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ENHANCEMENT OF THE HEAT TRANSFER RATE IN FREE CONVECTION SOLAR AIR HEATER USING PIN SHAPED ARTIFICIAL ROUGHNESS ON ABSORBER PLATE

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ABSTRACT

The technic of artificial roughness is used by researcher to augment the heat transfer coefficient in force convection between the absorber and air in solar air heater. In the present paper, a new artificial roughness (pin shape protrusion) on the absorber plate was used to achieve the enhancement in heat transfer coefficient of free convection between absorber plate and air. A specially designed test rig was fabricated for experimental measurements, comprising of four sections of 0.48 x 0.07 x 2.0 m, to acquire data of four different cases. The conical pins were used with three different relative height roughness, $e/D_{h,}$ = 0.01636, 0.0245 and 0.0327 and one standard smooth un-protrusion flat plate absorber was used as a basis for comparison. The data for from the four test rigs were recorded simultaneously. The measurements were carried out at five inclination angles 10°, 30°, 50°, 70°, and 90° to get the optimum angle of operation for free convection solar air heater. The results show that the conical pin artificial roughness has enhanced the heat transfer rate of the solar air heater by up to 41% as compared to the un-protrusion absorber plate heat transfer rate in free convection solar air heater. The heat transfer rate and Nusselt number are highest for relative height roughness e/Dh = 0.0327. The optimum inclination angle was found to be 50 degrees, at which the solar air heater performed most efficiently.

Keywords: solar air heater, pin turbulators, heat transfer enhancement, free convection.

INTRODUCTION

Flat plate solar collectors are special type of devices used to collect radiant heat energy from sun for various purposes such as water heating or space heating [1]. Flat plate solar air heater is a type of flat plate collector which is primarily used for pre heating air or for drying purposes. The performance of flat-plate solar air heater is generally low because of low heat transfer rate between air and absorber plate [2]. One of the reason for a lower convective heat transfer coefficient can be attributed to the fact that the flow of air over the heated plate is laminar and the heat transfer coefficient is lower in a laminar flow regime. In order to attain higher heat transfer coefficient, the flow close to heat transfer surface needs to be made turbulent. However for the flow to be turbulent excessive power is required to blow the air across the channel length. It is therefore desirable that the turbulence must be created only in the region very close to the heat transferring surface, i.e., in the laminar sub layer only where the heat exchange takes place and the flow should not be unduly disturbed so as to avoid excessive friction losses. This can be done by roughening the heated surface with small protrusions which in turn breaks the laminar sub layer and therefore increase the heat transfer coefficient [3].

Adel Hegazy [4] did a numerical analysis on different absorber plate shapes to enhance the thermo hydraulic performance of the solar air heater. He found out that changing the shape of absorber has little effect on the performance of solar air heater, but none the less suggested a trapezoidal shape as an alternate to rectangular one.

Many researchers have investigated the effect of different types of artificial roughness on the heat transfer rate between absorber plate and the air flowing over it. Dey and Dandotiya [5] summarized all the roughness geometries tested before and categorized them according to their shapes. They concluded that artificial rib roughnesses performs the best. Ebru Karak and Fatih Kocyigin [6] investigated experimentally four types of solar air collector one without obstacle and another three with different type of obstacle. The investigation done with low flow rate (0.0052 and 0.0074 kg/s). They found significant enhancement in solar air heater with used obstacle in the absorber plate and the efficiency is increased with rise of flow rate. Yasin Varol [7] performed an extensive numerical analyses on effect of thin fin in triangular cavity on the Nusselt Number. They found out that thin fin had a positive effect on the overall flow pattern and the heat transfer rate. Al-Kayiem and Mahdi [8] tried to enhance the heat transfer of a rotary air pre heater using pins as turbulators. They discovered overall thermal hydraulic performance is enhanced using pins with relative roughness pitch of 16.67. The setup was under forced convection.

So far the conical pins have not been tested under fee convective solar air heaters. This research focuses on finding the effect of conical pin turbulators on solar air heater under free convection mode.

EXPERIMENTAL SETUP

Test rig configurations

The experimental is investigated with four collector test rigs as shown in Figure-1. One with flat plate

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absorber and the other three test rigs with different relative roughness height of 0.01636, 0.0245, and 0.0327 respectively. The pins were stamped into the absorber plates using special dyes. Figure-2 shows the staggered arrangement of pins in which they were stamped onto the aluminum absorber plate according to the dimension shown. The conical pins had a constant diameter of 2 mm but each test rig had a different pin height (2, 3, and 4) mm on the absorber plate. The absorber plat was cut from aluminum sheet of gauge 1 mm. The rectangular duct was fabricated out of wood as can be seen in Figure-2, the internal dimensions of a rectangular duct of each test rig (0.48 x 0.07 x 2 m) with hydraulic diameter (D_h=0.1222 m). The bottom and side walls of duct were made from 20 mm thick wood. To minimizing the top losses 3 mm thick double glazed glass cover were used to cover the rectangular duct. The gap between the absorber plate and glass surface was kept at 5mm which is within the range of 4cm to 8cm as suggested by Tabor [9] to minimize heat losses through convection. The supporters are used to support the rectangular passage with adjustable lock to ensure the rectangular passage could be oriented or tilted to any desired angle (in this case 10°, 30°, 50°, 70° and 90° with respect to the horizontal base).

Figure-1. Experimental test rig.

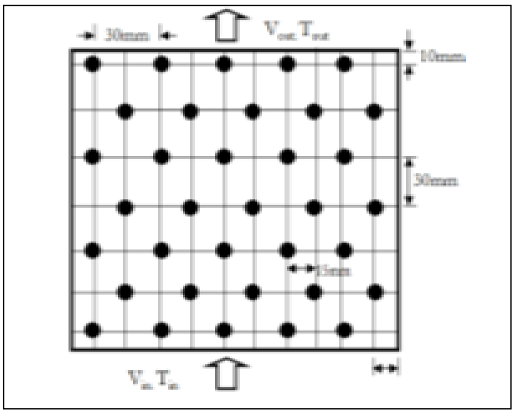

Figure-2. Staggered arrangement of pins on absorber plate.

The collection of data for each of the configurations (tilt angle) is repeated for 4 days to improve the reliability of the result and the final data is averaged. The data was recorded at two hours' interval and was collected throughout the day from 8 a.m. till 6 p.m. The data collection for all tilt angles started at the first week of November 2012 until the last week of December 2012.

Measuring instrument

To measure the surface temperatures, calibrated thermocouple type (k) wires were used with an accuracy of 0.1 percent. They are connected to GRAPHTEC data logger GL820 and are placed at three points along the length of the inner and outer glazing covers as well as the absorber plates. A probe thermocouple (type k) was placed at the outlet of each collector duct to measure the outlet air temperature. A hot wire flow sensor was used to measure the velocity of air at the channel outlet. A solarimeter was used to measure solar insolation at the solar site for each specified time interval. Figure 3 shows the configuration of the measuring instrument and the solar air heating duct.

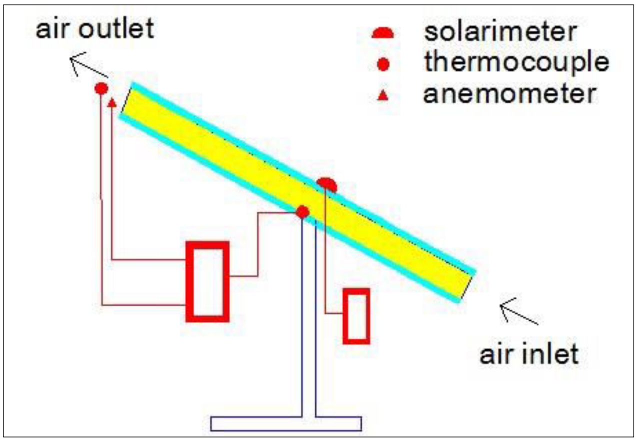

Figure-3. Test rig and measuring instruments configuration.

Calculation of heat transfer coefficient

The experimental heat gain from collector is calculated using Equation. (1).

$$Q = \dot{m} C_p (T_o - T_i) \quad (1)$$

Where m is the mass flow rate in kg/sec, C_p is the specific heat capacity of the fluid in this case the air, T_o and T_i are the air outlet and air inlet temperatures respectively. The experimental value of Nusselt number is calculated using Equation. (2).

$$Nu = \frac{Q\,S}{A_s k (T_b - T_{fm})} \quad (2)$$

Where, A_b is the base plate absorber area, S is the gap between absorber plate and transparent cover, $T_{fm} = \frac{T_i + T_o}{2}$ which is the fluid mean temperature and T_b is the Absorber plate temperature. The Rayleigh number is calculated using Equation. (3).

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$$Ra = \frac{\beta \Delta T g L^3}{\mu \alpha} \quad (3)$$

Where, β is the coefficient of thermal expansion ΔT is the temperature difference between absorber plate and outlet air, g is the gravitational acceleration constant, L is the distance between absorber plate and glass cover, μ is the kinematic viscosity and α is the thermal diffusivity.

Tiwari [10] proposed a relation between Nusselt and Rayleigh number for a flat plate absorber. Equation. (4) shows tiwari's Nu-Ra relation. The range for Rayleigh is $10^5 < Ra*\cos\theta < 10^{11}$.

$$Nu = 0.14 \left[Ra^{1/3} - Ra_c^{1/3}\right] + 0.56(Ra * \cos\theta)^{1/4} \quad (4)$$

The results for variation between the Nusselt number with Rayleigh number is verified by Figure-4. The experimental values for Nusselt number are compared with that of Tiwari's work. The result although is not completely in agreement with Tiwari's work but it is very close to Al-Kayiem and Yaseen [11] worked on natural convection. Al-Kayiem carried out the experiment in the same solar site as the present study therefore explaining the similarities in result.

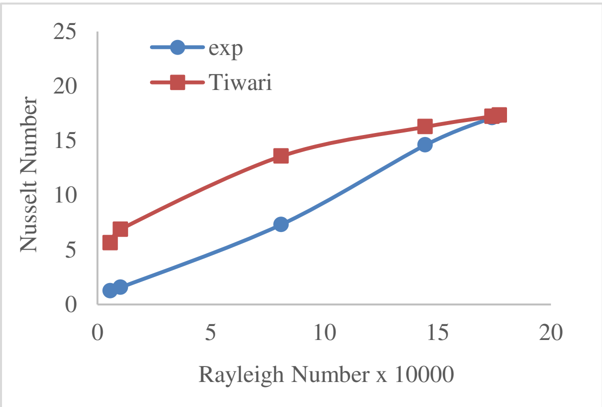

Figure-4. The variation between Nusselt number with Rayleigh number of the present work with the results of Tiwari [10].

The pressure drop across the duct was found to be negligible for all the absorber plates regardless of having pins or otherwise. This was due to the fact that under natural convection the fluid velocity through the duct is so low that the addition of pins on the absorber plate does not affect the pressure drop. It remains same across all the absorber plates.

RESULTS AND DISCUSSIONS

The effect of roughness on free convection heat transfer rate as well as Nusselt number from the absorber of a rectangular channel solar air heater is presented and discussed in the present section. As discussed earlier the experiment was carried out for duration of two months. Figure-5 shows the average variation of solar radiation throughout the day in which the experiments were conducted. The average solar radiation for the day vertical inclination was tested drops at 14 00 hrs. Due to cloud cover, apart from that the average solar radiations for each experiment varied at almost similar rate indicating consistency in data gathered. The maximum solar radiation recorded was 753 W/m^2 during noon for 10° inclination angle. The solarimeter was placed at the same angle at which the solar air heater duct was set. The solar radiation in Figure-5 was measured at the absorber.

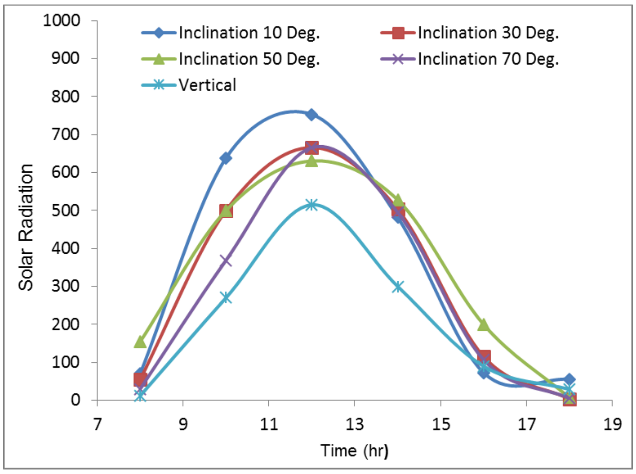

Figure-5. Average solar radiation of each test for inclination angle (10°, 30°, 50°, 70°, and vertical).

Figure-6 shows effect of relative roughness height on the Nusselt number at various angles. It can be observed that the highest Nusselt number is achieved at an angle of 50 degrees which can also be confirmed from figure 4. As the relative roughness height of the system increases the Nusselt number starts to increase. The relation between Nusselt number and relative roughness height is almost linear. The error is minimal for all inclination angles except that of 10 degrees. The variation in data points for 10-degree angle can be attributed to the fact that when the air passage is parallel to the direction of wind itself, the wind is able to travel freely inside the channel, thus displacing more hot air with cooler ambient air which results in larger and inconsistent variations of heat transfer rate therefore effecting the Nusselt number.

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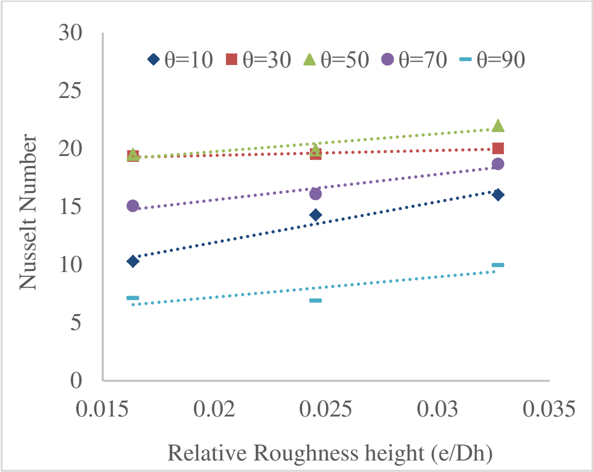

Figure-6. The graph of Nusselt number with respect to relative roughness height at various inclination angles.

As discussed earlier the Nusselt number is the highest at an angle of 50 degrees after which the Nusselt number starts to decrease as can be seen in Figure-7. These results are in agreement with Aminossadati and Ghasemi, [12]. Within the Rayleigh range of less than 10^6 the Nusselt number increase until the inclination angle 50 degrees and then it starts to decrease as the inclination is further increased. However, from the graph it is also evident that the Nusselt number is higher when the relative roughness height is increased. This shows the pins with higher heights causes more turbulence in the sub layer flow and thus the heat transfer rate is higher therefore, giving a higher Nusselt number across the tested range of inclination angles.

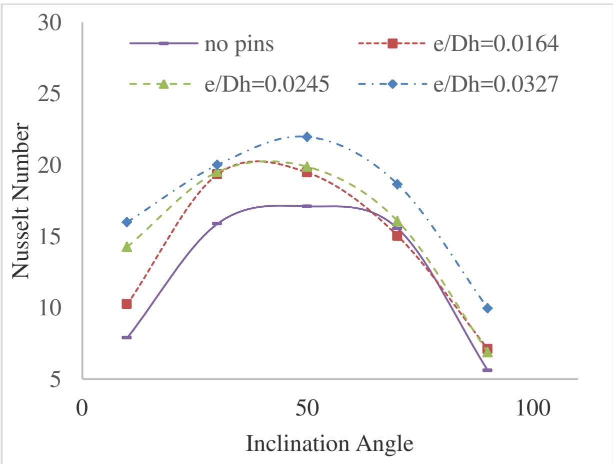

Figure-7. The graph of Nusselt number with respect to inclination angle.

The effect of heat input which is a function of incident solar radiations is compared with Nusselt number for the three values of relative roughness height in Figure-8. It can be seen that for similar heat flux, the absorber plate with longest pin (relative roughness height of 0.0327) produces the highest Nusselt number followed by relative roughness height of 0.01636 and 0.0327. The smooth plate with no pins produces the least Nusselt number indicating that the Nusselt number is enhanced as the pin height increases for given heat flux. [50 degrees]

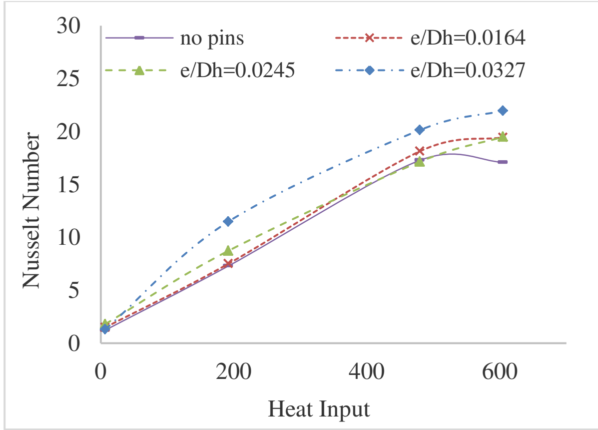

Figure-8. The graph of Nusselt number with respect to heat input.

Similarly, the duct with relative roughness height of 0.0327 increases the Nusselt number for a similar corresponding Rayleigh number of the smooth plate. This is evident in Figure-9. The relationship between Nusselt and Rayleigh for both cases is almost linear indicating a strong relation between the two properties. Figure-9 also shows that the use of pins on the absorber plate increases the thermo-hydraulic properties of the solar air heater.

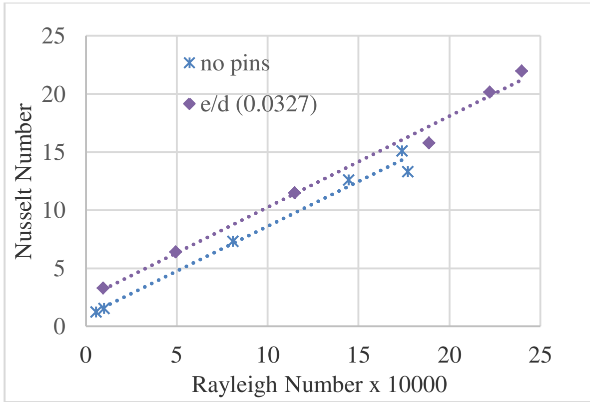

Figure-9. The Nusselt versus Rayleigh graph.

Figures-10 shows the comparison of heat transfer rate between flat smooth absorber plate and roughened absorber plate with different relative height roughness. The results show that for artificial pined roughened absorber plate the values of heat transfer rate is higher than that obtained for smooth absorber plate. The highest heat transfer rate occurs at noon time when maximum solar energy is available. During noon the enhancement in heat transfer coefficient is about (41 percent for relative roughness height of 0.0327, 34 percent for relative roughness height of 0.0245 and 29 percent for relative roughness height of 0.01636. It shows that the heat transfer rate is highest for relative height roughness of

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0.0327 followed by 0.0245 and 0.01636 respectively.

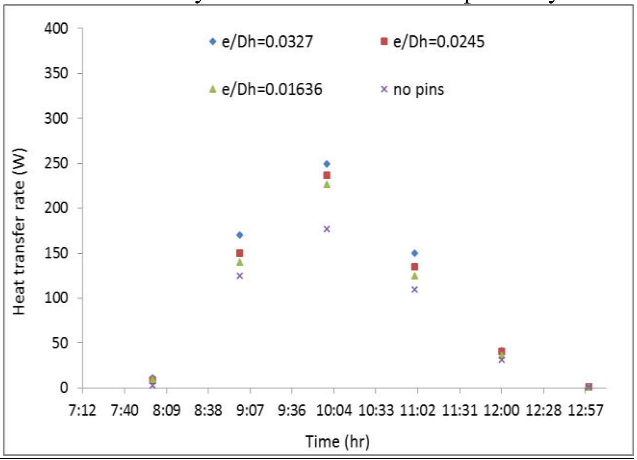

Figure-10. Comparison of heat transfer rate of different relative height roughness and smooth absorber plate at inclination angle 50 degree.

Despite the fact that the average readings were considered, it is necessary to clarify that the data collected after 4 pm are inconsistent due abrupt changes in weather. In most cases, the wind has greater impact on lower inclination angle configuration such as 10 °. This is because when the air passage is more parallel to the direction of wind itself, the wind is able to travel freely inside the channel. It is therefore displacing more hot air with cooler ambient temperature which results in lower heat transfer rate. Another reason for poor performance at low inclination angle is that at low inclination angle produces lower up drafting force which leads to low heat transfer rate. Lower angle configuration may be good in term of absorbing solar radiation but poor in transferring heat and enhancing buoyancy driven flow. Instead, for higher inclination angle configuration such as 90 °, because the absorber plate is not facing the solar radiation source, which in this case is the Sun, thus the solar insolation is lower compared to other configurations. But because it perpendicular to the direction of wind, the hot air remains inside the channel and is less displaced by cooler ambient air. However, the heat transfer rate is still lower because of lower solar insolation.

Therefore, the best configuration in this case as demonstrated by the graphs is a solar air heater with artificially roughened pinned absorber plate with relative roughness height of 0.0327 and an inclination angle set at 50°. This inclination angle is chosen since it has best position for higher solar radiation absorption and lower displacement of hot air by incoming wind and high up drafting force. This result is also in agreement with Jyotirmay *et al.* [13] which shows that the optimum absorber inclination at any place varies from 40 to 60 degrees depending upon the latitude.

CONCLUSIONS

From the experiment it was concluded that the presence of conical pin roughness on the absorber plate of solar air heater had a positive effect on its performance. The pin configuration with relative roughness height of 0.0327 performed better as compared to relative roughness height of 0.01636 and 0.0245. The best inclination angle was found to be 50 degrees from the ground. At 50 degrees' inclination angle highest Nusselt number was produced by all the absorber plates. The Nusselt number was found to be a function of heat input. For the 50-degree inclination angle, the highest Nusselt number was produced by absorber plate with relative roughness height of 0.0327 followed by 0.0245, 0.01636 and lastly the absorber plate with no pins.

It is therefore concluded that artificial roughness will enhance the performance of the solar air heater under free convection and there is scope for research in this area. It is recommended that other geometries of artificial roughness should also be tested in the free convective air heater.

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