
| 10.30 | 32.7 | 44.2 | 33.4 | 41.2 | 70.1 | 42.4 | 48.7 | 65.3 | 51.1 | 26.0 |
| 11.00 | 33.0 | 45.4 | 33.7 | 43.7 | 76.8 | 44.6 | 50.7 | 69.3 | 53.4 | 27.5 |
| 11.30 | 33.6 | 47.2 | 34.1 | 45.5 | 79.1 | 46.3 | 52.3 | 72.3 | 54.1 | 28.5 |
| 12.00 | 34.0 | 48.5 | 35.0 | 47.0 | 79.5 | 48.4 | 53.8 | 72.4 | 55.5 | 29.0 |
| 12.30 | 34.2 | 50.1 | 35.3 | 47.3 | 79.9 | 48.6 | 54.1 | 72.6 | 56.0 | 29.5 |
| 13.00 | 34.3 | 49.3 | 35.5 | 47.2 | 79.7 | 48.3 | 54.0 | 72.3 | 55.6 | 28.5 |
| 13.30 | 33.8 | 48.7 | 34.8 | 46.1 | 78.2 | 47.0 | 53.6 | 70.9 | 54.7 | 28.0 |
| 14.00 | 33.2 | 46.4 | 34.1 | 44.4 | 76.3 | 45.1 | 52.2 | 69.3 | 53.4 | 28.0 |
| 14.30 | 32.4 | 43.5 | 33.4 | 40.3 | 73.1 | 41.4 | 50.4 | 66.6 | 51.6 | 27.5 |
| 15.00 | 31.8 | 41.5 | 33.0 | 39.6 | 68.8 | 39.9 | 48.1 | 63.1 | 49.0 | 26.5 |
| 15.30 | 31.6 | 40.3 | 32.3 | 37.3 | 64.0 | 38.2 | 43.2 | 59.7 | 44.7 | 25.0 |
| 16.00 | 30.8 | 39.4 | 31.7 | 35.5 | 58.2 | 36.5 | 40.4 | 49.8 | 42.9 | 25.0 |
| 16.30 | 30.4 | 37.7 | 31.2 | 34.8 | 49.0 | 35.4 | 37.6 | 46.0 | 38.9 | 24.5 |
| 17.00 | 27.7 | 36.9 | 28.9 | 33.6 | 43.1 | 34.3 | 34.7 | 42.9 | 35.3 | 24.5 |

**TABLE A.6**: Measured data for air heater collector with plate sheet test under Jordanian climate conditions on 13/8 1995. Mass flow rate = 0.0215 Kg/sec.

| Time (hr) | I ($wh/m^2$) | Vw(m/sec) |
|---|---|---|
| 08:00-08:30 | 226.2 | 1.0 |
| 08:30-09:00 | 273.2 | 0.9 |
| 9:00-09:300 | 322.9 | 0.8 |
| 9:30-10:000 | 362.7 | 0.8 |
| 10:00-10:30 | 381.9 | 1.1 |
| 10:30-11:00 | 424.2 | 0.9 |
| 11:00-11:30 | 462.6 | 0.6 |
| 11:30-12:00 | 468.5 | 0.8 |
| 12:00-12:30 | 482.6 | 0.9 |
| 12:30-13:00 | 483.6 | 0.9 |
| 13:00-13:30 | 474.6 | 0.7 |
| 13:30-14:00 | 462.2 | 0.9 |
| 14:00-14:30 | 434.6 | 1.2 |
| 14:30-15:00 | 400.9 | 1.1 |
| 15:00-15:30 | 355.6 | 1.0 |
| 15:30-16:00 | 303.5 | 1.3 |
| 16:00-16:30 | 247.3 | 1.1 |
| 16:30-17:00 | 197.0 | 1.1 |

**TABLE A.7**: Meaasured data for air heter collector with plate sheets test under Jordanian climate conditions perfomed on 14/8/95 . Mass flow rate = 0.0166 kg/sec. All temperatures in (°C).

| Time(hr) | $T_{i1}$ | $T_{S1}$ | $T_{i2}$ | $T_{m1}$ | $T_{S2}$ | $T_{m2}$ | $T_{o1}$ | $T_{S3}$ | $T_{o2}$ | $T_a$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 8.00 | 24.5 | 30.8 | 25.2 | 29.3 | 39.8 | 30.2 | 32.8 | 38.8 | 33.4 | 21.5 |
| 8.30 | 25.0 | 32.3 | 25.8 | 30.4 | 44.5 | 31.1 | 37.1 | 42.1 | 37.9 | 22.5 |
| 9.00 | 26.4 | 34.4 | 27.1 | 33.2 | 52.2 | 34.1 | 42.4 | 48.2 | 43.6 | 24.5 |
| 9.30 | 28.2 | 35.9 | 28.9 | 36.6 | 58.3 | 37.4 | 46.9 | 52.7 | 48.0 | 26.0 |
| 10.00 | 29.3 | 37.1 | 30.1 | 39.9 | 63.2 | 40.8 | 49.3 | 57.0 | 50.9 | 27.0 |
| 10.30 | 29.8 | 38.8 | 30.4 | 42.7 | 67.8 | 43.5 | 52.7 | 61.2 | 54.1 | 27.5 |
| 11.00 | 30.6 | 41.7 | 31.3 | 44.0 | 69.9 | 44.9 | 53.6 | 64.1 | 55.1 | 28.0 |
| 11.30 | 31.2 | 42.2 | 31.8 | 45.2 | 74.5 | 46.1 | 54.8 | 66.7 | 56.9 | 28.5 |
| 12.00 | 31.3 | 44.4 | 32.1 | 46.4 | 75.8 | 47.3 | 55.4 | 68.3 | 57.3 | 29.0 |
| 12.30 | 31.6 | 44.5 | 32.2 | 46.5 | 76.3 | 47.4 | 55.5 | 68.7 | 57.3 | 29.0 |
| 13.00 | 31.2 | 44.2 | 31.8 | 46.2 | 76.2 | 47.1 | 55.3 | 68.2 | 57.1 | 29.5 |
| 13.30 | 30.2 | 43.4 | 31.4 | 45.2 | 75.0 | 46.3 | 54.5 | 67.6 | 55.9 | 29.0 |
| 14.00 | 30.1 | 41.2 | 31.2 | 44.6 | 73.5 | 45.4 | 52.2 | 65.7 | 54.1 | 27.0 |
| 14.30 | 29.6 | 39.8 | 30.9 | 43.2 | 70.7 | 44.2 | 50.8 | 63.4 | 52.0 | 26.0 |
| 15.00 | 28.8 | 38.4 | 30.4 | 40.3 | 66.1 | 41.5 | 46.4 | 59.4 | 47.8 | 25.5 |
| 15.30 | 28.4 | 38.1 | 30.1 | 37.8 | 61.2 | 39.0 | 43.6 | 55.0 | 44.9 | 24.5 |
| 16.00 | 28.0 | 37.6 | 29.2 | 35.9 | 54.1 | 36.4 | 39.3 | 50.1 | 40.9 | 24.0 |
| 16.30 | 27.2 | 37.3 | 28.4 | 33.3 | 49.2 | 34.1 | 35.0 | 46.5 | 36.8 | 24.0 |
| 17.00 | 26.3 | 35.9 | 27.4 | 32.4 | 45.3 | 33.0 | 34.6 | 42.8 | 36.4 | 23.0 |

**TABLE A.8** : Measured data for air heater collector with plate sheet test under Jordanian climate conditions on 14/8/ 1995. Mass flow rate = 0.0166 Kg/sec.

| Time (hr) | I ($wh/m^2$) | Vw(m/sec) |
|---|---|---|
| 08:00-08:30 | 224.7 | 1.3 |
| 08:30-09:00 | 293.4 | 1.1 |
| 9:00-09:300 | 350.2 | 1.2 |
| 9:30-10:000 | 396.0 | 0.9 |
| 10:00-10:30 | 436.3 | 1.1 |
| 10:30-11:00 | 460.4 | 0.7 |
| 11:00-11:30 | 477.9 | 0.8 |
| 11:30-12:00 | 493.8 | 0.8 |
| 12:00-12:30 | 507.2 | 0.9 |
| 12:30-13:00 | 511.7 | 0.8 |
| 13:00-13:30 | 504.4 | 1.0 |
| 13:30-14:00 | 484.6 | 1.4 |
| 14:00-14:30 | 451.3 | 1.6 |
| 14:30-15:00 | 404.4 | 1.3 |
| 15:00-15:30 | 351.8 | 1.8 |
| 15:30-16:00 | 297.0 | 1.7 |
| 16:00-16:30 | 228.8 | 2.1 |
| 16:30-17:00 | 202.3 | 2.2 |

**TABLE A.9:** Measured data for air heater collector with corrugated galvanized iron sheet under Jordanian climate conditions performed on 10/9/95.Mass flow rate = 0.0138 Kg/sec. All temperatures in (°C).

| Time(hr) | $T_{i1}$ | $T_{S1}$ | $T_{i2}$ | $T_{m1}$ | $T_{S2}$ | $T_{m2}$ | $T_{o1}$ | $T_{S3}$ | $T_{o2}$ | $T_a$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 8.00 | 24.1 | 33.8 | 24.6 | 30.3 | 46.1 | 30.2 | 38.1 | 45.0 | 38.4 | 20.0 |
| 8.30 | 25.4 | 35.4 | 26.2 | 34.8 | 50.9 | 35.1 | 43.7 | 51.3 | 43.9 | 21.5 |
| 9.00 | 26.7 | 38.3 | 27.3 | 38.3 | 53.4 | 57.8 | 48.4 | 57.1 | 49.8 | 23.0 |
| 9.30 | 28.7 | 40.0 | 29.2 | 42.8 | 60.8 | 42.7 | 54.3 | 62.0 | 55.8 | 24.0 |
| 10.00 | 30.1 | 43.3 | 30.6 | 46.2 | 66.6 | 46.3 | 59.0 | 68.0 | 60.2 | 25.5 |
| 10.30 | 31.2 | 46.1 | 31.4 | 49.5 | 71.6 | 49.3 | 61.9 | 73.8 | 63.1 | 26.5 |
| 11.00 | 31.9 | 47.9 | 32.6 | 52.0 | 75.4 | 51.9 | 66.5 | 74.7 | 66.7 | 27.5 |
| 11.30 | 32.1 | 48.2 | 33.0 | 50.2 | 76.1 | 52.5 | 67.1 | 76.2 | 67.3 | 28.5 |
| 12.00 | 32.7 | 48.3 | 33.3 | 50.4 | 76.8 | 52.9 | 70.1 | 76.7 | 70.3 | 29.5 |
| 12.30 | 32.9 | 48.5 | 33.4 | 50.7 | 77.1 | 53.0 | 70.3 | 77.2 | 70.9 | 30.0 |
| 13.00 | 33.0 | 48.6 | 33.8 | 50.6 | 76.5 | 52.5 | 69.7 | 76.8 | 70.2 | 30.0 |
| 13.30 | 33.1 | 47.1 | 33.9 | 50.0 | 74.2 | 52.1 | 67.6 | 75.2 | 67.9 | 30.5 |
| 14.00 | 33.2 | 47.2 | 33.9 | 50.1 | 72.6 | 51.4 | 66.6 | 74.3 | 67.0 | 30.5 |
| 14.30 | 33.4 | 46.8 | 33.6 | 49.8 | 72.1 | 50.9 | 62.5 | 70.3 | 63.9 | 30.0 |
| 15.00 | 32.5 | 45.6 | 33.3 | 48.6 | 67.7 | 49.8 | 58.9 | 65.9 | 59.6 | 29.0 |
| 15.30 | 32.2 | 43.4 | 33.1 | 45.4 | 61.8 | 47.0 | 52.9 | 60.2 | 54.1 | 28.5 |
| 16.00 | 31.1 | 41.7 | 31.8 | 41.7 | 57.9 | 43.4 | 47.6 | 56.0 | 49.1 | 27.0 |
| 16.30 | 29.4 | 39.5 | 30.0 | 35.8 | 53.0 | 37.0 | 40.8 | 52.7 | 42.6 | 26.5 |
| 17.00 | 28.1 | 35.4 | 28.9 | 33.4 | 48.4 | 34.1 | 37.3 | 48.2 | 38.5 | 25.5 |

**TABLE A.10** : Measured data for air heater collector with corrugated galvanized iron sheets test under Jordanian climate conditions on 10/9/ 1995.
Mass flow rate = 0.0138 Kg/sec.

| Time (hr) | I ($wh/m^2$) | Vw(m/sec) |
|---|---|---|
| 08:00-08:30 | 249.7 | 0.4 |
| 08:30-09:00 | 309.3 | 0.3 |
| 9:00-09:300 | 362.9 | 0.4 |
| 9:30-10:000 | 406.4 | 0.6 |
| 10:00-10:30 | 434.3 | 0.4 |
| 10:30-11:00 | 461.4 | 0.3 |
| 11:00-11:30 | 489.1 | 0.2 |
| 11:30-12:00 | 497.2 | 0.2 |
| 12:00-12:30 | 513.7 | 0.5 |
| 12:30-13:00 | 513.1 | 0.4 |
| 13:00-13:30 | 495.1 | 0.7 |
| 13:30-14:00 | 476.9 | 0.5 |
| 14:00-14:30 | 443.1 | 0.6 |
| 14:30-15:00 | 396.9 | 0.4 |
| 15:00-15:30 | 345.6 | 0.5 |
| 15:30-16:00 | 289.0 | 0.8 |
| 16:00-16:30 | 232.6 | 0.7 |
| 16:30-17:00 | 170.6 | 0.9 |

**TABLE A.11:** Measured data for air heater collector with plate sheet under Jordanian climate conditions performed on 11/9/95.Mass flow rate = 0.0138 Kg/sec. All temperatures in (°C).

| Time(hr) | $T_{i1}$ | $T_{S1}$ | $T_{i2}$ | $T_{m1}$ | $T_{S2}$ | $T_{m2}$ | $T_{o1}$ | $T_{S3}$ | $T_{o2}$ | $T_a$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 8.00 | 24.7 | 31.6 | 25.6 | 27.8 | 34.3 | 28.2 | 32.6 | 33.8 | 34.2 | 22.0 |
| 8.30 | 26.4 | 35.2 | 27.9 | 31.4 | 39.2 | 32.4 | 34.9 | 37.7 | 36.4 | 23.5 |
| 9.00 | 29.5 | 37.4 | 30.6 | 41.7 | 50.0 | 43.1 | 45.2 | 57.1 | 46.8 | 25.0 |
| 9.30 | 29.8 | 38.9 | 30.5 | 42.9 | 56.4 | 44.4 | 47.4 | 58.2 | 49.0 | 27.0 |
| 10.00 | 30.5 | 4.0 | 31.8 | 46.8 | 58.8 | 48.0 | 49.9 | 60.2 | 52.8 | 27.5 |
| 10.30 | 31.5 | 45.3 | 32.1 | 49.6 | 66.4 | 52.0 | 52.3 | 65.6 | 55.7 | 28.0 |
| 11.00 | 32.8 | 47.4 | 33.0 | 52.2 | 68.9 | 54.3 | 54.5 | 67.7 | 58.2 | 29.0 |
| 11.30 | 34.1 | 49.3 | 34.0 | 54.6 | 71.0 | 57.6 | 58.2 | 70.3 | 61.4 | 29.5 |
| 12.00 | 35.84 | 50.5 | 35.1 | 56.8 | 73.8 | 59.1 | 58.1 | 72.4 | 62.9 | 30.0 |
| 12.30 | 35.7 | 51.0 | 35.5 | 57.3 | 70.2 | 60.2 | 58.0 | 71.2 | 64.1 | 30.0 |
| 13.00 | 35.9 | 51.4 | 35.9 | 58.1 | 69.4 | 60.5 | 59.5 | 69.3 | 64.8 | 30.5 |
| 13.30 | 36.2 | 51.6 | 36.4 | 57.0 | 69.5 | 58.8 | 57.6 | 69.1 | 62.3 | 29.5 |
| 14.00 | 36.5 | 52.2 | 36.2 | 55.4 | 69.5 | 57.5 | 56.4 | 69.0 | 61.0 | 29.5 |
| 14.30 | 36.7 | 52.1 | 36.4 | 53.3 | 65.8 | 55.0 | 54.2 | 65.6 | 57.2 | 29.0 |
| 15.00 | 36.8 | 52.4 | 36.1 | 50.3 | 63.6 | 52.4 | 50.3 | 62.9 | 54.9 | 28.0 |
| 15.30 | 35.6 | 52.4 | 35.2 | 46.6 | 58.4 | 48.0 | 46.3 | 58.3 | 49.6 | 28.0 |
| 16.00 | 34.0 | 51.1 | 33.8 | 41.9 | 55.5 | 43.2 | 43.1 | 55.8 | 44.4 | 27.0 |
| 16.30 | 31.8 | 50.2 | 31.6 | 38.8 | 51.6 | 40.1 | 38.0 | 50.2 | 39.2 | 25.5 |
| 17.00 | 29.7 | 44.4 | 29.3 | 35.4 | 46.4 | 37.4 | 34.7 | 48.4 | 35.6 | 25.0 |

**TABLE A.12** : Mesured data for air heater collector with plate sheet test under Jordanian climate conditions on 11/9/1995. Mass flow rate = 0.0138 Kg/sec.

| Time (hr) | I (wh/m$^2$) | Vw(m/sec) |
|---|---|---|
| 08:00-08:30 | 180.1 | 0.6 |
| 08:30-09:00 | 221.8 | 0.8 |
| 9:00-09:300 | 311.0 | 0.7 |
| 9:30-10:000 | 376.6 | 0.5 |
| 10:00-10:30 | 409.4 | 0.6 |
| 10:30-11:00 | 438.4 | 0.4 |
| 11:00-11:30 | 464.4 | 0.5 |
| 11:30-12:00 | 482.7 | 0.7 |
| 12:00-12:30 | 490.7 | 0.6 |
| 12:30-13:00 | 495.2 | 0.4 |
| 13:00-13:30 | 482.9 | 0.3 |
| 13:30-14:00 | 451.5 | 0.5 |
| 14:00-14:30 | 408.6 | 0.6 |
| 14:30-15:00 | 367.0 | 0.9 |
| 15:00-15:30 | 315.0 | 0.7 |
| 15:30-16:00 | 264.9 | 0.8 |
| 16:00-16:30 | 214.2 | 0.6 |
| 16:30-17:00 | 159.9 | 0.9 |

**TABLE A.13:** Measured data for air heater collector with corrugated galvanized iron sheet under Jordanian climate conditions performed on 12/9/95.Mass flow rate = 0.0098 Kg/sec. All temperatures in (°C).

| Time(hr) | $T_{i1}$ | $T_{S1}$ | $T_{i2}$ | $T_{m1}$ | $T_{S2}$ | $T_{m2}$ | $T_{o1}$ | $T_{S3}$ | $T_{o2}$ | $T_a$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 8.00 | 23.2 | 35.1 | 23.9 | 32.2 | 47.4 | 31.9 | 35.4 | 41.6 | 36.2 | 20.5 |
| 8.30 | 25.1 | 37.5 | 25.7 | 35.1 | 51.3 | 35.5 | 39.3 | 48.4 | 39.5 | 21.5 |
| 9.00 | 26.7 | 40.4 | 27.0 | 39.4 | 54.2 | 39.6 | 43.5 | 55.5 | 43.7 | 22.5 |
| 9.30 | 28.4 | 42.9 | 28.8 | 43.5 | 59.6 | 43.2 | 46.9 | 57.9 | 47.6 | 23.5 |
| 10.00 | 29.8 | 45.0 | 30.3 | 46.6 | 65.4 | 46.8 | 50.3 | 61.8 | 51.0 | 25.0 |
| 10.30 | 30.1 | 48.1 | 30.8 | 49.3 | 70.8 | 49.4 | 52.8 | 64.9 | 53.2 | 27.0 |
| 11.00 | 30.0 | 50.3 | 30.9 | 52.7 | 74.5 | 52.9 | 54.2 | 68.2 | 54.6 | 28.0 |
| 11.30 | 31.2 | 50.5 | 31.4 | 54.2 | 76.2 | 53.8 | 57.4 | 69.1 | 58.0 | 29.0 |
| 12.00 | 31.6 | 51.6 | 31.7 | 54.4 | 76.9 | 54.1 | 58.5 | 70.3 | 59.5 | 29.5 |
| 12.30 | 32.3 | 51.9 | 32.2 | 54.3 | 77.8 | 54.3 | 59.6 | 72.2 | 60.7 | 30.0 |
| 13.00 | 32.5 | 51.8 | 32.4 | 53.7 | 77.9 | 54.4 | 60.4 | 72.5 | 61.1 | 30.5 |
| 13.30 | 32.8 | 52.0 | 32.7 | 53.8 | 78.0 | 53.9 | 60.5 | 72.4 | 61.0 | 30.0 |
| 14.00 | 32.8 | 52.1 | 32.3 | 51.6 | 75.4 | 52.2 | 57.8 | 70.7 | 58.7 | 30.0 |
| 14.30 | 32.1 | 50.7 | 31.6 | 50.5 | 70.7 | 50.7 | 55.7 | 65.6 | 56.0 | 30.0 |
| 15.00 | 30.6 | 48.3 | 30.3 | 47.5 | 66.1 | 47.8 | 53.4 | 60.2 | 53.8 | 29.5 |
| 15.30 | 30.2 | 46.2 | 30.1 | 44.8 | 60.5 | 44.9 | 50.0 | 54.3 | 50.3 | 28.0 |
| 16.00 | 29.6 | 42.2 | 29.3 | 41.0 | 56.4 | 41.3 | 45.5 | 50.8 | 45.7 | 27.0 |
| 16.30 | 28.8 | 39.3 | 28.6 | 37.0 | 54.2 | 37.1 | 40.6 | 48.9 | 40.9 | 26.5 |
| 17.00 | 28.1 | 36.4 | 27.7 | 33.0 | 49.1 | 33.4 | 35.5 | 46.1 | 35.9 | 26.0 |

**TABLE A.14** : Mesured data for air heater collector with corrugated galvanized iron sheets test under Jordanian climate conditions on 12/9 /1995.
Mass flow rate = 0.0098 Kg/sec.

| Time (hr) | I (wh/m$^2$) | Vw(m/sec) |
|---|---|---|
| 08:00-08:30 | 196.9 | 0.6 |
| 08:30-09:00 | 262.7 | 0.7 |
| 9:00-09:300 | 319.1 | 0.7 |
| 9:30-10:000 | 360.1 | 1.0 |
| 10:00-10:30 | 381.4 | 0.8 |
| 10:30-11:00 | 416.1 | 0.8 |
| 11:00-11:30 | 442.6 | 0.9 |
| 11:30-12:00 | 452.4 | 0.8 |
| 12:00-12:30 | 456.0 | 0.7 |
| 12:30-13:00 | 458.2 | 0.8 |
| 13:00-13:30 | 454.5 | 0.8 |
| 13:30-14:00 | 432.5 | 0.9 |
| 14:00-14:30 | 405.7 | 1.0 |
| 14:30-15:00 | 366.8 | 1.0 |
| 15:00-15:30 | 320.3 | 1.4 |
| 15:30-16:00 | 265.0 | 1.3 |
| 16:00-16:30 | 212.1 | 1.1 |
| 16:30-17:00 | 163.5 | 1.3 |

**TABLE A.15:** Measured data for air heater collector with plate sheet under Jordanian climate conditions performed on 13/9/95. Mass flow rate = 0.0098 Kg/sec. All temperatures in (°C).

| Time(hr) | $T_{i1}$ | $T_{S1}$ | $T_{i2}$ | $T_{m1}$ | $T_{S2}$ | $T_{m2}$ | $T_{o1}$ | $T_{S3}$ | $T_{o2}$ | $T_a$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 8.00 | 22.4 | 31.3 | 24.0 | 29.2 | 37.4 | 30.3 | 31.8 | 36.8 | 32.1 | 20.5 |
| 8.30 | 23.6 | 33.5 | 24.2 | 31.5 | 43.9 | 32.0 | 36.2 | 43.7 | 35.7 | 21.5 |
| 9.00 | 25.4 | 37.5 | 26.1 | 35.4 | 49.6 | 36.1 | 41.3 | 48.5 | 41.7 | 23.0 |
| 9.30 | 26.5 | 39.4 | 27.2 | 37.7 | 53.5 | 38.4 | 45.6 | 55.4 | 46.2 | 24.0 |
| 10.00 | 27.3 | 40.7 | 27.8 | 39.3 | 60.8 | 39.7 | 49.9 | 59.9 | 50.3 | 25.5 |
| 10.30 | 28.0 | 43.3 | 28.4 | 41.4 | 64.9 | 41.9 | 51.8 | 62.1 | 52.2 | 26.0 |
| 11.00 | 28.8 | 46.6 | 29.2 | 43.6 | 69.7 | 43.8 | 54.7 | 64.7 | 55.0 | 27.0 |
| 11.30 | 29.6 | 47.7 | 29.8 | 44.1 | 71.4 | 44.4 | 58.6 | 68.0 | 58.8 | 27.5 |
| 12.00 | 30.4 | 48.2 | 30.5 | 44.5 | 73.6 | 44.6 | 60.4 | 70.1 | 60.5 | 28.5 |
| 12.30 | 31.2 | 48.8 | 31.3 | 45.3 | 73.1 | 45.2 | 60.8 | 71.3 | 60.7 | 29.0 |
| 13.00 | 31.3 | 49.1 | 31.2 | 45.2 | 74.4 | 45.3 | 61.2 | 72.8 | 61.2 | 29.5 |
| 13.30 | 31.5 | 49.4 | 31.4 | 46.4 | 72.9 | 46.0 | 59.1 | 72.2 | 59.4 | 30.0 |
| 14.00 | 31.1 | 49.0 | 30.8 | 46.7 | 70.5 | 46.5 | 59.7 | 70.6 | 57.7 | 29.0 |
| 14.30 | 30.2 | 47.7 | 30.3 | 45.9 | 64.3 | 45.6 | 53.2 | 66.7 | 53.0 | 29.0 |
| 15.00 | 29.7 | 45.3 | 29.8 | 45.1 | 57.4 | 45.0 | 50.4 | 61.1 | 50.1 | 28.0 |
| 15.30 | 29.3 | 41.6 | 29.1 | 42.8 | 55.1 | 43.5 | 47.2 | 56.9 | 46.4 | 26.5 |
| 16.00 | 28.7 | 40.1 | 28.5 | 40.6 | 54.3 | 40.4 | 43.2 | 51.8 | 42.8 | 26.5 |
| 16.30 | 27.5 | 37.4 | 27.2 | 36.4 | 50.6 | 36.2 | 37.6 | 47.9 | 37.1 | 25.0 |
| 17.00 | 26.6 | 34.8 | 26.4 | 34.0 | 44.8 | 34.2 | 35.6 | 43.1 | 35.3 | 24.5 |

**TABLE A.16** : Mesured data for air heater collector with plate sheet test under Jordanian climate conditions on 13/9 /1995. Mass flow rate = 0.0098 Kg/sec.

| Time (hr) | I (wh/m$^2$) | Vw(m/sec) |
|---|---|---|
| 08:00-08:30 | 184.4 | 0.6 |
| 08:30-09:00 | 248.3 | 0.5 |
| 9:00-09:300 | 312.6 | 0.3 |
| 9:30-10:000 | 363.8 | 0.4 |
| 10:00-10:30 | 387.4 | 0.4 |
| 10:30-11:00 | 397.6 | 0.5 |
| 11:00-11:30 | 448.6 | 0.7 |
| 11:30-12:00 | 449.5 | 0.4 |
| 12:00-12:30 | 454.9 | 0.6 |
| 12:30-13:00 | 456.4 | 0.5 |
| 13:00-13:30 | 448.7 | 0.5 |
| 13:30-14:00 | 430.6 | 0.7 |
| 14:00-14:30 | 399.1 | 0.9 |
| 14:30-15:00 | 358.4 | 0.6 |
| 15:00-15:30 | 314.8 | 0.8 |
| 15:30-16:00 | 269.2 | 0.9 |
| 16:00-16:30 | 216.2 | 1.1 |
| 16:30-17:00 | 168.1 | 0.9 |

**TABLE A.17:** Data collected during time constant test performed on 10/9/95. All temperatures in (°C).
(For corrugated collector)

| Time (minutes) | $T_{i1}$ | $T_{S1}$ | $T_{i2}$ | $T_{o1}$ | $T_{S3}$ | $T_{o2}$ | $T_{iav}$ | $T_{oav}$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 31.7 | 39.5 | 33.1 | 48.3 | 60.7 | 50.1 | 32.40 | 49.20 |
| 1 | 31.4 | 36.2 | 32.3 | 45.5 | 53.0 | 46.6 | 31.85 | 46.05 |
| 2 | 30.9 | 34.2 | 31.3 | 43.7 | 48.1 | 44.5 | 31.10 | 44.10 |
| 3 | 30.1 | 32.6 | 30.4 | 41.9 | 43.0 | 42.6 | 30.25 | 42.25 |
| 4 | 30.0 | 32.1 | 30.6 | 39.8 | 42.2 | 40.4 | 30.30 | 40.10 |
| 5 | 29.9 | 31.5 | 29.8 | 38.6 | 40.1 | 39.2 | 29.35 | 38.90 |
| 6 | 30.0 | 31.4 | 30.1 | 37.9 | 39.9 | 38.3 | 30.05 | 38.10 |
| 7 | 29.9 | 31.2 | 30.0 | 37.3 | 38.3 | 37.6 | 29.95 | 37.40 |
| 8 | 30.0 | 31.1 | 30.0 | 36.7 | 37.9 | 36.6 | 30.00 | 36.65 |
| 9 | 29.8 | 30.7 | 29.9 | 35.6 | 36.1 | 35.8 | 29.85 | 35.70 |
| 10 | 29.7 | 30.5 | 29.7 | 34.8 | 35.8 | 34.7 | 29.70 | 34.75 |
| 11 | 29.7 | 30.8 | 30.0 | 33.9 | 35.7 | 33.8 | 29.85 | 33.85 |
| 12 | 29.9 | 30.6 | 29.8 | 33.2 | 35.2 | 33.1 | 29.85 | 33.15 |
| 13 | 29.7 | 30.6 | 29.8 | 33.0 | 34.6 | 33.0 | 29.75 | 33.00 |
| 14 | 29.7 | 30.5 | 29.9 | 32.8 | 34.5 | 32.9 | 29.80 | 32.85 |
| 15 | 28.9 | 30.2 | 29.2 | 32.7 | 34.2 | 32.7 | 29.05 | 32.70 |
| 16 | 29.7 | 30.3 | 29.8 | 32.5 | 34.1 | 32.6 | 29.75 | 32.55 |
| 17 | 30.0 | 30.1 | 29.9 | 32.3 | 33.9 | 32.5 | 29.95 | 32.40 |
| 18 | 29.8 | 30.1 | 29.9 | 32.2 | 33.8 | 32.2 | 29.85 | 32.20 |

**TABLE A.18:** Data collected during time constant test performed on 11/9/95. All temperatures in (°C). (conventional type)

| Time (minutes) | $T_{i1}$ | $T_{s1}$ | $T_{i2}$ | $T_{o1}$ | $T_{s3}$ | $T_{o2}$ | $T_{iav}$ | $T_{oav}$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 31.3 | 38.4 | 32.2 | 47.2 | 61.4 | 48.4 | 31.75 | 47.80 |
| 1 | 31.6 | 37.0 | 32.4 | 44.9 | 55.6 | 46.2 | 32.00 | 45.55 |
| 2 | 31.1 | 35.3 | 31.5 | 43.8 | 53.2 | 44.1 | 31.30 | 43.95 |
| 3 | 30.8 | 33.1 | 31.2 | 42.2 | 50.0 | 42.8 | 30.95 | 42.50 |
| 4 | 30.6 | 32.8 | 30.8 | 40.1 | 46.2 | 40.7 | 30.70 | 40.40 |
| 5 | 30.3 | 32.7 | 30.9 | 38.9 | 42.1 | 39.6 | 30.60 | 39.25 |
| 6 | 30.2 | 31.3 | 30.3 | 37.8 | 39.1 | 38.7 | 30.25 | 38.25 |
| 7 | 30.0 | 31.4 | 30.2 | 37.1 | 38.3 | 38.0 | 30.10 | 37.55 |
| 8 | 29.9 | 31.6 | 30.4 | 36.5 | 37.7 | 37.4 | 30.15 | 36.95 |
| 9 | 30.2 | 31.0 | 29.9 | 35.9 | 36.3 | 36.7 | 30.05 | 36.30 |
| 10 | 30.1 | 30.7 | 29.9 | 35.2 | 36.1 | 35.8 | 30.00 | 35.50 |
| 11 | 30.4 | 30.6 | 30.2 | 34.7 | 36.2 | 34.9 | 30.30 | 34.80 |
| 12 | 30.5 | 30.7 | 30.4 | 33.9 | 35.9 | 34.4 | 30.45 | 34.15 |
| 13 | 30.3 | 30.4 | 30.0 | 33.4 | 35.6 | 33.8 | 30.15 | 33.60 |
| 14 | 30.1 | 30.3 | 29.8 | 32.7 | 35.1 | 33.4 | 29.95 | 33.05 |
| 15 | 29.8 | 30.2 | 30.2 | 32.6 | 34.8 | 32.7 | 30.00 | 32.65 |
| 16 | 29.7 | 30.5 | 30.1 | 32.4 | 34.5 | 32.3 | 29.90 | 32.35 |
| 17 | 29.9 | 30.2 | 29.9 | 32.3 | 34.1 | 32.5 | 29.90 | 32.40 |
| 18 | 29.9 | 30.0 | 30.0 | 32.4 | 33.6 | 32.2 | 29.95 | 32.35 |

**TABLE A.20**:Data collected during stagnation test performed on 25/9/1995 . (Conventional type). All temperatures in (°C). Mass flow rate=0.0098 kg/s.

| Time interval | $T_{ic}$ | $T_{oc}$ | $T_{a,av}$ | I(Wh/m$^2$) | I(W/m$^2$) |
|---|---|---|---|---|---|
| 13:00-13:10 | 45.60 | 54.60 | 28.75 | 154.8 | 928.8 |
| 13:10-13:20 | 46.60 | 54.18 | 28.50 | 150.6 | 903.6 |
| 13:20-13:30 | 47.00 | 53.90 | 28.25 | 147.7 | 886.2 |
| 13:30-13:40 | 47.15 | 53.73 | 28.00 | 141.4 | 848.4 |
| 13:40-13:50 | 47.40 | 53.40 | 28.00 | 134.7 | 802.2 |
| 13:50-14:00 | 47.93 | 52.78 | 28.25 | 131.5 | 789.0 |
| 14:00-14:10 | 48.40 | 51.85 | 28.25 | 128.0 | 768.0 |
| 14:10-14:20 | 48.63 | 50.93 | 28.00 | 122.1 | 732.6 |
| 14:20-14:30 | 48.75 | 50.23 | 27.75 | 113.6 | 681.6 |
| 14:30-14:40 | 48.65 | 49.63 | 27.50 | 110.4 | 662.4 |
| 14:40-14:50 | 48.40 | 49.20 | 27.25 | 106.4 | 638.4 |
| 14:50-15:00 | 48.25 | 48.93 | 27.00 | 100.8 | 604.8 |
| 15:00-15:10 | 48.08 | 48.63 | 26.75 | 99.4 | 596.4 |
| 15:10-15:20 | 47.80 | 48.18 | 26.50 | 88.5 | 531.0 |
| 15:20-15:30 | 47.43 | 47.68 | 26.25 | 82.7 | 496.2 |
| 15:30-15:40 | 47.28 | 47.45 | 26.00 | 69.0 | 414.0 |
| 15:40-15:50 | 47.13 | 47.25 | 25.50 | 60.2 | 361.2 |
| 15:50-16:00 | 46.90 | 46.90 | 24.50 | 51.4 | 308.4 |
| 16:00-16:10 | 46.78 | 46.75 | 24.25 | 48.9 | 293.4 |

**TABLE A.21:** Data collected during stagnation test performed on 24/9/1995. (Corrugated type). All temperatures in (°C). Mass flow rate=0.0098 kg/s.

| Time | $T_{i1}$ | $T_{i2}$ | $T_{iav}$ | $T_{o1}$ | $T_{o2}$ | $T_{oav}$ | $T_a$ |
|---|---|---|---|---|---|---|---|
| 13:00 | 47.4 | 47.7 | 47.55 | 60.4 | 61.0 | 60.70 | 29.0 |
| 13:10 | 47.8 | 47.9 | 47.85 | 61.2 | 61.3 | 61.25 | 29.0 |
| 13:20 | 48.3 | 48.5 | 48.40 | 61.1 | 61.4 | 61.25 | 28.5 |
| 13:30 | 48.7 | 48.7 | 48.70 | 59.8 | 60.1 | 59.95 | 28.5 |
| 13:40 | 48.8 | 48.9 | 48.85 | 58.9 | 59.3 | 59.10 | 28.5 |
| 13:50 | 49.1 | 49.0 | 49.05 | 56.8 | 57.2 | 57.00 | 28.0 |
| 14:00 | 49.3 | 49.4 | 49.35 | 57.2 | 57.4 | 57.30 | 28.0 |
| 14:10 | 49.4 | 49.6 | 49.50 | 56.7 | 57.1 | 56.90 | 28.0 |
| 14:20 | 49.3 | 49.7 | 49.50 | 54.9 | 55.2 | 55.05 | 27.5 |
| 14:30 | 49.5 | 49.4 | 49.45 | 53.5 | 53.6 | 53.55 | 27.5 |
| 14:40 | 50.0 | 50.2 | 50.10 | 53.1 | 53.0 | 53.05 | 27.0 |
| 14:50 | 49.9 | 50.0 | 49.95 | 51.2 | 51.3 | 51.25 | 26.5 |
| 15:00 | 49.6 | 49.8 | 49.70 | 50.9 | 51.1 | 51.00 | 26.5 |
| 15:10 | 49.5 | 49.7 | 49.60 | 50.7 | 50.8 | 50.75 | 26.0 |
| 15:20 | 49.3 | 49.6 | 49.45 | 50.4 | 50.6 | 50.50 | 25.5 |
| 15:30 | 50.1 | 50.2 | 50.15 | 50.2 | 50.3 | 50.25 | 25.0 |
| 15:40 | 50.2 | 50.3 | 50.20 | 50.1 | 50.1 | 50.10 | 24.5 |

**TABLE A.22:** Data collected during stagnation test performed on 24/9/1995. ( Corrugated Type). All temperatures in (°C). Mass flow rate=0.0098 kg/s.

| Time interval | $T_{ic}$ | $T_{oc}$ | $T_{a,av}$ | $I(Wh/m^2)$ | $I(W/m^2)$ |
|---|---|---|---|---|---|
| 13:00-13:10 | 49.70 | 60.98 | 29.00 | 154.3 | 925.8 |
| 13:10-13:20 | 48.13 | 61.25 | 28.75 | 150.6 | 903.6 |
| 13:20-13:30 | 48.55 | 60.60 | 28.50 | 147.4 | 884.4 |
| 13:30-13:40 | 48.78 | 59.53 | 28.50 | 143.0 | 858.0 |
| 13:40-13:50 | 48.95 | 58.05 | 28.25 | 138.4 | 830.4 |
| 13:50-14:00 | 49.20 | 57.15 | 28.00 | 134.5 | 807.0 |
| 14:00-14:10 | 49.43 | 57.10 | 28.00 | 129.4 | 776.4 |
| 14:10-14:20 | 49.50 | 55.98 | 27.75 | 123.5 | 741.0 |
| 14:20-14:30 | 49.48 | 54.30 | 27.50 | 118.0 | 708.0 |
| 14:30-14:40 | 49.98 | 53.30 | 27.25 | 112.6 | 675.6 |
| 14:40-14:50 | 50.03 | 52.15 | 26.75 | 106.7 | 640.2 |
| 14:50-15:00 | 49.83 | 51.13 | 26.50 | 98.5 | 591.0 |
| 15:00-15:10 | 49.65 | 50.88 | 26.25 | 90.6 | 543.6 |
| 15:10-15:20 | 49.53 | 50.63 | 25.75 | 82.3 | 493.8 |
| 15:20-15:30 | 50.10 | 50.38 | 25.25 | 72.6 | 435.6 |
| 15:30-15:40 | 50.18 | 50.18 | 24.75 | 63.1 | 378.6 |

# APPENDIX B.
# RESULTS OBTAINED

**TABLE B.1**: Results obtained for air heated collector with corrugated galvanized iron sheets test at conditions performed on 15/8/1995 . Mass flow rate = 0.0215 kg/sec. All temperatures in (°C).

| Time (hr) | T -iav | T-mav | T-oav |
|---|---|---|---|
| 8:00 | 23.65 | 31.2 | 33.80 |
| 8:30 | 24.20 | 34.9 | 37.50 |
| 9:00 | 26.10 | 38.55 | 43.70 |
| 9:30 | 27.25 | 40.80 | 47.45 |
| 10:00 | 27.80 | 42.75 | 52.15 |
| 10:30 | 28.90 | 45.25 | 54.80 |
| 11:00 | 29.40 | 46.60 | 58.25 |
| 11:30 | 30.05 | 47.95 | 58.95 |
| 12:00 | 30.65 | 48.85 | 61.20 |
| 12:30 | 30.85 | 49.00 | 61.60 |
| 13:00 | 30.70 | 48.75 | 61.30 |
| 13:30 | 30.45 | 48.5 | 59.25 |
| 14:00 | 30.30 | 47.95 | 57.90 |
| 14:30 | 30.05 | 45.7 | 56.05 |
| 15:00 | 29.85 | 44.8 | 52.30 |
| 15:30 | 29.2 | 41.75 | 49.45 |
| 16:00 | 28.45 | 40.00 | 44.25 |
| 16:30 | 27.15 | 36.30 | 38.85 |
| 17:00 | 25.75 | 34.25 | 35.10 |

**TABLE B.2:** Results Obtained for Air Heater Collector with Corrugated Galvanized iron sheets test under Jordanian Climate conditions on 15 / 8 / 95 . Mass Flow Rate = 0.0215 kg/s. All temperatures in (°C).

| Time of day (hr) | I ($kJ/m^2$) | $T_{ic}$ | $T_{oc}$ | $T_{a,av}$ | $Q_{uc}$ (kJ) | $\frac{T_{ic}-T_{a.av.}}{I}*100$ | η (%) |
|---|---|---|---|---|---|---|---|
| 8:00-8:30 | 831.96 | 23.93 | 35.65 | 18.50 | 456.51 | 2.35 | 28.88 |
| 8:30-9:00 | 1048.68 | 25.15 | 40.60 | 19.75 | 601.80 | 1.85 | 30.20 |
| 9:00-9:30 | 1243.80 | 26.68 | 45.58 | 20.75 | 736.18 | 1.72 | 31.15 |
| 9:30-10:00 | 1431.36 | 27.30 | 49.80 | 21.50 | 876.41 | 1.52 | 32.23 |
| 10:00-10:30 | 1571.04 | 28.35 | 53.48 | 22.25 | 978.85 | 1.40 | 32.79 |
| 10:30-11:00 | 1666.8 | 29.15 | 56.53 | 22.75 | 1066.49 | 1.38 | 33.68 |
| 11:00-11:30 | 1743.48 | 29.73 | 58.60 | 23.50 | 1124.53 | 1.29 | 33.94 |
| 11:30-12:00 | 1801.44 | 30.35 | 60.088 | 24.75 | 1158.03 | 1.12 | 33.88 |
| 12:00-12:30 | 1832.04 | 30.75 | 61.40 | 26.0 | 1193.87 | 0.93 | 34.28 |
| 12:30-13:00 | 1842.89 | 30.78 | 61.45 | 26.25 | 1194.64 | 0.89 | 34.12 |
| 13:00-13:30 | 1815.38 | 30.58 | 60.28 | 25.75 | 1156.86 | 0.96 | 33.54 |
| 13:30-14:00 | 1745.64 | 30.38 | 58.58 | 25.25 | 1098.43 | 1.06 | 33.12 |
| 14:00-14:30 | 1640.16 | 30.18 | 56.98 | 25.00 | 1043.90 | 1.14 | 33.50 |
| 14:30-15:00 | 1486.08 | 29.95 | 54.18 | 24.75 | 943.80 | 1.26 | 33.43 |
| 15:00-15:30 | 1326.24 | 29.53 | 50.88 | 24.25 | 831.62 | 1.43 | 33.00 |
| 15:30-16:00 | 1134.72 | 28.83 | 46.85 | 23.50 | 701.91 | 1.69 | 32.56 |
| 16:00-16:30 | 938.52 | 27.80 | 41.55 | 22.75 | 535.58 | 2.03 | 30.03 |
| 16:30-17:00 | 745.20 | 26.45 | 36.98 | 22.25 | 410.16 | 2.03 | 28.97 |

**TABLE B.3:** Results obtained for air heated collector with corrugated galvanized iron sheets test at conditions performed on 16/8/1995 . Mass flow rate = 0.0166kg/sec. All temperatures in (°C).

| Time (hr) | T -iav | T-mav | T-oav |
|---|---|---|---|
| 8:00 | 19.95 | 28.35 | 32.55 |
| 8:30 | 20.85 | 30.60 | 36.20 |
| 9:00 | 21.70 | 33.15 | 43.45 |
| 9:30 | 23.20 | 37.45 | 47.25 |
| 10:0 | 24.70 | 41.35 | 53.50 |
| 10:30 | 26.85 | 43.95 | 58.90 |
| 11:00 | 27.70 | 46.25 | 59.95 |
| 11:30 | 28.45 | 47.45 | 63.20 |
| 12:00 | 28.75 | 48.25 | 64.15 |
| 12:30 | 29.20 | 45.65 | 65.00 |
| 13:00 | 29.30 | 48.75 | 64.75 |
| 13:30 | 29.20 | 48.60 | 63.25 |
| 14:00 | 29.05 | 47.50 | 61.80 |
| 14:30 | 28.80 | 45.65 | 58.55 |
| 15:00 | 28.50 | 43.85 | 55.65 |
| 15:30 | 28.00 | 41.35 | 49.45 |
| 16:00 | 27.25 | 38.85 | 45.35 |
| 16:30 | 26.60 | 35.80 | 39.40 |
| 17:00 | 25.50 | 32.75 | 36.40 |

**TABLE B.4:** Results obtained for Air Heater Collector with Corrugated Galvanized iron sheets test under Jordanian Climate conditions on 16/ 8 / 95 . Mass Flow Rate = 0.0166 kg/sec. All temperatures in (°C).

| Time (hr) | I ($kJ/m^2$) | $T_{ic}$ | $T_{oc}$ | $T_{a,av}$ | $Q_{uc}$ (kJ) | $\frac{T_{ic}-T_{a,av}}{I}*100$ | η(%) |
|---|---|---|---|---|---|---|---|
| 8:00-8:30 | 821.88 | 20.40 | 34.38 | 16.25 | 420.44 | 1.62 | 26.92 |
| 8:30-9:00 | 1055.52 | 21.28 | 39.83 | 16.75 | 557.88 | 1.54 | 27.81 |
| 9:00-9:30 | 1260.72 | 22.45 | 45.35 | 17.75 | 688.70 | 1.34 | 28.75 |
| 9:30-10:00 | 1436.76 | 23.95 | 50.38 | 19.25 | 794.86 | 1.26 | 29.12 |
| 10:00-10:30 | 1580.04 | 25.78 | 54.20 | 20.5 | 884.78 | 1.27 | 29.47 |
| 10:30-11:00 | 1678.32 | 26.53 | 58.43 | 21.75 | 959.37 | 1.03 | 30.09 |
| 11:00-11:30 | 1748.88 | 28.08 | 61.08 | 22.75 | 992.45 | 1.10 | 29.86 |
| 11:30-12:00 | 1794.6 | 28.6 | 63.18 | 23.75 | 1039.97 | 0.97 | 30.50 |
| 12:00-12:30 | 1847.88 | 28.98 | 64.58 | 25.0 | 1070.64 | 0.77 | 30.49 |
| 12:30-13:00 | 1849.68 | 29.25 | 64.88 | 25.75 | 1071.54 | 0.68 | 30.49 |
| 13:00-13:30 | 1816.56 | 29.25 | 64.00 | 25.75 | 1045.08 | 0.69 | 30.28 |
| 13:30-14:00 | 1742.76 | 29.13 | 62.53 | 25.25 | 1004.48 | 0.80 | 30.34 |
| 14:00-14:30 | 1634.4 | 28.93 | 59.45 | 25.0 | 917.87 | 0.87 | 29.56 |
| 14:30-15:00 | 1485.72 | 28.65 | 56.88 | 24.75 | 849.00 | 0.95 | 30.08 |
| 15:00-15:30 | 1316.04 | 28.25 | 52.55 | 24.25 | 730.80 | 1.10 | 29.22 |
| 15:30-16:00 | 1107.36 | 27.63 | 47.40 | 23.5 | 594.57 | 1.34 | 28.26 |
| 16:00-16:30 | 913.68 | 26.93 | 42.48 | 22.75 | 467.65 | 1.65 | 26.94 |
| 16:30-17:00 | 726.84 | 26.05 | 38.00 | 22.0 | 359.39 | 2.01 | 26.02 |

**TABLE B.5:** Results obtained for air heated collector with plate sheets test at conditions performed on 13/8/1995. Mass flow rate = 0.0215kg/sec. All temperatures in °C.

| Time (hr) | T -iav | T-mav | T-oav |
|---|---|---|---|
| 8:00 | 26.05 | 30.60 | 33.60 |
| 8:30 | 26.80 | 32.90 | 36.75 |
| 9:00 | 28.50 | 35.65 | 40.00 |
| 9:30 | 30.80 | 38.85 | 45.10 |
| 10:00 | 31.55 | 40.85 | 47.50 |
| 10:30 | 33.05 | 41.80 | 49.90 |
| 11:00 | 33.35 | 44.15 | 52.05 |
| 11:30 | 33.85 | 45.90 | 53.20 |
| 12:00 | 34.50 | 47.70 | 54.65 |
| 12:30 | 34.75 | 47.95 | 55.05 |
| 13:00 | 34.90 | 47.75 | 54.80 |
| 13:30 | 34.30 | 46.55 | 54.15 |
| 14:00 | 33.65 | 44.75 | 52.80 |
| 14:30 | 32.90 | 40.85 | 51.00 |
| 15:00 | 32.40 | 39.75 | 48.55 |
| 15:30 | 31.95 | 37.75 | 44.00 |
| 16:00 | 31.25 | 36.00 | 41.65 |
| 16:30 | 30.80 | 35.10 | 38.25 |
| 17:00 | 28.30 | 33.95 | 35.00 |

**TABLE B.6:** Results obtained for Air Heater Collector with plate sheets test under Jordanian climate conditions on 13/ 8/95 . Mass flow rate = 0.0215 kg/sec. All temperatures in (°C).

| Time (hr) | I ($kJ/m^2$) | $T_{ic}$ | $T_{oc}$ | $T_{a,av}$ | $Q_{uc}$ (kJ) | $\frac{Tic - Ta,av.}{I} * 100$ | η (%) |
|---|---|---|---|---|---|---|---|
| 8:00-8:30 | 0814.32 | 26.43 | 35.18 | 22.25 | 340.83 | 1.85 | 27.90 |
| 8:30-9:00 | 0983.52 | 27.65 | 38.38 | 23.00 | 417.95 | 1.70 | 28.33 |
| 9:00-9:30 | 1162.44 | 29.65 | 42.55 | 23.75 | 502.48 | 1.83 | 28.81 |
| 9:30-10:00 | 1305.72 | 31.18 | 46.30 | 24.50 | 588.95 | 1.84 | 30.07 |
| 10:00-10:30 | 1374.84 | 32.30 | 48.70 | 25.50 | 638.81 | 1.78 | 30.98 |
| 10:30-11:00 | 1527.12 | 33.20 | 50.98 | 26.50 | 692.43 | 1.58 | 30.23 |
| 11:00-11:30 | 1665.36 | 33.60 | 52.63 | 28.00 | 741.13 | 1.21 | 29.67 |
| 11:30-12:00 | 1686.6 | 34.18 | 53.93 | 28.75 | 769.95 | 1.16 | 30.41 |
| 12:00-12:30 | 1737.36 | 34.63 | 54.85 | 29.25 | 787.76 | 1.12 | 30.23 |
| 12:30-13:00 | 1740.96 | 34.83 | 54.93 | 29.00 | 783.00 | 1.21 | 29.99 |
| 13:00-13:30 | 1708.56 | 34.60 | 54.48 | 28.25 | 774.93 | 1.34 | 30.21 |
| 13:30-14:00 | 1663.92 | 33.98 | 53.48 | 28.00 | 759.51 | 1.29 | 30.43 |
| 14:00-14:30 | 1564.56 | 33.28 | 51.90 | 27.75 | 725.35 | 1.27 | 30.91 |
| 14:30-15:00 | 1443.24 | 32.65 | 49.78 | 27.00 | 667.31 | 1.41 | 30.83 |
| 15:00-15:30 | 1280.16 | 32.18 | 46.28 | 25.75 | 549.22 | 1.81 | 28.60 |
| 15:30-16:00 | 1092.60 | 31.60 | 42.83 | 25.00 | 437.43 | 2.17 | 26.69 |
| 16:00-16:30 | 0890.28 | 31.03 | 39.95 | 24.75 | 347.45 | 2.52 | 26.02 |
| 16:30-17:00 | 0709.20 | 29.55 | 36.63 | 24.50 | 275.78 | 2.56 | 25.92 |

**ABLE B.7:** Results obtained for air heater collector with plate sheet test at conditions performed on 14/8/1995 . Mass flow rate = 0.0166 kg/sec. All temperatures in (°C).

| Time (hr) | T -iav | T-mav | T-oav |
|---|---|---|---|
| 8:00 | 24.35 | 29.75 | 33.10 |
| 8:30 | 25.4 | 30.75 | 37.50 |
| 9:00 | 26.75 | 33.65 | 43.00 |
| 9:30 | 28.55 | 37.00 | 47.45 |
| 10:00 | 29.70 | 40.35 | 50.10 |
| 10:30 | 30.10 | 43.10 | 53.40 |
| 11:00 | 30.95 | 44.45 | 54.35 |
| 11:30 | 31.50 | 45.65 | 55.85 |
| 12:00 | 31.70 | 46.85 | 56.35 |
| 12:30 | 31.90 | 46.95 | 56.40 |
| 13:00 | 31.50 | 46.65 | 56.20 |
| 13:30 | 30.80 | 45.75 | 55.20 |
| 14:00 | 30.65 | 45.00 | 53.15 |
| 14:30 | 30.25 | 43.70 | 51.40 |
| 15:00 | 29.60 | 40.90 | 47.10 |
| 15:30 | 29.25 | 38.40 | 44.25 |
| 16:00 | 28.60 | 36.15 | 40.10 |
| 16:30 | 27.80 | 33.70 | 35.90 |
| 17:00 | 26.85 | 32.70 | 35.50 |

**TABLE B.8:** Results obtained for Air Heater Collector with plate sheet test under Jordanian Climate conditions on 14/ 8 / 95 .
Mass Flow Rate = 0.0166 kg/sec. All temperatures in (°C).

| Time (hr) | I ($kJ/m^2$) | $T_{ic}$ | $T_{oc}$ | $T_{a,av}$ | $Q_{uc}$ (kJ) | $\frac{T_{ic}-T_{a,av}}{I}*100$ | η (%) |
|---|---|---|---|---|---|---|---|
| 8:00-8:30 | 808.92 | 24.88 | 35.30 | 22.00 | 313.37 | 1.28 | 25.83 |
| 8:30-9:00 | 1056.24 | 26.08 | 40.25 | 23.50 | 426.15 | 0.88 | 26.90 |
| 9:00-9:30 | 1260.72 | 27.65 | 45.23 | 25.25 | 528.70 | 0.68 | 27.96 |
| 9:30-10:00 | 1425.60 | 29.13 | 48.78 | 26.50 | 590.96 | 0.67 | 27.64 |
| 10:00-10:30 | 1570.68 | 29.90 | 52.00 | 27.25 | 664.71 | 0.61 | 28.21 |
| 10:30-11:00 | 1657.44 | 30.53 | 54.35 | 27.75 | 702.15 | 0.61 | 28.24 |
| 11:00-11:30 | 1720.44 | 31.02 | 55.10 | 28.25 | 724.26 | 0.58 | 28.07 |
| 11:30-12:00 | 1777.68 | 31.60 | 56.10 | 28.75 | 736.97 | 0.58 | 27.64 |
| 12:00-12:30 | 1825.20 | 31.80 | 56.38 | 29.00 | 739.37 | 0.55 | 27.01 |
| 12:30-13:00 | 1842.12 | 31.70 | 56.30 | 29.25 | 739.97 | 0.48 | 26.78 |
| 13:00-13:30 | 1815.84 | 31.15 | 55.70 | 29.25 | 738.40 | 0.38 | 27.11 |
| 13:30-14:00 | 1744.56 | 30.73 | 54.43 | 28.00 | 712.68 | 0.57 | 27.23 |
| 14:00-14:30 | 1624.68 | 30.45 | 52.28 | 26.50 | 656.52 | 0.88 | 26.94 |
| 14:30-15:00 | 1455.84 | 29.93 | 49.25 | 25.75 | 581.03 | 1.03 | 26.61 |
| 15:00-15:30 | 1266.48 | 29.43 | 45.68 | 25.00 | 488.71 | 1.26 | 25.73 |
| 15:30-16:00 | 1069.20 | 28.93 | 42.18 | 24.25 | 398.48 | 1.58 | 24.85 |
| 16:00-16:30 | 823.68 | 28.20 | 38.00 | 24.00 | 294.73 | 1.84 | 23.85 |
| 16:30-17:00 | 728.28 | 27.33 | 35.70 | 23.50 | 251.72 | 1.89 | 23.04 |

**TABLE B.9:** Results obtained for air heater collector with corrugated galvanized iron sheet test at conditions performed on 10/9/1995 . Mass flow rate = 0.0138 kg/sec .All temperatures in(°C).

| Time (hr) | T -iav | T-mav | T-oav |
|---|---|---|---|
| 8:00 | 24.35 | 30.25 | 38.25 |
| 8:30 | 25.80 | 34.95 | 43.30 |
| 9:00 | 27.00 | 38.05 | 49.10 |
| 9:30 | 28.95 | 42.75 | 55.05 |
| 10:00 | 30.35 | 46.25 | 59.60 |
| 10:30 | 31.30 | 49.40 | 62.50 |
| 11:00 | 32.25 | 51.95 | 66.60 |
| 11:30 | 32.55 | 51.35 | 67.20 |
| 12:00 | 33.00 | 51.65 | 70.20 |
| 12:30 | 33.15 | 51.85 | 70.60 |
| 13:00 | 33.40 | 51.55 | 69.95 |
| 13:30 | 33.55 | 51.05 | 67.75 |
| 14:00 | 33.60 | 50.75 | 66.80 |
| 14:30 | 33.25 | 50.35 | 63.20 |
| 15:00 | 32.90 | 49.20 | 59.25 |
| 15:30 | 32.65 | 46.20 | 53.50 |
| 16:00 | 31.45 | 42.55 | 48.35 |
| 16:30 | 29.70 | 36.40 | 41.70 |
| 17:00 | 28.50 | 33.75 | 37.90 |

**TABLE B.10:** Results obtained for Air Heater Collector with Corrugated Galvanized iron sheets test under Jordanian climate conditions on 10/9 / 95. Mass Flow Rate = 0.0138 kg/sec .All temperatures in (°C).

| Time (hr) | I ($kJ/m^2$) | $T_{ic}$ | $T_{oc}$ | $T_{a,av}$ | $Q_{uc}$ (kJ) | $(T_{ic}-T_{a,av.}/I)$ * 100 | η (%) |
|---|---|---|---|---|---|---|---|
| 8:00-8:30 | 898.92 | 25.08 | 40.78 | 20.75 | 392.52 | 1.74 | 22.98 |
| 8:30-9:00 | 1113.48 | 26.40 | 46.20 | 22.25 | 495.03 | 1.34 | 23.40 |
| 9:00-9:30 | 1306.44 | 27.98 | 42.08 | 23.50 | 602.54 | 1.24 | 24.27 |
| 9:30-10:00 | 1463.04 | 29.65 | 57.33 | 24.75 | 692.04 | 1.21 | 24.90 |
| 10:00-10:30 | 1563.48 | 30.83 | 61.05 | 26.00 | 755.55 | 1.11 | 25.43 |
| 10:30-11:00 | 1661.04 | 31.78 | 64.55 | 27.00 | 819.30 | 1.04 | 25.96 |
| 11:00-11:30 | 1760.76 | 32.40 | 66.90 | 28.00 | 862.55 | 0.90 | 25.78 |
| 11:30-12:00 | 1789.92 | 32.78 | 68.70 | 29.00 | 898.05 | 0.76 | 26.41 |
| 12:00-12:30 | 1849.32 | 33.08 | 70.40 | 29.75 | 933.06 | 0.65 | 26.55 |
| 12:30-13:00 | 1847.16 | 33.28 | 70.18 | 30.00 | 922.56 | 0.64 | 26.29 |
| 13:00-13:30 | 1782.36 | 33.48 | 68.85 | 30.25 | 884.30 | 0.65 | 26.11 |
| 13:30-14:00 | 1716.84 | 33.58 | 67.28 | 30.50 | 842.55 | 0.64 | 25.83 |
| 14:00-14:30 | 1595.16 | 33.93 | 65.00 | 30.25 | 776.80 | 0.83 | 25.63 |
| 14:30-15:00 | 1428.84 | 33.08 | 61.23 | 29.75 | 703.79 | 0.90 | 25.92 |
| 15:00-15:30 | 1244.16 | 32.78 | 56.38 | 29.00 | 590.04 | 1.17 | 24.96 |
| 15:30-16:00 | 1040.40 | 32.05 | 50.43 | 27.75 | 472.03 | 1.49 | 23.88 |
| 16:00-16:30 | 827.36 | 30.23 | 45.03 | 26.75 | 370.02 | 1.59 | 23.54 |
| 16:30-17:00 | 614.16 | 29.10 | 39.80 | 26.00 | 267.52 | 1.82 | 22.93 |

**TABLE B.11**:Results obtained for air heated collector with plate sheets test at conditions performed on 11/9/1995 . Mass flow rate = 0.0138 kg/sec . All temperatures in(°C).

| Time (hr) | T -iav | T-mav | T-oav |
|---|---|---|---|
| 8:00 | 25.15 | 28.00 | 33.40 |
| 8:30 | 27.15 | 31.90 | 35.65 |
| 9:00 | 30.05 | 42.40 | 43.00 |
| 9:30 | 30.15 | 43.65 | 48.20 |
| 10:00 | 31.15 | 47.40 | 51.35 |
| 10:30 | 31.80 | 50.80 | 54.00 |
| 11:00 | 32.90 | 53.25 | 56.35 |
| 11:30 | 34.05 | 56.10 | 59.80 |
| 12:00 | 35.25 | 57.95 | 60.50 |
| 12:30 | 35.60 | 58.75 | 61.50 |
| 13:00 | 35.90 | 59.30 | 62.15 |
| 13:30 | 36.15 | 57.90 | 59.95 |
| 14:00 | 36.35 | 56.45 | 58.70 |
| 14:30 | 36.55 | 54.15 | 55.70 |
| 15:00 | 36.45 | 51.35 | 52.10 |
| 15:30 | 35.40 | 47.30 | 47.95 |
| 16:00 | 33.90 | 42.55 | 43.75 |
| 16:30 | 31.70 | 39.45 | 38.60 |
| 17:00 | 29.50 | 36.40 | 35. 15 |

**TABLE B.12:** Results obtained for Air Heater Collector with plate sheet test under Jordanian climate conditions on 11/9 / 95 .
Mass Flow Rate = 0.0138 kg/sec. All temperature in(°C).

| Time (hr) | I ($kJ/m^2$) | $T_{ic}$ | $T_{oc}$ | $T_{a,av}$ | $Q_{uc}$ (kJ) | ($T_{ic}$-$T_{a,av}$ /I) * 100 | η (%) |
|---|---|---|---|---|---|---|---|
| 8:00-8:30 | 648.36 | 26.15 | 34.53 | 22.75 | 209.51 | 2.16 | 21.54 |
| 8:30-9:00 | 798.48 | 28.60 | 39.33 | 24.25 | 268.27 | 1.96 | 22.40 |
| 9:00-9:30 | 1119.6 | 30.10 | 45.60 | 26.00 | 387.50 | 1.32 | 23.08 |
| 9:30-10:00 | 1355.76 | 30.65 | 49.78 | 27.25 | 478.28 | 0.90 | 23.51 |
| 10:00-10:30 | 1473.84 | 31.48 | 52.68 | 27.75 | 530.03 | 0.91 | 23.97 |
| 10:30-11:00 | 1578.24 | 32.35 | 55.18 | 28.50 | 570.78 | 0.88 | 24.11 |
| 11:00-11:30 | 1671.84 | 33.70 | 58.08 | 29.25 | 609.54 | 0.96 | 24.31 |
| 11:30-12:00 | 1737.72 | 34.65 | 60.15 | 29.75 | 637.54 | 1.02 | 24.46 |
| 12:00-12:30 | 1766.52 | 35.43 | 61.00 | 30.00 | 639.29 | 1.11 | 24.13 |
| 12:30-13:00 | 1782.72 | 35.75 | 61.83 | 30.25 | 652.04 | 1.11 | 24.38 |
| 13:00-13:30 | 1738.44 | 36.03 | 61.05 | 30.00 | 625.54 | 1.25 | 23.99 |
| 13:30-14:00 | 1625.40 | 36.25 | 59.33 | 29.50 | 577.03 | 1.49 | 23.67 |
| 14:00-14:30 | 1470.96 | 36.45 | 57.20 | 29.25 | 518.78 | 1.62 | 23.51 |
| 14:30-15:00 | 1321.20 | 36.50 | 53.90 | 28.50 | 435.03 | 2.18 | 21.95 |
| 15:00-15:30 | 1134.00 | 35.93 | 50.03 | 28.00 | 352.52 | 2.52 | 20.72 |
| 15:30-16:00 | 953.64 | 34.65 | 45.85 | 27.50 | 280.02 | 2.70 | 19.58 |
| 16:00-16:30 | 771.12 | 32.80 | 41.18 | 26.25 | 209.51 | 2.83 | 18.11 |
| 16:30-17:00 | 575.64 | 30.60 | 36.88 | 25.25 | 157.00 | 2.73 | 18.18 |

**TABLE B.13:** Results obtained for air heater collector with corrugated galvanized iron sheet test at conditions performed on 12/9/1995 . Mass flow rate = 0.0098 kg/sec. All temperatures in (°C).

| Time (hr) | T -iav | T-mav | T-oav |
|---|---|---|---|
| 8:00 | 22.55 | 32.05 | 33.80 |
| 8:30 | 24.40 | 35.30 | 40.40 |
| 9:00 | 25.85 | 39.50 | 47.60 |
| 9:30 | 26.60 | 43.35 | 52.25 |
| 10:00 | 27.05 | 46.70 | 56.65 |
| 10:30 | 27.45 | 49.35 | 58.00 |
| 11:00 | 27.45 | 52.80 | 62.40 |
| 11:30 | 28.30 | 54.00 | 63.70 |
| 12:00 | 28.65 | 54.25 | 67.05 |
| 12:30 | 29.25 | 54.30 | 68.15 |
| 13:00 | 29.50 | 54.05 | 68.75 |
| 13:30 | 29.75 | 53.85 | 68.75 |
| 14:00 | 29.55 | 51.90 | 66.25 |
| 14:30 | 28.85 | 50.60 | 63.85 |
| 15:00 | 28.45 | 47.65 | 59.60 |
| 15:30 | 28.15 | 44.85 | 55.15 |
| 16:00 | 27.95 | 41.15 | 47.10 |
| 16:30 | 27.70 | 37.05 | 41.75 |
| 17:00 | 27.40 | 33.20 | 37.20 |

**TABLE B.14:** Results obtained for air heater collector with corrugated galvanzed iron sheet test under Jordanian climate conditions on 12/9 / 95 . Mass Flow Rate = 0.0098 kg/sec. All temperatures in (°C).

| Time (hr) | I ($kJ/m^2$) | $T_{ic}$ | $T_{oc}$ | $T_{a,av}$ | $Q_{uc}$ (kJ) | $(T_{ic}-T_{a,av.}/I)$ * 100 | η (%) |
|---|---|---|---|---|---|---|---|
| 8:00-8:30 | 708.84 | 23.48 | 37.10 | 20.00 | 241.82 | 1.77 | 17.96 |
| 8:30-9:00 | 945.72 | 25.13 | 44.00 | 21.00 | 335.04 | 1.57 | 18.65 |
| 9:00-9:30 | 1148.76 | 26.23 | 49.93 | 21.50 | 420.79 | 1.48 | 19.28 |
| 9:30-10:00 | 1296.36 | 26.83 | 54.45 | 22.25 | 490.39 | 1.41 | 19.91 |
| 10:00-10:30 | 1373.04 | 27.25 | 57.33 | 24.00 | 534.07 | 1.12 | 20.47 |
| 10:30-11:00 | 1497.96 | 27.45 | 60.20 | 25.00 | 581.48 | 0.71 | 20.43 |
| 11:00-11:30 | 1593.36 | 27.88 | 64.05 | 25.50 | 642.20 | 0.54 | 21.21 |
| 11:30-12:00 | 1628.64 | 28.48 | 66.38 | 26.25 | 672.91 | 0.49 | 21.75 |
| 12:00-12:30 | 1641.60 | 28.95 | 67.60 | 26.75 | 686.23 | 0.48 | 22.00 |
| 12:30-13:00 | 1659.52 | 29.35 | 68.45 | 27.25 | 694.22 | 0.46 | 22.02 |
| 13:00-13:30 | 1636.20 | 29.60 | 68.75 | 27.25 | 695.11 | 0.52 | 22.36 |
| 13:30-14:00 | 1557.00 | 29.65 | 67.50 | 27.00 | 672.03 | 0.61 | 22.72 |
| 14:00-14:30 | 1460.52 | 29.20 | 65.05 | 27.00 | 636.52 | 0.54 | 22.94 |
| 14:30-15:00 | 1320.48 | 28.65 | 61.73 | 27.00 | 587.34 | 0.45 | 23.40 |
| 15:00-15:30 | 1153.08 | 28.30 | 57.33 | 27.00 | 516.32 | 0.41 | 23.57 |
| 15:30-16:00 | 954.00 | 28.05 | 51.13 | 26.50 | 409.79 | 0.87 | 22.61 |
| 16:00-16:30 | 763.56 | 27.83 | 44.43 | 25.50 | 294.73 | 1.10 | 20.32 |
| 16:30-17:00 | 588.60 | 27.55 | 39.48 | 25.00 | 211.82 | 1.56 | 18.94 |

**TABLE B.15**:Results obtained for air heater collector with plate sheet test at conditions performed on 13/9/1995 . Mass flow rate = 0.0098 kg/sec. All temperatures in (°C).

| Time (hr) | T -iav | T-mav | T-oav |
|---|---|---|---|
| 8:00 | 23.2 | 29.75 | 31.95 |
| 8:30 | 23.9 | 31.75 | 35.45 |
| 9:00 | 25.75 | 35.75 | 41.50 |
| 9:30 | 26.85 | 38.05 | 45.90 |
| 10:00 | 27.55 | 39.50 | 50.10 |
| 10:30 | 28.20 | 41.65 | 52.00 |
| 11:00 | 29.00 | 43.70 | 54.85 |
| 11:30 | 29.70 | 44.25 | 58.70 |
| 12:00 | 30.45 | 44.55 | 60.45 |
| 12:30 | 31.25 | 45.25 | 61.75 |
| 13:00 | 31.25 | 45.25 | 59.20 |
| 13:30 | 31.45 | 46.20 | 59.25 |
| 14:00 | 30.95 | 46.60 | 57.70 |
| 14:30 | 30.25 | 45.75 | 53.10 |
| 15:00 | 29.75 | 45.05 | 50.25 |
| 15:30 | 29.20 | 43.15 | 46.60 |
| 16:00 | 28.60 | 40.50 | 43.00 |
| 16:30 | 27.35 | 36.30 | 37.35 |
| 17:00 | 26.50 | 34.10 | 35.45 |

**TABLE B.17:** Obtained instantaneous efficiency expression for each collector.

| $\dot{m}$ (kg/s.) | η(%) for corrugated type | η(%) for conventional type |
|---|---|---|
| 0.0215 | $\eta = 0.367 - 3.954\left(\frac{T_i - T_a}{I}\right)$ | $\eta = 0.326 - 3.133\left(\frac{T_i - T_a}{I}\right)$ |
| 0.0166 | $\eta = 0.320 - 3.567\left(\frac{T_i - T_a}{I}\right)$ | $\eta = 0.282 - 2.841\left(\frac{T_i - T_a}{I}\right)$ |
| 0.0138 | $\eta = 0.273 - 3.115\left(\frac{T_i - T_a}{I}\right)$ | $\eta = 0.262 - 2.816\left(\frac{T_i - T_a}{I}\right)$ |
| 0.0098 | $\eta = 0.246 - 3.624\left(\frac{T_i - T_a}{I}\right)$ | $\eta = 0.221 - 3.083\left(\frac{T_i - T_a}{I}\right)$ |

# APPENDIX C.

# THE COMPUTER PROGRAMS

```
c_______________________________________________________________
c       PROGRAME [1]
c       THIS PROGRAME IS USED FOR OBTAINING THE
c       THEORETICAL RESULTS OF CORRUGATED TYPE.
c_______________________________________________________________
        IMPLICIT REAL*8 (A-Z)
      DIMENSION IO(20),IH(20),IB(20),ID(20),IT(20),fdp(20),se(20)
     +,W1(20),W2(20),WW(20),H(20),RB(20),KT(20),ul(20),c1(20)
     +,IBN(20),CCOS(20),DBF(20),IT1(20),hrc(20),ha(20),quu(20)
     +,ra(20),nu(20),r1(20),r2(20),r3(20),hcon(20),x(20),To(20)
     +,hk(20),Fp(20),Fr(20),qu(20),eff(20),ut(20),y(20),nu1(20)
        OPEN(1,FILE='S3.OUT',STATUS='NEW')
        open(2,file='s3.dat',status='old')
c       Cp:specific heat of air(J/kg. C)
c       m: mass flow rate of air (kg/s.)
c       tae:effective transmitive-absorbtance product.
c       Lt:Thickness of absorber plate.
c       KB:Thermal conductivity of insulation material.
c       dB:Thickness of insulation material(m).
c       A1:Area of cover(glass).
c       A2:Area of absorber plate.
c       ep1:transparent cover emisivit.
c       ep2:the absorber plate emissivity.
c       Vw:Average wind velocity
c       Tc:Cover Temperature(K).
c       S:Stefan Boltzman constant.
c       F12:the vew factor.
```

```
c     hw:wind convective transfer coefficient.
c     GA:surface azmith angle.
c     Gsc:solar constant.
c     ROG:reflectance solar of the ground.
c     N:the day number of year.
c     B:tilt angle of the model.
c     FI:latitude, the angular location north or south of
c    the equator.
c     omega:the angle, which is shown in figure(3.2 ) page( 31).
      Cp=1006.5
     m=0.0215
      tae=0.81
      lt=0.9e-3
      kB=.04
      dB=3.e-2
      A1=1.5
     A2=1.9
     ep1=.87
      ep2=0.1
      vw=1.4
      Tc=303.
     S=5.67e-8
      omega=103.
     F12=SIN(omega/2.)
     hw=2.8+(3.*vw)
      GA=0.0
      H(1)=3
      W1(1)=-60
```

```
      W2(1)=-45
C     CALCULATED SOLAR INCIDANT  [*]
c     IT:Incident Solar Radiation
      Write(1,11)
11    format(1x,'Time (hr)',2x,'Ta ( C)',2x,'Ti( C)',2x,'Ti-Ta/I',2x,
    + 'ul(W/m .C)',2x,'Qu(KJ)',2x,'To( C)',1x,'It(KJ/m)',1x,'eff(%)')
      write(1,*)'------------------------------------------------------------------'
      oo=8
      op=9
      do 10 IP=1,9
      zo=3.14159/180
     Gsc=1367.
      ROG=0.6
      N=227.
      B=30.
      FI=32.0
      If (IP.gt.1)then
      W1(IP)=W1(IP-1)+15
      W2(IP)=W2(IP-1)+15
     H(IP)=H(IP-1)+1
      endif
      FDE=(360*(284+N))/365
      DELTA=23.45*SIN(ZO*FDE)
      Io(Ip)=(12.*Gsc/3.14159)*(1+0.033*cos(0.986*N*zo))*
    = (cos(FI*zo)*cos(DELTA*zo)*(SIN(W2(IP)*ZO)-SIN(W1(IP)*ZO))+
    =  3.1459*(W2(IP)-W1(IP))*(SIN(FI*ZO)*SIN(DELTA*ZO))/180)
      AH=191.3343*(-1)+322.8383*H(IP)-32.851*(H(IP))**2+0.6137
    = *(H(IP))**3
```

```
      BH=142.1121+31.9338*H(IP)+0.4338*(H(IP))**2-0.2908*
   =  (H(IP))**3
      FH=75.1929+2.136*H(IP)+0.0779*(H(IP))**2-0.0194
   =  *(H(IP))**3
      IH(IP)=AH+BH*SIN((360*N/365-FH)*ZO)
      KT(IP)=IH(IP)/IO(IP)
      IF(KT(IP).GE.0.0.AND.KT(IP).LT.0.137)THEN
      ID(IP)=IH(IP)*(0.344+1.45*KT(IP))
      ENDIF
      IF(KT(IP).GE.0.137.AND.KT(IP).LT.0.785)THEN
      ID(IP)=IH(IP)*(0.636-0.670*KT(IP))
      ENDIF
      IF(KT(IP).GE.0.785)THEN
      ID(IP)=0.11*IH(IP)
      ENDIF
      WW(IP)=(W1(IP)+W2(IP))/2
      CCOS(IP)=COS(FI*ZO)*COS(DELTA*ZO)*COS(WW(IP)*ZO)+
   =  SIN(FI*ZO)*SIN(DELTA*ZO)
      IB(IP)=IH(IP)*(0.145+1.032*KT(IP))
      IBN(IP)=(IH(IP)-ID(IP))/CCOS(IP)
      DBF(IP)=COS(B*ZO)*(SIN(FI*ZO)*SIN(DELTA*ZO)+COS(FI*Z
O)
   =  *COS(DELTA*ZO)*COS(WW(IP)*ZO))
   =  +SIN(B*ZO)*COS(GA*ZO)*(TAN(FI*ZO)*(SIN(FI*ZO)


)
   =  -SIN(DELTA*ZO)*1/(COS(FI*ZO))
```

```
     = +SIN(GA*ZO)*COS(DELTA*ZO)*SIN(WW(IP)*ZO))
       IT1(IP)=IBN(IP)*DBF(IP)+(COS(.5*B*ZO))**2.*ID(IP)
     = +(SIN(.5*B*ZO))**2.*IH(IP)*ROG
      IT(IP)=IT1(IP)*3.6
c     calculated Ul(Over all heat loss coefficient)
c_______________________________________________________________
c      ta:Ambient temperature(K).
c      ti:Inlet temperature of air (K).
c      ts:Surface Temperature of absorber plate(K).
c      UB:the back loss coefficient.
       read(2,*)ta,ti,ts
       se(ip)=(Ti-Ta)*100/IT1(ip)
      UB=KB/dB
       f1=(1-ep1)/(ep1+1)
       f2=1/f12
       f3=(1-ep2)*A1/(ep2*A2)
c      hrc:radiative heat transfer between the cover and the
c     absorber plate.
c      Tsk:sky temperature (kelvin).
c      hrsk:radiative heat transfer coefficient between the sky
c     and the cover.
c      Bp:volumetric coefficient of expansion for fluid (air).
c      length:mean distance between the absorber plate.
c      g:gravitational constant.
c      nuu:kinematic viscosity.
c      Ka:thermal conductivity of air flow.
c      Alph:thermal diffusity.
c      Ra:Reyleih number.
```

```
c     Nu1:Nusselt number for nutural air flow.
c     mu:dynamic viscosity.
c     p:wetted perimeter.
c     Dh:hydraulic diameter.
c     Re:Renold number.
c     Hcon:the convective heat transfer between the cover and
c     absorber plate.
c     Ut:top heat transfer coefficient.
c     Ha:convective heat transfer coefficient for air flow rate
c     inside the collector.
      hrc(ip)=(s*(Tc**2+Ts**2)*(Tc+Ts))/(f1+f2+F3)
      TSK=0.0552*(TA**1.5)
      HRSK=S*EP2*(TSK**2+TC**2)*(TSK+TC)
      Bp=3.16e-3
      length=2.0e-2
      g=9.81
      nuu=1.7e-5
      ka=0.028
      ALPH=2.55E-5
      Ra(ip)=Bp*g*(length**3)*(ts-tc)/(nuu*alph)
      r1(ip)=1708./(Ra(ip)*cos(B*zo))
      r2(ip)=((sin(1.8*zo*B))**1.6)*1708/(Ra(ip)*cos(B*zo))
      r3(ip)=(Ra(ip)*cos(B*zo)/5830)**(1./3.)
      x(ip)=1-r1(ip)
      y(ip)=r3(ip)-1
      if(x(ip).lt.0)THEn
      x(ip)=0.0
      endif
```

```
      time=3600
```

```
      eff(IP)=Quu(IP)*100/(IT(IP)*A2)
      To(ip)=Ti-273.15+(Quu(ip)*1000/(m*cp*time))
      Tac=Ta-273
      Tic=Ti-273
      Tsc=Ts-273
      write(1,12)oo,op,tac,tic,se(ip),ul(ip),quu(ip),to(IP),
     +it(ip),eff(ip)
12    format(1x,f4.1,'-',f4.1,2x,f6.2,2x,f6.2,2x,f6.2,2x,f7.3,4x,
     + f6.1,2x,f6.2,2x,f7.2,3x,f5.2,/)
      oo=oo+1
      op=op+1
10    continue
      STOP
      END
```

* : Privet contact Abu Al-Qasem.

# INPUT FILE FOR PROGRAM # 1

## (FILE : S3.DAT)

| $T_a$ (k) | $T_i$ (k) | $T_s$ (K) |
|---|---|---|
| 292.28 | 297.69 | 316.2 |
| 294.28 | 300.14 | 327.7 |
| 295.65 | 300.90 | 336.4 |
| 297.28 | 303.19 | 341.9 |
| 299.28 | 303.34 | 343.7 |
| 299.15 | 303.63 | 341.2 |
| 298.03 | 303.22 | 335.3 |
| 297.03 | 302.33 | 326.9 |
| 295.65 | 300.28 | 316.6 |

# TABLE C.1: THEORETICAL RESULTS OF CORRUGATED TYPE (PROGRAM 1)

| Time (hr) | Ta (°C) | Ti(°C) | Ti-Ta/I | Ul(W/m².°C) | Qu(KJ) | To(°C) | It(KJ/m²) | eff(%) |
|---|---|---|---|---|---|---|---|---|
| 8.0- 9.0 | 19.28 | 24.69 | 0.85 | 9.334 | 1890.4 | 48.81 | 2292.39 | 43.40 |
| 9.0-10.0 | 21.28 | 27.14 | 0.73 | 9.447 | 2404.1 | 57.85 | 2888.38 | 43.81 |
| 10.0-11.0 | 22.65 | 27.90 | 0.58 | 9.486 | 2749.7 | 63.05 | 3248.18 | 44.55 |
| 11.0-12.0 | 24.28 | 30.19 | 0.63 | 9.508 | 2839.3 | 66.49 | 3377.62 | 44.24 |
| 12.0-13.0 | 26.28 | 30.92 | 0.51 | 9.519 | 2802.6 | 66.75 | 3285.29 | 44.90 |
| 13.0-14.0 | 26.15 | 30.63 | 0.54 | 9.513 | 2533.9 | 63.01 | 2981.56 | 44.73 |
| 14.0-15.0 | 25.03 | 30.22 | 0.75 | 9.491 | 2053.8 | 56.43 | 2480.32 | 43.58 |
| 15.0-16.0 | 24.03 | 29.33 | 1.06 | 9.452 | 1438.3 | 47.64 | 1803.89 | 41.96 |
| 16.0-17.0 | 22.65 | 27.28 | 1.67 | 9.352 | 734.8 | 36.56 | 996.91 | 38.79 |

```
c___________________________________________________________
c       PROGRAME [2]
c THIS PROGRAME IS USED FOR OBTAINING THE
c  THEORETICAL  RESULTS OF CONVENTIONAL TYPE.
c___________________________________________________________
        IMPLICIT REAL*8 (A-Z)
      DIMENSION IO(20),IH(20),IB(20),ID(20),IT(20),fdp(20),se(20)
     +,W1(20),W2(20),WW(20),H(20),RB(20),KT(20),ul(20),c1(20)
     +,IBN(20),CCOS(20),DBF(20),IT1(20),hrc(20),ha(20),quu(20)
     +,ra(20),nu(20),r1(20),r2(20),r3(20),hcon(20),x(20),To(20)
     +,hk(20),Fp(20),Fr(20),qu(20),eff(20),ut(20),y(20),nu1(20)
        OPEN(1,FILE='S5.OUT',STATUS='NEW')
        open(2,file='s5.dat',status='old')
c       Cp:specific heat of air(J/kg. C)
c       m: mass flow rate of air (kg/s.)
c       tae:effective transmitive-absorbtance product.
c       Lt:Thickness of absorber plate.
c       KB:Thermal conductivity of insulation material.
c       dB:Thickness of insulation material(m).
c       A1:Area of cover(glass).
c       A2:Area of absorber plate.
c       ep1:transparent cover emisivity.
c       ep2:the absorber plate emissivity.
c       Vw:Average wind velocity
c       Tc:Cover Temperature(K).
c       S:Stefan Boltzman constant.
c       F12:the vew factor.
```

```
c      hw:wind convective transfer coefficient.
c      GA:surface azmith angle.
c      Gsc:solar constant.
c      ROG:reflectance solar of the ground.
c      N:the day number of year.
c      B:tilt angle of the model.
c      FI:latitude, the angular location north or south of
c      the equator.
       Cp=1006.5
       m=0.0215
       tae=0.81
       lt=0.9e-3
       kB=.04
       dB=3.e-2
       A1=1.5
       A2=1.5
       ep1=.87
       ep2=0.074
       vw=0.94
       Tc=303.
       S=5.67e-8
       hw=2.8+(3.*vw)
       GA=0.0
       H(1)=3
       W1(1)=-60
       W2(1)=-45
C      CALCULATED SOLAR INCIDANT [*].
       Write(1,11)
```

```
 = *(H(IP))**3
      IH(IP)=AH+BH*SIN((360*N/365-FH)*ZO)
      KT(IP)=IH(IP)/IO(IP)
      IF(KT(IP).GE.0.0.AND.KT(IP).LT.0.137)THEN
      ID(IP)=IH(IP)*(0.344+1.45*KT(IP))
      ENDIF
      IF(KT(IP).GE.0.137.AND.KT(IP).LT.0.785)THEN
      ID(IP)=IH(IP)*(0.636-0.670*KT(IP))
      ENDIF
      IF(KT(IP).GE.0.785)THEN
      ID(IP)=0.11*IH(IP)
      ENDIF
      WW(IP)=(W1(IP)+W2(IP))/2
      CCOS(IP)=COS(FI*ZO)*COS(DELTA*ZO)*COS(WW(IP)*ZO)+
 = SIN(FI*ZO)*SIN(DELTA*ZO)
      IB(IP)=IH(IP)*(0.145+1.032*KT(IP))
      IBN(IP)=(IH(IP)-ID(IP))/CCOS(IP)
      DBF(IP)=COS(B*ZO)*(SIN(FI*ZO)*SIN(DELTA*ZO)+COS(FI*Z
O)
 = *COS(DELTA*ZO)*COS(WW(IP)*ZO))
 = +SIN(B*ZO)*COS(GA*ZO)*(TAN(FI*ZO)*(SIN(FI*ZO)
 =
*SIN(DELTA*ZO)+COS(FI*ZO)*COS(DELTA*ZO)*COS(WW(IP)*ZO))
 = -SIN(DELTA*ZO)*1/(COS(FI*ZO))
 = +SIN(GA*ZO)*COS(DELTA*ZO)*SIN(WW(IP)*ZO))
      IT1(IP)=IBN(IP)*DBF(IP)+(COS(.5*B*ZO))**2.*ID(IP)
 = +(SIN(.5*B*ZO))**2.*IH(IP)*ROG
      IT(IP)=IT1(IP)*3.6
```

```
c      calculate of Overall heat loss coefficient [Ul].
c___________________________________________________________
c       ta:Ambient temperature(K).
c       ti:Inlet temperature of air (K).
c       ts:Surface Temperature of absorber plate(K).
c       UB:the back loss coefficient.
        read(2,*)ta,ti,ts
        se(ip)=(Ti-Ta)*100/IT1(ip)
       UB=KB/dB
c       hrc:radiative heat transfer between the cover and the
c      absorber plate.
c       Tsk:sky temperature (kelvin).
c       hrsk:radiative heat transfer coefficient between the sky
c      and the cover.
c       Bp:volumetric coefficient of expansion for fluid (air).
c       length:mean distance between the absorber plate.
c       g:gravitational constant.
c       nuu:kinematic viscosity.
c       Ka:thermal conductivity of air flow.
c       Alph:thermal diffusity.
c       Ra:Reyleih number.
c       Nu1:Nusselt number at nutural air flow.
c       mu:dynamic viscosity.
c       p:wetted perimeter.
c       Dh:hydraulic diameter.
c       Re:Renold number.
c       Hcon:the convective heat transfer between the cover and
c      absorber plate.
```

```
c      Ut:top heat transfer coefficient.
c      Ha:convective heat transfer coefficient for air flow rate
c     inside the collector.
       TSK=0.0552*(TA**1.5)
       HRSK=S*EP2*(TSK**2+TC**2)*(TSK+TC)
       Bp=3.16e-3
       length=2.0e-2
       g=9.81
       nuu=1.7e-5
       ka=0.028
       ALPH=2.55E-5
       Ra(ip)=Bp*g*(length**3)*(ts-tc)/(nuu*alph)
       r1(ip)=1708./(Ra(ip)*cos(B*zo))
       r2(ip)=((sin(1.8*zo*B))**1.6)*1708/(Ra(ip)*cos(B*zo))
       r3(ip)=(Ra(ip)*cos(B*zo)/5830)**(1./3.)
       x(ip)=1-r1(ip)
       y(ip)=r3(ip)-1
       if(x(ip).lt.0)THen
       x(ip)=0.0
       endif
       if (y(ip).lt.0.0)then
       y(ip)=0.0
       endif
       nu1(ip)=1+1.44*x(ip)*(1-r2(ip))+y(ip)
       Af=0.79*0.02
       mu=1.38e-5
       p=0.79*2+0.04
       Dh=4*Af/p
```

```
      Re=m*Dh/(Af*mu)
c     By test: the flow is turb.
      nu(ip)=0.0158*(Re**.8)
      HCON(Ip)=NU1(IP)/Length
c     Tpav.: average temperature of the plate, (k).
      Tpav=340
      hr= 4.*S*(Tpav**3)/((1/ep1)+(1/ep2)-1.)
      Ut(IP)=1./((1/(hr+hcon(IP)))+(1/(hrsk+hw)))
      Ul(IP)=Ut(IP)+UB+1.
      Ha(ip)=(nu(ip)*ka)/Dh
c   CALCULATE HEAT REMOVAL FACTOR(Fr):
c_____________________________________________________________
      hk(IP)=1./((1./ha(ip))+(1./hr))
      Fp(IP)=1./(1.+Ul(ip)/(ha(ip)+hk(ip)))
      c1(ip)=m*cp/(A1*ul(ip)*fp(ip))
      fdp(ip)=c1(ip)*(1-exp(-1./c1(ip)))
      fr(ip)=fp(ip)*fdp(ip)
c     Useful energy  (quu:kJ), efficiency(eff:%)and outlet
c   temperature (To:K) Calculations
c_____________________________________________________________
      Qu(IP)=A2*Fr(IP)*(tae*IT1(IP)-Ul(IP)*(Ti-Ta))
      Quu(ip)=Qu(ip)*3.6
     time=3600
      eff(IP)=Quu(IP)*100/(IT(IP)*A2)
      To(ip)=Ti-273+(Quu(ip)*1000/(m*cp*time))
     Tac=Ta-273
     Tic=Ti-273
     Tsc=Ts-273
```

## INPUT FILE FOR PROGRAM # 2 (FILE : S5.DAT)

| $T_a$ (k) | $T_i$ (k) | $T_s$ (k) |
|---|---|---|
| 295.90 | 300.04 | 321.22 |
| 297.28 | 303.57 | 335.18 |
| 299.15 | 305.90 | 344.35 |
| 301.53 | 307.04 | 351.62 |
| 302.23 | 307.88 | 352.85 |
| 301.23 | 307.44 | 351.22 |
| 300.23 | 306.11 | 345.88 |
| 298.48 | 305.04 | 336.82 |
| 297.73 | 303.44 | 323.25 |

# TABLE C.2: THEORETICAL RESULTS OF COVENTIONAL TYPE(PROGRAM 2)

| Time (hr) | Ta (°C) | Ti(°C) | Ti-Ta/I | Ul(W/m²°C) | Qu(KJ) | To( C) | It(KJ/m²) | eff(%) |
|---|---|---|---|---|---|---|---|---|
| 8.0- 9.0 | 22.90 | 27.04 | 0.65 | 8.055 | 1192.0 | 42.34 | 2297.15 | 34.59 |
| 9.0-10.0 | 24.28 | 30.57 | 0.78 | 8.107 | 1475.3 | 49.51 | 2895.75 | 33.96 |
| 10.0-11.0 | 26.15 | 32.90 | 0.75 | 8.129 | 1663.4 | 54.25 | 3257.68 | 34.04 |
| 11.0-12.0 | 28.53 | 34.04 | 0.59 | 8.145 | 1758.2 | 56.61 | 3388.43 | 34.59 |
| 12.0-13.0 | 29.23 | 34.88 | 0.62 | 8.149 | 1704.2 | 56.76 | 3296.49 | 34.47 |
| 13.0-14.0 | 28.23 | 34.44 | 0.75 | 8.144 | 1525.9 | 54.03 | 2992.23 | 34.00 |
| 14.0-15.0 | 27.23 | 33.11 | 0.85 | 8.134 | 1256.3 | 49.24 | 2489.61 | 33.64 |
| 15.0-16.0 | 25.48 | 32.04 | 1.30 | 8.114 | 870.0 | 43.21 | 1811.19 | 32.02 |
| 16.0-17.0 | 24.73 | 30.44 | 2.05 | 8.071 | 441.9 | 36.11 | 1002.35 | 29.39 |

# APPEDIX D
# UNCERTAINITY ANALYSIS.

# Uncertainty Analysis

## D.1 Introduction

The errors occurring in the calculation of useful heat gain, instantaneous efficiency and daily efficiency, can be attributed to the following [23]:

1. Uncertainties in the temperature measurements.
2. Inaccuracies in the recording of the flow rate.
3. Inaccuracies in the recording of the solar intensity.

## D.2 Combination of Component Errors in Overall System Accuracy Calculations

Computing a quantity M, which is a known function of n independent variables $u_1, u_2, u_3, \ldots, u_n$. That is

$$M = f(u_1, u_2, u_3, \ldots, u_n) \qquad \text{(D.1)}$$

The u`s are the measured quantities (instrument or component outputs) and are in error by $\pm\Delta u_1$, $\pm\Delta u_2$, $\pm\Delta u_3$, ..., $\pm\Delta u_n$ respectively. These errors will cause an error $\Delta M$ in the computed result M. That is

$$M \pm \Delta M = f(u_1 \pm \Delta u_2, u_2 \pm \Delta u_2, u_3 \pm \Delta u_3, \ldots, u_n \pm \Delta u_n) \qquad \text{(D.2)}$$

Expanding the function f in Taylor series, to get

$$f(u_1 \pm \Delta u_1, u_2 \pm \Delta u_2, \ldots, u_n \pm \Delta u_n) = (u_1, u_2, \ldots, u_n) +$$

$$+ \Delta u_1 \frac{\partial f}{\partial u_1} + \Delta u_2 \frac{\partial f}{\partial u_2} + \ldots\ldots + \Delta u_n \frac{\partial f}{\partial u_n} + \frac{1}{2}(\Delta u_1)^2 \frac{\partial^2 f}{\partial u_1^2} + \ldots + \ldots \qquad \text{(D.3)}$$

the $\Delta u$'s are small quantities (estimated errors), and thus terms such as $(\Delta u)^2$ will be negligible and dropped from the equation. Then equation (D.3) may be given approximately as

$$f(u_1 \pm \Delta u_1, u_2 \pm \Delta u_2, \ldots, u_n \pm \Delta u_n) = f(u_1, u_2, \ldots, u_n) + \Delta u_1 \frac{\partial f}{\partial u_1} + \Delta u_2 \frac{\partial f}{\partial u_2} + \ldots + \Delta u_n \frac{\partial f}{\partial u_n}. \quad \text{(D.4)}$$

So that the absolute error $E_a$ is given by

$$E_a = \Delta M = \left|\Delta u_1 \frac{\partial f}{\partial u_1}\right| + \left|\Delta u_2 \frac{\partial f}{\partial u_2}\right| + \ldots + \left|\Delta u_n \frac{\partial f}{\partial u_n}\right|. \quad \text{(D.5)}$$

So the computed result is expressed as

$$M \pm E_a. \quad \text{(D.6)}$$

### D.3 The Error in Calculating the Useful Heat Gain

The useful heat gain was evaluated from

$$Q_u = \dot{m}\, C_p (T_0 - T_i) t \quad \text{(D.7)}$$

To find the error associated in calculating $Q_u$, one must find the error in measuring $\dot{m}$, $T_o$, and $T_i$, since $C_p$ is constant. It is recommended that the error in T (that is $\Delta T$) is taken to be ±0.05C, and in $\dot{m}$ (that is $\Delta \dot{m}$) is taken to be ±0.0005, thus

$$\frac{\partial Q_u}{\partial \dot{m}} = C_p (T_o - T_i) \quad \text{(D.8)}$$

$$\frac{\partial Q_u}{\partial T_i} = -\dot{m}C_p \quad \text{(D.9)}$$

$$\frac{\partial Q_u}{\partial T_o} = \dot{m}C_p \quad \text{(D.10)}$$

Substituting equation (D.8) to (D.10) into (D.5)

$$E_a = C_p(T_o - T_i)\Delta\dot{m} + \dot{m}C_p\Delta T_i + \dot{m}C_p\Delta T_o \quad \text{(D.11)}$$

Now, substituting equations (D.7) and (D.11) into (D.6) we get

$$C_p(T_o - T_i) \pm [C_p(T_o - T_i)\Delta\dot{m} + \dot{m}C_p\Delta T_i + \dot{m}C_p\Delta T_o] \quad \text{(D.12)}$$

Thus, by substituting numerical values, the maximum associated error in calculating Qu was 5.7%.

**D.4 The Error in Evaluating the Instantaneous Efficiency**

The instantaneous efficiency was calculated from the equation

$$\eta_i = \frac{Q_u}{A_c I} * 100\% \quad \text{(D.13)}$$

When the values of the useful heat gain is substituted in equation (D.13), it becomes

$$\eta_i = \frac{\dot{m}C_p(T_o - T_i)t}{A_c \mathrm{I}} * 100\% \quad \text{(D.14)}$$

When substituting numerical values, and following the same procedure utilized in the previously mentioned quantities, the maximum error was 0.3%.

# ملخص

## أداء سخان هواء شمسي يستخدم ألواح الصاج المجلفن المموج، المتوفر محلياً، كسطح ماص


إعداد

ايادمحمد الدبعي

إشراف

أ.د. محمد السعد



تبحث هذه الدراسة في تصميم و تصنيع ودراسة أداء مجمعين شمسيين لتسخين الهواء، أحدهما يستخدم ألواح الصاج المجلفن المموج، المتوفر محلياً، كسطح ماص. والأخر يستخدم الواح الفولاذ العادي كسطح ماص.

وقد أجريت على النموذجين الفحوصات التالية: فحص الحمل القسري، فحص التدفق الطبيعي، وفحص ثابت الزمن. وقد تمت هذه الفحوصات في الهواء الطلق تحت ظروف الأردن المناخية. وقد أجريت هذه الفحوص في شهري آب و أيلول من عام ١٩٩٥ بواسطة التدفق الهوائي القسري لأربعة تدفقات هي ٠,٠٠٩٨، ٠,٠١٣٨، ٠,٠١٦٦، ٠,٠٢١٥ كغم/ث. وقد امتدت فترة الفحص من الساعة الثامنة صباحاً وحتى الخامسة عصراً. وقد دلت هذه الدراسة ان اداء المجمع الذي يستخدم ألواح الصاج المجلفن المموج يتفوق على المجمع الذي يحتوي على ألواح الفولاذ العادية. وكما ان الكفاءه اليومية للمجمع ذا السطح المموج اعلى من كفاءة المجمع المصنوع من الواح الفولاذ العادي . ومن جانب آخر كان معامل فقد الحرارة أقل حساسية في حالة المجمع ذو اللوح الفولاذي. وقد تم ايجاد معادله رياضية لكفاءة المجمعين تحت معدلات تدفق مختلفة و قد بينت النتائج العملية ان اداء كل مجمع يكون افضل كلما زاد معدل التدفق .

وبصفة عامة، عندما قورن المجمع الذي يستخدم ألواح الصاج المجلفن المموج مع المجمع ذو اللوح الفولاذي وجد أن الأول يتفوق على الثاني في كل شيء تقريباً.