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Effect of conical pin arrangement on heat transfer efficiency of a free convective solar air heater

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ABSTRACT

The artificial roughnesses on absorber plate have been known to enhance the performance of the solar air heater under forced convection. The objective of this paper is to study the effect of conical pin arrangement on the heat transfer enhancement of free convective solar air heater. The conical pins were arranged in-line and in staggered arrangement with the pitch-to-height ratio of eight. The height of the conical pin was fixed at 0.2 cm. The measurement results revealed that the use of conical pin on the surface of absorber plate helped to improve the overall efficiency of the solar air heater. The staggered arrangement of the conical pins performed better compared to the case of the in-line arrangement. The performance of the solar air heater with the staggered arrangement was 42% higher than that of the flat absorber plate with no pins at 435 W/m^2 while the in-line arrangement showed an increase of 28%. Hence, the use of the artificial pin roughening technique with the staggered arrangement is recommended in the free convection solar air heater.

***Keywords**:* Artificial roughness; solar air heater; enhanced heat transfer; pin shape turbulators

INTRODUCTION

Since the past century most of our energy demands have been provided by the burning of different types of fuels, most of which are non-renewable [1]. It is a well-known fact that this type of fuel is not abundant to fulfil the energy demands in future as well as its environmental impact has pushed researchers to venture into other forms of heat sources to fulfil the world energy demands [2, 3]. Therefore, it is very important to harness other sources of renewable energy. The quest to utilize renewable energy has pushed researchers to make the existing structure more energy efficient [4-8]. The solar air heater is one of the many devices used to harness heat energy from the sun. Basically, the solar air heaters consist of an absorber plate and a glass cover connected through walls which either open or close at the ends. The absorber plate collects heat from the solar radiations which pass through the glass cover. The air passed through the heated absorber plate extracts the heat from the surface and thus increase the temperature of air [9]. In order to increase the efficiency of such system, different techniques of heat transfer enhancement have been studied. Heat transfer enhancement is of great importance in many industrial applications such as the gas turbines, heat exchangers, and various cooling devices because the higher heat transfer rate increases system efficiency and reduces thermal load [10]. The concept of heat transfer from a flat surface into the air flowing above it has many uses such as the air heating, fruit drying application or surface cooling application.

Flat plate collectors are commonly used to draw solar energy for various thermal applications [11-14]. The thermal efficiency of a flat plate solar air heater is low because it uses air as a medium to transfer heat. Air has a very low heat transfer coefficient, therefore, an effective method of increasing the heat transfer rate is by introducing artificial roughness [15]. By using small artificial roughness the heat transfer rate is increased but there is a penalty of pressure drop. These artificial roughnesses convert the laminar sub-layer of the flow to turbulent. It was reported that when the transition from laminar to turbulent takes place, the heat transfer rate becomes relatively higher than the one for the laminar flow [16]. The advantage of using these roughnesses over extended fins is that they are small in size and the pressure drop is relatively low, reduces the pumping power required to push the air through the channel. Various shapes, sizes, and arrangement of such artificial protrusion are used in order to increase the heat transfer rate.

Table 1 Roughness geometries used on the absorber plate with forced convection (Experimental results)

Author	**Roughness geometries**	**Remarks (compared to flat plat)**	
		Nusselt number (Nu)	**Friction Factor (F**
Karwa et al.[17]	Chamfered rib roughness	Nu increased by 4.00 folds	FF increased by 5.00 folds
Bhagoria et al.[18]	Wedge shaped ribs	Nu increased by 2.4 folds	FF increased by 5.3 folds
Jaurker et al. [19]	Squared rib groove	Nu increased by 2.70 folds	FF increased by 3.60 folds
Layek et al. [20]	Chamfered rib groove	Nu increased by 2.64 folds	FF increased by 3.35 folds
Kumar et al. [21]	Discreet W-shape	Nu increased by 2.16 folds	FF increased by 2.69 folds
Saini and Saini. [22]	Wire metal mesh	Nu increased by 4.00 folds	FF increased by 5 folds
Yadhav et al. [11]	Circular protrusion	Nu increased by 2.89 folds	FF increased by 2.93 folds
Gongnan et al. [23]	Dimpled protrusion & Pins	Nu increased by 2.00 folds	FF increased by 1.11 fold
		Nu increased by 3.00 folds	FF increased by 1.05 fold

Some of the geometries investigated earlier are enlisted in Table 1. It can be seen that all the geometries used in the forced convection solar air heaters have increased the Nusselt number, therefore, increasing the heat transfer rate from the absorber plate to the air flowing over the top of it. In addition to an increase in the Nusselt number, the friction factor also increases, which shows that the higher power is required in order to force the air over the absorber plates. The effects of conical pins on the heat transfer enhancement were studied in a regenerative Ljongstrom type air preheater in the past [24]. The results showed that conical pins improve the heat transfer rate of the regenerative Ljongstrom type air preheater under forced convection. From the literature, it is evident that the roughness geometries have not been used in free convection solar air heater. In this research, experimental studies were carried out on a solar air heater (SAH) with conical pins on absorber plate. The effects of conical pins on the absorber plates of a solar air heater were investigated under natural or free convection. The effects of arrangement, staggered and in-line configurations, of the conical pins on the heat transfer rate, were also studied in order to enhance the efficiency of the solar air collector. The selected pin height was 2.0 mm and the pitch-to-height ratio was 8.0.

EXPERIMENTAL IMPLEMENTATIONS

The investigations were carried out experimentally using the designed and fabricated set equipped with suitable measuring instrumentations to allow the evaluation of the SAH at various operational conditions.

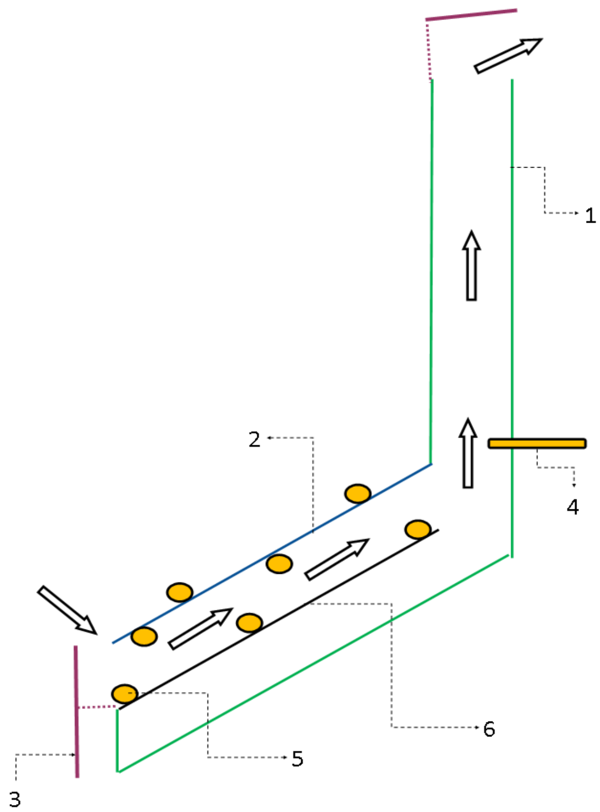

Figure 1. A single pass solar air heater (1) the chimney, (2) Double-glaze glass top cover, (3) wind protector, (4) probe thermocouple, (5) thermocouple, and (6) aluminum absorber plate.

Experimental Design

In order to conduct the experiment, a solar air heater was designed and fabricated. The length of air channel was 1100 mm, width 150 mm, and it had a fix air channel gap of 120 mm which was the height of the duct. The aspect ratio (t/w) of the duct, therefore, was 7.3 which according to a research conducted by Yeh et al. [25] gives the best thermal efficiency. The duct was covered with a double-glaze glass to minimize heat losses from the top and at the outlet of the solar collector a chimney was attached to create a stack effect for the air to flow out from the outlet more efficiently. This modification was inspired by Chen et al. [26]. According to them, the inclined absorber duct coupled with a long chimney ensures a higher more consistent flow rate of the air on top of the absorber plate A plastic shield that was attached at the entrance and exit of the solar air heater. The function of the plastic shield was to protect the channels from rain and also disable the flow of wind into the channels as it may affect the mass flow rate developed in the channel and thus would make the readings less reliable. The material used for Absorber plates is Aluminium and all the absorber plates were coated with black paint to enhance heat absorption during their exposure to the solar radiations as suggested by Majid et al. [27]. The convective rate of heat transfer from the absorber plate to air was measured by investigating the temperature and velocity of air at the outlet of the solar collector as well as the temperature of absorber plates at the same time.

The experiment was conducted using a single pass for the air. Figure 1 shows the side view of one channel of single pass solar air heater. The black arrows represent the flow of air within one of the channels of the solar air heater. The heated absorber plate caused a convective flow within the chamber. The hot air was released from the outlet of the channel into the chimney where it rose up the chimney and eventually went out from the outlet of the chimney. At the same time, cold air was sucked into the channel from the inlet due to the loss of pressure developed by hot air that escaped. This natural convection cycle was continued throughout the whole day. A mechanism to change the inclination angle of the solar air heater was installed as well. The solar air heater was placed in the solar site at Universiti Teknologi PETRONAS.

Table 2. Range and accuracy of equipment used.

Equipment Type	Measurement Parameter	Operational Range	Accuracy
K-type wire Thermocouple	Surface temperature	-270 to 1250°C	± 0.75%
K-type probe thermocouple	Air temperature	0-59°C	± 0.75%
Solarimeter	Solar irradiations	0-1300 W/m^2	± 5.0%
Hot wire anemometer	Air Velocity	0-40 m/sec	± 0.01 m/sec

Instrumentation for the Solar Air Collector

The experiment was conducted in November 2015 in the solar research site at Universiti Teknologi PETRONAS (Malaysia). The experimental test rig was pointed towards the geographic north direction. The experiment was conducted for three sunny days and the average data of those three days was considered for analysis. A total of 20 K-type thermocouples with accuracy 0.75% were used to measure the temperature at different points of the rig. Two K-type thermocouples were placed on the inside of the double-glazing panel in each of the three ducts used for experimentation. Three K-type thermocouples were placed on the absorber plate in each duct, one in the middle and one at each end. The circular dots in Figure 1 represent the locations of the thermocouples in the test rig on a single duct. Three K-type probe thermocouples were used to measure the outlet temperature of the air. The velocity of the outlet air was measured using a hot wire anemometer with an accuracy of ±0.01 m/s. The thermocouples were all connected to a 20 channel graph tech data logger. Table 2 shows the range and accuracy of the measuring instruments used for the experimentation. The velocities of the outlet air were measured manually every hour. The temperature was recorded with a 5-minute interval and an hourly average of the temperature was used for calculations of the instantaneous efficiency of the solar air heater. The experimental solar air heater used for the testing of the absorber plates can be viewed in Figure 2. The angle of absorber plate was set at 15° to absorb the maximum solar irradiation in the afternoon since the higher solar radiation was received at a lower inclination angle as suggested by Mathur et al. [28].

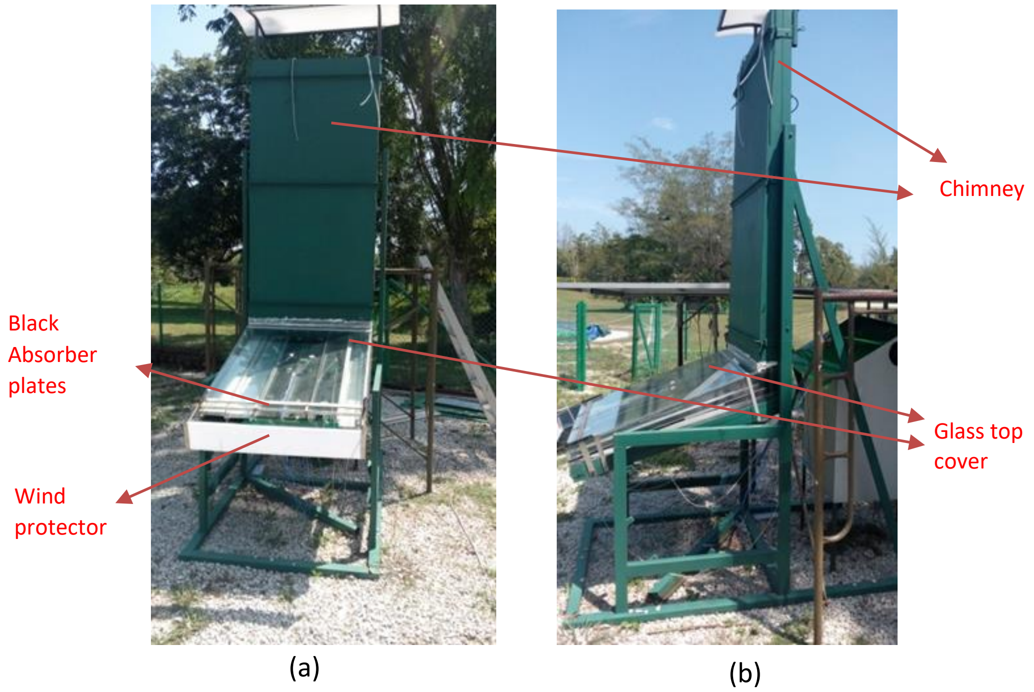

Figure 2 The experimental solar air heater (a) The front view with chimney, and (b) side view with 15° inclination angle

The conical pin profile was punched into the 0.5 mm aluminium absorber plate using a specialized dye. The arrangement of the conical pins tested on the absorber plate can be viewed in Figure 3. Two types of the arrangements namely, straight in-line and staggered were tested and a flat absorber plate (without the pins) was used for comparison. All the three absorber plates were tested at the same time with different channels of the solar air heater to ensure that all variables were kept constant for the three plates. Each channel has a dimension of (*15* × *1100* × *8*) mm. The pitch of the pins for the in-line arrangement was kept at 16 mm, whereas the pitch of the pin for the staggered arrangement was kept at 23 mm. The absorber plates were painted dull black to absorb maximum solar irradiations. The height of each conical pin was 0.2 mm.

The heat transfer between the metal plate and air was increased drastically if the air was flowing above the metal plate so therefore an important factor in increasing the heat transfer rate was the mass flow rate which is given by Eq. (1):

$$\dot{m} = \rho v A_{CR} \tag{1}$$

where, ρ is the density of air (kg/m^3), v is the velocity of air at the outlet and A is the cross-section of the channel (m^2). The mass flow rate was used to calculate the efficiency of the solar air heater. The efficiency η was calculated using Eq. (2) which was adapted from the research by Yaseen et al. [29]:

$$\eta = \frac{\dot{m}C_p(T_o - T_{amb})}{IA_{BP}} \tag{2}$$

where, $\dot{m}$ is the mass flow rate (kg/s), C_p is the specific heat capacity of air (J/kg-K), T_o is the air outlet temperature, T_{amb} is the ambient air temperature, I is the solar irradiation (W/m^2) and A_{BP} is the top surface area of absorber plate. The numerator $\dot{m}C_p\,(T_o - T_{amb})$ is used to calculate the power gained by air flowing over the absorber plate and the denominator is the heat absorbed by the absorber plate.

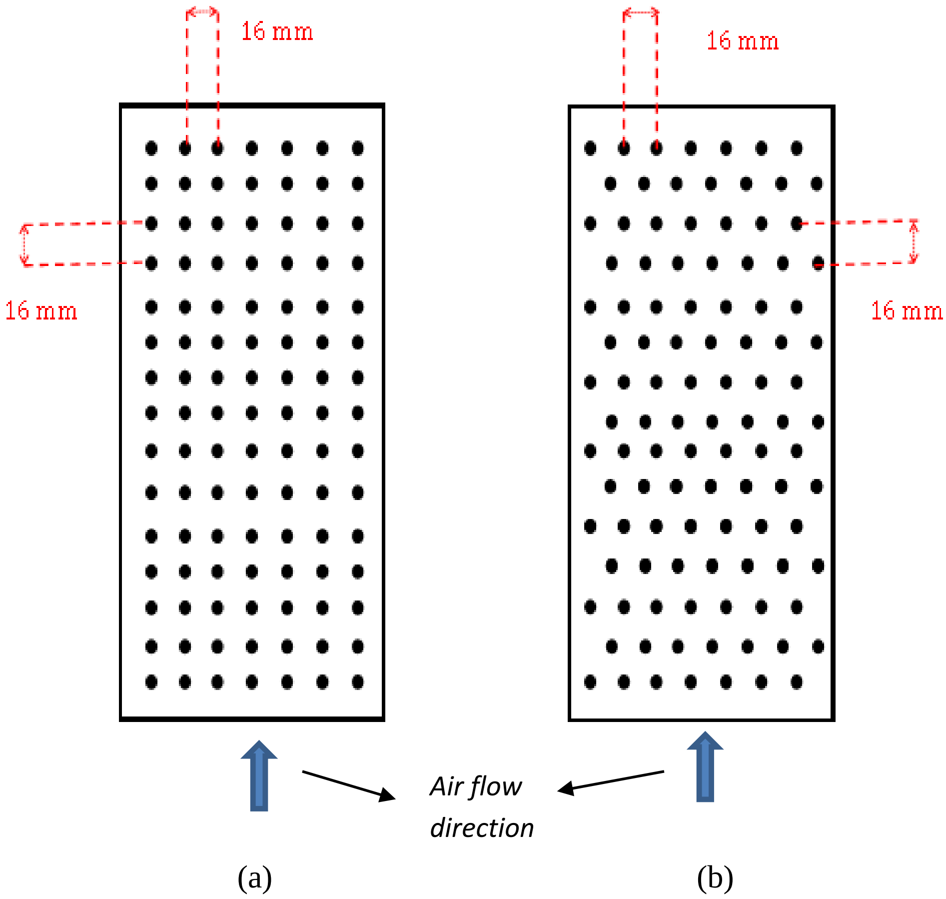

Figure 3. (a) The conical pins arrangement (a) straight in-line 16 mm pitch, and (b) staggered 16 mm pitch.

$$PIAT = \frac{(T_{pin} - T_{amb})}{T_{amb}} * 100 \tag{3}$$

In Eq. (3), PIAT represents the increasing percentage in the air temperature, T_{pin} is the outlet temperature (℃) of air from the pinned absorber plate and T_{amb} is the ambient air temperature (℃) which is also the inlet air temperature.

$$PIE = \frac{(\eta_{pin} - \eta_{flat})}{\eta_{flat}} *100 \tag{4}$$

In Eq. (4), PIE represents the percentage increase in efficiency, η_{pin} represents the efficiency of the solar air heater with pinned absorber plate (in-line or staggered) and η_{flat} represents the efficiency of the solar air heater with flat absorber plate.

It was pointed out that different authors [30, 31] used different values for the collector areas (absorber area, cover area, and gross area) for the estimation of the collector's efficiency. In this case, the gross area of the air collector in each channel was used for the calculations of performance for solar air heater.

RESULTS AND DISCUSSION

During the experimentation of the variations in ambient air temperature, solar irradiation, and collector's outlet dry bulb temperature were recorded and plotted. Figure 4 shows the variation of hourly solar irradiation with respect to time. The curve in Figure 4 is the average solar radiation for three days. From Figure 4 the solar irradiations were recorded every hour from 9.00 *a.m.* till 4.00 *p.m.* The maximum solar irradiance of 810 W/m^2 was obtained at 12.00 *p.m*. The solar irradiance in the morning (10 *a.m.* – 11 *a.m.*) was almost similar as compared to evening (1 *p.m.* – 2 *p.m.*). The solar radiation dropped to 310 W/m^2 at 4 *p.m.* The variation in data between each day is represented by the error bar on the curve at each hour. This maximum error percentage of around ±6.13% was observed at 9 *a.m.* which is an acceptable range and it showed that the weather for the three days was relatively clear. From Figure 4 the standard deviation in solar radiation was ±26.27 W/m^2 (4.55%) which is relatively low [32].

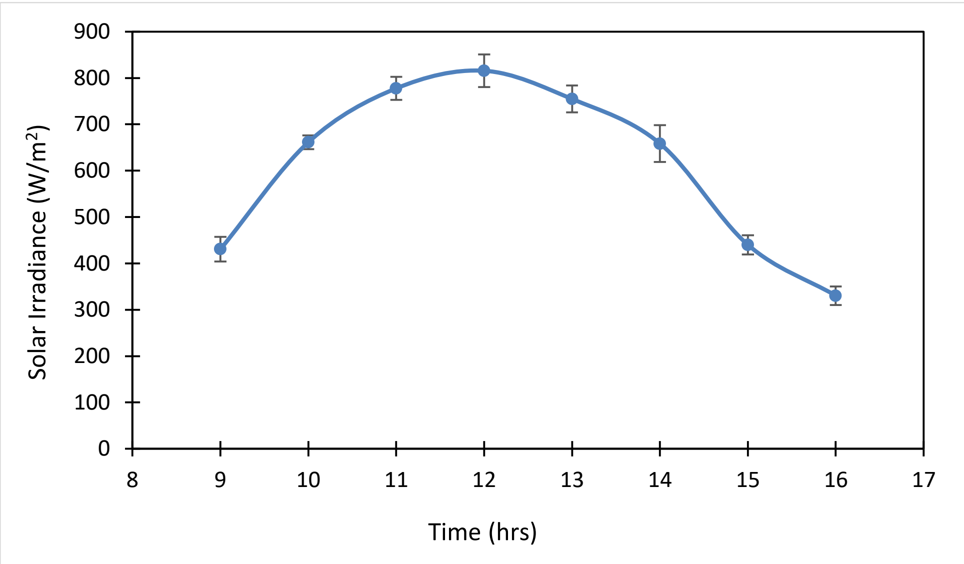

Figure 4. Solar irradiation against time of day.

Figure 5 shows the change in the collector outlet dry bulb temperature with respect to the drying hours of the day. It is evident that by keeping all other variables constant, the plate with the staggered arrangement of pins gives out the highest dry bulb air outlet temperature followed closely by the straight in-line arrangement. By the staggered arrangement, most of the streamlines of the flow are exposed to break down near the surface and local region of vortices which enhance the heat transfer. For all the plates, the highest outlet air temperature recorded was at 1.00 p.m. At this time of the day the staggered plate gives an outlet temperature of 46.37°C, the straight in-line plate had a maximum temperature of 45.83°C and the flat plate with no pins had a dry bulb outlet air temperature of 44.52°C at 1.00 p.m. All three types of absorber plate managed to increase the ambient air temperature, which at 1.00 p.m. was 36.13°C. The increase in average air outlet temperature was 2.96% and 4.18% for the straight in-line and staggered arrangement as compared to the flat plate with no pins. The reason for this increase can again be contributed to the increase in the convective heat transfer coefficient due to the installation of conical pins on the absorber plate. Once the convective heat transfer coefficient increased the heat transfer from the absorber plate to the air flowing above it also increased which results in higher air outlet temperature for the absorber plate with conical pins [33]. However, the percentage increase of air temperature as compared to the ambient air temperature using Eq. (3) was 26.85%, 28.36% and 23.21% for the in-line, staggered and flat smooth absorber plates respectively. It is evident from the results that the additions of conical pins increase the temperature of the outlet air, thus they are better as compared to the flat smooth absorber plate. The heat transfer takes place near the surface specifically in the laminar sub-layer region. As the nature of the flow was laminar, then the heat transfer was expected to be lower than if it was disturbed near the surface. Hence, when the sub-layer was broken down the flow became turbulent and the heat transfer in the turbulent flow was greater compared to the laminar flow. The inclusion of conical pins on the flat plate serves as artificial roughness. The pins broke down the viscous laminar sub-layer and imposed the flow near the surface to be turbulent within the sub-layer region. The pin presence in the thermal surface would destroy the laminar sub-layer but not over the whole cross-section perpendicular to the flow. When the pins were arranged in an in-line manner, there were large parts of the flow moving in between the line of pins without disturbance of the sub-layer. In the case of the staggered manner, the chances of disturbing the sub-layer were higher. This was the reason why the enhancement in the staggered case was higher.

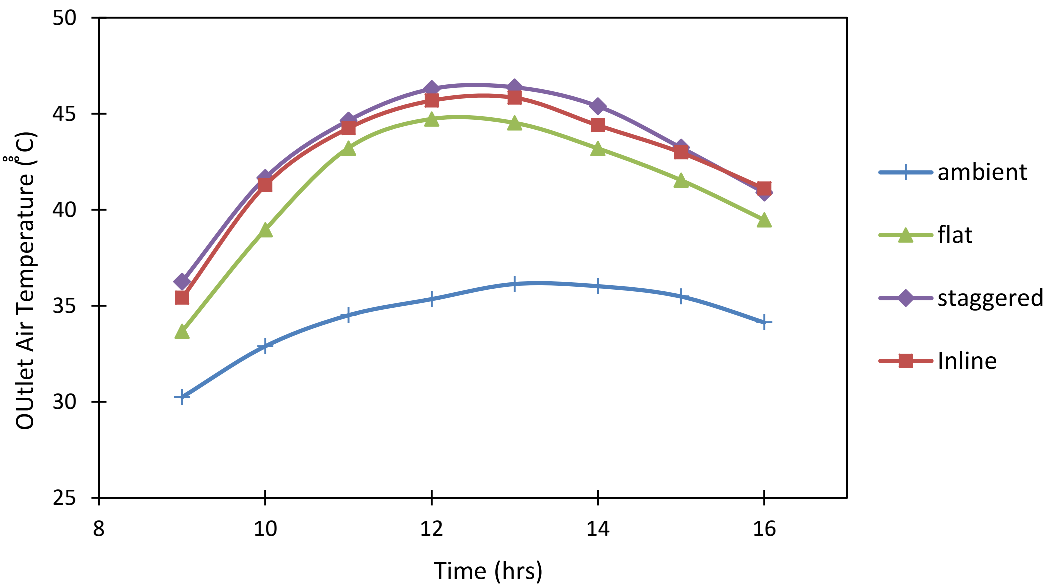

Figure 5. Dry bulb air outlet temperatures at different time of the day.

The predicted efficiency, η against the solar irradiance is shown in Figure 6. The efficiency was calculated using Eq. (2). From Figure 6, it is evident that the highest efficiency was produced at a solar irradiance of around 435 W/m^2. The absorber plate with the staggered arrangement of pins was by far the most efficient of the three. It had a maximum efficiency of 31% whereas the straight in-line pin arrangement gave an efficiency of about 28% and the flat plate with no pins had a maximum efficiency of 22%. This showed that the staggered pin arrangement increased the performance of the solar air heater by 42% and the in-line straight pins arrangement increased the performance by 28% at the solar irradiance of 435 W/m^2. The increasing percentage in the efficiency of the solar air heater was calculated using Eq. (4). The reason for the drop in efficiency after 435 W/m can be attributed to the fact that at the higher solar radiation specifically after the noon time the outlet air temperature starts to drop rapidly whereas the ambient temperature of the air remains constant or decreases at a slower rate. Due to this, the temperature difference between the outlet and inlet air temperature decreased and therefore the overall instantaneous efficiency of the solar air heater started to drop as the solar radiation increased after 435 W/m^2 slowly. In other words, the peak ambient temperature was reached in the afternoon (1.00 p.m.) whereas the peak outlet air temperature was achieved at noon (12.00 p.m.) as can be seen in Figure 5 which results in the trend observed in Figure 6.

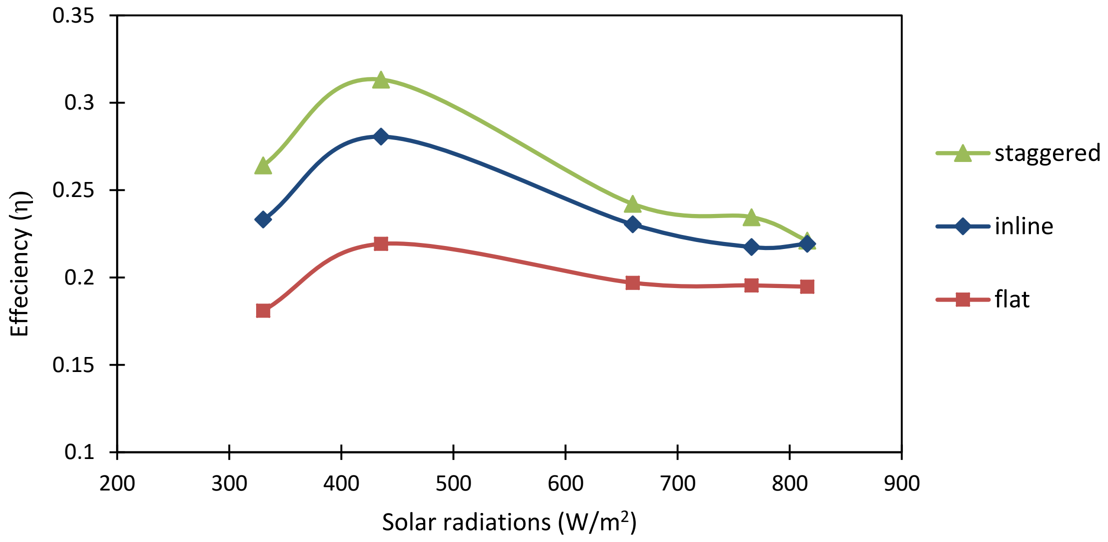

Figure 6. Efficiency comparison.

These trends are in agreement with the Zhang et al. [34] who tested the heat transfer enhancement mechanisms in the in-line and staggered parallel-plate fin heat exchangers. The fin arrangement in their work was similar to the pin arrangement in at present. They concluded that the velocity and the temperature profile around the fin increased for both the in-line and staggered arrangement, therefore, resulting in an increase in the heat transfer coefficient and friction factor. The reason for such result could be attributed to the fact that the spacing between the pins in the in-line was less in the direction of flow which results in the slight drop in the mass flow rate. This caused a slight drop in the efficiency of the in-line arrangement as compared to the staggered arrangement.

CONCLUSIONS

A solar air heater with and without pin turbulators was investigated experimentally. From the experimental results, it can be concluded that the surface roughening increased the performance of a free convective solar air heater. The staggered arrangement of pins produced a maximum system efficiency of 31% while the in-line arrangement produced 28%. The maximum performance was at a low solar irradiance of around 435 W/m^2. The developed natural convection solar air heater was capable of increasing the ambient temperature of air by 12% whereas in the case of staggered and in-line pins arrangement on the absorber plate, the air outlet temperature raised by 16.5% and 15.7%, respectively. The efficiency of the solar air heater with respect to the solar irradiance also increased by 28% and 42% as compared to the flat plate absorber without pins for the in-line and staggered pin arrangements, respectively. The highest efficiency of the solar air heater was achieved at the solar irradiance of 435 W/m^2. It is recommended to extend the work and investigate more cases of the pin-to-height ratios and pitch-to-pin height ratios. The heat transfer mechanism that is taking place inside the solar air heater is also of great significance and should be looked into via thermal imaging camera or should be studied via simulation.

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