Numerical study on heat transfer enhancement of laminar flow through a circular tube with artificial rib roughness

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Abstract - This work presents the configuration optimization of a typical square roughness in a circular tube for laminar heat transfer in air using computational fluid dynamics (CFD) modelling. Conjugate heat transfer 2D numerical model has been developed and successfully carried out. CFD numerical simulations were carried out to analyze the flow and heat transfer in the air duct of a solar air heater provided with rectangular ribs. The laminar flow model is used for formulation, since the flow is laminar. A two-dimensional non uniform grid was generated, in order to critically examine the flow and heat transfer in the inter-rib region. The effects of Reynolds number, Nusselt number, friction factor, convective heat transfer coefficient is examined and discussed. The using of artificial roughness supplies considerable increase on heat transfer and pressure drop when compared with the literature. The Nusselt number increases with the increase of Reynolds number. This result is useful for the design of solar thermal heaters and heat exchangers.

KEY WORDS: laminar flow, forced convection, heat transfer enhancement, artificial roughness

1. Introduction:

Energy efficiency and energy saving are one of the major scientists concern in the last decade because of the increase in energy global demand and consumption as result of economic development and population growth. The thermal efficiency of solar air heaters (SAHs) has been found to be generally poor because of the inherent poor thermal conductivity of air. In order to make the solar air heaters economically viable, their thermal efficiency needs to be improved by enhancing the heat transfer coefficient. There are different factors affecting the SAH efficiency. The shape factor of the absorber plate is the most important parameter in the design for any type of SAH. Increasing the absorber plate shape area will increase the heat transfer to the flowing air. Solar air heaters are used to convert solar radiation into heat using flowing air. They are composed of a glazing, an absorber, and an insulated box. SAH’s thermal efficiency is actually poor because of the bad heat transfer between the flowing air and the heated absorber. This is due to the low thermo physical properties of the air in part, and to the viscous sub-layer that appears in the vicinity of the absorber and which is resistant to the heat transfer in the other part. In order to make solar air heaters more efficient, their thermal efficiency needs to be improved. Many techniques based on both active and passive methods have been proposed to enhance heat transfer in these applications. The main applications of SAHs are space heating and drying. The SAHs occupy an important place among solar heating systems because of minimal use of materials. The conventional solar air heaters are generally improved by means of various
augmentation techniques with emphasis on many types of surface enhancements. Augmented surfaces can create one or more combinations of the following conditions that are favorable for the increase in heat transfer rate with an undesirable rise of friction: (1) interruption of boundary layer development and increasing turbulence intensity, (2) increase in heat transfer area, and (3) generating of vortex and/or secondary flows. Transverse rib is made as integral surface to the duct wall. Farrel et al. [1] tested one fully ribbed and two broken ribbed flat radiator tube. Olsson and Sunden [2] tested two ribbed radiator tubes with airflow. The enhanced tubes showed higher friction factors than the smooth tube in both laminar and turbulent regions. Olsson and Sunden [3] investigated the effect of rib configurations for the multiple V-ribbed channel. Initially, only full-length twisted-tape extending all over the length of the duct had been used. Subsequently, many variations of twisted tapes have been used to improve the thermohydraulic performance. Also, twisted tapes in combination with other enhancement techniques have been used. Saha and Dutta [4] have observed that, for regularly spaced twisted-tape elements, thermohydraulic performance of twisted tapes with multiple twists in the tape module is not much different from that with single twist in the tape module. Twisted tapes with gradually decreasing pitch perform worse than their uniform-pitch counterparts [5]. Patil [6] has worked with varying width twisted-tape inserts for which both friction factor and Nusselt number are lower than those with full-width twisted tapes. Saha et al. [7] and Date and Saha [8] have introduced regularly spaced twisted-tape elements which are better than full-length twisted tapes under certain circumstances.

In the present work the effect of relative roughness height and relative obstacles longitudinal pitch on thermal performance of solar air heater over a wide range of Reynolds number are going to be investigated numerically. And further the thermal performances of solar air heater with surface roughness obstacles are going to be compared with those of smooth one.

2. Physical Model:

The geometrical configurations of the artificial ribs discussed in the present work are shown in Fig. 2. The length of the tube is 2000 mm and the inner diameter of the tube is 100 mm, which are fixed in this research. The artificial ribs are made by uniformly 20mm length and 30 mm height, which are fixed in the present study. In this section, tubes fitted with artificial rib roughness are mainly investigated, and the results are compared with that of the smooth tube with no rib roughness.

Fig.1: Flow separation and reattachment over the ribs
3. Grid Generation and Numerical Method:

A 2D non-uniform grid was generated according to the geometry used. In order to examine the flow and heat transfer critically in the inter-rib region, a refining of the grid near the wall was necessary. The grid generations and numerical simulations are performed using commercial Ansys 15 software package Gambit and Fluent respectively. Fig. 3 presents the mesh generation of the computation domain using hybrid method of size function and boundary layer technique. Medium grid is employed to generate mesh in the interior of tube and boundary layers, respectively. In all cases, the grid is finer close to the wall.

4. Numerical Solution:

Theoretical equations for laminar model in a circular tube of a 100 mm in diameter and a 1000 mm long with artificial rib roughness were numerically solved for heating of air. The artificial rib roughness 2D geometry-data file was created by AutoCAD Design Engineering Software Tools. The control volume discretization equations were derived from these fundamental equations by using the hybrid scheme (Patankar, 1980). The thermo-physical properties for each control volume are given as those at each volume-temperature. The procedure for the calculation of the flow field is the SIMPLEST algorithm which stands for semi-implicit method for pressure-linked equations (Patankar and Spalding, 1972). The two-dimensional grid system is established using the commercial code ANSYS ICEM CFD 15.0 (ANSYS, Inc.). Considering the air flow in the channel with heat transfer, the mathematical model applied is composed of the conservation equations of mass, momentum and energy for incompressible flow in two dimensions with the following assumptions:

- The flow is two-dimensional, turbulent and stationary.
- The thermo-physical properties of the air are supposed to be constant.
- The thermal conductivity of the walls and ribs is supposed to be constant.

The Reynolds number of air flow in the duct is calculated from,
\[ Re = \frac{VDh}{v} = \frac{\rho VDh}{\mu} \]

Steady state values of the plate and air temperatures in the duct at various locations were used to determine the values of useful parameters, namely heat supplied to the air “\( Q_u \)” and heat transfer coefficient “\( h \)” calculated as:

\[ Q_u = \dot{m}C_p(T_{a\infty} - T_{a'}) \]

\[ h = \frac{Q_u}{\Delta p(T_p - T_f)} \]

The convective heat transfer coefficient is then used to obtain Nusselt number, \( \text{Nu} \), as,

\[ \text{Nu} = \frac{hD_h}{k} \]

The friction factor is determined from the measured values of pressure drop (\( \Delta P \)), across the test section length.

\[ f = \frac{2(\Delta P)D_h}{4\rho LV^2} \quad \text{Or} \quad f = \frac{2(\Delta P)\rho D_h}{4L\rho^2} \]

Where, \( G = \frac{m}{WH} \) is the mass velocity of air.

To evaluate the effect of heat transfer enhancement under given pumping power, the formula of performance evaluation criteria is employed as

\[ \text{PEC} = \frac{(\text{Nu}/\text{Nu}_0)}{(f/f_0)^{0.33}} \]

Where \( \text{Nu} \) and \( \text{Nu}_0 \) are Nusselt numbers for the enhanced tube and the smooth tube respectively, \( f \) and \( f_0 \) are friction coefficients for enhanced tube and smooth tube respectively.

5. Result and Discussion:

Continuity, momentum and energy equations in laminar mode using four closure models (two equations models) solved. The test problem is the laminar convection in a tube with artificial rib roughness.

The Fig. 4 represents the Nusselt number mean evolution according Reynolds number for artificial ribs. We observed that \( \text{Nu} \) increases in an almost linear way with \( Re \). This result was foreseeable because of swirling effects created from the use of the artificial rib roughness, making temperature more uniform in the core flow. Furthermore, the swirl enhances the flow, leading to more efficient convection heat transfer.
One can note that the heat transfer coefficient \(hc\) evolution’s curve has the same shape as that of Nusselt number Fig. 5. Indeed, this one increases regularly with the Reynolds number. However, a high value of Num or hc coefficient doesn’t guarantee a good thermal efficiency. Because when the Reynolds number increases, the generated vortex causes also losses of pressure.

For this reason it is significant to estimate the friction factor for the surfaces provided with roughness. This parameter variation has been plotted in Fig. 6. As found in the literature, the friction factor decreases with the increase in the Reynolds number. We can also observe that the values of the factor of friction remain moderate in all the range of Reynolds numbers.
On Fig. 7, we plotted the curve of the global thermo-hydraulic performance parameter PEC. The typical nature of the curve due to swirl flow, whereas there is additional fluid mixing due to flow separation, reattachment and recirculation of fluid in presence of artificial ribs.
7. Conclusion

A numerical study of the flow of air in a circular duct with artificial rib roughness mounted on wall subjected to uniform heat flux for investigation of heat transfer behavior near the ribs using CFD. The conditions and geometrical configuration correspond to the flow in the actual solar air heater duct. Investigations have been carried out over a range of Reynolds number (Re = 100–1000) and results have been compared with those of a smooth duct under similar flow conditions to determine enhancement in heat transfer coefficient and friction factor. In general, it can be said that the enhancement of heat transfer for any arrangement of artificial rib roughness on the surface is caused due to the increased turbulence and the vortex generated due to the recirculation and secondary flow of air produced along the obstacles increases the heat transfer from the heated plate to the moving air.

Reference:


