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Experimental Analysis of Solar Air Heater Duct having Square Protrusions as Roughness Geometry

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ABSTRACT

An experimental investigation has been carried out on heat transfer and friction characteristics by using square type protrusions as roughness geometry in the solar air heater duct Data have been generated for both the smooth as well as roughened absorber plate for fully turbulent flow in the range of system and operating parameters. Nusselt number and friction factor correlations have been developed by using the experimental data for predicting performance of the system having investigated type of roughness geometry.

Keywords: *SAW; Hard facing; Bead geometry; Ferro alloys; Alloying.*

1.0 Introduction

Solar collectors (air heaters) are widely used in various equipment's for utilization of solar thermal energy. But thermal efficiency of solar air heaters is generally considered poor because of low heat transfer capability between absorber plate and air flowing through the duct. It is due to the formation of laminar sub- layer on the heat transferring surface. So efficiency could be increase by enhancing the heat transfer coefficient between absorber plate and flowing air. One of the methods for enhancement of convective heat transfer is by creating turbulence at heat transfer surface with the help of artificial roughness on absorber plate. Artificial roughness breaks the laminar sub-layer on the heat transferring surface due to which thermal resistance between the heat transferring surface and flowing air decreases.

However, use of artificial roughness results in higher friction and hence higher pumping power requirements. Therefore, it is desirable that the turbulence should be created in the vicinity of the wall i.e. only in the laminar sub-layer region, which is responsible for thermal resistance. Many investigators have attempted to design a roughness element, which can enhance convective heat transfer coefficient with minimum increase in friction loss. However, generating artificial roughness with a method other than performing protrusions is a very tedious task. Artificial roughness on the surface of absorber plate can be provided by fixing small diameter wires, ribs formed by machining process, wire mesh or expanded metal mesh and by forming dimple/protrusion shape geometry as has been reported by Bhushan and Singh (2010), Hans et al. (2009) and Varun et al. (2009).

Experimental investigations on heat transfer and friction in artificially roughened solar air heater duct have been reported by Gupta et al. (1993), Jaurker et al. (2006), Karwa (2003), Karmare and Tikekar (2007), Prasad and Saini (1998), Saini and Saini (1997). Nusselt number and friction factor correlations have been developed by these investigators by using experimental data. Considerable amount of experimentation has been reported in literature to study effect of different type of roughness geometries on heat transfer and friction in duct of solar air heaters. Formation of protrusions on the absorber plate is the latest and simple technique as protrusions are easy to fabricate and do not add extra weight to the absorber plate. In the present paper, an experimental investigation has been carried out on solar air heater duct having protrusions as roughness geometry. Nusselt number and friction factor correlations as a function of system and operating parameters have been developed by using experimental data.

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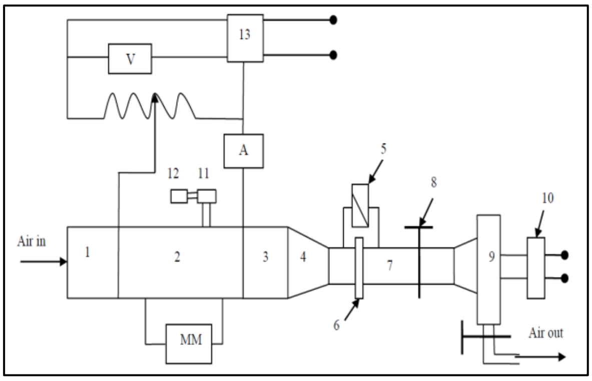
2.0 Experimental Program

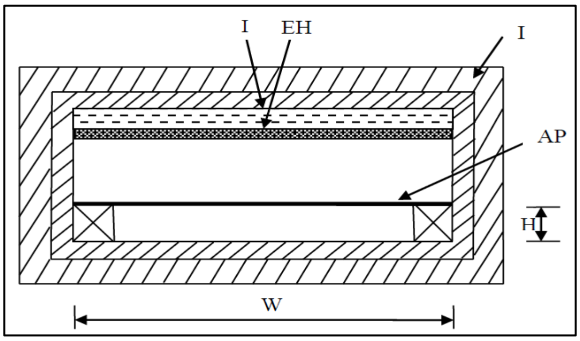
In order to carry out present experimental work, a test rig was used. The rig has been designed and fabricated as per the guidelines proposed in the literature for similar experimental investigations reported by Saini and Saini, (1997) and Saini and Verma, 2008. Schematic diagram and sectional view of experimental set-up is shown in Fig. 1. Aspect ratio of rectangular duct is 10; generally it is kept in the range of 9 to 11 for solar air heaters. Aspect ratio of rectangular duct channel is the ratio of its width (W) and height (H). The length of test section was kept as 1000 mm, whereas lengths of entry and exit sections were kept as 900 mm and 500 mm respectively which were in accordance with the ASHRAE standard (1977). Therefore the total length of air duct was 2400 (900+1000+500) mm. An orifice plate of 40 mm internal diameter and 3 mm thickness was installed in the pipeline of 80 mm diameter with U-tube manometer, for measuring air flow rate .Micro-manometer was used to measure the pressure drop across test section of the duct. Calibrated copper-constantan thermocouples were used for measuring plate and air temperatures. Control valves were provided at inlet and outlet of centrifugal blower for control of air flow rate through the duct. Twelve thermocouples were installed in the air duct and twelve thermocouples were fixed on test section of the test section of the absorber plate for measuring plate temperature.

Figure 1 (a): Schematic of Experimental Set-up



1. Entry section, 2. Test section, 3. Exit section, 4. Plenum, 5. U-Tube Manometer, 6. Orifice plate, 7. GI pipe, 8. Control valves, 9. Centrifugal valve, 10. Electric motor, 11.Selector switch, 12. Temperature indicator, 13. Variac

Figure 1 (b): Sectional View of Duct from Entry Side



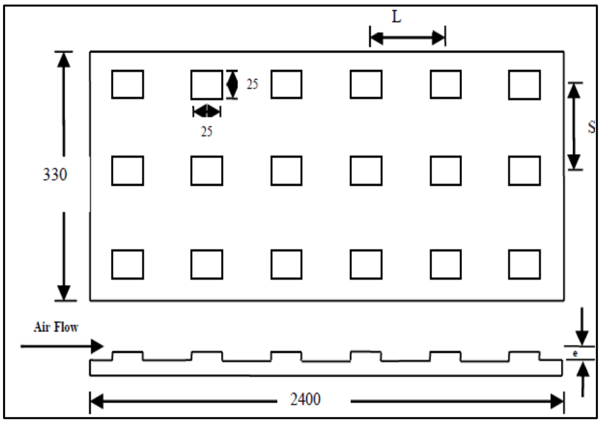
I Insulation;
H Duct height;
W Duct width
V Voltmeter;
A Ammeter;
MM Micro manometer
EH Electric Heater
AP Absorber Plate

3.0 Roughness Geometry and Range of parameters

In the present investigation, the absorber plate was roughened by the formation of square type protrusions. Photographic view of absorber plate roughened by formation of square protrusions is shown in Fig. 2. Arrangement and shape of artificial roughness geometry used in the present experimental investigation is shown in Fig. 3. The range/value of system and operating parameters used in investigation is listed in Table 3.1

Figure 2: Photographic View of Absorber Plate Roughened by Formation of Square Protrusions

Figure 3: Schematic of Roughened Absorber Plate



4.0 Data Reduction

Numerical values of heat transfer coefficient 'h', Nusselt number 'Nu', Reynolds number 'Re' and friction factor 'f' were obtained by reducing the experimental data as described in the following steps.

$$\Delta P_o = \rho_w g(\Delta h_1) \quad \ldots(1)$$

$$\dot{m} = C_d A_t \left[\frac{2\rho \Delta P_o \sin\theta}{1-\beta^4}\right]^{0.5} \quad \ldots(2)$$

$$\mathrm{Re} = \frac{\rho V D_h}{\mu} \quad \ldots(3)$$

$$h = \frac{Q_u}{A_c(T_{pm} - T_{am})} \quad \ldots(4)$$

Table 1: Range/Value of System and Operating Parameters

S. No.	Parameter	Range/Value
1.	Reynolds number (Re)	4000-20000
2.	Relative long way length (L/e)	43.75
3.	Relative short way length (S/e)	37.5
4.	Relative roughness height (e/D)	0.03
5.	Duct aspect ratio	10

$$Nu = \frac{hD_h}{k} \quad \ldots(5)$$

$$\Delta P = \rho_k g(\Delta h_2) \quad \ldots(6)$$

$$f = \frac{2(\Delta P)D_h}{4\rho L V^2} \quad \ldots(7)$$

5.0 Validity Test of Experimental Set-Up

A thorough check of experimental set-up was carried out by conducting experimentation on smooth duct. Accuracy of Nusselt number and friction factor data collected for smooth duct was verified by comparing it with the data obtained from following Nusselt number and friction factor correlations reported by Hans et al. (2010) for rectangular smooth duct.

(Dittus –Boelter Correlation)

$f = 0.085\,\mathrm{Re}^{-0.25}$ (Modified Blasius Correlation)

Comparison of experimental and predicted data of Nusselt number and friction factor is shown in Figs. 4 and 5 respectively. A reasonably good argument between experimental and predicted data ensures accuracy of the data being collected from the experimental set-up.

Figure 4: Comparison of Experimental and Predicted Data of Nusselt Number for Smooth Plate

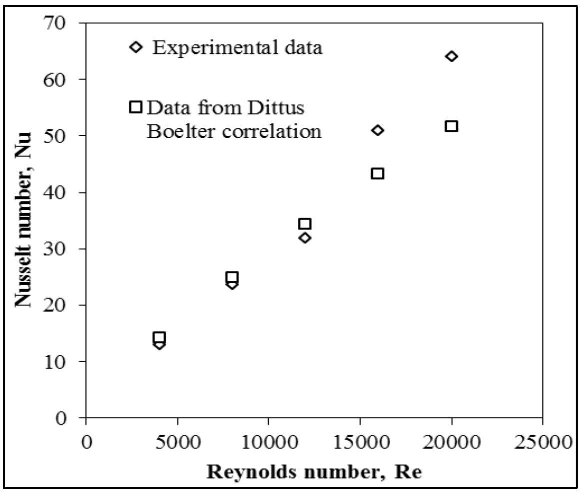
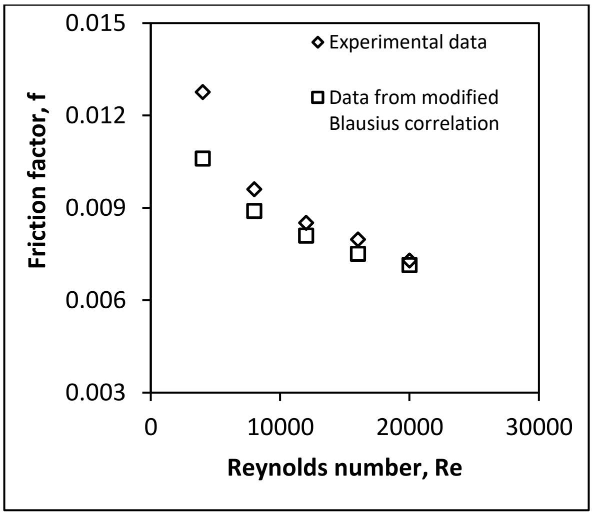


Figure 5: Comparison of Experimental and Predicted Data of Friction Factor for Smooth Plate



6.0 Results and Discussions

Effect of system and operating parametres on heat transfer and friction characteristics of artificially roughened duct have been reported and discussed in the present section.

Figure 6: Variation of Nusselt Number with Reynolds Number for Smooth and Protruded Absorber Plate

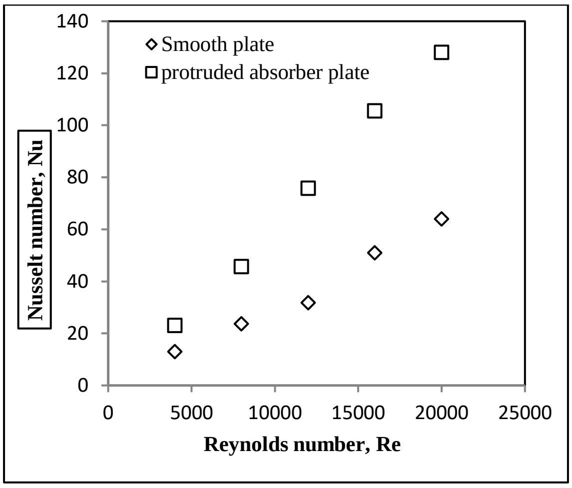
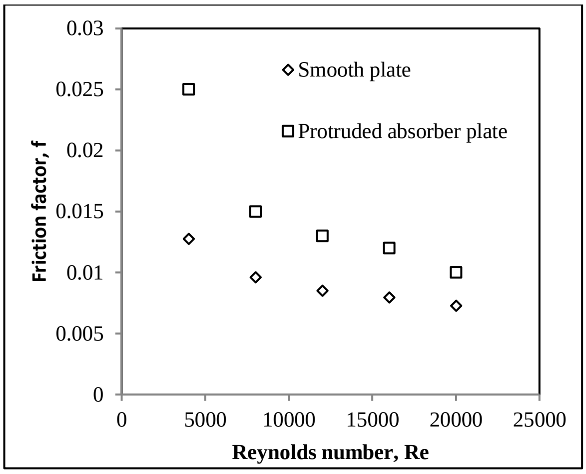


Fig.6 shows variation of Nusselt number as a function of Reynolds number for smooth plate as well as for protruded absorber plate. The protruded absorber plate have relative longway length (L/e) of 43.75, relative shortway length (S/e) of 37.5, and relative roughness height of 0.03. It is observed that Nusselt number increases monotonously with increase in Reynolds number. Moreover value of Nusselt number for protruded absorber plate is much higher than that of the smooth plate due to the enhanced heat transfer coefficient. Enhanced heat transfer coefficient may be due to main flow impingement, vortex generation on both sides of the protrusion and flow separation. Because, decelerating motion is accompanied by adverse pressure gradient which promotes separation, instability, eddy formation and large energy dissipation as has been reported by Vennard and Street (1982) and Landau and Lifshitz (2000). Main flow impinges is on the front side of protrusion and vortices are generated due to hindrance created by protrusions. In addition, vortex originated at the former protrusion affects the downstream protrusions located in diagonal direction and augments heat transfer coefficients as has been reported by Sang et al. (2008). It can be observed that at low Reynolds number, Nusselt number for both the plates almost have same value, which might be due to less disturbance of laminar sub-layer. At higher Reynolds number, this layer is disturbed by the roughened surface; hence the boundary layer thickness decreases which increases the heat transfer coefficient and results into higher values of Nusselt number as has been reported by Karmare et al. (2007).

Figure 7 shows the variation of friction factor with Reynolds number for the range of system and operating parameters. It can be observed that friction factor decreases monotonously with increase in Reynolds number. However in case of protruded absorber plate friction factor is more as compared to smooth absorber plate. It may happen due to change in the fluid flow characteristics as a result of roughness provided on the absorber plate. It implies that an augmentation of heat transfer coefficient is feasible to achieve by protrusions but at the cost of some additional friction loss.

7.0 Development of Nusselt Number and Friction Factor Correlations

Figure 7: Variation of Friction Factor with Reynolds Number for Smooth and Protruded Absorber Plate



Nusselt number and friction factor are strong functions of system and operating parameters. So, in order to predict performance of artificially roughened duct it is necessary to develop Nusselt number and friction factor correlations. In the present section Nusselt number and friction factor correlations have been developed using the experimental data reported in the previous section following the procedure described by Singh et al. (2006) and using Sigma plot software as given in the below equations :

$Nu = 0.00316 \times Re^{1.12}$ …(8)

$f = 1.254 \times Re^{-0.542}$ …(9)

Figs. 8 and 9 show comparison of experimental data and that predicted from the developed Nusselt number and friction factor correlations for absorber plate roughened with investigated type of roughness geometry. An average absolute percentage deviation of -10% for Nusselt number and +10% for friction factor have shown good agreement between experimental data and that predicted from the Nusselt number and friction factor correlations.

Figure 8: Comparison of Experimental and Predicted Data of Nusselt Number

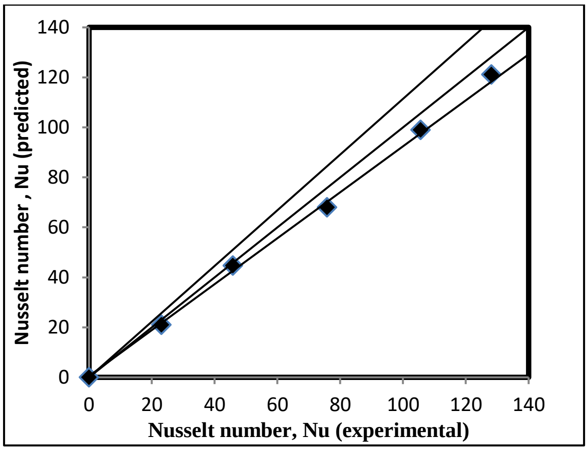
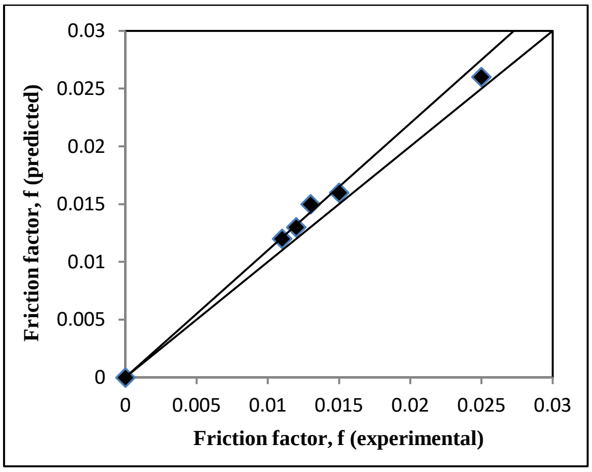


Figure 9: Comparison of Experimental Data and Predicted Data of Friction Factor



8.0 Conclusions

Application of artificial roughness in the form of protrusion on absorber plate may be considered as an innovative technique for improving thermal performance of solar air heaters as it does not require complicated manufacturing process. Effect of artificial roughness (created by formation of square type protrusions on absorber plate) on heat transfer and friction has been investigated. In order to investigate heat transfer and flow characteristics of duct having smooth and roughened absorber plate, experimental data have been generated for fully developed turbulent flow in the range of system and operating parameters. It has been found that Nusselt number increases monotonously with increase in Reynolds number for smooth as well as protruded absorber plate whereas friction factor decreases with in increase in Reynolds number for both the plates. By using experimental data, correlations have been developed for Nusselt number and friction factor for predicting performance of such type of a system.

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