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Numerical Study on Heat Transfer Enhancement in a Rectangular Duct with V-Shaped Ribs

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This research aims to study the numerical investigation of heat transfer and fluid flow characteristics of multiple cylinder v-rib with combined staggered rib in a rectangular duct. The conventional heat exchangers were usually used as flat plate rib shape leading to increase pressure drop from obstructive flow. Therefore, the inclined cylinder V-shaped rib was modified to use in this work. The cylinder shape rib increases pressure drop (less than flat plate rib) because of the rounded shape of cylinder v-rib creating the smooth flow of the fluid. The heat transfer and the pressure drop are represented in term of Nusselt number (Nu) Friction factor (f), respectively. The relation of Nu with f values was analysed to obtain the Thermal performance enhancement factor (TEF). The velocity vector and temperature contours were examined by the Computational Fluid Dynamics (CFD). The data was compared with the experimental result. The channel size was simulated at the rectangular duct height (H) of 30 mm and width (W) of 300 mm with rib-to channel-height ratios (e/H) at 0.1, 0.2, 0.3 and the angle of attack (α) at 30°. Air was used as the test fluid. Reynolds number (Re) was varied from 12,681 to 35,000 with constant heat flux on the bottom wall of the tested section. Simulation results represented the velocity vectors and temperature contours. It was found that the increasing of e/H leading to provide high co-rotating of the flow. The highest TEF (TEF = 2.05) was observed at 30°, e/H 0.3 and Re 12,618.

1. Introduction

In the industrial process related to thermal energy, most of heat exchangers are basic element such as Oil industry. Heat exchangers are used for increasing temperature of crude oil to change steam phase condensed to liquid phase. It is pretty similar to fertilizer industry, synthetic fibre industry and other industries that using application of heat exchanger to increase or decrease temperature. The main function of the heat exchanger is to apply heat energy correctly and effectively. Several investigations on turbulent flow of the heat transfer characteristics for various rib shape in pipe have been studied. In the experiment of Sriromreun et al. (2012), the ribs were placed in a zigzag shape (Z-shaped rib) to find the optimum thermal performance for the Reynolds number (Re) from 4,400 to 20,400. The Z-ribs inclined to 45° relative to the main flow direction were characterized at three rib-to channel-height ratios (e/H = 0.1, 0.2 and 0.3) and rib pitch ratios (P/H=1.5, 2 and 3). The result of in-phase Z-rib with e/H= 0.1, P/H= 1.5 provided the highest TEF at the lowest Re. Gawande et al. (2016) found that the highest TEF (TEF=1.90) was observed by using the reverse L-shaped rib. The finite volume method and SIMPLE algorithm were applied to present the numerical simulation (Boonloi et al., 2015). The mathematical results were discovered at α of 30° and 45° for wavy-ribs at the blockage ratio (b/H) of 0.05–0.25 and Re of 3,000–20,000. The results showed the optimum TEF (TEF = 1.52) at α=45°, b/H=0.10, and the lowest Re=3,000. Most of research has been developed the V-rib shaped. A numerical investigation of heat transfer and fluid flow characteristics having multi V-shaped ribs on the absorber plate was presented in Dongxu et al. (2015). The maximum value of the TEF (TEF = 1.93) was found at 45°. Daungkumsawat et al. (2015) studied on the heat transfer enhancement in a heat exchanger with incline shaped ribs. This research aimed to enhance TEF by reducing the friction factor (f) with curve V-rib. In order to simulate the heat transfer and flow

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characteristic, the turbulence equation was used k-ε model and Re was varied from 12,500-35,000 comparing with Butprom et al. (2014) experiment. Kumar et al. (2016a) studied the shaped V-pattern rib in rectangular duct at Re of 5,000-20,000, e/H = 0.04, P/H = 10 and α = 60 °. The results showed that the discrete multiple V-rib with staggered rib roughness shapes provided high TEF. Kumar et al. (2016b) studied on the heat transfer behaviour and optimum relative width parameter of the solar air channel of aspect ratio of 10.0 with 60° angled discrete multiple V-type ribs at Re = 3,000 - 8,000. The obtained experimental results showed the highest TEF occurred at e/H = 5.0. Moreover, the results revealed that the discrete multiple V-type ribs represented the highest TEF. According to above researches, the discrete multiple V-shaped ribs provided the highest TEF. Therefore, the discrete multiple V-type ribs was studied in this work. The discrete multiple V-shaped cylindrical rib was used instead of the discrete multiple V-shaped flat rib. The curve surface of cylindrical rib would probably reduce the pressure drop and increase TEF.

2. Computational Models and Numerical Method

For a simulation study, to understand the heat transfer and fluid flow characteristics. The simulation is validated with the experimental data from the experiment of Butprom et al. (2014). The detail of assumptions and simulation are developed under the same condition as shown in Sriromreun et al. (2012).

2.1 Mathematical modeling

The channel models were analyzed by Continuity equation (Eq(1)), Momentum equation (Eq(2)), Energy equation (Eq(3)) in the Cartesian tensor these equations can be seen in Sriromreun et al., 2012.
Continuity equation:

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

Momentum equation:

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

Energy equation:

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

where the length of test section is x, the density is ρ, the velocity is u, the pressure is P, and the temperature is T.
The molecular thermal diffusivity, Γ, and turbulent thermal diffusivity, Γ_t, are approximated from the viscosity, μ, the turbulent viscosity, μ_t, the Prandtl number, Pr and the turbulent Prandtl number, Pr_t, as follows:

$$\Gamma = \frac{\mu}{Pr} \quad \text{and} \quad \Gamma_t = \frac{\mu_t}{Pr_t} \tag{4}$$

There are three parameters of interest in the present work (Sriromreun et al., 2017), 1) Friction factor (f), 2) Nusselt number (Nu) and 3) Thermal enhancement factor (TEF), The f was computed by pressure drop (Δp) across the length of the periodic channel (L), as shown in Eq(5).

$$\Delta p = f\,\frac{\rho L \bar{v}^2}{2D} \tag{5}$$

The Nusselt number which can be written as Eq(6).

$$Nu = \frac{hD}{k} \tag{6}$$

Where h, k are heat transfer coefficient and thermal conductivity of air, respectively.

The TEF is defined as Eq(7).

$$TEF = \left(\frac{Nu}{Nu_0}\right)\left(\frac{f}{f_0}\right)^{-1/3} \tag{7}$$

Where Nu_0 and f_0 stand for Nusselt number and friction factor of the smooth channel, respectively. Nu and f represent for the variables of cylinder discrete multiple v-ribs channel.

3. Simulation of flow configuration

The cylinder discrete multiple v-ribs with combined staggered are repeatedly placed on lower wall of a horizontal rectangular duct. The channel width (W) is 300 mm. The duct is divided into 3 sections including the inlet (450 mm), test section (0.38 m) with constant heat flux (12.5 kW/m^2) on lower wall, and outlet (80 mm). The duct height (H) is 30 mm. The detail of the full length rib channel is shown in Figure 1a and 1b whereas a module of the computational domain due to periodical flow along the cylinder discrete multiple v-rib with combined staggered is displayed in Figure 1c. The rib angle (α) of 30° and rib-to channel-height ratios (e/H) of 0.1, 0.2, 0.3 are studied. For the simulation, the bottom channel is heated with a uniform heat-flux. The bottom channel is assumed at adiabatic surface conditions (Sarghini et al., 2017).

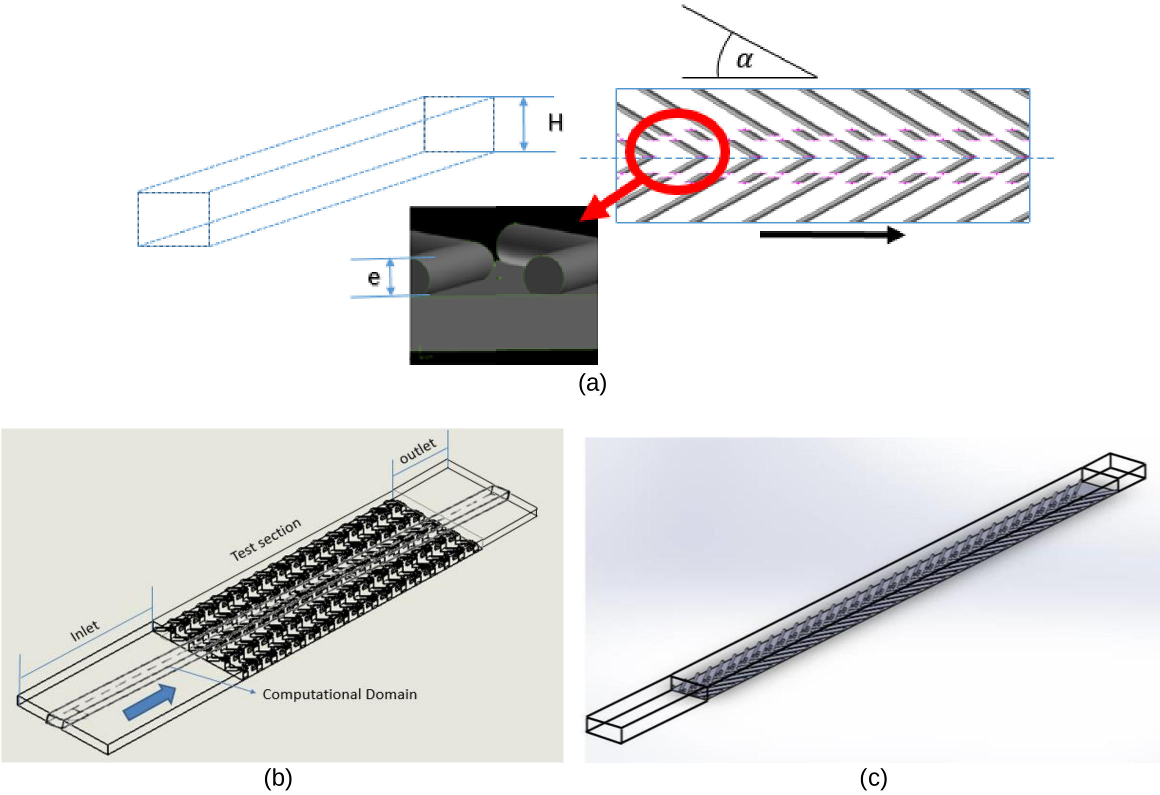


Figure 1: (a) Cylinder discrete multiple v-rib with combined staggered rib in rectangular duct. (b) Channel geometry. (c) Computational domain of flow.

4. The results from simulation

4.1 Verify the accuracy of the simulation

Figure 2 demonstrates the results from simulation with the experiment of Butprom et al. (2014). Heat transfer and pressure loss are represented in form of Nusselt number (Nu) and friction factor (f), respectively. The diagram shows that there is a good agreement between the results of this model and Butprom et al. (2014). The maximum difference is less than 5 %. Therefore, the simulation model can be used to calculate Nu and f. In addition, these simulations can be applied to develop other ribs to enhance TEF.

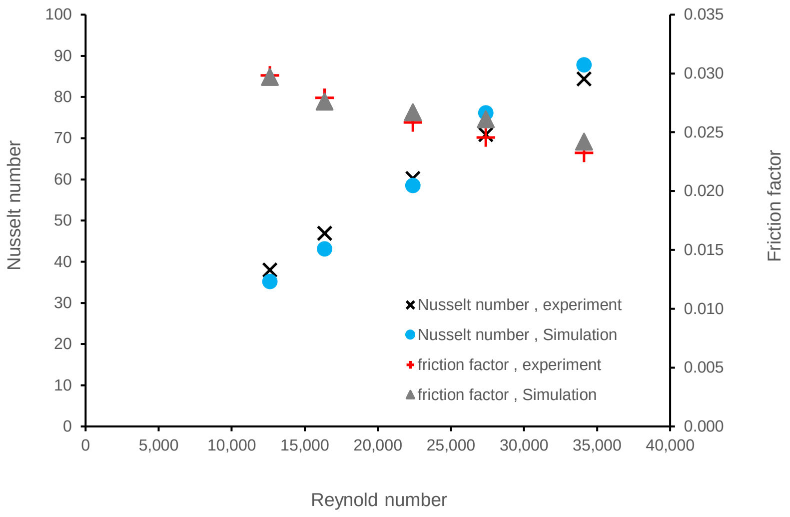
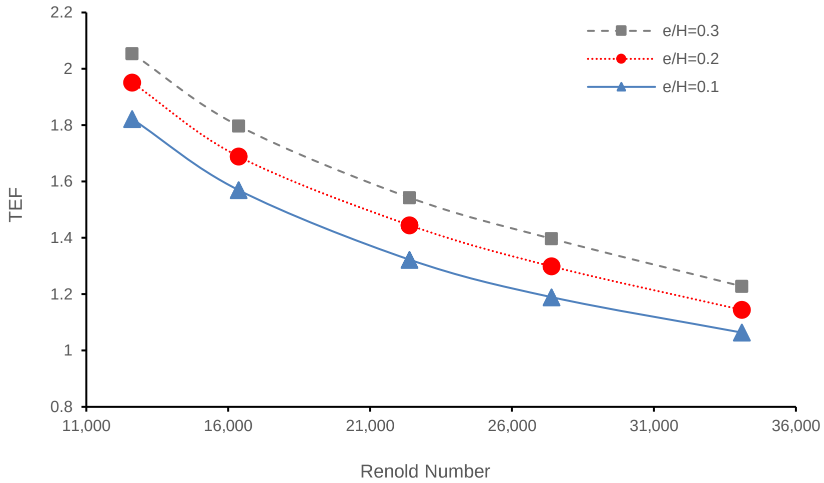
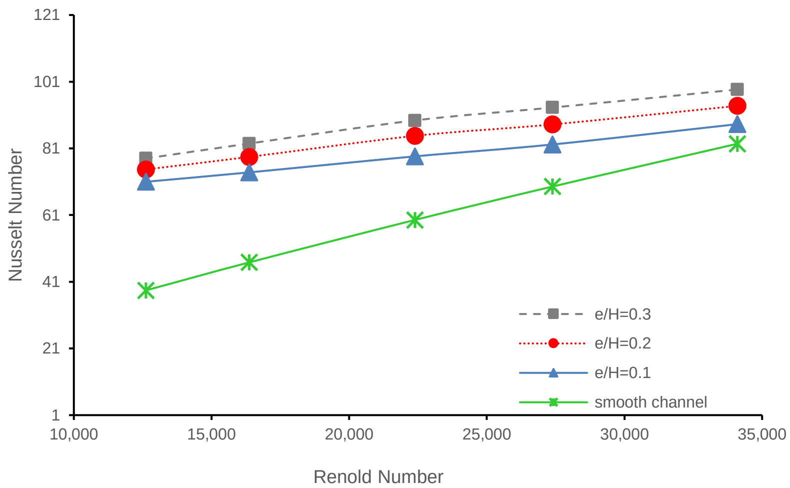


Figure 2: Verification of Nu and f for smooth channel.



(a)



(b)

Figure 3: Variation of (a) Nu and (b) TEF with Re for cylindrical rib at $\alpha = 30°$.

4.2 Effect of Re

Figure 3 shows the effect of Re on the heat transfer represented in the term of Nu and TEF with an angle of 30°and smooth pipe. Result shows that higher Re can bring about the increase in the Nu and decrease in the TEF. According to this diagram, it indicates that the higher turbulent flow causes the greatest increase in heat transfer rate and pressure drop. Higher pressure drop leads to obtain the decreasing of TEF. The results in Figures 3 show similar trend as observed in Sriromreun et al. (2017).

4.3 Effect of height ratio (e/H)

Figure 3 shows the effect of different height ratio (e/H) at 0.1, 0.2, 0.3 on the Nusselt number and TEF. The diagrams present that the channel with rip provides the higher Nu and TEF than smooth channel. Increase in height ratio (e/H) increases Nu and TEF. The velocity vector and temperature contours from simulation result can be seen in Figure 4. Figure 4a shows the effect of Re in four different rib positions along the channel at the height ratios (e/H) of 0.3 and the angle of 30°. It is also found that the co-vortex flow along the test channel occurring at the rectangular duct with rib. The higher e/H causes the higher turbulent intensity. For the temperature contours along the rectangular duct, the longer distance from the channel inlet (position 4) shows higher fluid temperature (see the color shade). It is apparent that increase Re cause to high velocity fluid flow and reduce the fluid temperature due to shortage of the heat transfer time. The comparison of the velocity vector and temperature contours in different e/H for Re of 12,618 at the outlet position (position 4) is shown in Figure 4b. It was found that higher e/H provides the spread of colour temperature throughout rectangular duct. The high temperature colour shades are observed all the picture at e/H 0.3. These results can be concluded that the e/H effect to the heat transfer characteristic. Higher e/H indicates the higher heat transfer enhancement.

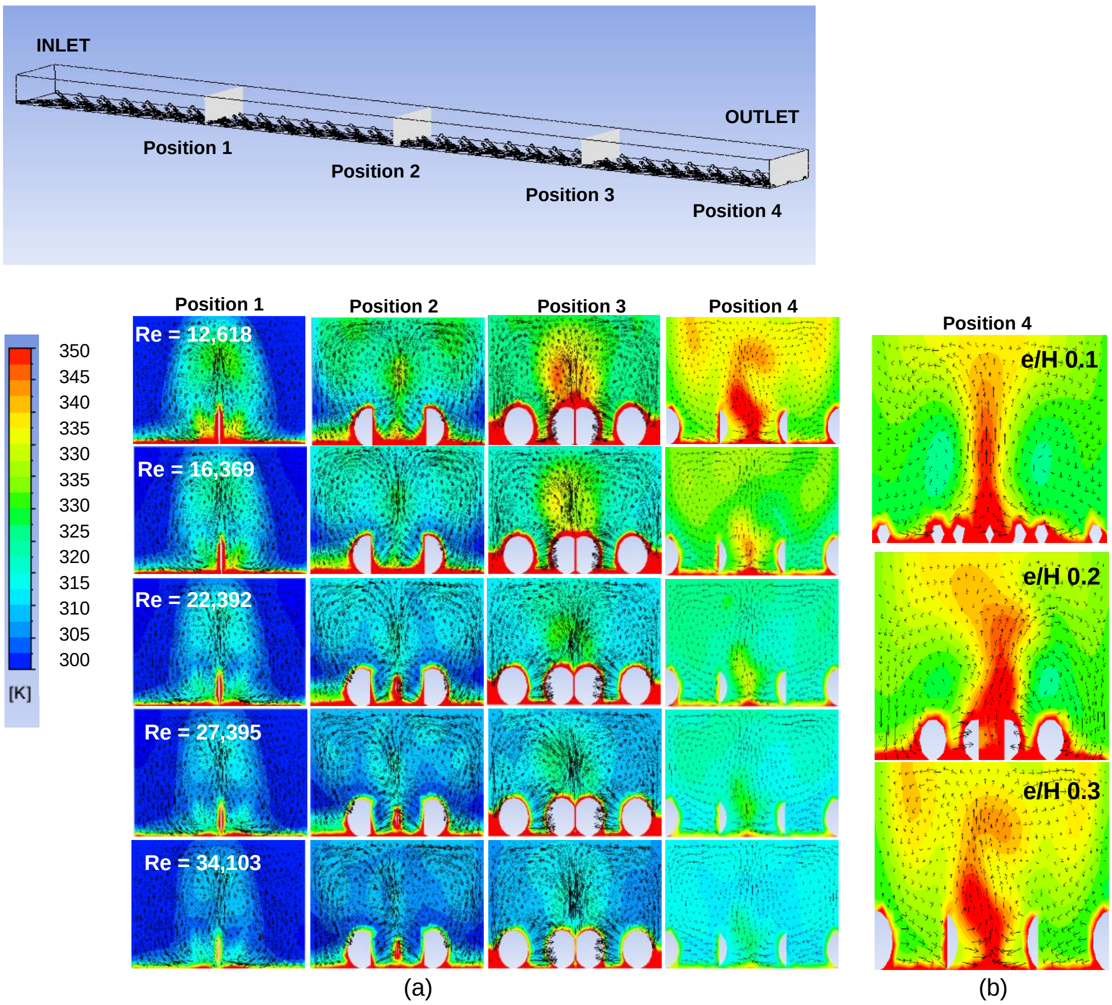


Figure 4: (a) Velocity vector and temperature contour at $\alpha = 30°$ at e/H = 0.3, (b) Velocity vector and temperature contour at Re =12,618, and $\alpha = 30°$.

5. Conclusions

The simulation in heat exchanger with discrete multiple cylinder v-rib with combined staggered was examined. The results showed that higher Nu and TEF was observed in the channel with ribs than without ribs. Increasing Re provided the higher Nu but lower TEF, while increasing e/H presented the higher both of Nu and TEF. The highest TEF (TEF=2.05) was found at e/H=0.3 and Re=12,618. The velocity vector and temperature contour indicated the co-vortex flow as increasing e/H. The cylinder v-shaped rib reduced the friction factor (f) observed from higher TEF at higher e/H. In contrast, for the general ribs, higher e/H represented higher friction factor (f) leading to obtain lower TEF. The cylinder shaped rib can be applied to use in heat exchanger for increasing Nu and TEF. In industry, it can reduce heat exchanger cost and operating expense.

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