Sādhanā Vol. 42, No. 9, September 2017, pp. 1585–1593
DOI 10.1007/s12046-017-0711-z

Experimental study on a solar air heater with various perforated covers

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MS received 20 April 2015; revised 29 September 2016; accepted 19 January 2017; published 8 August 2017

Abstract. In this study, the thermal performances of single- and counter-flow solar air heaters with a normal cover and with quarter- and half-perforated covers were investigated experimentally. In this work, on two of the perforated covers, the holes were made in the first quarter at the top side of the covers. As for the other two covers, half of the cover area on the top side was perforated. The hole diameter, *D*, was 0.3 cm. The holes in the covers had a centre-to-centre distance of 20*D* (6 cm) or 10*D* (3 cm). It was found that the efficiency of the air heater with the quarter-perforated cover was slightly higher than that of the one with the half-perforated cover for both single- and counter-flow collectors. The average efficiencies of the double-pass solar collector with 20*D* and 10*D* quarter-perforated covers were 51.38% and 54.76%, respectively, and the ones for the collector with 20*D* and 10*D* half-perforated covers were 48.21% and 51.17%, respectively, at mass flow rate of 0.032 kg/s. At the same mass flow rate, the average efficiency of the double-pass air heater with normal cover was 50.92%.

Keywords. Perforated cover; solar air heater; wire mesh layers; thermal efficiency.

1. Introduction

For the utilization of solar thermal energy, solar collectors are widely used in different equipment. Solar air heaters are inexpensive due to their simple design and are mostly used in solar energy collection devices [1]. A simple operation mechanism, low construction cost, and utilization of both direct and diffuse solar radiation are the advantages of flat-plate collectors.

Flat-plate solar air heaters utilize solar energy to heat air. The low heat transfer coefficient between the air and the absorber plate reduces the thermal efficiency of solar air heaters. Another reason for the low thermal performance of solar air heaters is the heat losses through the top cover (glazing), as all the sides and the bottom of the collector are thermally insulated. Various studies have been performed in order to increase the thermal performance of the solar collectors by modifying the absorber plate configuration. Making a cross-corrugated absorber plate [2], putting porous material inside the collector instead of the metal sheet [3] or adding fins on the absorber plate [4] are a few examples of these modifications.

In another study by Yeh *et al* [5], an absorber plate was constructed with fins and baffles on it to create turbulence and extend the heat transfer area. The distance between the absorber and the lower glass was 5.5 cm, and the results proved that the baffled solar air heater had better efficiency compared with the conventional air heaters.

A cross-corrugated solar air collector with two wavelike plates was studied by Wenxian *et al* [2]. In their study, the mass flow rate ranged between 0.001 and 0.25 kg/m^2s and it was concluded that a higher thermal efficiency can be reached at higher air mass flow rates.

Mittal and Varshney [6] investigated a packed bed solar air heater whose duct was packed with wire screen matrices of different geometrical parameters. The resulting values of effective efficiency indicated higher thermal gain with packed bed collectors compared with smooth collectors. Also, it was found that the pressure drop increased across the collector with wire matrices. It was previously proved [7] that a solar collector with a packed bed has higher efficiency compared with a conventional one with a normal absorber plate.

Cordeau and Barrington [8] examined an unglazed solar air pre-heater consisting of a perforated corrugated siding and found that the efficiency of the unglazed solar air heater depended on the wind velocity. An experimental study of a rectangular duct with perforated baffles was performed by Rajendra *et al* [9]. They examined baffles with various open area ratios and found that those with an open area ratio of 46.8% gave the best performance. In a study by Velmurugan and Kalaivanan [10], for different types of solar air

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heaters the effects of various mass flow rates and solar intensity on temperature rise of air, energy efficiency, exergy gain and pressure drop at steady-state condition were examined. They found that the temperature rise of air, thermal efficiency and exergy gain depend on mass flow rate, surface geometry of absorber and solar intensity, whereas the pressure drop depends on mass flow rate and surface geometries of absorber. An experimental analysis on a single-pass solar air collector with and without using baffle fins was performed by Chabane *et al* [11]. In this work, the values of Nusselt number were determined for different configurations and operating parameters. In order to find an optimum shape of obstacles attached to a solar air heater, Kulkarni and Kim [12] performed an investigation and found that the pentagonal obstacle shape shows the highest performance regardless of the Reynolds number.

During the last few decades, many numerical and experimental works have been performed by scientists in order to improve the performance of solar air heaters. These works included making a double glazing collector to minimize heat losses through the top cover [13, 14], making a double-pass channel inside the duct where air passes from above and below the absorber plate at the same time [15–17], testing single- and counter-flow air heaters with fins and wire mesh layers [18] and others [19–22] but to the best of our knowledge no experimental investigation analysing the performance of a solar air collector with a partly perforated cover has been reported.

The main purpose of this study is to experimentally investigate the efficiency of a solar air heater with a partially perforated cover. The solar air heater was tested with various quarter- and half-perforated covers, which were made of Plexiglas and had various hole-to-hole spacing distances. In this study, the absorber plate is also replaced by porous media (i.e., wire mesh layers). The height of the duct, that is, the distance between the bottom of the collector and the lower cover, was fixed at 3 cm in order to examine the effect of small duct height on the performance of the solar air heater.

2. Experimental set-up and equipment

The experimental analysis of the single- and counter-flow solar air heaters was conducted in the city of Famagusta in the north of Cyprus. Figure 1 demonstrates a schematic view of the constructed solar air heater. The length and width of the collector were 150 and 100 cm, respectively. The distance between the second cover and the bottom of the collector (duct height) was 3 cm (figure 1a). In the case of the counter-flow collector, the distance between the second cover and the first cover was 2 cm. On removing the first glass, the collector became a single-pass air heater. The frame of the solar collector was made of plywood of 1.8 cm thickness and the whole frame was painted black. To minimize the heat losses, the sides and bottom of the frame were insulated with 3-cm-thick Styrofoam. Fourteen steel wire mesh layers with a cross-section opening of 0.2×0.2 cm^2 and a diameter of 0.025 cm were fixed inside the collector's duct parallel to the glazing. The wire meshes used in this collector were similar to the ones used by El-Khawajah *et al* [4], Omojaro and Aldabbagh [18] and Aldabbagh *et al* [23]. The arrangement of the wire mesh layers was as follows: six wire mesh layers were attached to each other, as one matrix, and placed at the bottom of the collector, five more layers were attached to each other and placed in the middle, and the last three meshes were connected to each other and located on top of the other layers. The distance between the three sets of wire meshes was 0.5 cm. Moreover, 0.5-cm spacing was left between the second glazing and the upper layers. In order to increase the absorptivity of the mesh layers, they were painted black.

The absorber plate was removed since the wire mesh layers acted as an absorber plate and, as a result, the cost of the solar air heater was reduced significantly because the wire mesh is much cheaper than the sheet metal absorber plate and is readily available in the market. In addition, the new arrangement of wire mesh layers in the collector gave high porosity of $\Phi = 0.83$, reducing the pressure drop through the collector.

In this experimental work, specific attention was paid to the cover, as it was known that the major heat loss from flat-plate collectors was through the cover. Therefore, to minimize the heat losses through the cover and to cool it, the normal cover was replaced with the perforated one. In this case the ambient air has two functions: cooling the cover while penetrating through it as well as supplying air to the solar air heater. The velocity of the air is small enough through and around the hole to prevent heat transfer by conduction or convection. To simplify the making of the holes in the cover, transparent Plexiglas was used instead of normal glass. The length, width and thickness of the Plexiglas were 150, 100 and 0.3 cm, respectively. Four different perforated covers were used in the experiments. They differed with respect to the number of holes made in them and the hole-to-hole spacing between the hole centres.

In this work, on two of the perforated covers, the holes were made in the first quarter at the top side of the cover on the opposite side of the outlet flow in an area of 100×36 cm^2 (figure 1b). As for the other two covers, half of the cover area (i.e., 100×72 cm^2) was perforated on the top side (figure 1c). The holes were arranged in line format. The hole diameter, D, was fixed as 0.3 cm. To examine the effect of hole-to-hole spacing on the solar air heater performance, the holes made in one of the quarter-perforated and one of the half-perforated covers had a centre-to-centre distance (d_c) of $20D$ (6 cm); in the other two covers, d_c was $10D$ (3 cm) (figure 1b and c). In the counter-flow solar collector, a normal glass with a thickness of 0.4 cm was used on top of the perforated cover, as the cover of the second channel, to reduce heat losses from the top side of the collector.

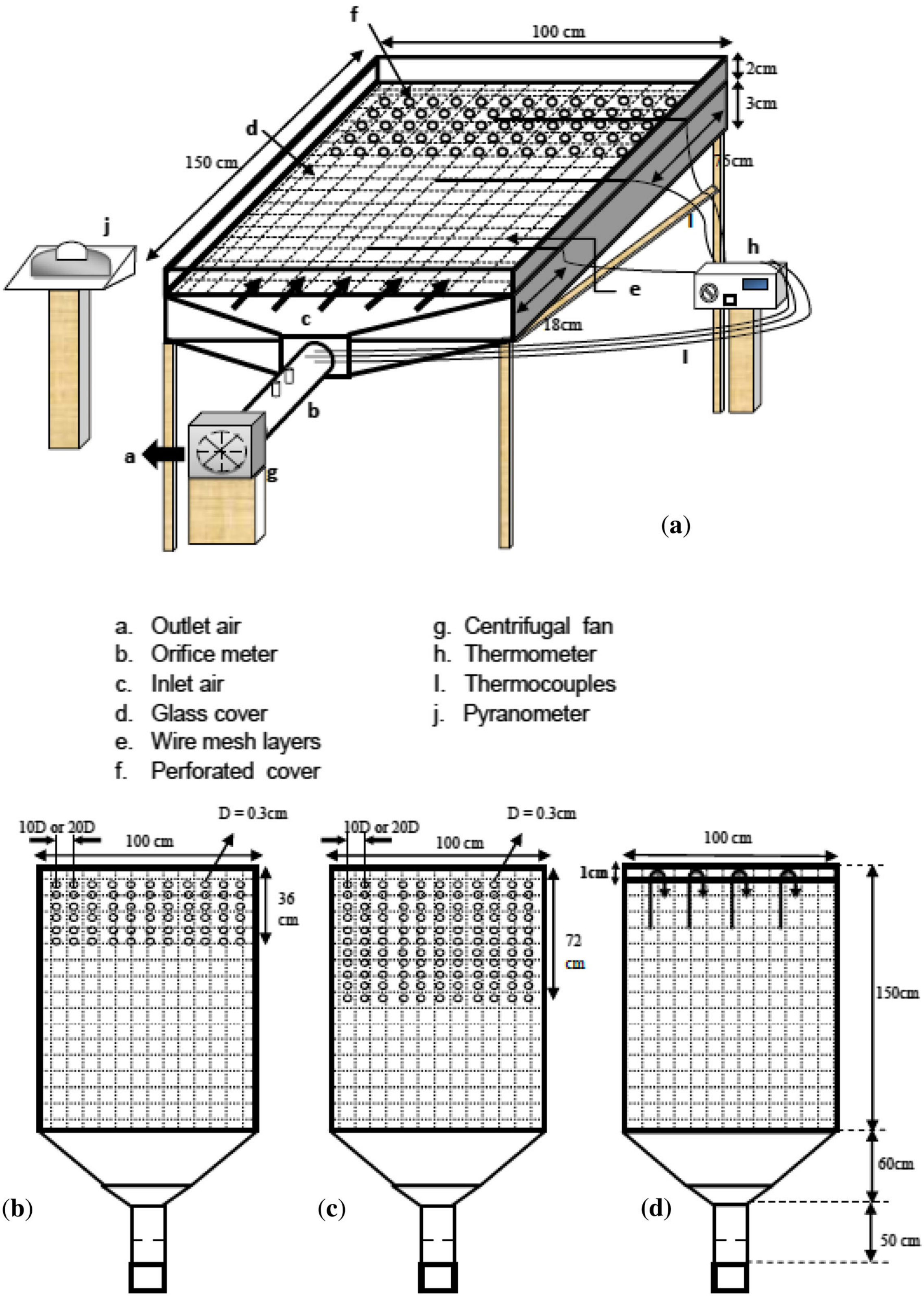

Figure 1. (**a**) Schematic assembly of the manufactured solar air heater with perforated cover. Top views of the solar collector with (**b**) quarter-perforated cover, (**c**) half-perforated cover and (**d**) normal Plexiglas cover.

As the aim was to compare the results obtained for the solar air heater with the perforated cover with those for the heater with the normal cover, the same solar collector was tested with a normal Plexiglas as its glazing. Air entered the collector through an opening made on the top side of the collector as shown in figure 1d. The area of the opening was 100 cm^2.

Flow straighteners were placed before and after the orifice meter to create a uniform flow through it. These straighteners were plastic straw tubes 0.46 cm in diameter and 2 cm in length. The orifice meter was designed according to Holman [24] and placed in a galvanized pipe with a diameter of 8 cm. A calibrated orifice flow meter (Omega) was used to calibrate the one used in this experiment. The correction factor due to calibration was added to the factor used in Eq. (3). The pipe was located between the converging section of the collector and a single-inlet centrifugal fan. The fan type was OBR 200 M-2 K. The pressure difference through the orifice was calculated by an inclined tube manometer with a 15° angle. In order to increase the accuracy of the inclined manometer, a low-density fluid (alcohol with density of 803 kg/m^3) was used. Different air mass flow rates can be achieved using a speed controller. The speed controller was connected to the fan to allow the user to adjust the speed to the desired value. T-type thermocouples were used to measure the air temperatures at the inlet, outlet and different places inside the solar collector and on the glazing. Three thermocouples were located at the outlet of the solar collector inside the galvanized pipe, before the orifice meter, in order to measure the outlet temperature, T_{out}, of the air (figure 1a). The ambient or inlet temperature, T_{in}, was measured by three more thermocouples, which were placed underneath the collector in a perforated box. Three thermocouples were also placed at the top, middle and bottom of the glazing and the bed (inside the wire mesh layers) to record their temperatures hourly throughout the day.

A ten-channel digital thermometer (MDSSi8 Series digital, Omega, ±0.5°C accuracy) was used to record the temperature readings. The solar intensity was measured every hour with an Eppley Precision Spectral Pyranometer (PSP), which was coupled with an instantaneous solar radiation meter (HHM1A digital Omega, with a resolution of ± 0.5% from 0 to 2800 W/m^2). The solar collector faced south in order to receive the maximum radiation and its tilt angle was fixed at 39.5° due to the geographical location of Cyprus (latitude 35.125°N and longitude 33.95°E).

The tests and readings started at 08.00 h and continued until 17.00 h on each day of the experiment. The outlet and inlet temperatures of the air, the ambient temperature and the bed and glazing temperatures were recorded hourly in each experiment. In addition, the solar radiation and the inclined tube manometer reading were read as well. Wind speed and humidity values were taken hourly from the web page of the Northern Cyprus Department of Meteorology.

3. Uncertainty analysis

The percentage uncertainties in air mass flow rate and thermal performance of the solar air heater are calculated according to Esen [15] and Holman [24]. In the calculations, the uncertainties associated with the measurements are considered.

To compute the thermal performance of the solar collector, it is necessary to calculate the air mass flow rate ($\dot{m}$). Air mass flow rate is calculated as follows:

$$\dot{m} = \rho Q \tag{1}$$

where ρ_{air} is the density of air at film temperature ($T_{\mathrm{air}} = \frac{T_{\mathrm{in}}+T_{\mathrm{out}}}{2}$) and Q is the air volume flow rate, which can be found from Eqs. (2) and (3) [24]. The pressure difference through the orifice (ΔP), which is measured from the inclined tube manometer ($\theta = 15°$), is used to find the volume flow rate:

$$\Delta P = gh\left(\frac{A_2}{A_1} + 1\right)(\rho_{\mathrm{alcohol}} - \rho_{\mathrm{air}}) \sin\theta \tag{2}$$

$$Q = CMA_2\sqrt{\frac{2}{\rho}}\sqrt{\Delta P}. \tag{3}$$

The mass flow rate fractional uncertainty, $\omega_{\dot{m}}/\dot{m}$, is calculated as follows:

$$\frac{\omega_{\dot{m}}}{\dot{m}} = \left[{}^1/_4\left(\frac{\omega_{T_{air}}}{T_{air}}\right)^2 + {}^1/_4\left(\frac{\omega_{\Delta P}}{\Delta P}\right)^2\right]^{1/2}. \tag{4}$$

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

$$\eta = \frac{\dot{m}c_P(T_{out} - T_{in})}{IA_c} \tag{5}$$

where I is the solar intensity, c_{P} is the specific heat of the fluid and A_{c} is the area of the collector. According to Eq. (5), the fractional uncertainty of efficiency, ω_η/η, is a function of ΔT, $\dot{m}$ and I. A_{c} is 1.5 m^2 and c_{p} ranges between 1.007 and 1.008 kJ/kg°C.

$$\frac{\omega_\eta}{\eta} = \left[\left(\frac{\omega_{\dot{m}}}{\dot{m}}\right)^2 + \left(\frac{\omega_{\Delta T}}{\Delta T}\right)^2 + \left(\frac{\omega_I}{I}\right)^2\right]^{1/2}. \tag{6}$$

The percentage uncertainties in mass flow rate and thermal efficiency are calculated to be 1.43% and 2.8%, respectively.

4. Results and discussion

A solar air heater with various configurations was constructed and examined in the city of Famagusta (latitude 35.125°N, longitude 33.95°E) in Cyprus. Different arrangements, including changing the cover of the solar collector, were set up in order to examine the effect of a perforated cover on the performance of the solar collector. Four different perforated covers made of Plexiglas were used in the tests. The holes were made in the first quarter at the top side of two perforated covers in an area of 100×36 cm^2. As for the other two covers, half of the cover area (i.e., 100×72 cm^2) on the top side was perforated. No holes were located near the outlet or in the lower half side of cover. Cold ambient air entering from the lower side of the cover has no time to carry heat from the bed, due to the small path, but it may reduce the temperature of the outlet air as it mixes with it. As a result, the thermal performance of the collector may decrease. The hole diameter, D, was 0.3 cm. The holes made in one of the quarters and one of the half-perforated covers had a centre-to-centre distance (d_c) of 20D (6 cm); in the other two covers, d_c was 10D (3 cm). The solar air collector was also tested with a normal Plexiglas cover in which air entered the collector through an opening made in the top side of the cover. The area of the opening was 100 cm^2. All the different covers were examined in both a single- and a double-pass solar air collector in order to find the best arrangement leading to the highest thermal performance. The tests were performed in summer time under clear sky conditions. The mean value of wind speed as measured hourly during all days of the experiment was 4.86 m/s. The thermal efficiencies of all of the different arrangements of the solar air heater with wire mesh layers as the absorber plate and a small duct height of 3 cm were studied at two different air mass flow rates (0.011 and 0.032 kg/s).

The highest daily solar radiation was 1155 W/m^2 and was measured on a single-pass solar air heater with a normal Plexiglas cover at 13:00 h. A similar amount of solar radiation (1134 W/m^2) was also measured at 13:00 h, when the single-pass solar collector with the 10D quarter-perforated cover was tested. The average solar intensity on the single- and double-pass solar air heaters with a packed bed and normal Plexiglas cover was 740.2 and 709.3 W/m^2, respectively, during all days of the experiment. For the single- and double-pass collectors with quarter-perforated covers, the mean solar intensities on all days were 715.8 and 724.5 W/m^2, respectively, while for the single- and double-pass collectors with half-perforated covers, they were measured as 708.7 and 690.6 W/m^2, respectively. It was found that all the average values of solar intensity were within a close range during the experiment.

In general, the ambient temperature increased during the day and a slight reduction occurred at 17.00 h; a small fluctuation also happened on some of the days depending on the wind speed of that day. The average ambient temperature for single- and double-pass solar air heaters with a packed bed and normal Plexiglas cover was 33.7 and 35.42°C, respectively, during all days of the experiment.

For the single- and double-pass collectors with quarter-perforated covers, the mean inlet temperatures of all days were 28.09 and 25.2°C, respectively, while for the single- and double-pass collectors with half-perforated covers, they were measured as 35.19 and 35.7°C, respectively. As for the solar intensity, the average values of inlet temperature were also within a close range during the experiment.

The temperature difference between the outlet and inlet air, $\Delta T = T_{out}–T_{in}$, versus time of day at two different air mass flow rates for single- and double-pass glass solar air collectors with a normal Plexiglas cover and with quarter- and half-perforated covers is shown in figure 2a–d. It is found that the solar air heater with the quarter-perforated cover reaches a higher ΔT than the half-perforated or normal Plexiglas cover. The temperature differences of both single- and double-glass solar collectors with either quarter- or half-perforated covers at low mass flow rate ($\dot{m} = 0.011$ kg/s) were higher than those with the normal Plexiglas cover. Only the single-pass collector with a 10D half-perforated cover (figure 2a) showed a lower ΔT than the one with the normal Plexiglas cover. The reason for this can be explained as follows. Air enters the collector through the upper holes and absorbs heat from the mesh layers as it propagates inside the collector. This happens at the time at which hot air reaches the holes close to the middle of the collector, and ambient air of lower temperature enters the collector and mixes with the hot air that comes from the top side of the bed. As a result, the whole air temperature decreases. In case of the double-pass collector, the low temperature ambient air is preheated in the upper channel before it enters the lower channel via the holes, and as a result, ΔT increases. The situation is almost the same at $\dot{m} = 0.032$ kg/s but at a higher flow rate, and the obtained results are very close to each other in magnitude. In such a situation, the high-velocity air has insufficient time to carry heat from the bed. The maximum temperature difference obtained with the single-pass air heater with the quarter-perforated cover with a hole-to-hole spacing of 10D (3 cm) was 46.25°C at 13:00 h at $\dot{m} = 0.011$ kg/s (figure 2a). At the same mass flow rate, ΔT increases more when double-glass solar air heater is used. The maximum temperature difference was 52.5°C at 13:00 h when the double-pass collector was tested with the 10D quarter-perforated cover at $\dot{m} = 0.011$ kg/s (figure 2c). Generally, the highest ΔT was obtained at the lowest air flow rate. The maximum ΔT obtained for the counter-flow collector with a normal Plexiglas cover at $\dot{m} = 0.011$ kg/s was 34.8°C at 12:00 h. At the same mass flow rate, the temperature difference for the single- and double-pass solar air heater with the quarter-perforated cover was greater in magnitude than that with the normal Plexiglas cover. The reason is that as air enters the collector through the holes on the cover, it cools the cover and as a result reduces the heat loses through the cover, as mentioned earlier in section 2.

El-Sebaii *et al* [25] investigated a double-pass solar air collector with packed bed iron scraps placed in a channel with a height of 12 cm, and Aldabbagh *et al* [23]

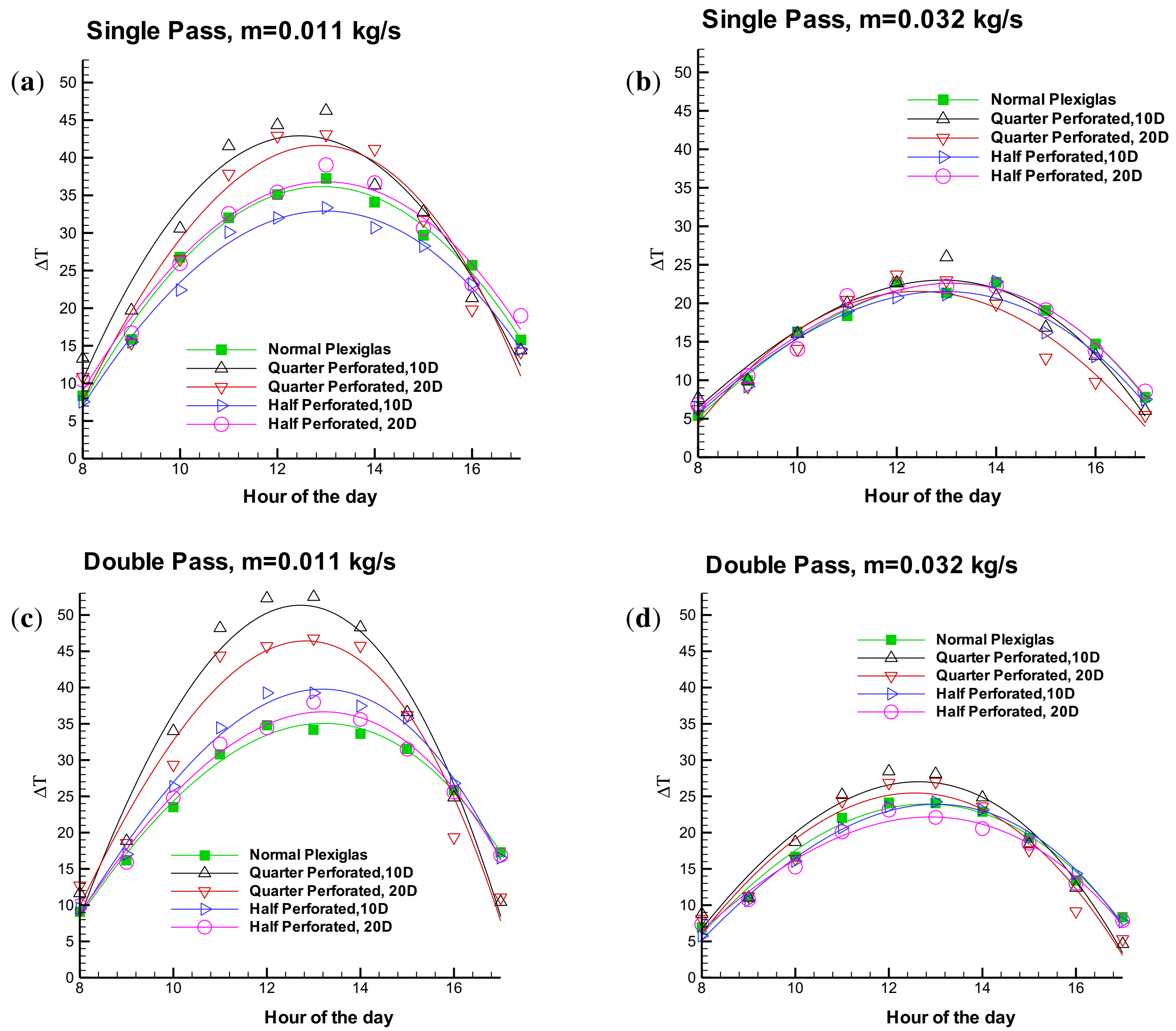

Figure 2. Temperature difference versus time of the day for single- and double-pass solar air collectors with a normal Plexiglas cover and with quarter- and half-perforated covers (10*D* and 20*D*) with (**a**) single pass, $\dot{m} = 0.011$ kg/s, (**b**) single pass, $\dot{m} = 0.032$ kg/s, (**c**) double glass, $\dot{m} = 0.011$ kg/s and (**d**) double glass, $\dot{m} = 0.032$ kg/s.

investigated a single-pass solar air heater with 10 wire mesh layers in a channel with a height of 10 cm, and the maximum values of ΔT obtained by those air heaters were 48°C at $\dot{m} = 0.0105$ kg/s and 27°C at $\dot{m} = 0.012$ kg/s, respectively.

The thermal efficiencies versus time of day at two different air mass flow rates for single- and counter-flow solar air collectors with a normal Plexiglas cover and with quarter- and half-perforated covers are shown in figure 3a–d. In general, at a high air mass flow rate ($\dot{m} = 0.032$ kg/s), thermal efficiency increases from morning until around 13:00 h and then shows a slight decrease in the afternoons. At low $\dot{m}$, the efficiency continues to increase even throughout the afternoon. Similar results were reported by El-Khawajah *et al* [4], Omojaro and Aldabbagh [18] and Aldabbagh *et al* [23]. In all the experiments, thermal efficiency increased as the air mass flow rate increased. The maximum thermal efficiency of the single- and double-pass solar air heaters with a normal Plexiglas cover at the mass flow rate of 0.032 kg/s was found to be 54.62% at 16:00 h and 56.36% at 15:00 h, respectively (figure 3b and d). As shown in figure 3d, at a mass flow rate of 0.032 kg/s, the maximum efficiencies of the double-pass solar collector with 20*D* and 10*D* quarter-perforated covers are 57.60% at 13:00 h and 60.49% at 15:00 h, respectively. At the same $\dot{m}$ and for the same collector with 20*D* and 10*D* half-perforated covers, the maximum values of efficiencies obtained were 52.66% at 12:00 h and 57.93% at 15:00 h, respectively.

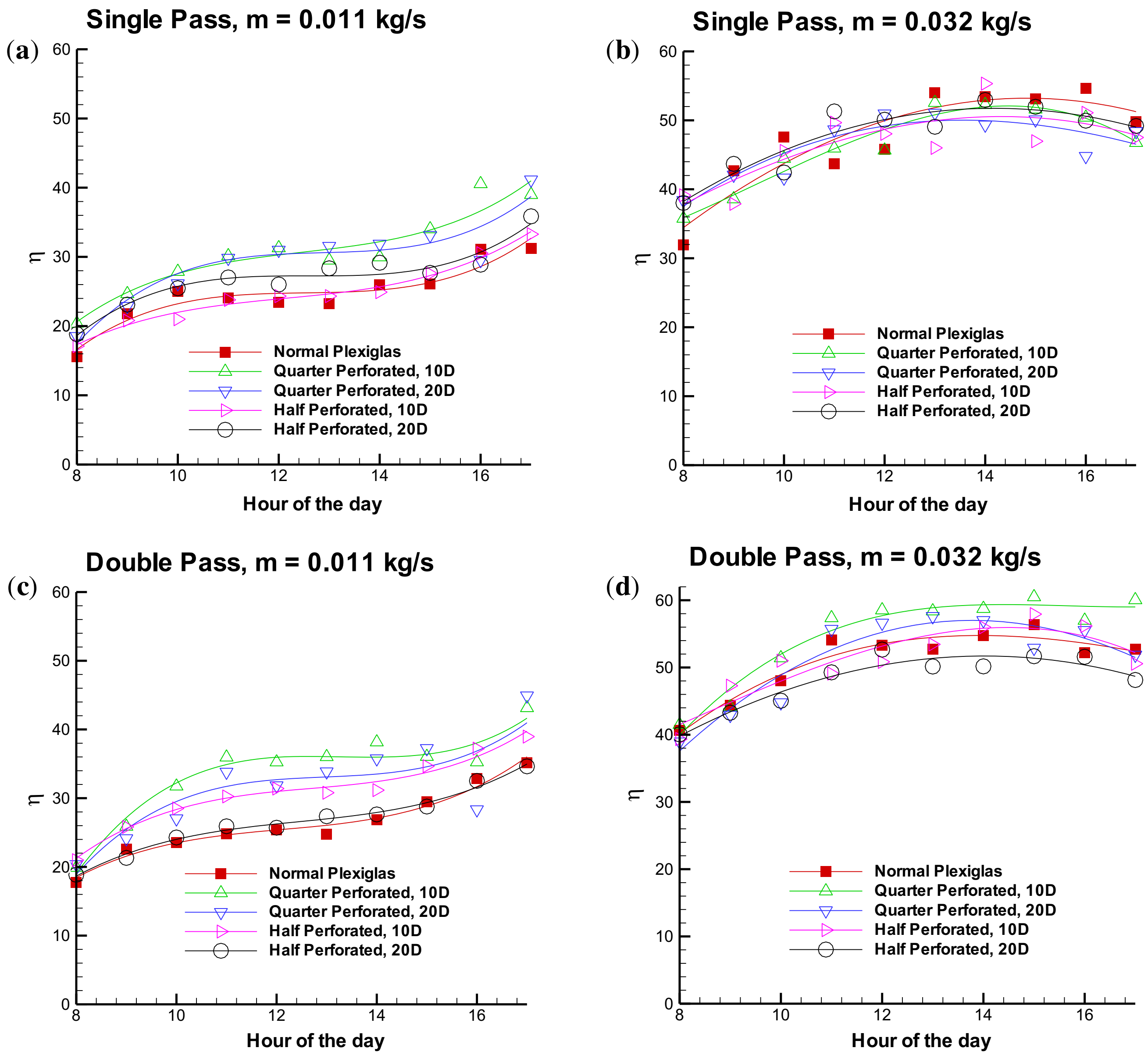

Figure 3. Efficiency versus time of day for single- and double-pass solar air collectors with normal Plexiglas cover and quarter- and half-perforated covers (10*D* and 20*D*) at (**a**) $\dot{m} = 0.011$ kg/s, (**b**) $\dot{m} = 0.032$ kg/s, (**c**) $\dot{m} = 0.011$ kg/s and (**d**) $\dot{m} = 0.032$ kg/s.

The average efficiencies of the single-pass solar collector with 20*D* and 10*D* quarter-perforated covers were 46.54% and 46.40%, respectively, and the ones for double-pass solar collector with 20*D* and 10*D* quarter-perforated covers were 51.38% and 54.76%, respectively, at mass flow rate of 0.032 kg/s. At the same mass flow rate, the average efficiencies of the single-pass solar collector with 20*D* and 10*D* half-perforated covers were 47.86% and 46.72%, respectively, and the ones for double-pass solar collectors with 20*D* and 10*D* half-perforated covers were 48.21% and 51.17%, respectively. The average efficiencies of the single- and double-pass solar air heaters with a normal Plexiglas cover were 47.67% and 50.92% at $\dot{m} = 0.032$ kg/s, respectively.

In the present study, the maximum thermal performance of the solar air heater was obtained with the 10*D* quarter-perforated cover; therefore the thermal efficiency of the air heater with the 10*D* quarter-perforated cover was compared to the thermal performances of various air heaters in the literature and the results are shown in figure 4.

5. Conclusion

An experimental study of single- and counter-flow solar air heaters with different covers and without an absorber plate was conducted in the city of Famagusta in the north of Cyprus. In order to examine the effect of the cover on the

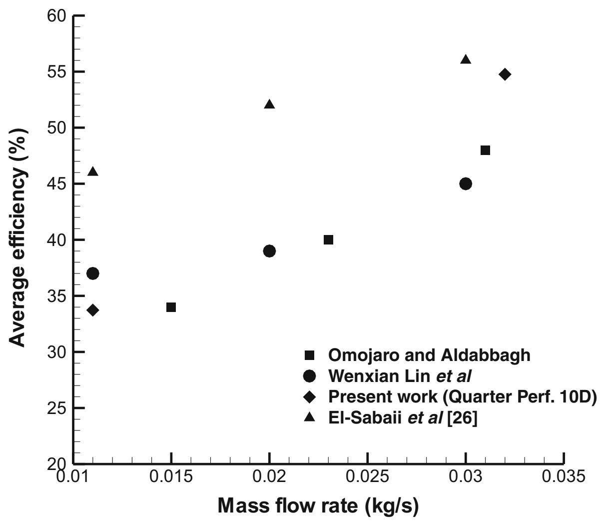

Figure 4. Comparison between the average thermal efficiency of the air heater with a quarter-perforated cover (10*D*) and other published data.

performance of the air heater, the solar collector was tested with a normal cover and also with various quarter- and half-perforated covers.

Four different perforated covers were used in the experiments. In this work, on two of the perforated covers, the holes were made in the first quarter at the top side of the covers. As for the other two covers, half of the cover area on the top side was perforated. The hole diameter (D) was 0.3 cm. The holes made in one of the quarter-perforated covers and one of the half-perforated covers had a centre-to-centre distance (d_c) of 20D (6 cm); in the other two perforated covers, d_c was 10D (3 cm).

It was found that the solar air heater with the quarter-perforated cover reached a higher ΔT (temperature difference between the outlet and inlet air) compared with the ones with the half-perforated or normal Plexiglas covers. The maximum temperature difference obtained from the collector was 52.5°C at 13:00 h when the counter-flow collector was tested with the 10D quarter-perforated cover at $\dot{m} = 0.011$ kg/s. Generally, the highest ΔT was obtained at the lowest air flow rate. The maximum ΔT obtained from the counter-flow collector with a normal Plexiglas cover was 34.8°C at 12:00 h and $\dot{m} = 0.011$ kg/s.

The average efficiencies of single-pass solar collector with 20D and 10D quarter-perforated covers were 46.54% and 46.40%, respectively, and the ones for double-pass solar collector with 20D and 10D quarter-perforated covers were 51.38% and 54.76%, respectively, at mass flow rate of 0.032 kg/s. At the same mass flow rate, the average efficiencies of the single-pass solar collector with 20D and 10D half-perforated covers were 47.86% and 46.72%, respectively, and the ones for double-pass solar collectors with 20D and 10D half-perforated covers were 48.21% and 51.17%, respectively. The average efficiencies of the single- and double-pass solar air heaters with a normal Plexiglas cover were 47.67% and 50.92% at $\dot{m} = 0.032$ kg/s, respectively.

Nomenclature

Latin symbols

A_1	area of manometer container (m^2)
A_2	area of manometer tube (m^2)
CM	flow coefficient
c_P	air specific heat (J/kg K)
g	gravitational acceleration (m/s^2)
h	manometer reading (m)
I	incident solar radiation (W/m^2)
$\dot{m}$	air mass flow rate (kg/s)
ΔP	pressure drop (Pa)
Q	air volume flow rate (m^3/s)
T_{in}	inlet temperature (°C)
T_{out}	outlet temperature (°C)

Greek symbols

η_{th}	thermal efficiency
ρ	density (kg/m^3)
θ	manometer tilt angle (deg)
ω	uncertainty

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