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A numerical investigation of square sectioned transverse rib roughened solar air heater

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ABSTRACT

The use of artificial roughness in the form of repeated ribs on a surface is an effective technique to enhance the rate of heat transfer. A numerical investigation on the heat transfer and fluid flow characteristics of fully developed turbulent flow in a rectangular duct having repeated transverse square sectioned rib roughness on the absorber plate has been carried out. The commercial finite-volume CFD code ANSYS FLUENT (ver. 12.1) is used to simulate turbulent airflow through artificially roughened solar air heater. The Navier–Stokes equations and the energy equation are solved in conjunction with a low Reynolds number RNG $k-\varepsilon$ turbulence model. Twelve different configurations of square sectioned rib (P/e = 7.14–35.71 and e/D = 0.021–0.042) have been considered. The flow Reynolds number of the duct varied in the range of 3800–18,000, most suitable for solar air heater. The effects of relative roughness pitch and relative roughness height on Nusselt number and friction factor have been discussed and the results are compared with the square sectioned rib roughened duct and smooth duct under similar flow conditions to investigate the enhancement in Nusselt number and friction factor. Roughness and flow parameters for artificially roughened solar air heater have been optimized by considering the thermo-hydraulic performance parameter based on constant pumping power requirement. It has been found that the square sectioned transverse rib roughened duct with $P/e = 10.71$ and $e/D = 0.042$ offers the best thermo-hydraulic performance parameter for the investigated range of parameters.

1. Introduction

A solar air heater is a type of energy collector in which energy from the sun is captured by an absorbing medium and used to heat air. Solar air heater has myriad of uses and applications. The main applications of solar air heater are drying of crops, seasoning of timber, space heating, fresh air ventilation etc. A solar air heater is very simple in design and requires little maintenance. It is observed that the heat transfer coefficient between the absorber plate and air of solar air heater is generally poor and this result in lower efficiency [1]. For this reason, the surfaces are sometimes roughened for the airflow passage. The use of artificial roughness in the form of repeated ribs on the surface is an effective technique to enhance the rate of heat transfer to fluid flowing in a solar air heater. It is found that the artificial roughness applied on the absorber plate breaks the laminar sub-layer, which reduces thermal resistance and promotes turbulence in a region close to artificially roughened surface. However, it would also result in increase in friction losses and hence greater pumping power requirements for air through the duct. In order to keep the friction losses at a low level, the turbulence must be created only in the region very close to the duct surface, i.e. in the laminar sub-layer.

A lot of studies have been reported in the literature on artificially roughened surfaces for heat transfer enhancement but most of the studies were carried out with two opposite or all the four walls roughened for high Reynolds number range in the area of gas turbine airfoil cooling system, gas cooled nuclear reactors, cooling of electronic equipment, shipping machineries, combustion chamber liners, missiles, re-entry vehicles, ship hulls and piping networks etc. Several investigators have attempted to design an artificially roughened rectangular duct which can enhance the heat transfer with minimum pumping losses with two or four roughened surfaces. Artificial roughness in the form of fine wires of different shapes and in various arrangements has been used to create turbulence near the wall or to break the boundary layer. Various researchers have investigated the effects of rib shapes on the heat transfer and friction in a rectangular channel with two or four roughened surfaces. Wang and Sunden [2] experimentally

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examined the characteristics of the heat transfer and friction in a square duct roughened by transversely placed, various-shaped ribs. The shapes of the ribs were square, equilateral-triangular, trapezoidal with decreasing height in the flow direction and trapezoidal with increasing height in the flow direction. It was shown that the trapezoidal-shaped rib with decreasing height has the highest heat transfer enhancement factor than any other rib shapes for same rib pitch (P) and rib height (e). Ahn [3] experimentally investigated the effect of rib shapes on the heat transfer and friction in a square duct. It was shown that the triangular-shaped rib has the highest heat transfer performance than any other rib profile for same rib pitch (P) and rib height (e). Chandra et al. [4] experimentally investigated the effect of rib shapes on the heat transfer and friction in a square channel. It was shown that the square ribs produce higher heat transfer augmentation for same rib pitch (P) and rib height (e) than any other rib shapes. Liou and Hwang [5] experimentally examined the fully developed turbulent flow in a rectangular duct roughened with three rib shapes, namely square, semicircular and triangular cross section. The results showed that the for same rib pitch (P) and rib height (e) highest thermal performance was obtained for the square-ribbed duct and lowest friction factor was obtained for the semicircular ribbed duct.

But geometric and operating parameters relevant to solar air heater are different from the above mentioned applications. In the case of solar air heaters, roughness elements have to be considered only on one wall, which is the only heated wall comprising the absorber plate. These applications make the fluid flow and heat-transfer characteristics distinctly different from those found in case of two roughened walls and four heated wall duct. In the case of solar air heaters, only one wall of the rectangular air passage is subjected to uniform heat flux while the remaining three walls are insulated. Literature also revealed that the practically most suitable range of Reynolds number for solar air heater lies between 3800 and 18,000.

A number of experimental investigations have been carried out to investigate the effect of different shapes and geometries of artificial roughness on heat transfer and friction factor characteristics of solar air heaters. Different experimental investigations on artificially roughened solar air heater can be found in review papers by Varun et al. [6], Hans et al. [7], Bhushan and Singh [8] and Kumar et al. [9] who presented comprehensive literature review about different experimental investigations on roughness elements of different shapes, sizes and orientations carried out in solar air heater in order to obtain an optimum arrangement of roughness element geometry. For complete information, readers may also refer individual research articles cited in the reference section of the review papers [6–9]. Bhagoria et al. [10] performed an experiment and proposed a model of flow pattern for different cross-section of rib viz square, chamfered and wedge shaped for same rib pitch (P) and rib height (e). The proposed model clearly showed the effect of eddies on both sides of the ribs. Authors also reported that eddies not only reduce the heat transfer but also increase the pressure drop. The proposed model clearly indicated that for a given value of rib pitch (P), rib height (e) and Reynolds number (Re) the heat transfer was strongly dependent only on the rib shape.

A literature search in the area of interest has revealed that a number of experimental investigations have been carried out to optimize roughness parameters for heat transfer enhancement in roughened duct of solar air heaters. But literature search in this area has also revealed that very few attempts of CFD investigation of artificially roughened solar air heater have been made so far. Chaube et al. [11] conducted a CFD based analysis of heat transfer and fluid flow characteristics of an artificially roughened solar air heater. Two dimensional analysis of heat transfer and fluid flow through a rectangular duct of a solar air heater having ten different rib shapes viz. circular, semicircular, rectangular, chamfered, triangular, etc., provided on the absorber plate were carried out using CFD software, FLUENT 6.1. Shear stress transport $k-\omega$ turbulence model was used to simulate turbulent airflow through artificially roughened solar air heater. Authors reported that for same rib height, the best performance was found with rectangular rib among the ten different types of rib shapes used. Authors also observed that the results obtained by CFD simulations were in good agreement with the available experimental observations. Kumar and Saini [12] performed a CFD analysis of fluid flow and heat transfer characteristics of a solar air heaters having arc shaped rib roughness on the absorber plate. The heat transfer and flow analysis of artificially roughened solar air heater were carried out using 3-D model. FLUENT 6.3.26 commercial CFD code was used as a solver. In order to find out the best turbulent model, authors tested four different turbulent models namely shear stress transport $k-\omega$, standard $k-\varepsilon$, Renormalization group (RNG) $k-\varepsilon$ and realizable $k-\varepsilon$ for smooth solar air heater. Renormalization group (RNG) $k-\varepsilon$ model was employed to simulate the fluid flow and heat transfer. The results of the simulation were successfully validated with experimental results. Overall enhancement ratio with a maximum value of 1.7 was obtained for the roughness geometry corresponding to relative arc angle ($\alpha/90$) of 0.333 and relative roughness height (e/D) of 0.0426 by adopting CFD approach. Karmare and Tikekar [13] carried out CFD investigation of fluid flow and heat transfer in a solar air heater duct with metal grit ribs as roughness elements on the absorber plate. Commercial CFD code FLUENT 6.2.16 was used as a solver. Standard $k-\varepsilon$ turbulence model was used to simulate turbulent airflow through artificially roughened solar air heater. Circular, triangular and square shape rib grits with the angle of attack of 54°, 56°, 58°, 60° and 62° were tested for the same Reynolds number. Authors reported that amongst the different shapes and orientations analyzed, the absorber plate of square cross-section rib with 58° angle of attack gave the best results. The percentage increase in the heat transfer for 58° rib inclination plate over smooth plate was found to be about 30%. In order to validate CFD results, experimental investigations were carried out in the laboratory. Gandhi and Singh [14] performed a numerical investigation to investigate the effect of artificial surface roughness on flow through a rectangular duct having bottom wall roughened with repeated transverse ribs of wedge shaped cross-section. Two dimensional numerical modeling of the duct flow using FLUENT showed reasonably good agreement with the experimental observations except for the friction factor. Numerical results obtained by commercial computational fluid dynamics (CFD) code FLUENT were compared with the experimental results. Sharma and Thakur [15] conducted a CFD study to investigate the heat transfer and friction loss characteristics in a solar air heater having attachments of V-shaped ribs roughness at 60° relative to flow direction pointing downstream on underside of the absorber plate. The computations based on the finite volume method with the SIMPLE algorithm were conducted for the airflow. For validating the accuracy of numerical solutions, the computations of fully developed turbulent flow forced convection in a smooth rectangular duct was carried out to compare with the exact solution for the Nusselt number and friction factor, respectively. Yadav and Bhagoria [16] carried out a numerical investigation and reported that the flow-field, average Nusselt number, and average friction factor are strongly dependent on the relative roughness height. Yadav and Bhagoria [17] presented the study of heat transfer and fluid flow in an artificially roughened solar air heater provided with circular transverse wire rib roughness on the absorber plate by using computational fluid dynamics (CFD). A two-dimensional CFD simulation was performed using the ANSYS FLUENT 12.1 code. The Renormalization-group (RNG) $k-\varepsilon$ model was selected as the most