# Numerical Investigation of Heat Transfer Augmentation in a Rectangular Solar Air Heater Duct

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***Abstract*— The use of an artificial roughness on a surface is an effective technique to improve the rate of heat transfer to fluid flow in the duct of a solar air heater. Inclusion of artificial roughness, however, results in a higher friction factor and consequently higher pumping power is required. Number of roughness elements has been investigated to study the heat transfer and friction characteristics of solar air heater ducts.**

**A 3 D computational analysis of heat transfer augmentation and flow characteristics due to three different artificial roughness geometries in the form of turbulator, pin-fin and conical fins (conceptual roughness element), on heated wall of rectangular solar air heater duct for turbulent flow (Reynolds number ranges from 3800 to 18000) has been carried out. A new strategy, multiblock is used to create hex mesh for CFD analysis has been studied through this work. Realizable k-ε turbulence model with enhance wall treatment to capture physics at near wall. This turbulence model selected on the basis of size of cell adjacent to the heated wall. This CFD model is first validated by comparing CFD results with analytical results of smooth duct. Using same CFD model, the analysis is carried out for rough duct with different roughness geometries. The CFD results for enhancement ratio, friction factor ratio and average performance index are compared with the experimental results available in the literature. CFD investigations are carried out on different types of roughness geometries which are used for heat transfer enhancement. It is seen that solar air heater duct roughened by inverted rectangular U-shaped turbulator shows better performance with average heat transfer enhancement 1.698 and friction factor ratio 1.338. However, solar air heater roughened by conical fins is advantages over pin-fin duct, with avg. heat enhancement 1.513 and that of pin-fin is 1.478. The performance index calculated by CFD analysis for turbulator, pin-fin and conical fin ducts are 1.541, 1.326 and 1.378 respectively.**

***Keywords*— Aartificial roughness, solar air heater, turbulator, pin-fin, conical fins, CFD analysis.**

## I. INTRODUCTION

Solar air heater is special kind of heat exchanger that transforms solar radiant energy into heat Conventional solar air heater generally consist of an absorber plate with a parallel plate below forming a passage of high aspect ratio through which the air to be heated.

One of the major limitations or problems encountered in solar air heater is poor heat transfer coefficient at the heat transferring surface. When a moving fluid comes in contact with a stationary surface, a thin boundary layer develops adjacent to the wall and in this layer there is no relative velocity with respect to the surface. In a heat exchange process, the near surface layer is called laminar sub layer, viscous sub layer or stagnant film and the heat flow in this layer is covered both by conduction and convection processes. Since thermal conductivity of air is low, the heat flow from the wall to the moving fluid is mainly due to convection which is also low due to less velocity near the surface. Trials are taken to overcome this problem up to some extent by using artificial roughness technique in the present work.



This convective heat transfer coefficient can be increased by providing the artificial roughness on the heat transferring surface [4]. It has been found that the artificial roughness (in the form of interruptions) applied on the heat transferring surface breaks the viscous sub-layer, which reduces thermal resistance and promotes turbulence in a region close to artificially roughened surface. The purpose of providing extended surfaces on the absorber plate of a solar air heater duct is to increase the heat transfer rate and thereby reducing the absorber plate temperature and heat losses to the atmosphere thereby keeping pumping losses as low as possible. The presence of rib may enhance heat transfer because of interruption in the viscous sub-layer, which yields flow turbulence, separation and reattachment leading to a higher heat transfer coefficient. The enhancement of heat transfer by flow separation and reattachment caused by ribs is significantly higher compared to that by the increased heat transfer area due to ribs (fin-effect).

The present work is based on CFD investigation of heat transfer augmentation in solar air heater duct using different artificial roughness geometries. Literature review reveals that a number of studies were carried out dealing with experimental investigations for finding out the optimum enhancement ratio and friction factor ratio for particular geometries and hence, optimum performance index. At the same time it is observed that computational studies are relatively less. Computational Fluid Dynamics (CFD) simulation must be first validated with standard experimental or analytical data. After validating the CFD model, it can be used for simulation of other geometries which are to be analyzed or investigated. Present study deals with CFD analysis of a smooth duct. CFD results from this analysis are validated with analytical results of smooth air heater duct. Using same CFD model, CFD analysis is to be carried out for different roughness geometries.

CFD investigations of following cases are carried out:

1. Solar air heater duct roughened by Turbulator along with smooth duct
2. Solar air heater duct roughened by pin-fin along with smooth duct
3. Solar air heater duct roughened by conical fin (frustum of cone).

## II. SOLAR AIR HEATER DUCT ROUGHENED BY TURBULATOR

- Pre-processing software: ICEM-CFD
- Mesh type: structured hex (Multi-blocking strategy)
- Number of blocks: 4975
- Total number cell count: 2.10 million
- Quality of mesh: > 0.6

Following solver setting are used in ANSYS-FLUENT

- Solver Type : Segregated and Steady State Solver
- Turbulence Model : k-$\varepsilon$ standard turbulence model
- Pressure velocity coupling : SIMPLE
- Discritization method : Second order upwind

The tubulator with pitch $p$ = 10mm and roughness height $e$ = 0.7 mm are used to create turbulence to enhance the heat transfer from absorber plat. Test duct is roughened by using artificial roughness called turbulator. These turbulators are modeled as integral part of absorber plate i.e. top wall. The dimension of the duct is 1240 mm× 65 mm × 22 mm. The angle of inclination of the turbulator is about $9^0$ so mesh creation on such geometry is challenging part of the pre-processor. Hex mesh on turbulator duct is generated by using multiblock strategy.

Simulation is carried out for roughened duct to get Nusselt number ($Nu_r$) and friction factor ($f_r$). To achieve this objective the following post-processing is done. The post-processing gives the general idea about the physics in the Table 1 and figures from fig.1 to fig.4.

Table 1: Deviation of experimental and simulation results

| Re No | Experimental $Nu_r/Nu_s$ | Simulation $Nu_r/Nu_s$ | % Deviation in $Nu_r/Nu_s$ |
|---|---|---|---|
| 3800 | 2.3882 | 2.05437 | 13.97831 |
| 5000 | 2.7855 | 2.12316 | 23.7781368 |
| 8000 | 2.5544 | 2.202 | 13.7958033 |
| 12000 | 2.7535 | 2.2482 | 18.3511894 |
| 16000 | 2.8187 | 2.2746 | 19.3032249 |
| 18000 | 2.8219 | 2.2889 | 18.8879833 |

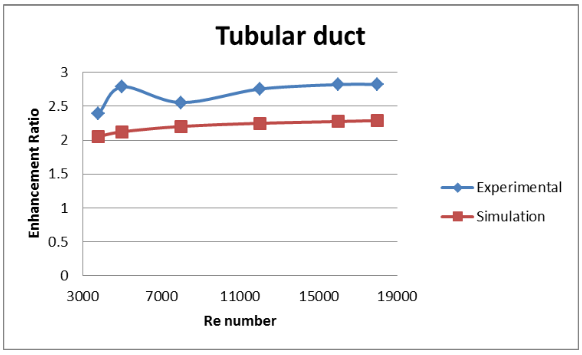


Fig. 1 Plot of Enhancement Ratio ($Nu_r/Nu_s$) vs Reynolds No. ($Re$) for Turbulator Duct.

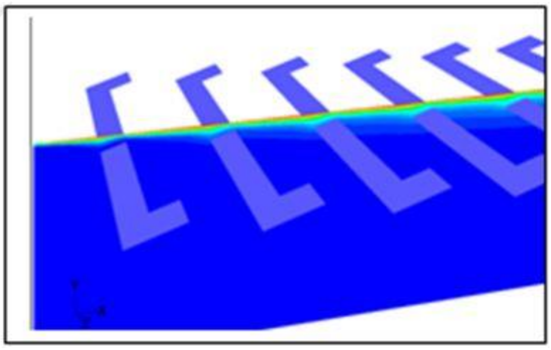

Fig. 2: Temperature contour on X-Y plane at entry

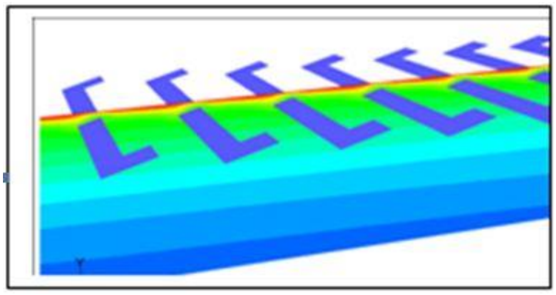

Fig. 3: Temperature contour on X-Y plane at center

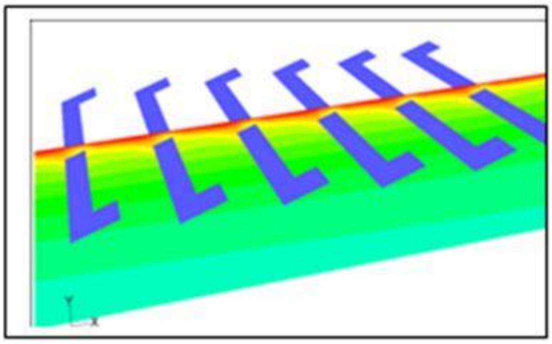

Fig. 4: Temperature contour on X-Y plane at outlet

## III. SOLAR AIR HEATER ROUGHENED BY PIN-FIN

- Pre-processing software: ICEM-CFD
- Mesh type: structured hex (Multi-blocking strategy)
- Number of blocks: 3200
- Total number cell count:1.30 million
- Quality of mesh: > 0.47

From fig.5 and fig.6, it is concluded that CFD results are closely matches with Experimental results with maximum % deviation in Nusselt number and friction factor is 9.30 and 29.30 respectively.

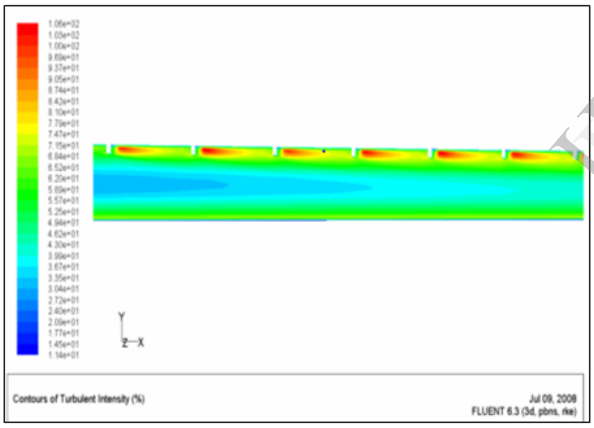


Fig .5: Turbulent Intensity (%) Contour on X-Y Plane (Pin-Fin Duct)

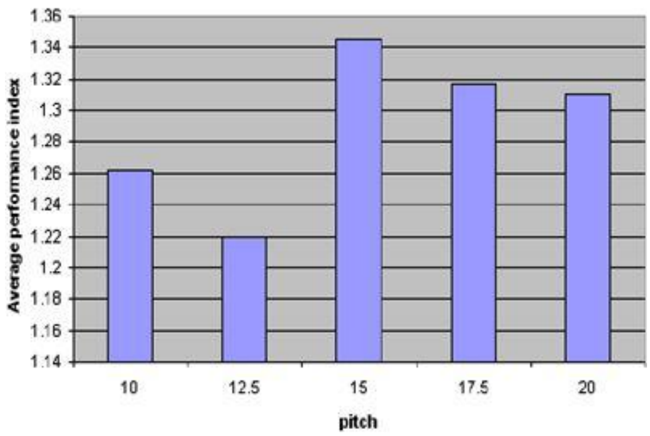


Fig. 6: Plot of Average Performance Index vs. Relative roughness pitch

Average performance index for CFD investigation $\left[\frac{Nu_r / Nu_s}{(f_r / f_s)^{1/3}}\right]_{CFD}$ is 1.326 at pitch 15.

## IV. SOLAR AIR HEATER DUCT ROUGHEN BY CONE FINS

CFD Results of Conical Fin Duct are as shown in fig.7 to fig.9.

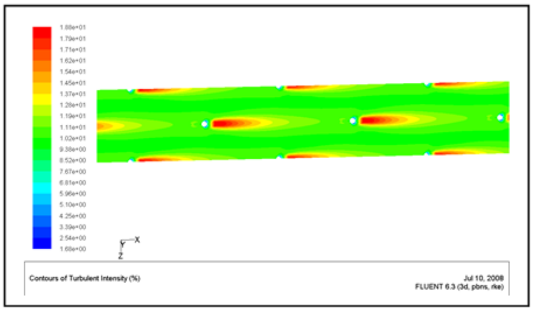


Fig. 7: Turbulent Intensity (%) Contours on X-Z Plane for Conical Fin Duct

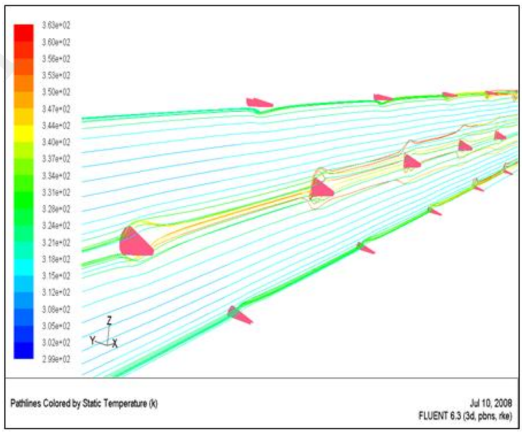


Fig. 8: Path lines Colored by Temperature on X-Z Plane for Conical Fin Duct

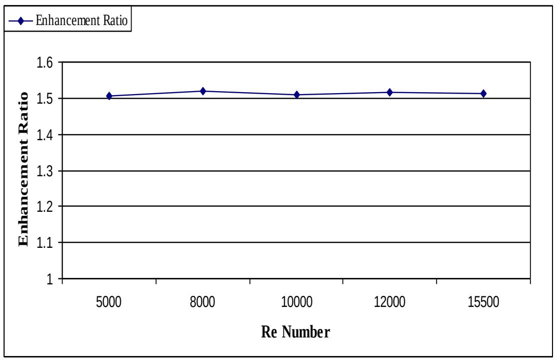


Fig. 9: Plot of CFD Enhancement Ratio (Nur/Nus) vs Re No. for Conical Fin Duct

Average performance index for CFD investigation $\left[\frac{Nu_r/Nu_s}{(f_r/f_s)^{1/3}}\right]_{CFD}$ is 1.378.

## V. DISCUSSION

The physics of artificial roughness pin-fin attached to the absorber plate is to increase the turbulence in the form of wake. Path lines are drawn in X-Y and X-Z plane to interpret the behavior of fluid flow across the pin-fin. Pressure drop caused due to formation of wake as well as skin frication. From CFD investigation it is seen that maximum enhancement ratio improves to 1.478 with friction factor ratio 1.327. Because of less improvement in enhancement ratio, average performance index is found to be 1.326.

Basic physics of this type of geometry (conical fin) is same as that of pin-fin. Conical fin is advantages over pin-fin in two predicted aspects; 1) flow gets disturbed due to cone shape but wake region found to be less, 2) reduction in skin friction results in less pressure drop.

Table 2: Enhancement Ratio, Friction Factor Ratio and Avg. Performance Index of Three Geometries

| | **Tarbulator duct** | **Pin-fin duct** | **Conical duct** |
|---|---|---|---|
| $(Nu_r/Nu_s)_{avg}$ | 1.698 | 1.478 | 1.513 |
| $(f_r/f_s)_{avg}$ | 1.338 | 1.327 | 1.274 |
| Avg. performance index | **1.541** | **1.326** | **1.378** |

Table 2 shows that performance of tarbulator duct is good as compared to pin-fin and conical duct. In the view of present analysis the following conclusion are drawn

- The CFD results of turbulator duct are more closely matches with experimental results.
- The average performance index of turbulator duct is higher than that of other two roughened duct which are studied in present work. The physics behind the heat transfer enhancement is due to momentum lift of air caused by attachment of turbulator is clearly understand by pathlines drawn in the domain, which is predicted at the time of experimentation.
- From contour plot of percentage turbulence intensity, it is found that maximum turbulence intensity occurs just under side of the turbulator.
- In case of pin-fin duct and conical fin duct, it is found that there is no reattachment point and momentum lift of fluid which is essential to enhance the heat transfer in the solar air heater, so heat transfer enhancement in pin-fin and conical fin duct is less.
- The conical fin duct (conceptual geometry) gives better performance than that of pin-fin duct. It is found that in case of conical fin duct turbulence created not only weak region (vortex formation) but also by disturbing fluid layer due to conical shape of the fins.

Future scope concern with the 3D CFD analysis of solar air heater are CFD results can be improved by using very fine mesh which is computationally expensive, but problem can solved by using high configuration machine (servers). Artificial roughness on heated plate which are difficult to manufacture, but can be analyzed using CFD approach. Design of roughness geometries can be first optimized by CFD analysis before going for experimentation, which can reduce experimentation time as well as expenses in manufacturing and experimentation. To understand or to find the physics behind heat transfer enhancement for newly innovative geometry, CFD is best tool to visualize it.

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