Performance Analysis of a Shallow Duct Flat Plate Solar Air Heater with and without Porous Media

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Abstract

In this study a flat plate solar air heater with a shallow duct is analyzed experimentally. The collector consists of a 4.5m long air duct with a (20×5)cm cross-sectional area. The air duct consists of four channels so that the collector becomes more compact. The collector is studied under the weather conditions of Hilla city – Iraq with latitude and longitude equal 32.3° N and 44.25° E respectively and it is tilted by 45° with the horizontal plane. The effect of the air mass flow rate on the collector performance is also studied.The performance of the collector is analyzed with and without porous media stuffing. The measured parameters are the air and absorber temperatures, air speed and pressure drop. The temperatures are measured by means of type (K) thermocouples as this type covers the temperature range of the studied system. The values of the temperature are displayed by temperature data logger devices. The air speed and pressure drop are measured by digital anemometer and manometer devices respectively. The results of the studied system show that as the air mass flow rate increases, the temperature of both the flowing air and the absorber decrease, whilst the efficiency of the collector increases. The results also show that the addition of the steel wool porous material inside the air duct increases the temperature of both the flowing air and the absorber, and by that increases the efficiency of the collector. The porous media also caused an increase in the pressure drop between the outlet air and the atmosphere. This pressure drop increased with the increase in the air mass flow rate.

Keywords*:* Flat plate; Absorber; Solar collector; Efficiency; Porous media

الخلاصة

في هذه الدراسة تم القيام بتحليل عملي لمسخن هوائي شمسي ذو صفيحة مستوية وبمجرى هواء ضحل. المنظومة تتألف من مجرى هوائي بطول 4.5m وبمساحة مقطع عرضي مقدارها (20×5)cm. المجرى الهوائي يتألف من اربعة قنوات لكي تصبح المنظومة اصغر حجما. تمت دراسة المنظومة عند الظروف الجوية لمدينة الحلة في العراق عند خط عرض وخط طول يساويان (32.3°N) و (44.25°E) على التوالي وبزاوية ميلان مقدارها 45° مع الافق. كذلك تمت دراسة تأثير معدل جريان الهواء على أداء المنظومة وتمت دراسة أداء المنظومة بوجود وبعدم وجود حشوة مسامية. العوامل التي تم قياسها هي درجات حرارة الهواء واللوح الماص، سرعة الهواء وهبوط الضغط. تم قياس درجات الحرارة بواسطة اسلاك ثيرموكبل من نوع (K) حيث ان هذا النوع يغطي مدى درجات الحرارة للمنظومة. قيم درجات الحرارة تم عرضها بواسطة جهاز مسجل للبيانات. سرعة الهواء وهبوط الضغط تم قياسهما بواسطة جهازي انيموميتير رقمي ومايكرومانوميتير رقمي على التوالي. نتائج الدراسة بينت انه بزيادة سرعة الهواء تقل درجات الحرارة للهواء الخارج واللوح الماص، في حين ان كفاءة المنظومة تزيد. كما بينت النتائج ان اضافة مادة الصوف الفلاذي المسامية داخل المجرى الهوائي أدت الى زيادة درجات حرارة الهواء واللوح الماص وبذلك تزداد كفائة المنظومة. الوسط المسامي كذلك ادى الى زيادة في هبوط الضغط بين الهواء الخارج والضغط الجوي. هبوط الضغط هذا ازداد بزيادة معدل جريان الهواء.

الكلمات المفتاحية: صفيحة مستعرية، ماص، مجمع شمسي، كفاءة، وسط مسامي

Nomenclature

Symbol	*Meaning*	*Units*
A_c	Cross-sectional area of the flow	m^2
A_s	Surface area of the absorber	m^2
C_p	Specific heat at constant pressure	J/kg.°C
f_c	Efficiency function	m^2.°C/W
I_T	Total incident solar radiation	W/m^2
La	Latitude	deg.
$\dot{m}$	Mass flow rate	kg/s
N	Number of day in the year	—

P	Pressure	N/m^2
Q_{ga}	Rate of heat gain	W
$S.N.$	Solar noon	hr
T_a	Ambient temperature	°C
T_{ab}	Absorber temperature	°C
T_{in}	Inlet air temperature	°C
T_{out}	Outlet air temperature	°C
U_L	Combined collector heat loss coefficient	W/°C.m^2
V	Velocity of the fluid	m/s
w_s	Hour angle at sunrise or sunset	hr

Greek Symbols

Symbol	***Meaning***	***Units***
α	Absorptivity of the absorber plate	—
Δ	Difference between values	—
δ	Solar declination	deg.
η	Thermal efficiency	—
ρ	Density	kg/m^3
τ	Transmissivity of the transparent cover	—

I. Introduction

Solar energy is the energy provided by the sun and it has been used by mankind since ancient times for drying agricultural products and space heating during cold seasons. Only a small fraction of the sun's radiation reaches the earth's surface, the rest is either reflected back to space or absorbed by clouds and oceans. The radiation that does reach the Earth is the indirect source of nearly every type of energy used today, the exceptions are geothermal and nuclear energies. Even fossil fuels owe their origins to the sun as they were once living plants and animals whose life was dependent upon the sun. Much of mankind's need for energy can be provided by the sun either directly or indirectly in both cases proper technologies are required to convert that energy into useful power. Solar energy requires two components to be used by humans. These two components are a collector and a storage unit.The collector simply collects the solar radiation and converts it to the required form of energy, while the storage unit stores the converted energy for future use and it is required because of the nature of the solar energy as it is available only for a portion of the day and sometimes natural factors such as clouds and dust would prevent the solar ray from reaching the earth. Hence during these times the stored energy will fulfil our needs for power. There are three types of solar collectors that have been invented and evolved throughout the years which are: flat plate collectors, evacuated tube collectors and concentrating collectors.

This study is concerned with flat plate solar collectors. Flat plate collectors consist of an absorber made of a high absorptivity metal and painted by a selective dark coating that increases the collector's absorptivity to the solar radiation. The back side of the collector is thermally insulated in order to reduce heat losses and the top is covered by a transparent cover such as glass or plastic. The fluid passes under the absorber or through pipes that are attached to the absorber. Flat plate solar collectors are widely used throughout the world. This type of collectors is the simplest and least expensive among all other types. It is mainly used for space and water heating for low temperatures up to 80°C. These collectors can benefit from both direct and diffuse solar radiation and require no tracking system. (Ion Ion and Jorge Martins, 2006) described the design and testing of a solar air collector in order to develop more efficient and cost effective energy process. In this design the energy and exergy analysis were used to establish the appropriate components and the optimum working parameters. (Irfan and Turgut, 2006) investigated a solar air heater with free and fixed fins and found that fixed fin collector is more effective than free fin collector. (Sopian *et. al*.,2008) studied a double-pass solar collector with and without porous media in the lower channel.The porous media has been arranged in different porosities to increase heat transfer, area density and the total heat transfer rate. (Yousef and Adam, 2008)investigated theoretically the performance of a flat plate solar collector with and without porous media. Various operating parameters were studied such as mass flow rate, flow channel depth and collector length on the system thermal performance and pressure drop through the collector. These parameters were studied with single and double flow modes. (Ebru and Fatih, 2010) studied experimentally the performance of a flat plate solar air heater with three different types of obstacles (leaf type, rectangular type and triangular type)and without obstacles.(Ahmad *et. al*.,2010) studied the performances of a double-pass solar collector with longitudinal fins on the absorber plate. This study involves a theoretical investigation of the effect of mass flow rate, number and height of fins on the efficiency. Three types of finned collectors were studied (with upper fins, with lower fins and with upper and lower fins). (Herrero *et. al*.,2011) designed an experimental side-by-side solar collector test bed. The collector was designed and constructed to characterize the thermo-hydraulic behavior of a standard and an enhanced solar collector under the same testing conditions (operating parameters and radiant conditions).(Nagham,2011) studied experimentally the performance of a flat plate solar air heater under the climate conditions of Hilla city – Iraq and with a 45° tilt angle. The air duct was 4.5m long with a (10×10)cm cross-sectional area. The effects of the collector's direction and the glass cover condition were also studied.(Qusai,2012) studied theoretically the flow field, temperature field and the performance of a single-pass flat plate solar air heater under the climate conditions of Hilla city–Iraq.A program was developed by (FORTRAN 90) to solve the governing equations by finite volume method.Three duct configurations were studied, with three different aspect ratios (height/width) which are (1/1, 1/4 and 1/11) and with 4.5m duct length. (Ajay and Sharma, 2012) conducted an experimental study of a single-pass solar air heater with different types of porous media. The experiments were conducted by changing the parameter that influences the thermal efficiency of the collector. The efficiency of solar air heater has been examined by changing the mass flow rate and using different types of porous media. (Silvina *et. al*., 2012) studied experimentally and theoretically the thermal efficiency of a double-pass solar air heater. The solar collector has a useful collection area of $2m^2$ and a channel size of 0.025m high. The edge and bottom surfaces are thermally +insulated with a 0.05m thick glass wool layer. The air flow is forced by a tangential fan installed in a 0.18m diameter pipe that is connected to the flow outlet. The collector was mounted with a slope of 34° facing north, in order to maximize the intensity of solar irradiance during winter. (Basharia and Adam,2012) studied the effect of mass flow, channel depth and collector length on the thermal performance and cost benefit ratio for two types of solar air heaters in double flow mode, one flat plate collector has porous media and the other has a V-groove absorber. The thermal performance was determined over a wide range of operating conditions. (Vettrivel1 and Mathiaragan, 2013) performed experimental and theoretical studies on a flat plate solar collector.They varied several parameters and studied the effect of those parameters on the performance of the flat plate solar collector. (Arun and Arun, 2013) conducted a simulation study on a modified dual purpose solar collector. The modification was achieved by adding porous media to the solar collector. Modelling and simulation studies of the system were carried out using ANSYS 13 software and associated Fluent CFD package. (Vipin *et. al.*,2013)analyzed the thermal performance of double glazed flat plate solar collectors using MATLAB software. The calculations were performed with different tilt angles and the effect of changing the tilt angle on the temperatures of the glass covers was observed. (Bhupendra *et. al.*, 2013) analyzed experimentally a double-pass flat plate solar collector and compared its performance with the single-pass collector. The analysis was carried out with and without porous media at different mass flow rates.

The present study concentrates on the design and construction of a flat plate solar collector and the effect of different operating parameters that affect the performance of a flat plate solar air heater. This study is built on the knowledge gained from previous researches.Also in this study we try to improve the performance of flat plate solar air heaters by changing the design of the collector and adding porous media inside the air duct.

II. Experimental Setup

The flat plate solar collector used in this study consists of a stainless-steel absorber plate type (304) that is fabricated into a 4.5m long rectangular duct with a cross-sectional area of (20×5)cm and four channels. The air duct has a lower plate welded to it made from the same material as the absorber (full rectangular section). The absorber was painted by a mixture of (50% by weight black car paint matt 890 and 50% river sand with a grain size of 50μm) in order to increase its absorptivity to the solar radiation (Nagham Yass, 2011).Ten extended surfaces (fins) are welded inside the air duct. These fins are (5×5)cm and tilted 45° degree with the direction of flow. The locations of the fins are showed in figure (1).The bottom of the collector is made of a 1.8cm thick wooden plate. The sides of the collector consist of three layers which are (wood-insulating foam-wood).The insulation reduces the heat losses through the sides and bottom of the collector. The air duct is fixed on the base of the wooden box using (M10) bolts.The glazing of the collector consists of a 4mm thick glass sheet that is fixed at 4cm above the air duct. The glass cover is used for two purposes: reducing heat losses from the absorber by convection and radiation and preventing rain and dust from coming in contact with the absorber. The glass cover is fixed on the wooden box using aluminum tapes which are fixed by screws to the sides of the wooden box. The gap between the glazing and the box is filled with rubber-sponge tapes and the sides of the aluminum tapes are filled with silicon-rubber to prevent air leakage and heat losses to the environment. The collector is then fixed on a steel frame that is tilted 45° with the horizontal plane. A variable air speed blower is connected to the air duct by a 10cm diameter and 2m long flexible connecting duct. The mass flow rate of the air is varied in order to study its effect on the collector performance. The test rig is shown in figure (2).

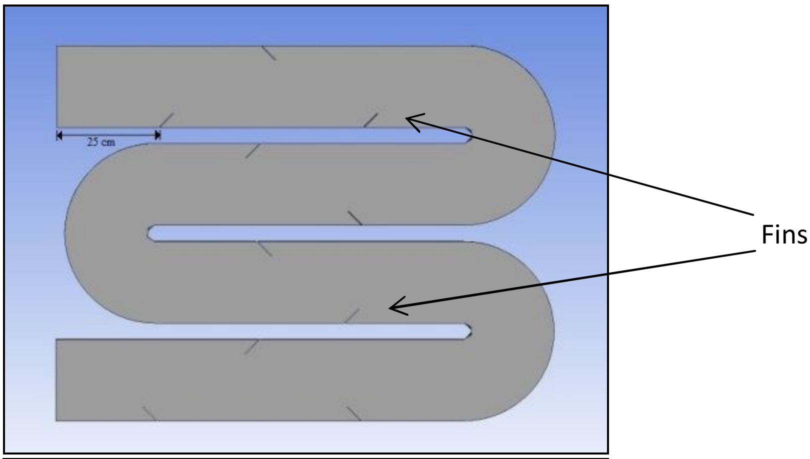

Figure (1) The Locations of the Fins

Figure (2) The Test Rig

The temperatures of the flowing air and the absorber plate are measured using type (K) thermocouple wires. This type was used as it covers the temperature range of the system. Fifteen points for the flowing air are measured in order to study the temperature growth of the air as it moves through the duct. Two points for the upper plate and two points for the lower plate are measured. The locations of the thermocouples are showed in figure (3). All the thermocouples are connected to data logger devices to record the temperature values. The air speed is measured by a digital anemometer device. The pressure difference between the atmosphere and the outlet air is measured by a digital micro-manometer device.Figure (4) shows all the measurement devices.

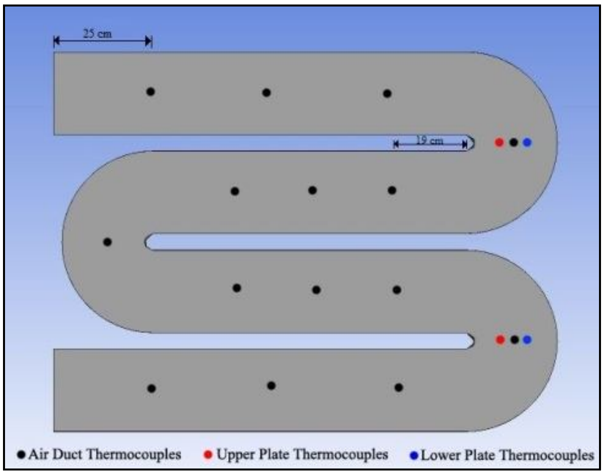

Figure (3) The Locations of the Thermocouples

Figure (4) The Measurement Devices

III. Experimental Procedure

The collector was directed to the South-East direction since according to (Nagham,2011) it delivers the highest absorber and air temperature rise in the location of the tests. It should be mentioned that the glass covers for both collectors are cleaned every day before the tests were started so that the highest amount of incident solar radiation can reach the absorbers. The data of the incident solar radiation are taken from the weather station of the Mechanical Department of the University of Babylon.

The blowers were operated from (9:00 AM to 2:00 PM) for all the testing days.The tests were conducted in Hilla city–Iraq during June, July, September and December. The data loggers are set to record the temperature values every 10 minutes.

IV. Adding Porous Media

Porous media is inserted inside the air duct of a solar collector to improve the heat transfer between the flowing air and the absorber. In this study steel wool is used as a porous material inside the air duct. The duct is partially stuffed for practical reasons in the first and last straight channels. The collector is operated with and without the porous material in order to study its effect on the performance of the collector. The porosity of steel wool given by (Abdulrahman *et. al.*, 2010) is 91.6%.

V. Collector Performance Calculations

The thermal efficiency of the collector given by (Fabio Struckmann, 2008) is:

$$\eta = \frac{Q_{ga}}{A_s \cdot I_T} \qquad (1)$$

where: A_s=1.4 $\mathbf{m^2}$ and (Q_{ga}) is the heat gained by the air and equals:

$$Q_{ga} = \dot{m} \cdot C_p \cdot (T_{out} - T_{in}) \qquad (2)$$

$$\dot{m} = p. Ac. V \qquad (3)$$

where: ρ=1.2 kg/s and A_c=0.01 m^2.

The collector efficiency curve is the relationship between the collector efficiency (η) and the efficiency function (f_c). These two variables given by (Peter, 1980) are:

$$\eta = \tau\alpha - U_L \frac{(T_{ab} - T_a)}{I_T} \qquad (4)$$

and

$$f_c = \frac{(T_{ab} - T_a)}{I_T} \qquad (5)$$

The product of the transparent cover transmissivity (τ) and the absorber plate absorptivity (α) is referred to as the optical efficiency. U_L is the combined collector heat loss coefficient. If U_L and $\tau\alpha$ are considered constant then the relationship between η and f_c will be a straight line. The values of $\tau\alpha$ and U_L, given by (Peter, 1980), are assumed to be 0.8 and 5.22 respectively.

VI. Solar Noon Calculation

The solar noon is the time of the day in which the incident solar radiation reaches its maximum value on the specified location. Calculating the solar noon is very crucial when studying a solar collector performance. The solar noon time given by (Peter J. Lunde, 1980) is:

$$S.N. = \frac{Sunrise + Sunset}{2} \qquad (6)$$

$$Sunrise = 12 - w_s \qquad (7)$$

$$Sunset = 12 + w_s \qquad (8)$$

$$w_s = \frac{\pm 24}{360} \, arcos(-\tan La \times \tan \delta) \qquad (9)$$

$$\delta = 23.45^o Sin\left[\left(\frac{N-80}{370}\right) \times 360\right] \qquad (10)$$

where: w_s is the hour angle at sunrise or sunset and it is negative for sunrise and positive for sunset, *La* is the latitude of the location and δ is the solar declination.

VII. Results and Discussion

The results show the effect of various parameters such as (mass flow rate, porous media and test conditions) on the performance of the solar air heater.

Fig (5) shows the variation of the absorber plate temperature and the ambient air temperature during the day.By investigating this figure, it can be seen that the absorber temperature increases with time as the solar radiation keeps increasing until the solar noon, then the temperature starts decreasing with the decrease in the incident solar radiation.Also by investigating the specified points of the absorber plate temperature, it can be noticed that the temperature for point (1) which is near the inlet is lower than that of point (2) which is near the exit.The reason for this increase is that as the fluid moves further in the air duct and its temperature increases the heat transfer between the air and the absorber decreases which makes the absorber temperature near the exit higher than that near the inlet.

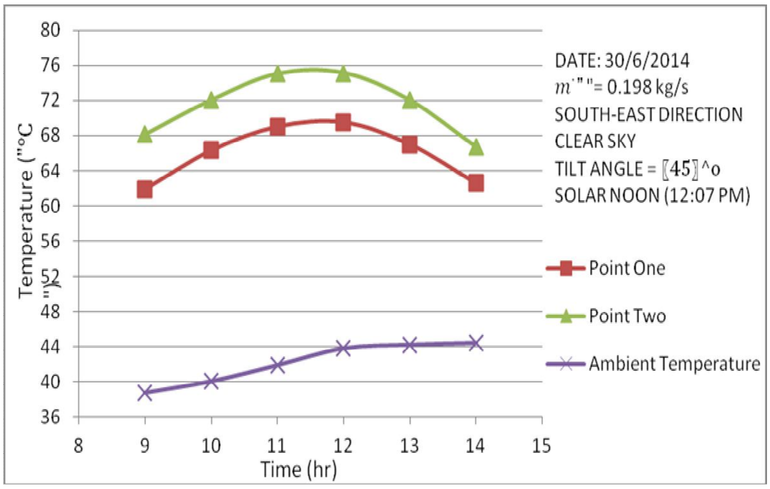

Figure (5) Variation of the Absorber Plate Temperature with Time

Figs (6 and 7) show the variation of the upper plate,lower plate and ambient temperatures during the day with and without porous material stuffing. From these figures, it can be seen that the upper plate temperature is higher than the lower plate temperature because the upper plate is exposed directly to the solar radiation while the lower plate is heated by conduction from the upper plate.The temperature for both plates increased with the addition of the porous material due to the increase in the air temperature which in turn decreases the heat transfer between the plates and the air.

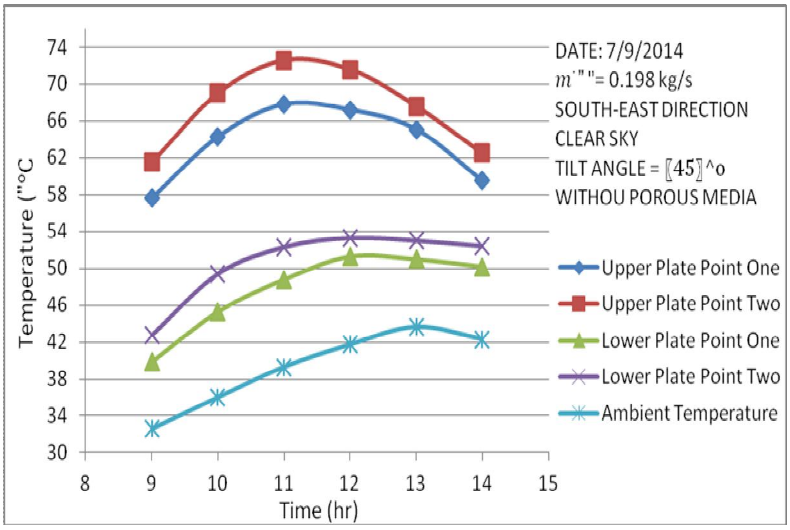

Figure (6) Variation of the Upper and Lower Plate Temperature with Time

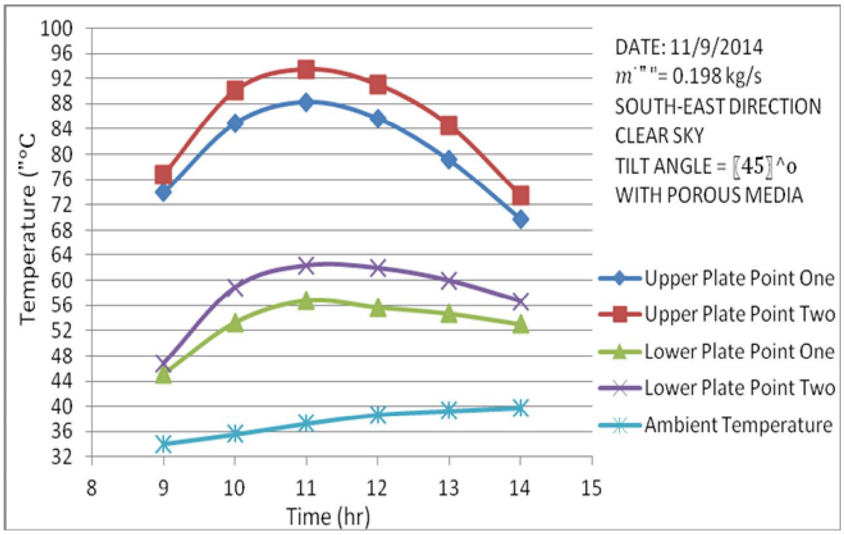

Figure (7) Variation of the Upper and Lower Plate Temperature with Time

Fig (8) shows the variation of the outlet air temperature and the ambient temperature during the day. From this figure, it can be seen that the outlet air temperature increases during the day because more solar radiation incidents on the absorber.The outlet air temperature reaches its maximum value at the solar noon when the solar radiation is at its maximum value.

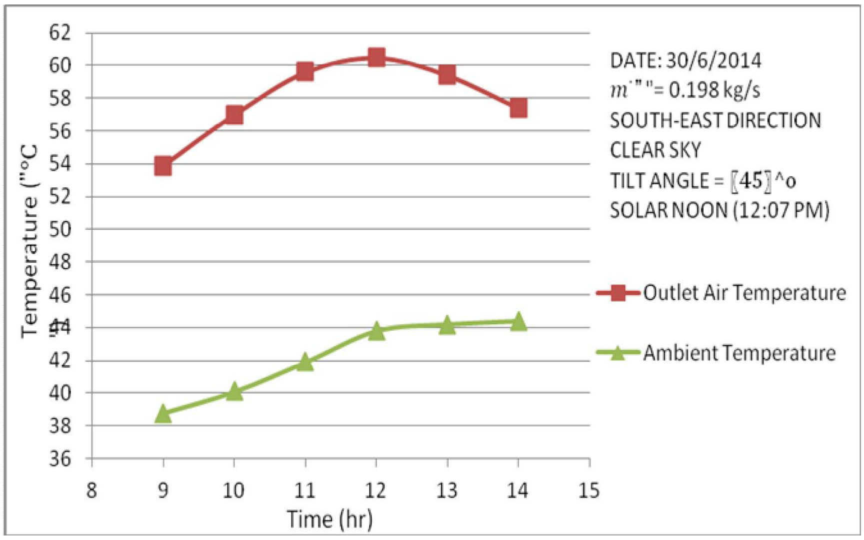

Figure (8) Variation of the Outlet Air Temperature with Time

Fig (9) shows the variation of the outlet air temperature with time with and without porous media. From this figure, it can be seen that the values of the air temperature with porous media are higher than that without porous media because the porous material increases the heat transfer area.

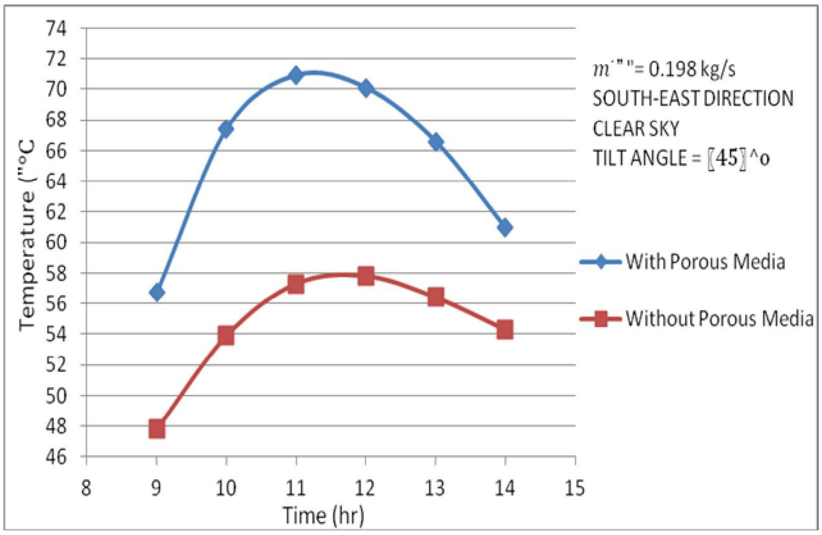

Figure (9) Effect of Adding Porous Media on the Outlet Air Temperature

Fig (10) shows the variation of the outlet air temperature with time for different months. These tests were conducted in the same weather conditions (clear sky) and for the same mass flow rate and tilt angle. From this figure, it can be seen that the air temperature during September is much higher than that during December due to the increase in the incident solar radiation and the ambient air temperature.

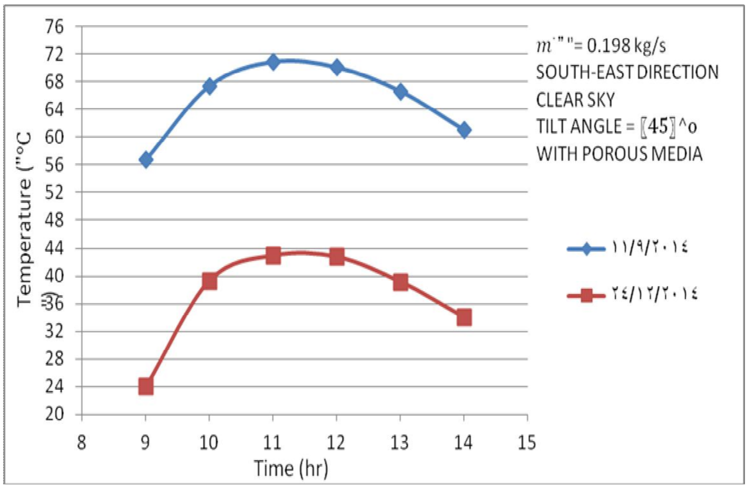

Figure (10) Effect of Test Date on the Outlet Air Temperature

Fig (11) shows the variation of the local air temperature as it flows through the air duct and for different times during the day. By observing this figure, it can be seen that the local air temperature increases uniformly through the straight ducts and then jumps at each bend. Also from this figure, it can be seen that the local air temperature increases with time and the maximum value is at the solar noon when the solar radiation is at its maximum value.

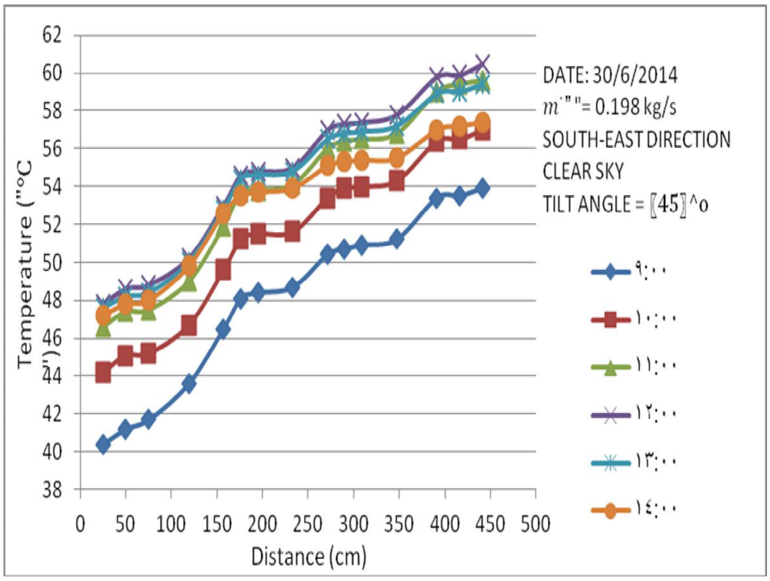

Figure (11) Growth of Air Temperature along the Duct

Fig (12) shows the growth of the air temperature as it flows through the air duct and for three different mass flow rates together. From this figure, it can be seen that the temperature of the air decreases as the mass flow rate increases. The reduction in the air temperature is due to the increase in the air velocity which decreases the heat transfer between the absorber and the air.

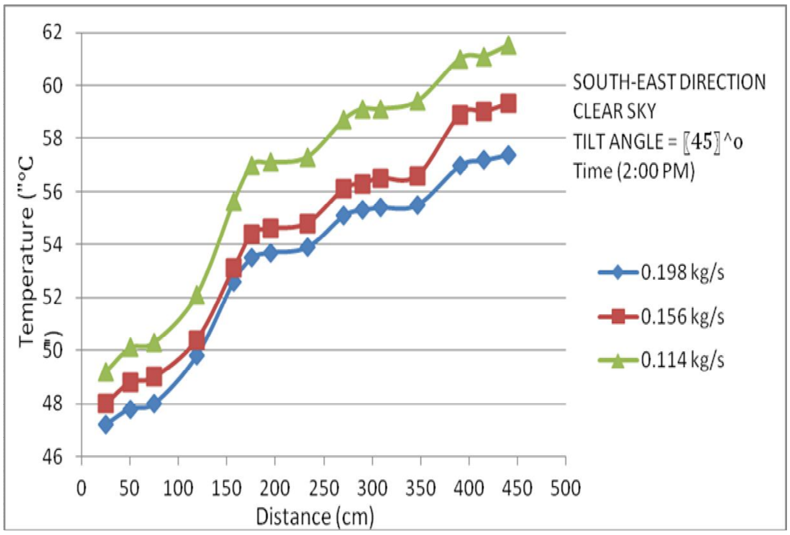

Figure (12) Effect of Mass Flow Rate on the Air Temperature

Fig (13) shows the variation of the local air temperature as it flows through the air duct with and without porous material stuffing and for almost the same inlet air temperature. From this figure, it can be seen that the temperature growth with the addition of the porous material is higher than that without the porous material.This is due to the increase in the area of heat transfer from the addition of the porous material.

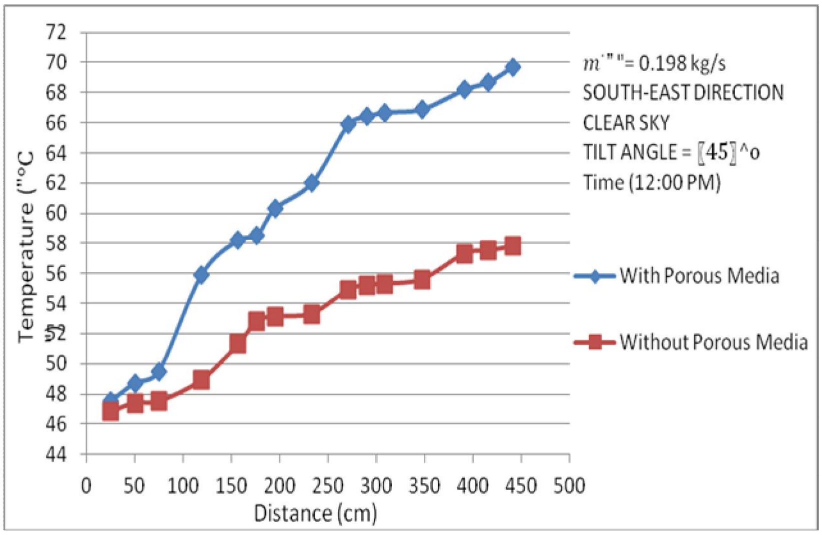

Figure (13) Air Temperature Growth with and without Porous Media

Fig (14) shows the drop between the exit pressure and the atmospheric pressure with porous media and for different air mass flow rates. From this figure, it can be seen that the pressure drop increases with increase in the air mass flow rate because, and according to Bernoulli's principle, for a constant area duct the increase in the air velocity increases the friction losses which makes the air require more force to be pushed through the air channel and this force equals the pressure multiplied by the area of the duct.

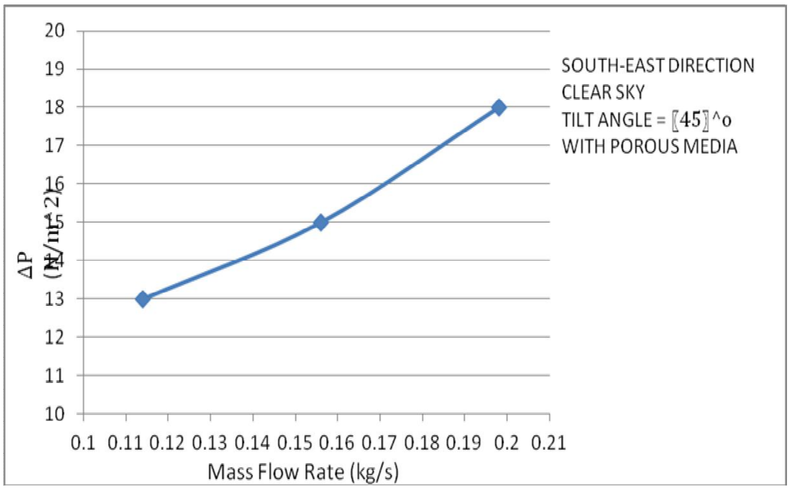

Figure (14) Effect of Mass flow Rate on the Pressure Drop

Fig (15) shows the variation of the efficiency with mass flow rate. The efficiency values of this figure are calculated from equation (1).By observing this figure,it can be seen that the thermal efficiency of the collector increases with the increase in the air mass flow rate.

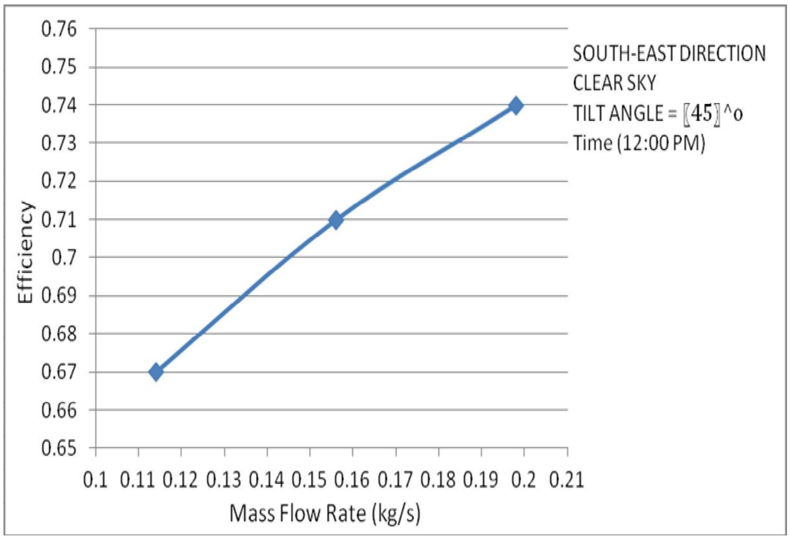

Figure (15) Effect of Mass Flow Rate on the Efficiency of the Collector

Fig (16) shows the thermal efficiency of the collector with and without porous media. The efficiency values of this figure are also calculated from equation (1). From this figure, it can be seen that the thermal efficiency of the collector increased with the addition of the porous material due to the increase in the outlet air temperature that resulted from the increase in the heat transfer area.

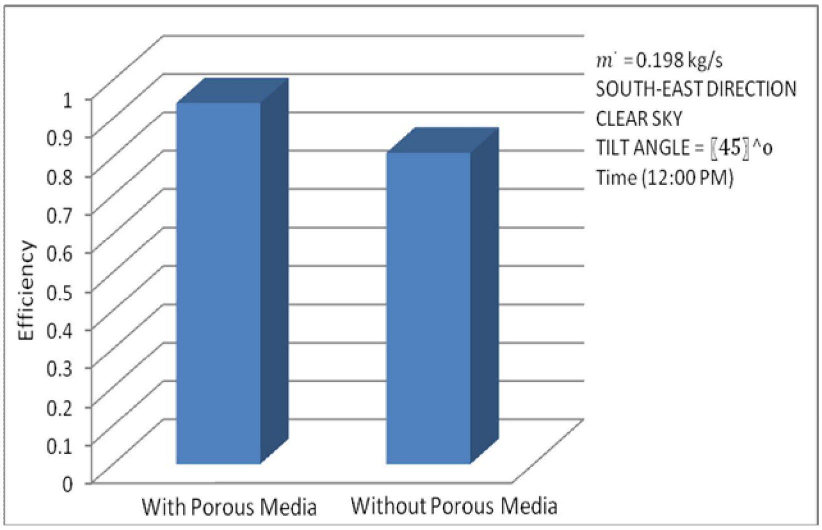

Figure (16) Effect of Porous Media on the Efficiency of the Collector

Fig (17) shows the performance curve of the collector. The efficiency values in this curve are calculated from equation (4).From this figure two points of interest can be noticed. The first point is called the maximum collection efficiency which is the intersection with the y-axis and results when ($T_{ab} = T_a$),this makes $f_c = 0$ and the heat transfer between the absorber and the ambient air stops. The second point is the intersection with the x-axis which occurs when the fluid flow through the collector stops.

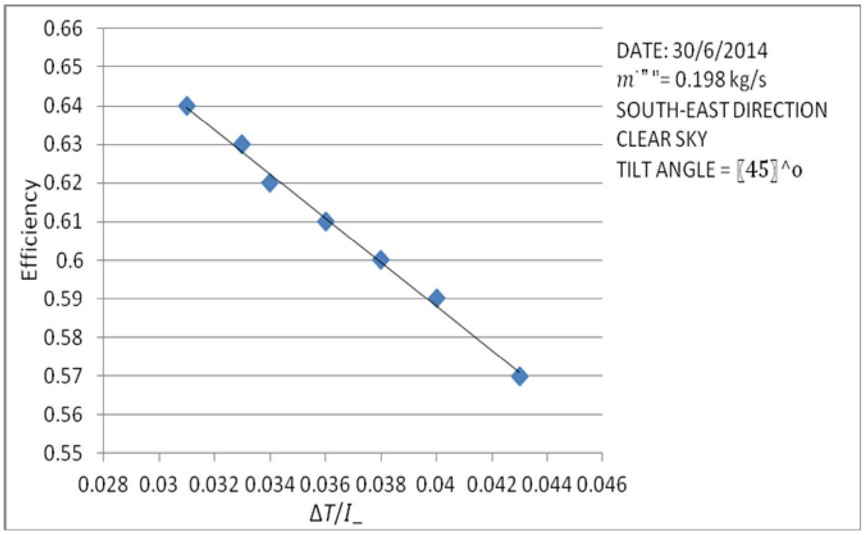

Figure (17) Performance Curve of the Collector

VIII. Conclusions

The following conclusions have been drawn from the results of the present study:

1. The absorber plate temperature and the outlet air temperature increase with time until the solar noon is reached, after that both temperatures start decreasing.
2. The upper plate temperature is higher than the lower plate temperature for all the locations of the air duct.
3. The temperature of the air decreases with the increase in the mass flow rate.
4. Adding a porous material inside the air duct increases the temperatures of both the air and the absorber.
5. Adding a porous material inside the air duct increases the efficiency of the collector.
6. The efficiency of the collector increases with the increase in the air mass flow rate.

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