Numerical Analysis on the Influence of a Novel Semi-D shaped Turbulator on Heat Transfer Enhancement of Solar Air Heater

Manjunath M.S[1], K.Vasudeva Karanth[1] and N.Yagnesh Sharma[1]

Abstract— Flat plate solar air heater is commonly used for domestic and industrial space heating and drying applications owing to its simplicity in construction and low maintenance cost. Unfortunately, it is generally found to have exhibit lower thermal performance owing to the poor thermal characteristics of working fluid, which is air. Hence, in order to enhance the heat transfer capability, the present work makes use of a novel semi-D shaped turbulator which promotes turbulence in the air flow. Two-dimensional numerical analysis is carried out to evaluate the efficacy of semi D-shaped turbulator on heat transfer enhancement for various flow rates corresponding to the Reynolds number ranging between 6000 and 27000. The relative roughness pitch (P/e) is varied between 7.14 and 42.86 for a fixed relative roughness height (e/D) of 0.042. The results show that the heat transfer is significantly augmented with a maximum increase in the Nusselt number of about 2.43 at P/e=7.14 for the Reynolds number of about 6000. It is also found that the lower values of relative roughness pitch exhibits higher heat transfer rates, though are also associated with relatively higher pressure drop. The maximum thermal enhancement factor and friction factor enhancement ratio is found to be about 1.84 and 2.32 for the turbulator configuration of P/e =7.14 at the Reynolds number of about 6000.

Keywords— Solar air heater, Semi-D shaped turbulator, CFD, Thermal performance.

I. INTRODUCTION

Flat plate solar air heaters, though are a simple device to use, are also found to operate at lower thermal efficiency levels owing to larger heat losses and poor heat transfer ability of the working fluid. Several studies in the past have proposed different techniques for improving the thermal performance of such systems using the extended surfaces, packing a porous conductive material in the air flow, using turbulators on the absorber plate and deflector plates in the duct. Previous studies have shown that the turbulators can be an effective heat transfer enhancement device for a wide range of flow rates of air. Several turbulator designs have been used in the past which offer varying extents of heat transfer enhancement. This has led to the development of better designs which has increased heat transfer capabilities. Prasad and Mullick [1] made use of circular wire ribs on the absorber plate for the Reynolds number range of 10,000 to 40,000 and found that there was about 14% improvement in the thermal performance as compared to the smooth duct. Karwa et al. [2] showed that the use of chamfering on the square ribs can enhance the Nusselt number by about 50-120%. They used various relative roughness pitch (P/e) which were in the range of 4.58 and 7.09 and the chamfer angle was fixed at 15^o. Momin et al.[3] have shown that the v-shaped turbulators can enhance the heat transfer by about 2.3 times for a relative pitch of 10 and for various angle of attack of 30^o to 90^o. Layek et al. [4] used the concept of chamfered rib turbulator with grooves in the inter-rib region. They have shown that the performance increased by about 3.8 times as compared to the smooth duct for the Reynolds number ranging between 4,000 and 17,000. Multiple v-ribs [5] were found to provide higher heat transfer rates by about 6 times for the Reynolds number range of 2,000 to 20,000. However, they were also found to produce relatively greater pressure drop by about 5 times. Manjunath et al.[6] carried out a comprehensive three dimensional CFD analysis on the influence of spherical turbulence generators on the effective thermal performance of flat plate solar air heater using Discrete Ordinates radiation model. They have shown that the average percentage increase in thermal efficiency was about 24% as compared to the smooth duct. Thus, the literature reveals that there have been various designs proposed with diverse enhancement abilities for different flow rate conditions and geometric parameters. This paper presents a two dimensional numerical analysis to evaluate the effect of semi-D shaped turbulator on heat transfer enhancement of flat plate solar air heater for the Reynolds number ranging between 6000 and 27000.

II. CFD ANALYSIS

A. Computational Domain and Boundary Conditions

The computational domain consists of an air duct which has three sections such as entry, test and exit section as shown in Fig.1. The test section is 500 mm long and is fitted with an absorber plate of thickness 1 mm and the semi-D shaped turbulators are attached below the absorber plate as shown in Fig.1. The height of the turbulator is fixed at 1.4 mm while the pitch is varied as 10 mm, 20 mm, 40 mm and 60 mm. The various configurations considered in the analysis are outlined

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in TABLE I. The mesh of a portion of computational domain is shown in Fig.2. The thermo-physical properties of air are listed in TABLE II.

TABLE I:
VARIOUS TURBULATOR CONFIGURATIONS

Pitch (mm)	Rib height (mm)	Relative roughness pitch (P/e)	Hydraulic diameter (mm)
10	1.4	7.14	33.33
20		14.3	
40		28.6	
60		42.9	

TABLE II:
THERMO-PHYSICAL PROPERTIES OF AIR

Properties	Value
Viscosity (Ns/m^2)	1.85e-5
Density (kg/m^3)	1.18
Thermal conductivity (W/mK)	0.02624
Specific heat (J/kgK)	1006.43

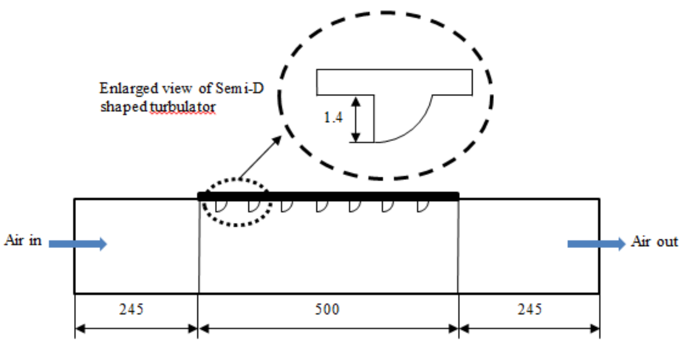

Fig.1. Geometric details of computational domain of solar air heater with roughened absorber plate using semi-D shaped turbulator. (All dimensions are in mm)

The boundary conditions are applied in accordance with the operational conditions of the solar air heater. The top surface of absorber plate is applied with a constant heat flux of $1000W/m^2$. The inlet of duct is specified with the velocity of air and is varied as 3 to 12.7 m/s corresponding to the Reynolds number range of 6,000-27,000. The exit of duct is specified with atmospheric pressure of 101,323 Pa. No-slip and impermeable condition is applied at the solid-fluid interface. All other boundaries are set as adiabatic wall. The flow is assumed to be steady and fully developed.

B. Solution Setup

The analysis is carried out using pressure based segregated solver. The spatial discretization is carried out using the upwind schemes of second order accuracy. The iterative solution process is terminated for convergence when the weighted average of residuals at all control volumes fell below 10^{-6} for continuity, velocity and energy and 10^{-3} for turbulence parameters. The RNG k-ε turbulence model [6-10] is used in the analysis to capture the turbulent characteristics of flow.

C. Grid Independence Study and Validatio

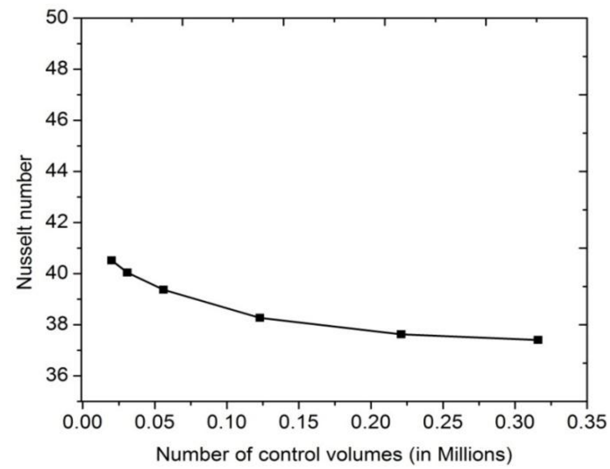

Fig.4. Grid independence test.

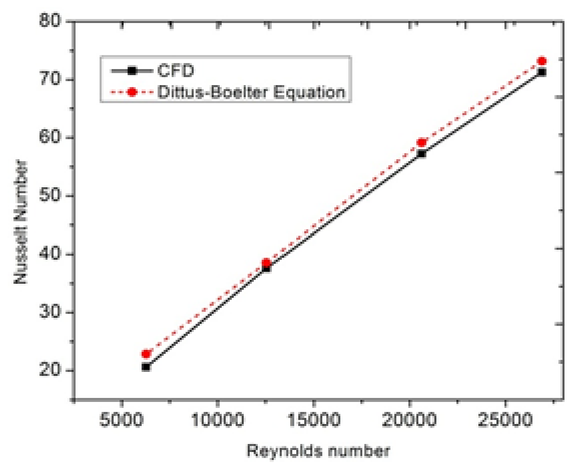

Fig.5(a). Validation for Nusselt number.

Grid test is carried out by varying the number of control volumes in the computational domain viz, 0.02, 0.031, 0.056, 0.123, 0.221 and 0.316 millions and the average Nusselt number is noted for each case as shown in Fig.4. From Fig.4, it is clear that there is negligible variation, not more than 1%, in Nusselt number as the number of control volume increases from 0.221 to 0.316 millions. Hence, the computational domain consisting of 0.221 million control volumes is considered to be optimal and all the configurations used in the analysis were meshed with atleast 0.221 million control volumes. The results of Nusselt number and friction factor obtained from the simulation study are compared with the Nusselt numbers obtained from Dittus-Boelter correlation and Blasius equation [6-10] as given in (1) and (2) to validate the CFD solution. Fig.5(a) and Fig.5(b) shows that the CFD results match very closely with the theoretical correlations with an average deviation of about ±4.5% for Nusselt number ± 2.1% for friction factor. Thus, the results of CFD model with the specified boundary and operating conditions used in the analysis can be used with higher level of confidence.

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \quad (1)$$

$$f = 0.079\,\mathrm{Re}^{-0.25} \quad (2)$$

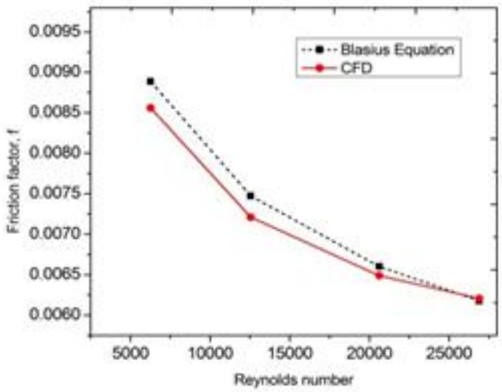

Fig.5(b). Validation for friction

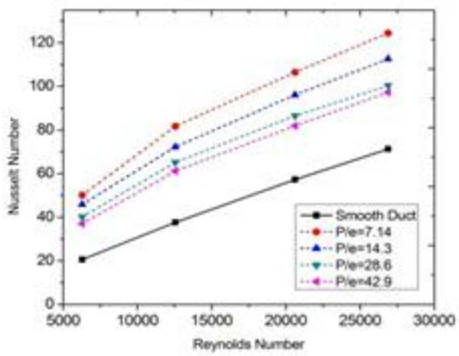

Fig.6. Effect of relative roughness pitch on Nusselt number

III. Results and Discussions

A two dimensional numerical analysis is carried to evaluate the efficacy of semi-D shaped turbulator on the flow and thermal characteristics of flat plate solar air heater. Fig.6 shows the variation of Nusselt number for different Reynolds number of the flow and varying relative roughness pitch.

A. Heat Transfer Characteristics

From Fig.6, it can be seen that the presence of turbulator significantly increases the Nusselt number at all flow rate conditions considered in the analysis. This is due to the disturbances generated in the flow due to the presence of turbulator as seen in Fig.7. It can be seen that the flow impinges on the upstream side of the turbulator and gets deflected thereby undergoing flow separation on the top surface of turbulator. This separated flow interacts with the main flow stream leading to increased fluid mixing and hence increased heat energy exchange. Further, the separated flow consequently reattaches with the absorber surface in the downstream region as shown in Fig.7. The presence of turbulator also leads to the formation of two recirculation zones on either sides of the turbulator. The recirculation zones facilitate fluid mixing and ensure that the relatively colder air from the main flow stream is brought closer to the absorber surface thus enhancing the heat energy exchange.

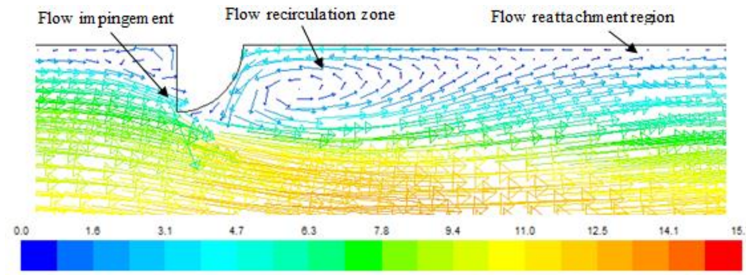

Fig.7. Velocity vector plot showing the flow disturbances around the turbulator region.

This is further verified from Fig.8 which shows that the turbulent intensity is relatively high around the turbulator region with its peak value occurring on the immediate downstream of the turbulator in close proximity to the absorber surface. Thus, the combined effect of flow separation, recirculation and reattachment leads to increased fluid mixing and hence enhanced heat transfer. From Fig.6, it can be seen that the Nusselt number increases with reducing values of relative roughness pitch. This is due to the fact that the number of turbulator increases with decreasing pitch values. As a result, there will be increased instances of flow recirculation, separation and reattachment which lead to increased heat transfer. The enhancement in Nusselt number is found to be higher for the relative roughness pitch value of 7.14 with a maximum enhancement of about 2.43 times as compared to the smooth duct at the Reynolds number of about 6000.

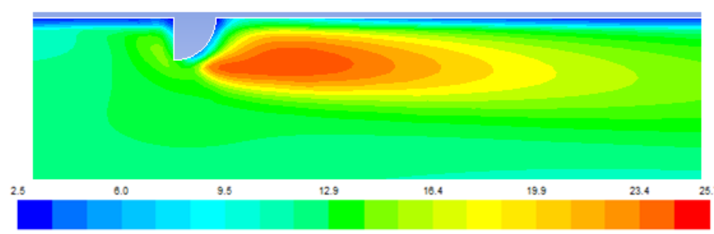

Fig.8. Contour plot of turbulent intensity (%) around the turbulator region

B. Friction Factor Characteristics

Fig.9 shows the effect of relative roughness pitch on the variation of friction factor for different flow rate conditions. In general, it is observed that irrespective of the configuration used, the flow friction decreases as the flow rate through the duct increases. This is due to the fact that the thickness of boundary layer below the absorber plate decreases with increasing flow velocities thereby reducing the drag effect on the flow in the boundary layer region. This leads to reduced pressure drop in the flow and hence the friction factor. Fig.10 also shows that the friction factor is relatively lower at higher relative roughness pitch values. This is due to the reduced number of turbulators at higher relative pitch values which poses lower resistance to the flow leading to reduced pressure drop across the duct and hence the friction factor.

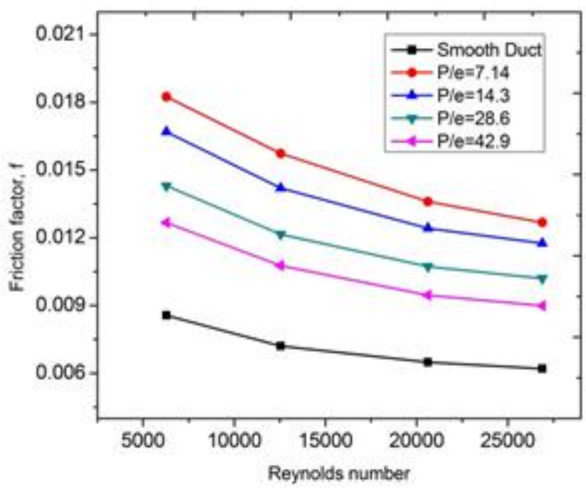

Fig.9. Effect of relative roughness pitch on friction factor.

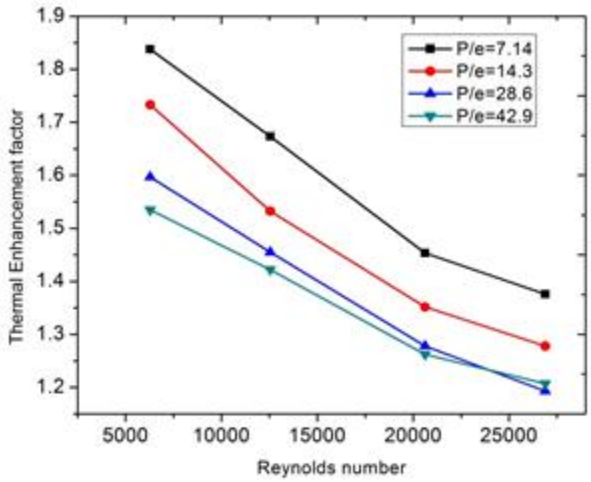

Fig.10. Effect of turbulator on thermal enhancement factor.

C. Effective Thermal Performance

The effective thermal performance is indicated by using the parameter called thermal enhancement factor (TEF) as given by (3).

$$TEF = \frac{\left(\frac{Nu_r}{Nu_s}\right)}{\left(\frac{f_r}{f_s}\right)^{1/3}} \quad (3)$$

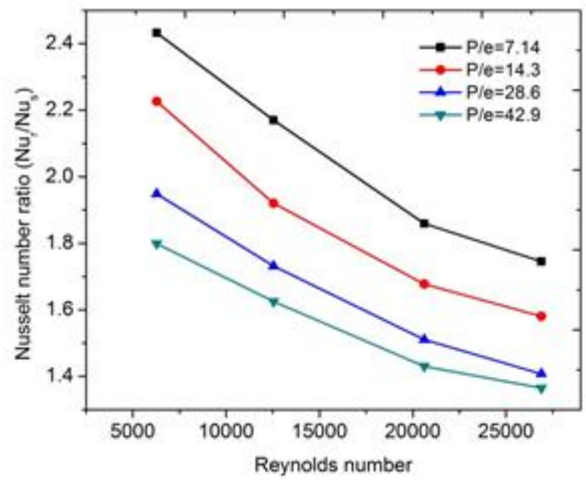

Fig.11. Variation of Nusselt number enhancement ratio.

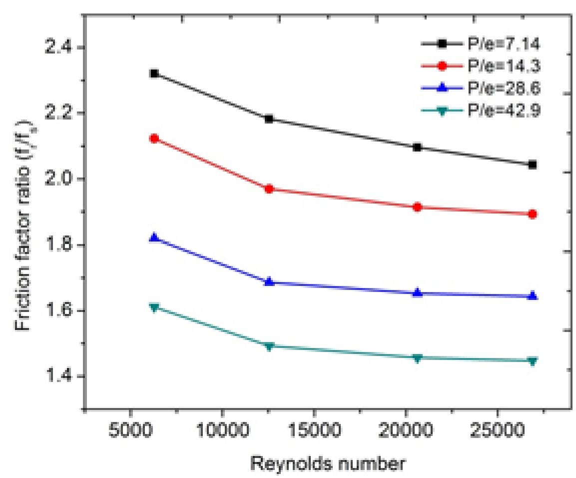

Fig.12. Variation of friction factor enhancement ratio.

Fig.10 shows the influence of semi-D shaped turbulator on the thermal enhancement factor of solar air heater for various relative roughness pitches at different flow rates of air. It can be seen that the presence of semi-D shaped turbulator significantly high effective thermal performance for all relative roughness pitch values considered in the analysis. It is noted that the enhancement factor decreases as the flow rate increases for all pitch values considered in the analysis. This can be due to the fact that the Nusselt number enhancement ratio (Nu_r/Nu_s) decreases with increasing Reynolds number as shown in Fig.11. However, the friction factor ratio (f_r/f_s) remains almost constant at higher flow rate values as shown in Fig.12. As a result, the thermal enhancement factor decreases at higher Reynolds number of the flow as shown in Fig.10. The thermal enhancement factor is found to be in the range of 1.19 and 1.84 for various configurations of turbulator considered in the analysis. The turbulator configurations having lower roughness pitch values are found to exhibit relatively higher thermal enhancement factor owing to relatively higher enhancement in Nusselt number as shown in Fig.11. The maximum enhancement in thermal enhancement factor is found to be about 1.84 for the turbulator configuration of P/e =7.14 at the Reynolds number of about 6000. Thus, it is noted that the semi-D shaped turbulator significantly enhances the effective thermal performance of solar air heater within the range of operating parameters considered in the analysis.

IV. Conclusions

The following conclusions can be drawn from the analysis:

- The Nusselt number enhancement is found to be higher for the relative roughness pitch value of 7.14 with a maximum enhancement of about 2.43 times as compared to the smooth duct at the Reynolds number of about 6000.
- The thermal enhancement factor is found to be in the range of 1.19 and 1.84 for various configurations of turbulator considered in the analysis.
- The maximum increase in thermal enhancement factor is found to be about 1.84 for the turbulator configuration of P/e =7.14 at the Reynolds number of about 6000.
- The maximum increase in friction factor is found to be about 2.32 times as compared to the smooth duct at the Reynolds number of about 600.

V. Acknowledgement

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