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EXPERIMENTAL STUDY ON DOUBLE PASS SOLAR AIR HEATER WITH MESH LAYERS AS ABSORBER PLATE

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ABSTRACT

The double pass solar air heater is constructed and tested for thermal efficiency at a geographic location of Cyprus in the city of Famagusta. The absorber plate was replaced by fourteen steel wire mesh layers, 0.2 × 0.2 cm in cross section opening, and they were fixed in the duct parallel to the glazing. The distance between each set of wire mesh layers is 0.5cm to reduce the pressure drop. The wire mesh layers were painted with black before installing them into the collector. The obtained results show that as the mass flow rate increases, the efficiency of the system also increases. The temperature difference (ΔT) between the inlet and outlet air through the system increases as the mass flow rate decreases. The maximum ΔT (53°C) is achieved at the flow rate of 0.011 kg/s. The range of the mass flow rate used in this work is between 0.011 and 0.037 kg/s. It is also found that the average efficiency obtained for the double pass air collector is 53.7% for the mass flow rate of 0.037 kg/s.

keywords: SOLAR AIR HEATER, PACKED BED, THERMAL EFFICIENCY.

1. INTRODUCTION

Solar air heater is a simple device that heats air by utilizing solar energy from the sun. Its wide range of applications involves drying of agricultural products, such as seeds, fruits, vegetables and space heating [1]. Also, solar air heaters are used as pre heaters in industries and as auxiliary heaters in buildings to save energy during winter times [2] Conventional solar air heaters mainly consist of a panel, insulated hot air ducts, a glass cover and air blowers if it is an active system. The panel consists of an absorber plate which is placed inside the hot air duct. The hot air duct is made from either wood or other metallic and non-metallic materials. This is thermally insulated from the bottom and all the sides are also insulated. A glass or plastic cover is fixed above the absorber plate to form a passage for air flows. There are different factors affecting the air heater efficiency, these include collector length, collector depth, type of the absorber plate, glass cover, wind speed, inlet temperature, etc. Among all, the collector glass cover and the absorber plate shape factor are the most important parameters in the design of any type of air heater [3]. The heat transfer

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coefficient between the air stream and the absorber plate is an important factor in solar air heaters. The air heater will have low thermal efficiency as a result of a low heat transfer coefficient between the absorber plate and the air flow.

A solution to this problem is to modify the absorber plate. Different adjustments on the absorber part of the air heater were done by researchers to increase the thermal efficiency of the solar systems. Using fin on the absorber plate [4], adding porous material inside the collector [5], or making a cross-corrugated absorber plate [6]are the samples of these modifications. The thermal performance of a single and double pass solar air heater with fins attached and using steel wire mesh layers as absorber plate was investigated experimentally by A.P. Omojaro and Aldabbagh [3]. For the single pass solar air heater, they were used seven steel wire mesh layers and the range of the air mass flow rate was between 0.012 kg/s and 0.038 kg/s. Also the distance between the glass and the bottom of the collector, was 7 cm. According to their study the maximum efficiency obtained for this single pass air heater was 59.62% for air mass flow rate of 0.038 kg/s. To achieve high thermal efficiencies and reducing heat losses from the cover, a novel solar air collector of pin-fin integrated absorber was designed by [7]. In their design the gap between the glazing and the absorber plate was 5cm. According to their experimental results, the average thermal efficiency of pin-fin arrays collector reaches 50–74% compared to the solar transmittance of 83% for the glazing, for the air volume flow rate of 19m3/h. The investigations on a packed bed solar air heater having its duct packed with blackened wire screen matrices of different geometrical parameters (wire diameter and pitch) were performed by Mittal and Varshney [8] and their resulting values of effective efficiency clearly indicate that the thermal gain of packed bed collectors is relatively higher as compared to smooth collectors, although the pressure drop across the duct increases significantly. A single-glazed solar matrix air collector was tested by Kolb A. et al. [9].

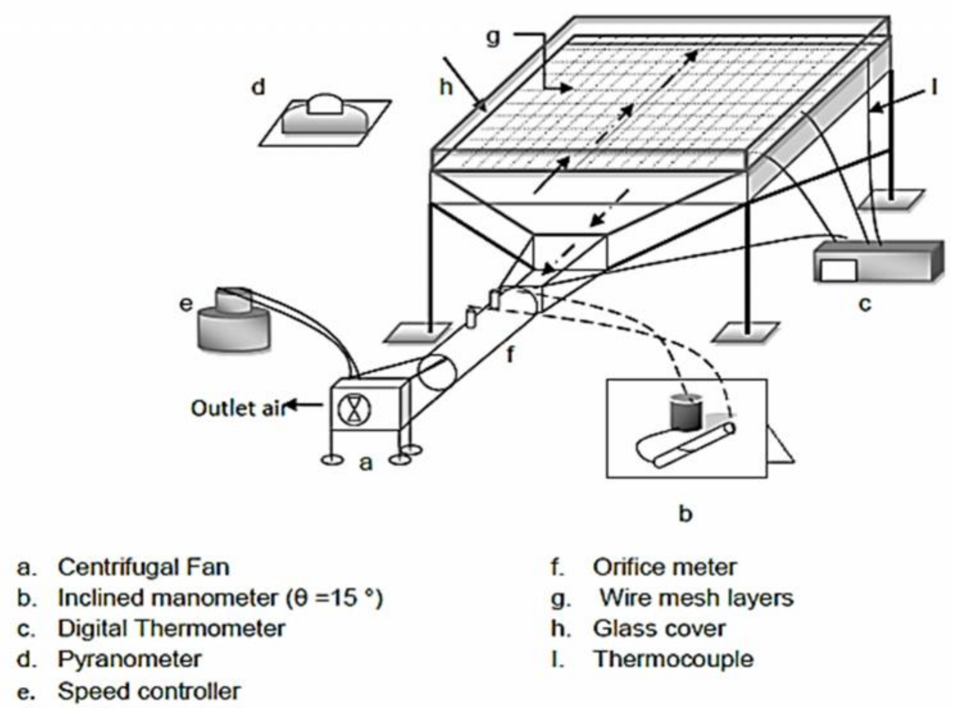
Their collector consists of two parallel sheets of black galvanized industrial woven, fine-meshed wire screens made of copper. Their results show that at the duct height of 4 cm and mass flow rate of 0.04 kg/s, the thermal efficiency of the solar air heater is around 70%. Ho-Ming Yeh et al. [10] has designed a solar air heater in which the absorber plate was constructed with fins and the fins have been attached by the baffles to create turbulence and extend the heat transfer area. In their work, the distance between the second glass and the absorber plate was 5.5 cm and they were found that the collector efficiency of baffled solar air heaters is larger than that of flat plate heaters without fins and baffles. The thermal performance of cross-corrugated solar air collectors was studied by [6]. The cross-corrugated collectors consist of a wavelike absorbing plate and a wavelike bottom plate, which are crosswise positioned to form the air flow channel. In their study, the mass flow rate ($\dot{m}$) changes in the range of 0.001- 0.25 kg/m2s. Their results show that the efficiencies of collectors increase monotonically and dramatically with $\dot{m}$, therefore, to achieve a better thermal performance of the solar air collectors it is essential to maintain a higher air mass flow rate. Several configurations of copper screen meshes were investigated experimentally by [5]. They were found that the overall heat transfer depends on porosity and surface area density.

The aim of this study is to investigate experimentally the efficiency of a double pass solar air heater with porous media acting as an absorber plate. The length and the width of the collector are 150cm and 100cm, respectively. The distance between the first glass cover, and the bottom of the collector (duct height), is 3cm and the distance between the two covers is 2cm. The porous media in this system consists of steel wire mesh layers arranged in a way to give low pressure drop across the collector.

2. EXPERIMENTAL SET-UP AND EQUIPMENT

The experimental work on the double pass solar air heater was conducted at a geographic location of Cyprus in the city of Famagusta. The schematic view of the constructed solar air collector is shown in Figure 1. The collector length and width were 150cm and 100cm respectively. The distance between the first glass cover and the bottom of the collector, duct height, was 3cm and the distance between the two covers is 2cm. The frame of the solar collector was made from plywood of 1.8 cm in thickness and the whole frame was painted with black. To minimize the heat losses, the sides and bottom of the frame were insulated with 3cm thick Styrofoam. Normal window glass of 0.4cm thickness was used as glazing. Fourteen steel wires mesh layers, 0.2 × 0.2 cm in cross section opening and 0.025cm in diameter, were fixed in the collector parallel to the glazing. The wire meshes are actually the ordinary wire screens which everyone uses on the windows in order to prevent the winged insects to enter the house. The wire meshes which are used in our collector are similar to the ones which were used by [3, 4 and 11]. The arrangement of the wire mesh layers is as follows:

6 wire mesh layers were attached to each other, as one matrix, and placed at the bottom of the collector, 5 more layers were attached with each other and placed at the middle and the last 3 meshes were connected to each other and located on top of the other layers. The distance between the three sets of wire meshes were fixed to be 0.5 cm. Moreover, 0.5cm spacing was left between the cover and the upper layers. In order to increase the absorptivity of the wire mesh layers, they were painted with matt black before being installed into the system. There was no need for absorber plate since the wire mesh layers were acting as an absorber plate and as a result the cost of the solar air heater were reduced significantly because the wire mesh is really cheap and it is always available in the market. In addition, the new arrangement of the wire mesh layers in the collector which gives high porosity, $\Phi = 0.83$, will reduce the pressure drop through the collector. In order to get a uniform flow through the orifice meter, two flow straighteners, made from plastic straw tubes of 0.46 cm in diameter and 2 cm length, were fixed before and after the orifice meter. The orifice meter was designed according to Holman J.P. [12] and installed in the pipe with diameter of 8 cm. The pipe was placed between the converging section of the collector and the single inlet Centrifugal fan. The fan type was OBR 200 M-2K. The pressure difference through the orifice was calculated by using an incline tube manometer of 15° angle. In order to increase the accuracy of the inclined manometer, a low density fluid such as alcohol (803 kg/m^3) was used in the tests. Different air mass flow rates can be achieved by using a speed controller.



The speed controller was connected to the fan to allow the user to adjust the speed on the desired value. The air was entered to the collector through the upper channel (2cm) and then was entered to the lower channel (3cm) through 100 cm^2 opening, made on the top side of the first glazing as shown in Figure 1. T-type thermocouples were used to measure the air temperatures at the inlet, outlet, and different places inside the solar collector. Three thermocouples were located at the beginning of the pipe, before the orifice meter, in order to measure the outlet temperature, T_{out}, of the air. The inlet temperature (ambient temperature), T_{in}, was measured by three more thermocouples which were placed underneath the collector. A Ten-channel Digital Thermometer (MDSSi8 Series digital, Omega, ±0.5°C accuracy) was used to record the temperature readings. Three thermocouples were also placed at the top, middle and bottom of the first glazing and the bed (inside the wire mesh layers) to record their temperatures at different hours of the day. The incident solar radiation on the collector glazing was measured hourly with an Eppley Precision Spectral Pyranometer (PSP). An instantaneous solar radiation meter model HHM1A digital Omega, 0.25% basic dc accuracy with the resolution of ±0.5% from 0 to 2800 Wm-^{2} was coupled to the PSP. The solar collector was faced toward south in order to receive the maximum radiation and its tilt angle was fixed at 39.5° according to the geographical location of Cyprus (35.125^{o}N and 33.95^{o}E longitude).

The tests were started at 8 AM and ended at 5 PM. The outlet and inlet temperatures of the air, the ambient temperature, the bed and the glazing temperatures were recorded hourly at each experiment. Also the solar radiation and the incline tube manometer reading were read as well. Wind speed and humidity values were taken hourly from the Northern Cyprus Department of Meteorology's webpage.

3. UNCERTAINTY ANALYSIS

The uncertainty of the air mass flow rate and the thermal efficiency are demonstrated in this section. The mass flow rate (ṁ), is calculated by equation (1),

$$\dot{m} = \rho \qquad (1)$$

where, ϱ is the density of air and Q is the air volume flow rate. The pressure difference at the orifice, which is measured from the inclined tube manometer, is used to find the volume flow rate.

The fractional uncertainty, ωṁ/ṁ, for the mass flow rate is calculated according to [12, 13]:

$$\frac{\omega_{\dot{m}}}{\dot{m}} = \left[\left(\frac{\omega_{T_{air}}}{T_{air}}\right)^2 + \left(\frac{\omega_{\Delta P}}{\Delta P}\right)^2\right]^{1/2} \qquad (2)$$

where, Tair is the film air temperature between the outlet and inlet.

The ratio of energy gain to solar radiation incident on the collector plane is the efficiency of solar collector, η, and is:

$$\eta = \frac{\dot{m}c_P\left(T_{out} - T_{in}\right)}{IA_c} \qquad (3)$$

where, ṁ is the air mass flow rate, cp is the specific heat of the fluid and AC is the area of the collector. According to Eq. (3), the fractional uncertainty for efficiency, ωη/η, is a function of ΔT, ṁ, and I. cp and AC are considered to be constant.

$$\frac{\omega_\eta}{\eta} = \left[\left(\frac{\omega_{\dot{m}}}{\dot{m}}\right)^2 + \left(\frac{\omega_{\Delta T}}{\Delta T}\right)^2 + \left(\frac{\omega_I}{I}\right)^2\right]^{1/2} \qquad (4)$$

For the double pass air heater, the mean value of all variables for each day was calculated separately. Then, the mean value (of the variable mean values) for all the days was obtained separately and used to calculate the fractional uncertainty. The fractional uncertainty of the mass flow rate and the efficiency are found to be 0.0033 and 0.0079, respectively.

4. RESULTS AND DISCUSSION

The performance analysis of the double pass solar air heater is done experimentally in the city of Famagusta, 35.125°N and 33.95°E longitude, which is located in Cyprus. The tests are performed in August 2011 with clear sky condition. The thermal efficiency of the solar air heater with wire mesh layers as absorber plate and small duct height of 3cm, at different mass flow rates is studied. The mass flow rate of the air was varied from 0.011 to 0.037 kg/s.

The solar intensity versus standard local time of the day for different days and various mass flow rates are shown in Figure 2a. The highest daily solar radiation obtained with double pass solar air collector, which was at the mass flow rate of 0.024 kg/s, was 1092 W/m2 at 13:00 h. The mean solar intensity for each day is calculated and it is found that all mean averages are within the close range and it shows that a stable amount of solar radiation measured for each day of the experiment. The average solar intensity for

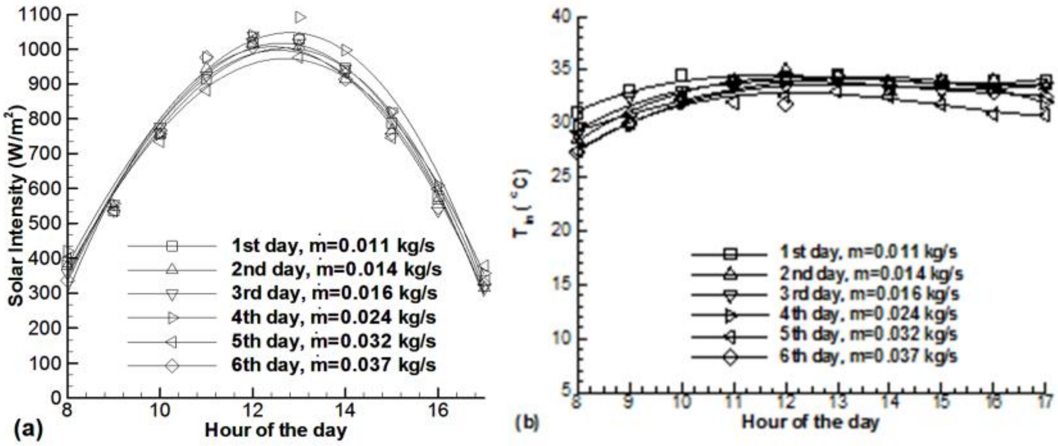


Figure 2: Solar intensity versus time of the day (a), ambient temperatures versus time of the day (b), for different mass flow rates of air at different days.

all days of experiment was about 730.3 W/m2.

The inlet ambient temperature, Tin, versus time of the day for all the days in which the experiment was carried out is presented in Figure 2b. In general, the input temperature was found to be increasing from the morning to evening with little fluctuation during some of the days.

The temperature differences, ΔT = Tout - Tin, versus time of the day for different air mass flow rates are shown in Figure 3. In general, ΔT decreases with increasing air mass flow rate. Moreover, the temperature difference was increasing from morning to a peak value at noon and then was decreasing in the afternoon until sun sets, in a similar manner as the solar radiation. The maximum temperature difference was about 53°C at 14:00h and it was obtained at the minimum mass flow rate of 0.011 kg/s. L.B.Y. Aldabbagh et al. [11] was investigated a single pass solar air heater with 10 wire mesh layers as absorber plate. They were found that the maximum value of ΔT was around 27°C at the mass flow rate of 0.012 kg/s.

Efficiency versus time of the day at different mass flow rates of air for the single pass air heater is shown in Figure 4. As the behavior of inlet air temperature, the efficiency for most of the cases was found to be increased with the standard local time of the day from morning until 13:00 PM with slight decrease in the afternoons. The continued increase in the efficiency, not following the solar intensity curve, is due to the increase in the inlet air temperature and the energy stored in the wire mesh layers. The average efficiency for the double pass solar air heater is 53.7% at $\dot{m}$=0.037 kg/s. Generally the thermal efficiency increased as the air mass flow rate was increased.

El-Sebaii et al. [14] Indicated that the thermal efficiency increases with increasing the mass flow rate until a typical value of $\dot{m}$ = 0.05 kg/s beyond which the increase in thermal efficiency becomes insignificant. [14, 15] recommended to operate the system with or without the packed bed, with the mass flow rate of 0.05 kg/s or lower to have a lower pressure drop across the system and a reasonably high thermal efficiency, more than 70%.

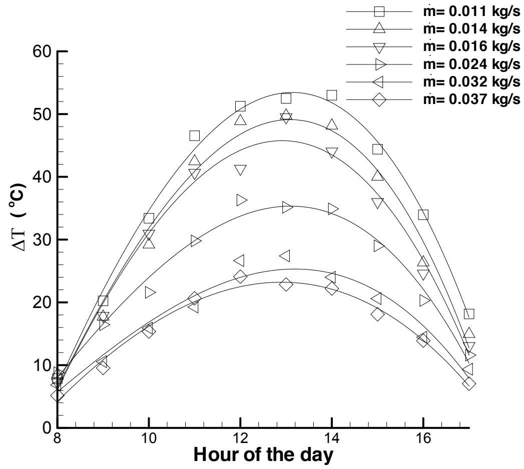


Figure 3: The outlet and inlet air difference (ΔT) versus time of the day for various mass flow rates.

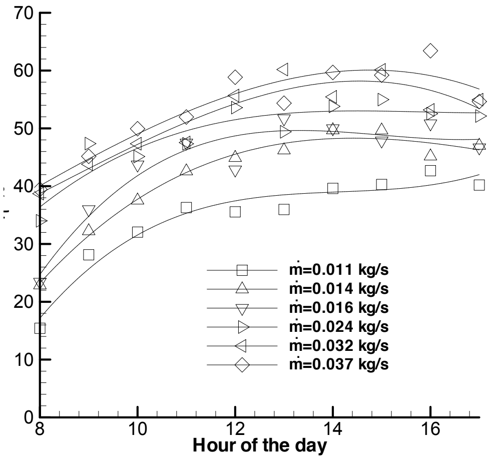


Figure 4: Efficiency versus time for different temperature mass flow rates of air.

Comparison of the results of a packed bed collector with those of a conventional collector shows a substantial enhancement in the thermal efficiency. Generally, increasing the spacing between the bed and the glass cover reduces the average flow velocity and decreases the heat transfer coefficient. Moreover, using small depth channel will also reduce the pumping power. But on other hand the porous media, increase the pressure drop, which becomes important at high volume flow rates of air. Hence, the spacing of the pass channel has a significant effect on the performance of the solar air heater. The effect of changes in the channel depth on the thermal efficiency, with and without the porous media was studied by [16, 17]. They recommended building collector with an upper channel depth of 3.5cm and lower channel depth of 7cm. [14] recommends using the same height for both upper and lower channel to give higher temperature output when porous media is used along with it.

5. CONCLUSION

The thermal performance of the double pass solar air heater was investigated experimentally at a geographic location of Cyprus in the city of Famagusta. The results of the study showed that the average efficiency obtained by the proposed solar air heater with the porous media instead of an absorber plate and the duct height of 3cm, was 53.7% at air mass flow rate of 0.037 kg/s. It was found that increasing the mass flow rate has opposite effect on the temperature differences. The thermal efficiency increased as the air mass flow rate increased but, the temperature difference between the inlet and outlet air, ΔT, decreased due to increasing the mass flow rate. Also it was seen that as the solar intensity, I, increases during a day the temperature differences also increases. The measured average solar intensity for all the days of the experiment was 730.3 W/m2 and the input temperature was found to be increasing from the morning to evening with little fluctuation.

NOMENCLATURE

cP	Specific heat of air, kJ/kg.K
E	East
$\dot{m}$	Mass flow rate of air, kg/s
N	North
ΔP	Pressure difference, N/m2
Q	Volume flow rate, m3/s
Tin	Inlet temperature of air, °C
Tout	Outlet temperature of air, °C
ΔT	Temperature difference (Tout - Tin), °C

Greek Letters

ϱ	Density, kg/m3
η	Thermal efficiency
I	Intensity of solar radiation, W/m2
Φ	Porosity
$\omega\dot{m}$	Uncertainty for the mass flow rate
ωη	Uncertainty for the thermal efficiency

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