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Performance enhancement of free convective solar air heater by pin protrusions on the absorber

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ABSTRACT

This paper is aimed to present enhancing technique of the low performing free convective solar air heaters. In order to increase the efficiency of this process, small sized turbulators have been used on the absorber plate that is breaking the viscous layer/sub-layer of the air flowing over the surface. To conduct the experimental investigation, a special test rig was designed and fabricated to measure the effect of these turbulators. The turbulators used in this project are conical shaped pin protrusions on the surface of the absorber. The test rig was a special type of free convective solar air heater comparing 6 different type of absorber plates at once. The results demonstrated that optimum inclination angle of the absorber plate for Malaysian condition was 45 degrees. Staggered arrangement of conical pins were found to be more effective compared to inline arrangement. A total of 3 different pitch of conical pins (16 mm, 32 mm & 48 mm) and 3 different heights of conical pins (2 mm, 3 mm & 4 mm) were tested all in staggered conical pin arrangement. The results showed that pin pitch of 16 mm increased the Nusselt number the most. The efficiency was increased by up to 26.5% for absorber plate with 16 mm pin pitch as compared to flat smooth plate. The pin height of 4 mm proved to be the best in enhancing the Nusselt number. In addition, a correlation was developed to predict the Nusselt number for conical pin protruded plates of dimensional ranges (*16 mm < pin pitch < 48 mm*) and (*2 mm < pin height < 4 mm*) under free convective flow for staggered arrangement. The accuracy of the correlation for the entire experimented range is ±27%, and at optimum operating parameters, it is reduced to ±8.0%.

1. Introduction

A review on techniques used for heat transfer enhancement was made by Bergles (1999) whereby heat transfer enhancement techniques were classified as either passive methods, whereby no external power is required or active methods which requires the use of external power. An application where both of these enhancement methods may be used is the thermal energy storage systems, high efficiency thermal energy storage systems require development of technologies that enhance the heat transfer rate. An example of thermal energy system is the solar air heaters which can be used to pre heat the ambient air for applications ranging from crop drying to space heating.

Performance enhancement of solar air heater can be achieved in numerous ways as discussed by Close (1963) each of these parameters have been studied and investigated by various authors. The effects of heater configuration on heat transfer was studied by Yeh and Lin (1995) who basically investigated the effect of collector aspect ratio on the performance of collector. The effect of air mass flow rate was investigated by Chabane et al. (2012) who varied the mass flow rate of air and investigated its effect on the outlet air temperature, the heat transfer rate and thermal efficiency of a solar air collector. Other parameters, which have been investigated and reported, that resulting in heat transfer enhancement are the material used in solar air heater (Whillier, 1964), color of coatings on absorber plate (Tripanagnostopoulos et al., 2000; Kalogirou et al., 2005) and the insulation on the glass glazing (Kaushika and Arulanantham, 1996). But perhaps, the most effective technique of enhancing the heat transfer in solar air heater through convection is by purposely making the surface of the absorber plate rough using small turbulators. The purpose of such turbulators is to cause turbulence by breaking the laminar air flow over

Abbreviations: FPAH, Flat Plate Air Heater; RRP, Relative Roughness Pitch; RRH, Relative Roughness Height; D_h, Hydraulic Diameter; *Nu*, Nusselt Number; *Ra*, Rayleigh Number; A_{cr}, Cross Sectional Area; A_{bp}, Absorber Plate Area.

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the absorber plate. As suggested by Bhushan and Singh (2011), the laminar flow acts as a hindrance to heat transfer between a flowing fluid and hot surface. The turbulence in flow ensures higher thermal dissipation. The common methods of creating turbulence are by the introduction of protrusions, ribs, dimples or using sand on the absorber plate.

On the subject of heat transfer enhancement methods for free convective air heater, El-Sherbiny et al. (1978) investigated the effect of replacing flat absorber plate with a V-corrugated plate. They used the same facility and equipment as Hollands et al. (1976) and the experiment was conducted in a Rayleigh range of 10 and 4×106 and inclination angles of 0°, 30°, 45° and 60° degrees. Three different aspect ratios of the V-corrugated plates were studied and a correlation was obtained. From the research El-Shirbiny et al. concluded that for the same average plate spacing, the convective heat losses across air layers bounded by one V-corrugated and one flat plate are greater than those for two parallel flat plates by up to 50 percent for the range studied. This proved that heat transfer can be enhanced for free convection air heaters by altering the surface of the heated plate.

Li and Tong (2016) conducted a research on free convective heat transfer in an inclined rectangular cavities with low width to height ratios through both experimental and computational fluid dynamics (CFD) analyses. They used a width to height ratio of 1, 2, 4 and 8 and conducted the experiment at inclination angle range of 15⁻90°. They concluded that the increases of both the width-to-height ratio and cavity inclination increased the rate of natural convection flow and enhanced the convective heat transfer in the cavity. Furthermore, the impact of cavity's width-to-height ratio on the performance of the collector starts to decrease as it passes 4.

On the modification of absorber plate of a free convective air heater, Fakoor Pakdaman et al. (2011) inserted longitudinal rectangular fin array along the area of the absorber plate of a free convective solar air heater. They observed that by increasing the surface area of absorber plate by 60%, the heat transfer can be enhanced by up to 20%. They also suggested that heat transfer enhancement is not dependent on the inclination angle. They also concluded that the effect of the solar radiation on the thermal performance of the system is 79 times greater than that of ambient temperature, i.e. the main independent parameter that controls the thermal performance of the system is solar radiation and not ambient temperature.

The general concept about free convective air heater is that convective heat transfer coefficient is very low. The insight view in the literature reveal that most of the research for heat transfer enhancement by surface roughening have been investigated under forced convection heat transfer, while very little work has been done to enhance free convective heat transfer.

This research aims to experimentally investigate the heat transfer enhancement in a free convective solar air heater while using conical pin type surface roughening on the absorber plate. The effect of quantity, dimension and configuration of the conical pins on the free convective heat transfer have been studied. In addition to that, the optimum inclination angle of a free convective solar air heater was also examined. The results obtained were validated using current correlations on free convective heat transfer.

2. Experimental setup

2.1. Test rig construction and setup

In order to conduct the experiment a test rig was designed and fabricated in a workshop and installed in the Solar Research Site in Universiti Teknologi PETRONAS (4°37′0″N 100.96°′0″E). The test rig was designed to replicate a flat plate solar air heater. The prime purpose of this test rig was to carry out the experiment using various absorber plates and compare the results. The test rig was divided into six ducts of equal dimensions. The data from each duct was obtained simultaneously via the sensors and the data logger.

A chimney like structure was directly coupled at the outlet of each duct. The main purpose of the chimney was to enhance the air flow within the duct. The chimney ensured that air could flow consistently over the absorber plates in the duct as the air flow in the duct is usually very low under natural convection. This modification was inspired from Chen and Qu (2014) according to them the inclined absorber duct coupled with a long chimney ensures a more consistent flow rate of the air in the absorber duct. The test rig can be viewed in Fig. 1.

The height of the chimney was kept at 2000 mm. A double glazing glass was used for this experiment to minimize top cover heat losses. The dimension of the double glazed glass pane is 1100 mm × 950 mm. Each duct has a length of 1100 mm, width of 150 mm and a total height of 150 mm as well. The absorber plates were positioned in the duct so that the distance between the absorber plate and the glass pane, L is 102 mm. The aspect ratio (length/width) of the duct therefore was 7.3 which is high enough, where according to Yeh and Lin (1995), an aspect ratio of 6 or more gives better efficiency. The hydraulic diameter of each air flow passage is therefore 0.122 m. The bottom half is closed to replicate single pass flow and it can be opened to replicate a single pass double duct flow. The absorber plates are painted black to absorb more solar radiations. The back walls of all the six ducts are insulated to reduce the back heat losses.

The absorber plates were cut from a 0.75 mm thick sheet of aluminum. The aluminum absorber plates had dimension of 1100 mm by 150 mm by 0.75 mm. The aluminum was used for the experiment because it has a higher conductive heat transfer coefficient as compared to copper or iron and therefore it can absorb more heat energy from the solar radiation as suggested by Majid et al. (2015). The conical pins were punched on the absorber plate using a customizable dye. Two important dimensionless parameters that are used to control installation configuration and the size of the conical pins are their relative roughness height (RRH) and their relative roughness pitch (RRP). They are effecting the performance of the FPAH and therefore will indeed be part of the general correlations for convective heat transfer. Fig. 2 shows the pitch, p, pin height, e, and the pin diameter, d. The RRP is the ratio of pin height, e to pin pitch, p. The RRH is the ratio of pin height, e to the hydraulic diameter, D_h of the air flow passage in the collector.

The experimental measurements were conducted from November 2015 till March 2016 at the UTP solar site. The coordinates of the UTP solar site are latitude 4.38712 north and longitude 100.9735 east. The test rig was aligned with the geographical south direction azimuth angle 0° as the declination angle fluctuates from −14.87° in November 2015 to −6.37° in March 2016. The declination angle stayed negative during the duration of the experiment at UTP solar site. Since there is a chimney at the exit of the absorber duct, the whole test rig had to face the direction of the sun at solar noon so the shadow of the chimney does not fall on the inclined absorber duct which would otherwise not be able to absorb the maximum solar irradiation.

2.2. Measurement system

The section view of the test rig can be seen in Fig. 3 which shows the inside of each of the air flow passage between the absorber and the glass cover. In Fig. 3 the label (1) is the chimney, (2) is the Double glaze glass top cover, (3) is the wind protector, (4) is the probe thermocouple, (5) is the wire thermocouple, (6) is the aluminum absorber plate, (7) is the position of hot wire anemometer