Effect of combined U-shaped and semi-circular rib on heat transfer augmentation of solar air heater-A CFD study

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Abstract. This paper presents the numerical analysis on the impact of combined U-shaped rib and semi-circular rib on heat transfer augmentation of flat plate solar air heater system. The analysis is done using the ANSYS Fluent software for various flow Reynolds number ranging from 8000 to 17000. The ribs are placed alternately on the underside of heated plate for a fixed stream-wise pitch of 35mm. The rib height is so chosen that the diameter of semi-circular rib equals the rib height of U-shaped rib. The rib height (e) is varied as 2mm, 3mm and 4mm. The analysis reveals that the combined ribs augment the heat transfer to a maximum extent of about 1.67 times as compared to the smooth duct. Ribs of greater height are found to produce greater enhancement in heat transfer due to increased flow mixing effect. The friction factor is found to increase with rib height and the highest increase is found to be about 1.73 times as compared to smooth duct for Re=8000.

1. Introduction

Solar air heater are widely used in industrial drying applications and can be used in active as well as passive mode. Solar air heaters make use of solar energy for heating the air which is then used for drying purposes. However, these devices have limited heat transfer capability due to the use of air which has poor thermal conductivity. This limitation could be overcome in several ways and the use of artificial roughness to introduce local fluid turbulence is one such commonly adopted method. Various geometries of artificial roughness elements such as square, rectangle, trapezium, circle, and triangle have been used and each of them have been found to provide varying thermal performance enhancement. Srivastava et al [1] conducted numerical studies using circular rib arranged in arc shape with gaps as well as in V-shape with gaps. They found that the V-shaped arrangement provided greater enhancement factor of about 2.21 relative to arc pattern. Wang et al [2] made use of S-shaped ribs in their experimental study and have reported an increase in thermal efficiency by about 48%. The presence of S-ribs introduce fluid mixing thereby enhancing the heat transfer. Aerofoil shaped ribs have been used by Yogesh et al [3] for the flow rate corresponding to Re=6000-18000 under constant heat flux heating condition. They found that the ribs provided an effective thermal performance enhancement of about 2.53 at Re=6000 indicating their usefulness as heat transfer enhancement device. Saravanakumar [4] made use of arc shaped ribs along with fins and baffle plate to determine its thermal characteristics through analytical technique. They found that the use of 8 number of fins and a mass flow rate of 0.012 kg/s along with arc shaped ribs enhance the performance to an optimum value. Twisted ribs [5] have been shown to augment the thermal performance by introducing flow mixing effects owing to the profile of the ribs. A twist ratio of 3 along with the orientation inclination of 60° have been shown to provide an effective performance of about 1.79 times that of smooth duct. Multiple arc shaped ribs with gaps have also been tried and have shown that the performance increased by 3.85 times that of smooth duct when the number of gaps between the ribs were
maintained at 3 [6]. Shivakandan et al [7] conducted analytical study on a hybrid duct in the presence of inclined ribs. They have reported an increase in the effective efficiency by 18.1% for the normalised pitch value of 8 and normalised rib height of 0.021. Jin et al [8] made use of multiple V-shaped ribs which have been show to significantly improve effective performance by about 2.35 as compared to smooth duct. Patel and Lanjewar [9] made use of a novel V-rib for various rib pitch, height and inclination and have shown that the rib pitch has greater influence on the thermal and friction behaviour. The Nusselt number enhancement was found to be about 2.26 times higher that of smooth duct. Thakur et al [10] made use of hyperbolic ribs in transverse and V-shaped arrangements. The CFD analysis reveals the formation of secondary eddies along the inclined ribs which provide improved heat transfer. The inclination angle of 60° has been found to provide highest heat transfer improvement. Manjunath et al [11] have shown that the novel U-shaped rib exhibits about 15% higher effective thermal performance than that of circular ribs. However, the combination of U-shaped ribs and a circular or a semi-circular rib have not been reported in the literature and needs to be analysed to bring out its thermal performance characteristics. This paper details the Computational Fluid Dynamics (CFD) analysis of solar air heater using combined U-shaped rib and semi-circular rib that are placed alternately on the heated plate. The semi-circular ribs have been shown in the past by previous researchers to exhibit lower friction factor penalty. This aspect can be used advantageously by combining them with the U-shaped ribs.

2. CFD Analysis

2.1. Geometry selection

The computational domain chosen for the CFD analysis consists of the two dimensional flow domain of a flat plate solar air heater duct as shown in figure 1. The duct consists of three sections such as entry, test and exit sections of lengths 450mm, 800 mm and 250 mm respectively. The height of the duct is chosen as 30 mm, the hydraulic diameter \(D_h\) of the rectangular air duct is found to be about 50 mm. the absorber plate of thickness 1 mm is provided on top of the test section on which a constant heat flux heating is provided to simulate the solar heat energy input to the device. The absorber plate is provided with combined ribs of semi-circular and U-shaped geometry as shown in figure 2. The stream wise pitch is fixed as 35 mm in the analysis and the effect of rib height is studied where the rib height \(e\) is varied as 2 mm, 3 mm and 4 mm for different Reynolds number ranging from 8000 to 17000. The ribs are placed alternatively and the rib heights are so chosen that diameter of semi-circular rib will be equal to the rib height of U-shaped rib as shown in figure 2.

![Figure 1. Details of computational domain of smooth duct solar air heater system.](image1)

![Figure 2. Arrangement of combined U-shaped ribs and semi-circular ribs on absorber plate.](image2)

2.2. Details of boundary conditions, meshing and numerical schemes

The working fluid used is air with an entry temperature of 300 K and flow velocities ranging from 2.55 m/s to 5.36 m/s. The duct exit is specified with a gauge pressure values of zero pascal. The absorber surface is provided with 1000 W/m² of contact heat flux heating. The meshing is carried out using the ANSYS meshing tool and a view of the mesh of the CFD model is shown in figure 3. The
flow and energy equations are discretised using second order upwind schemes and the convergence
criterion is set as $10^{-5}$ for flow equations and $10^{-8}$ for energy equation. RNG k-ε turbulence model is
used to capture the turbulence flow parameters.

![Figure 3. Discretisation of computational domain.](image)

2.3. Grid test and validation
The mesh density in the CFD model for smooth duct is varied from 25,000 to 305362 so as to verify
the mesh independency of CFD results. The Nusselt number is noted for different mesh density as
shown in table 1. It is seen that the variation of Nusselt number is only about 0.17% when the number
of elements increases from 203791 to 305362. Hence, the CFD model is meshed with atleast 203791
number of elements for all further analysis. Additional elements are provided around the rib regions as
compared to smooth duct to capture the wall gradients effectively.

| Number of elements | Nusselt number | Change in Nusselt number (%) |
|--------------------|----------------|-----------------------------|
| 25000              | 55.36          | -                           |
| 56123              | 53.46          | -3.43                       |
| 125000             | 52.21          | -2.33                       |
| 203791             | 51.92          | -0.55                       |
| 305362             | 51.83          | -0.17                       |

3. Results and discussions
A two dimensional CFD analysis is carried out on a flat plate solar air heater in the presence of
combined U-shaped rib and semi-circular rib for varying rib height values. The effect of rib heights on
the thermal performance is brought out for various flow Reynolds number.

3.1. Heat transfer performance
The variation of Nusselt number for varying rib heights in comparison to smooth duct for different
Reynolds number is shown in figure 4. It is seen that the combined ribs provide augmented heat
transfer as indicated by higher values of Nusselt number relative to smooth duct. This is due to
increased interaction in the air flow owing to enhanced turbulence arising out of increased flow
agitation in the presence of ribs. As a result, heat transfer in the presence of ribs is greater as compared
to smooth duct. It is also seen that the Nusselt number increases with increases with increasing rib
heights as shown in figure 4 for all flow Reynolds number used in the analysis. This can be due to
increased flow agitation introduced by greater heights of the U-shaped and semi-circular ribs. As the
rib height increases, the disturbances caused in the air follow will also increase thereby augmenting the momentum energy.

![Figure 4](image)

Figure 4. Nusselt number variation for combined ribs of different rib heights.

![Figure 5](image)

Figure 5. Comparison of turbulence intensity (in %) for combined ribs having (a) e=2mm (b) e=3mm and (c) e=4mm.

transfer which in turn augments the thermal energy transfer. At lower rib heights, the fluid agitation is relatively lower and hence is characterized by lower Nusselt number values. This is evidenced by the
presence of higher turbulence intensity for increasing rib heights as shown in figure 5. It is seen that
the turbulence intensity is generally higher with increasing rib heights. It is also observed from figure
5 that the turbulence intensity is relatively higher for U-shaped ribs as compared to semi-circular ribs.
This can be due to reduced flow interference by semi-circular ribs owing to its geometry which is
more streamlined to the flow. On the contrary, the U-shaped rib is basically a semi-circular rib placed
on top of a rectangular rib and has greater interference in the flow thereby causing increased fluid
disturbances and hence greater turbulence intensity. Also, the turbulence intensity is found to be
higher for larger region of air flow at greater rib heights as clearly seen in figure 5 owing to enhanced
fluid mixing. The Nusselt number is found to increase by about 1.68 times as compared to smooth
duct for the rib height value of 4 mm at Re=8000.

3.2. Friction factor characteristics

The variation of friction factor for varying rib heights in comparison to smooth duct for different
Reynolds number is shown in figure 6. It is seen that the combined ribs have higher friction factor
number relative to smooth duct. For the case of smooth duct, since the flow is unrestricted, the friction
factor is understandable lower than the roughened duct where the combined ribs are used. However,
with the introduction of combined ribs, the flow is obstructed at the wall surface which causes greater
pressure energy loss and hence greater friction factor. It is seen that the friction factor is higher for
greater rib height values. This can be due to increased flow interference by the combined ribs which
cause greater pressure drop across the ribs. This is clearly seen from the pressure distribution plots as
shown in figure 7. It is seen that the pressure drop across the ribs are higher for increasing rib heights.
The presence of ribs causes breakup of boundary layer leading to flow separation on the rib tip. This
will be followed by a region of recirculation flow in the downstream side of each ribs which are
characterized by lower pressure values. However, the upstream edge of the rib experiences greater
pressure region owing to flow impact during which the kinetic energy of the flow manifests as
pressure energy. Thus, there exists pressure differential across the ribs as shown in figure 7 which
increases for greater rib heights. Therefore, the friction factor is higher for increasing rib height values.
The highest friction factor is found to be about 1.73 times higher as compared to smooth duct at
Re=8000.

Figure 6. Friction factor variation for combined ribs of different rib heights.
Figure 7. Comparison of pressure drop across the ribs for combined ribs having (a) e=2mm (b) e=3mm and (c) e=4mm.

4. Conclusions
A two dimensional CFD analysis on the effect of combined U-shaped ribs and semi-circular ribs for the Reynolds number range of 8000-17000 is carried out. The rib pitch is fixed at 35 mm while the rib height is varied as 2mm, 3mm and 4 mm. The analysis brings out the comparative thermal and friction factor characteristics of combined ribs vis-à-vis smooth duct at constant heat flux conditions. The following are the major conclusions:

- The presence of combined ribs provide increased fluid mixing and exhibit greater range of turbulence intensity around the ribs.
- The Nusselt number is found to increase with increasing rib height and the Nusselt number is found to increase by about 1.68 times as compared to smooth duct for the rib height value of 4 mm at Re=8000.
- The friction factor is higher for increasing rib height values. The highest friction factor is found to be about 1.73 times higher as compared to smooth duct at Re=8000.

Acknowledgements
The authors hereby acknowledge the facilities provided by the Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology for carrying out the research work.

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