NUMERICAL STUDY OF LANIMAR FLOW AND HEAT TRANSFER IN SQUARE DUCT WITH 30^{O} DIAGONAL M RIBS

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Abstract

In the current work, a three-dimensional numerical simulation was performed to investigate a periodic laminar flow and heat transfer characteristics in an isothermal wall square duct fitted with 30° diagonal M ribs. The computations based on a finite volume method with the SIMPLE algorithm for decoupling the governing equations have been conducted for the fluid flow in terms of Reynolds numbers ranging from 100 to 1200. The baffles with the attack angle of 30° mounted periodically on the square duct wall were used to generate a flow of four streamwise counter-vortices through the tested duct. Effects of four different ribs height ratios (BR) and one axial pitch length ratios (PR) on heat transfer and flow behaviors in the square duct were examined. It was apparent that the streamwise vortex flow could induce impingement/attachment flows on the inter-rib cavity wall region at lower Reynolds number (Re) and BR; and on almost the wall at higher Re and BR, resulting in drastic increase in heat transfer rate over the test duct. The computational results revealed that the maximum thermal enhancement factors for the ribs with BR=0.05, 0.10, 0.15 and 0.2 are found to be about 1.30, 1.85, 2.17 and 2.24 at Re=1200 and PR=1, respectively.

Keywords: periodic flow, laminar flow, heat transfer, angled rib, square duct.

Introduction

The application of ribs/baffles/winglets mounted in the cooling/heating ducts or heat exchanger tubes is one of the commonly used passive heat transfer enhancement technique in single-phase internal flows since periodically positioned ribs in the ducts interrupt hydrodynamic and thermal boundary layers, apart from inducing recirculation flow. Downstream of each rib/ baffle the flow separates, recirculates, and impinges on the duct wall and these effects are the vital reasons for heat transfer enhancement in such ducts. The use of ribs/baffles/winglets [1-3] increases not only the heat transfer rate but also substantial the pressure loss. It is, thus, difficult to realize the advantage of rib/baffle arrangements and the staggered rib/baffle with its pitch spacing of 1 time the duct height is often recommended in most of previous work.

The first work on the numerical investigation of flow and heat transfer characteristics in a duct with the concept of periodically fully developed flow was conducted by Patankar et al. [4] and since then, periodic duct flows for laminar and turbulent regimes have been applied extensively. Berner et al. [5] suggested that a laminar behavior for a channel with transverse baffles mounted on two opposite walls is found at a Reynolds number below 600 and for such conditions the flow is free of vortex shedding. Lopez et al. [6] carried out a numerical investigation on laminar forced convection in a three-dimensional channel with baffles for periodically fully developed flow and with a uniform heat flux in the top and bottom walls. Promvonge et al. [7] studied numerically the laminar heat transfer enhancement in a square channel with 45° inclined baffle on one wall and a single baffle pitch. They found that a single streamwise vortex flow is created by the baffle throughout the channel and a vortex flow exists and helps to induce impingement jets on the upper, lower and baffle trailing end (BTE) side walls. The appearance of vortex–induced impingement (VI) flows leaded to the maximum thermal enhancement factor of about 2.2 at BR=0.4 and Re=1200. Promvonge et al. [8] also investigated numerically the laminar flow structure and thermal behaviors in a square channel with 45° inline baffles on two opposite walls. Two streamwise counter-rotating vortex flows were created along the channel and VI jets appeared on the upper, lower and baffle leading end (BLE) side walls. The maximum thermal enhancement factors of about 2.6 at BR=0.2, PR=1 and Re=1000 were reported, respectively. A numerical investigation of Murata and Mochizuki [9] on heat transfer characteristics in a ribbed square duct with e/D=0.1, P/e=10 and 60° orientation using a large eddy simulation provided that the flow reattachment at the midpoint between ribs caused a significant increase in the local heat transfer.

Most of the investigations, cited above, have considered the heat transfer characteristics for transverse ribs/baffles placed repeatedly in square/rectangular channels only. The application of 30° M ribs attached on diagonal plate in square duct has rarely been reported. In the present work, the numerical computations for three dimensional laminar periodic square duct flows over the 30° M ribs attached on diagonal plate in square duct were conducted with the main aim being to examine the changes in the flow structure and heat transfer behaviors. The application of the 30° M ribs attached on diagonal plate in square duct of the tested duct was expected to generate a longitudinal vortex flow through the square duct to better mixing of flows between the core and the wall resulting in higher heat transfer rate in the square duct.

Mathematical Modeling

The numerical model for fluid flow and heat transfer in the square duct was developed under the following assumptions: steady three-dimensional, laminar and periodic incompressible fluid flow and ignoring body forces, viscous dissipation and radiation heat transfer. Based on the assumptions, the tube flow is governed by the continuity, the Navier-Stokes equations and the energy equation. In the Cartesian tensor system these equations can be written in Eqn. (1)-(3)

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \tag{2}$$

Energy equation:

$$\frac{\partial(\rho u_i T)}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\Gamma\frac{\partial T}{\partial x_j}\right) \tag{3}$$

where Γ is the thermal diffusivity and is given by Eqn.(4)

$$\Gamma = \frac{\mu}{\Pr} \tag{4}$$

Apart from the energy equation discretized by the QUICK scheme, the governing equations were discretized by the power law differencing scheme, decoupling with the SIMPLE algorithm and solved using a finite volume approach [10]. The solutions were considered to be converged when the normalized residual values were less than 10^{-5} for all variables but less than 10^{-9} only for the energy equation.

Four parameters of interest in the present work are the Reynolds number (Re), friction factor (f), Nusselt number (Nu) and thermal enhancement factor (η). The Reynolds number is defined in Eqn.(5) as follow

$$\mathrm{Re} = \rho \bar{u} D / \mu \tag{5}$$

The friction factor, f is computed by pressure drop, Δp across the length of the periodic tube, L show in Eqn.(6)

$$f = \frac{(\Delta p / L) D}{\frac{1}{2} \rho \bar{u}^2} \tag{6}$$

The heat transfer is measured by local Nusselt number which can be written in Eqn.(7)

$$Nu_x = \frac{h_x D}{k} \tag{7}$$

The average Nusselt number can be obtained by Eqn.(8)

$$Nu = \frac{1}{A} \int Nu_x \partial A \tag{8}$$

The thermal enhancement factor (η) is defined as the ratio of the heat transfer coefficient of an augmented surface, h to that of a smooth surface, h_0, at an equal pumping power and given by Eqn.(9)

$$TEF = \left.\frac{h}{h_0}\right|_{pp} = \left.\frac{Nu}{Nu_0}\right|_{pp} = \left(Nu / Nu_0\right) / \left(f / f_0\right)^{1/3} \tag{9}$$

where Nu_0 and f_0 stand for Nusselt number and friction factor for the smooth square duct, respectively.

Flow configuration

Baffle geometry and arrangement

The system of interest is a horizontal square duct with the 30° M ribs placed on the diagonal plate as shown in Fig. 1. The flow under consideration is expected to attain a periodic flow condition in which the velocity field repeats itself from one cell to another. The concept of periodically fully developed flow and its solution procedure has been described in Ref. [4]. The air enters the tube at an inlet temperature, T_{in}, and flows over the 30°-angled rib where b is the rib height, H set to 0.05 m, is the hydraulic diameter and b/H is known as the blockage ratio, BR. The axial pitch, L is a distance between the baffle cell set to $L = H$ in which L/H is defined as the pitch ratios, PR=1. To investigate an effect of the interaction between ribs, the baffle blockage ratio, BR is varied in a range of BR=0.05, 0.10, 0.15 and 0.2 for α = 30° in the current investigation.

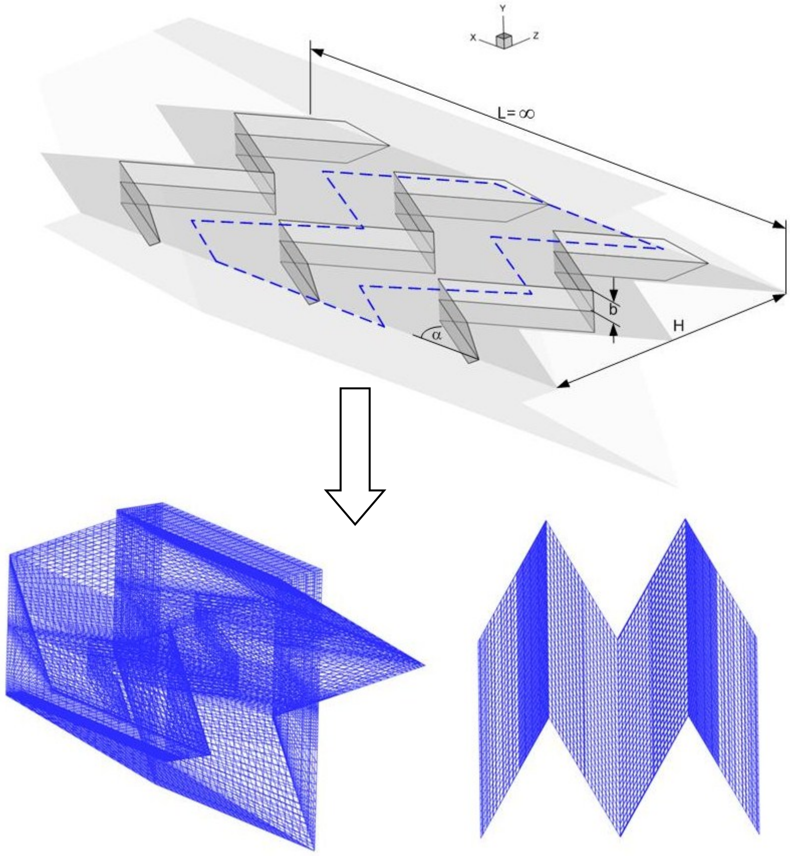
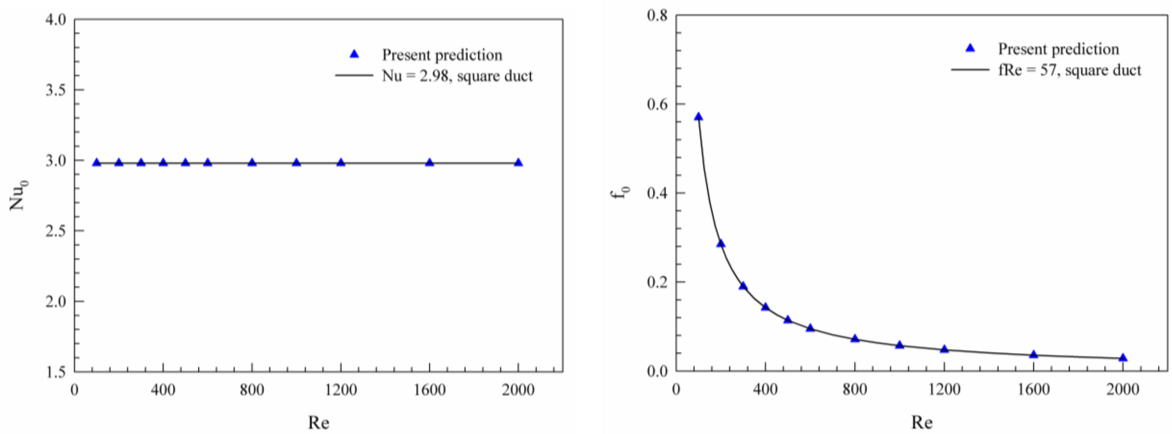


Figure1 Rib geometry and computational domain of periodic flow



(a) (b)

Figure 2 Verification of (a) Nusselt number and (b) friction factor for smooth square duct

Boundary conditions

Periodic boundaries were used for the inlet and outlet of the flow domain. Constant mass flow rate of air with 300 K (Pr = 0.707) was assumed due to periodic flow conditions. The physical properties of the air have been assumed to remain constant at mean bulk temperature. Impermeable boundary and no-slip wall conditions have been implemented over the square channel walls as well as the baffle. The constant temperature of the square duct walls was maintained at 310 K while the diagonal plate and ribs was assumed at adiabatic wall conditions.

The computational domain was resolved by regular Cartesian elements and four grids of 40,000, 80,000, and 120,000 cells are used to investigate the grid independence solution. In the test, the variation in *Nu* and *f* values for the 30° diagonal M ribs at BR=0.05 and Re=800 is marginal (<0.3%) when increasing the number of cells from 80,000 to 120,000, hence the grid system of 80,000 cells was adopted for the current computation.

Verification of the heat transfer and friction factor of the smooth square duct without rib is performed by comparing with the previous values under a similar operating condition as shown in Fig. 2*a* and *b*, respectively. The present numerical smooth square duct result was found to be in excellent agreement with exact solution values obtained from the literatures [11] for both the Nusselt number and the friction factor, less than ±0.5 % deviation. The exact solutions [11] of the Nusselt number and the friction factor for laminar flows over square duct with constant wall temperature were $Nu_0 = 2.98$ and $f_0 = 57/\mathrm{Re}$, respectively. Therefore, these exact solutions were used to normalize the numerical results of the Nusselt number and the friction factor values

Results and discussion

Flow structure

The flow and vortex coherent structure in a square duct with 30° diagonal M ribs can be displayed by considering the streamline plots as depicted in Figs. 3. Here streamlines for using the rib is presented for BR=0.20, Re=1200 and PR=1. Because flow behaviors of the periodic flow is not completed by itself in one calculated module, the calculated module will be copied and then connected together in a series to become a long duct with several modules as desired to shed light its flow characteristics.

Fig. 3 shows the streamlines in transverse planes at Re=1200 for the rib with BR=0.20. In the figure, a longitudinal vortex flow created by the 30° diagonal M ribs appears for all cases. A closer examination reveals that the baffle generates vortex flow having a direction along the middle region of the rib cavity.

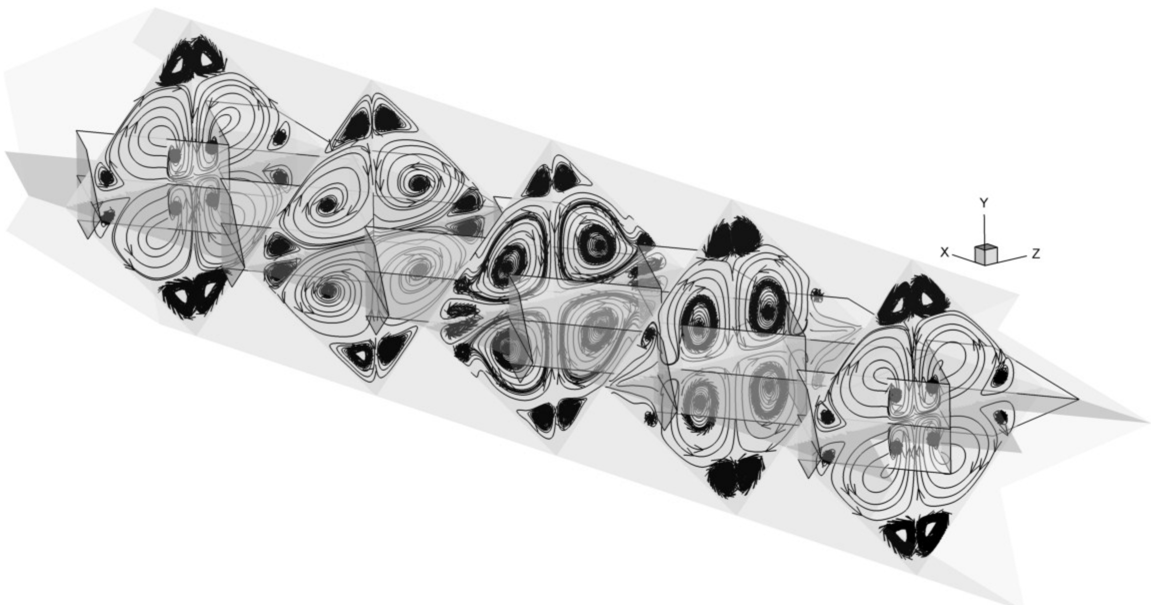


Figure 3 Streamlines in transverse planes for BR=0.20, at Re=1200 and PR=1

Heat transfer and friction loss

Fig. 4 displays the contour plots of temperature field in streamwise planes, at Re=1200 and PR=1 for the rib with BR=0.20. The figure shows that there is a major change in the temperature field over the duct. This means that the vortex flows provide a significant influence on the temperature field, because it can induce better fluid mixing between the middle and the wall flow regions, leading to a high temperature gradient over the heating wall.

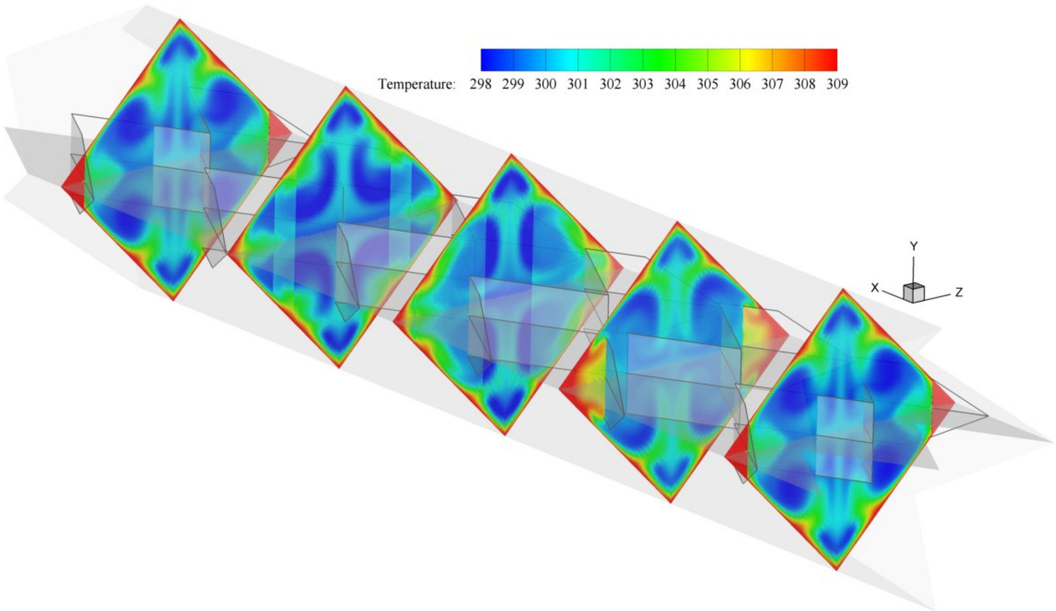


Figure 4 Temperature contours streamwise planes for BR=0.20, at Re=1200 and PR=1

Fig. 5 exhibit local Nu contours of the square duct wall for the rib with PR=1 at Re=1200, BR=0.20. It is visible in the figure that a larger area of high Nu values can be observed for this case.

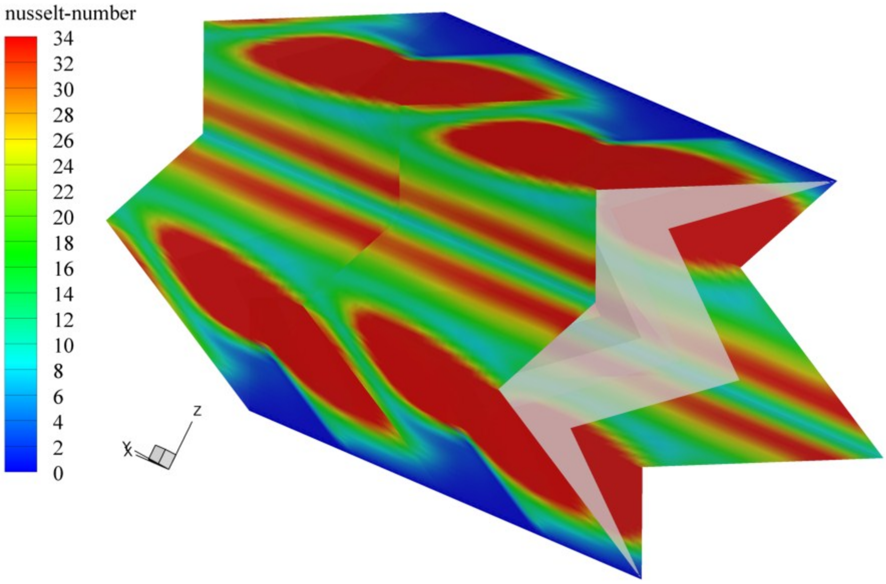


Figure 5 Nu_x Contours streamwise planes for BR=0.20, at Re=1200 and PR=1

The variation of the average Nu/Nu_0 ratio with Re for the ribs with various BRs is presented in Fig. 6. In the figure, it is visible that the Nu/Nu_0 value tends to increase with the rise of Re for all BR values. The use of higher BR value leads to the increase in Nu/Nu_0. The angled baffle with BR=0.20 provides the highest Nu/Nu_0 value. The maximum Nu/Nu_0 values at BR=0.20 were found to be about 6.09. A closer examination revealsed that the use of the 30° diagonal M ribs with studied BR ranges yields the average heat transfer rate of about 1.10–6.09 times over the square duct without ribs, depending on the BR values.

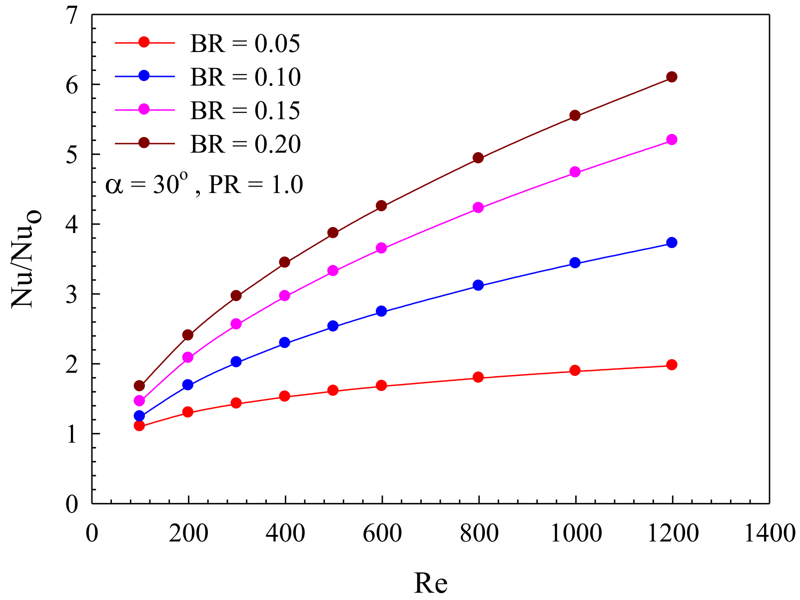


Figure 6 Nu/Nu_0 versus Reynolds number at various rib BRs

Fig.7 displays the variation of the friction factor ratio, f/f_0 with Re for various BR. In the figure, it is noted that the f/f_0 tends to increase with the rise of Re and BR values. The rib with BR=0.20 gives the highest f/f_0 value. The friction factor for the 30° diagonal M ribs appearsed to be about 2.55–19.73 times above that for the smooth square duct with no rib. Thus the flow blockage due to the presence of the ribs is a vital factor to cause a high pressure drop in the duct.

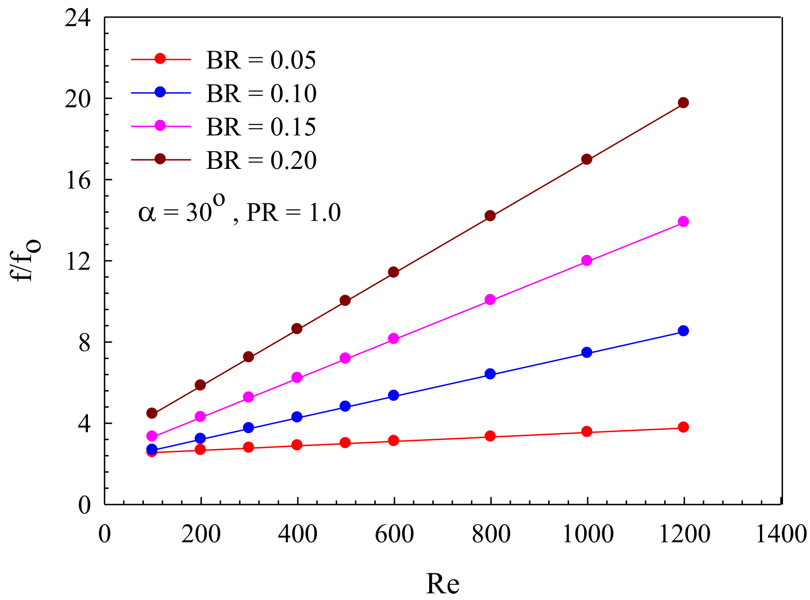


Figure 7 f/f_0 versus Reynolds number at various rib BRs

Performance evaluation

Fig. 8 shows the variation of thermal enhancement factor (TEF). In the figure, the enhancement factor of using the rib tends to increase with the rise in Re and BR values. It is found that the rib with BR=0.20 provides the highest enhancement factor of 2.24. The enhancement factor of the rib is seen to vary between 0.77 and 2.24, depending on the BR, and Re values.

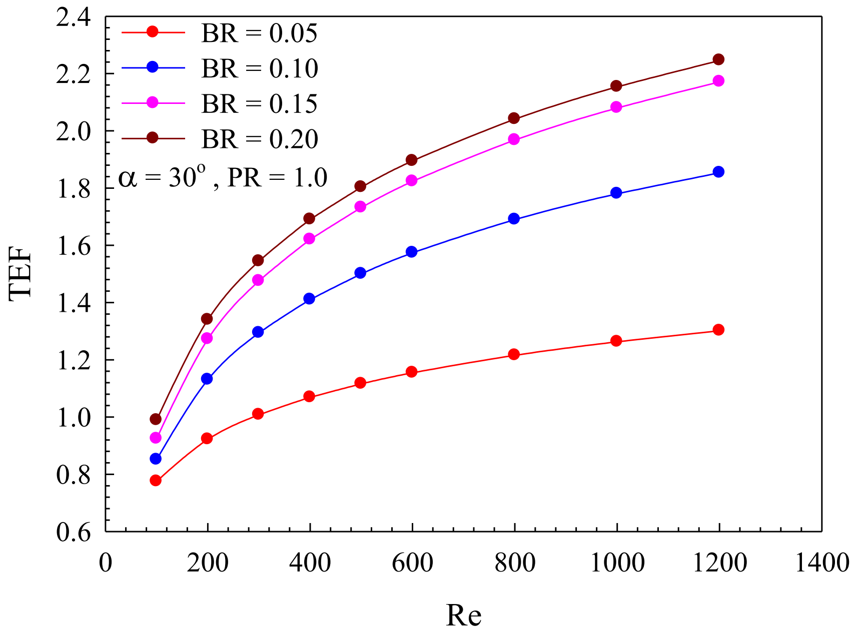


Figure 8 Thermal enhancement factor at various rib BRs

Conclusions

A numerical investigation has been conducted to examine laminar periodic flow and heat transfer characteristics in a square duct fitted with 30° diagonal M ribs inserted periodically in the square duct. The main vortex flow created by the 30° diagonal M ribs and helped to induce impingement flows over the duct wall leading to drastic increase in heat transfer in the square duct. The order of heat transfer enhancement was about 0.77-2.24 times when using the rib with BR=0.05, 0.10, 0.15 and 0.20 at PR=1. The enlarged pressure loss was in a range of 2.55 to 19.73 times above the smooth square duct. Thermal enhancement factor for the 30° diagonal M ribs was higher than unity and its maximum value was about 2.24 at BR=0.20, indicating higher performance over the smooth square duct.

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