Chapter

Thermal-Hydrodynamic Characteristics of Turbulent Flow in Corrugated Channels

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Abstract

The heat transfer-flow characteristics of turbulent flow inside corrugated channels heated by constant heat flux are numerically investigated. The rate of heat transfer, pressure drop, and performance evaluation criterion is determined for smooth channel and various designs of corrugated channels at the Reynolds number ranged from 5000 to 60,000. The effect of rib arrangement distributions of inward, outward, and inward-outward ribs are examined. The various rib configurations of corrugated channels are also tested. In addition, the influences of rib roughness parameters (height, pitch, and width) and rib shapes (semicircular, trapezoidal, and rectangular) are researched. The Reynolds-averaged Navier-Stokes equations (RANS) are used to model the governing flow equations. The computational model is validated through a reasonable agreement between the present numerical results and the outcomes of related works. For different geometrical and operating conditions, the results revealed that the rate of heat exchange in corrugated channels exceeds higher than that of smooth ones but with additional pressure loss. Moreover, the rib arrangements, rib configuration, and rib roughness parameters exhibit a relatively significant effect on the performance of the corrugated channels. On the other hand, the influence of the rib shapes seems to be small.

Keywords: thermal-flow performance, corrugated channel, rib distribution, rib configuration, rib shapes

1. Introduction

The reliable efficient heat exchangers transfer the maximum rate of heat with minimum friction losses. The rate of heat transfer of most fluids is restricted by their low thermal conductivity. Thus, the thermal systems adopt techniques of heat transfer enhancement to reduce the effect of this issue. There are three techniques of enhancing heat transfer, namely, active methods (require external power) [1], passive methods (fins, corrugation, ribs, etc.) [2], and compound techniques (simultaneous use of active and passive techniques) [3]. Corrugation of tubes and channels is considered an efficient passive method to augment the rate of heat exchange. The thermal-flow features of turbulent flow in corrugated tubes are reported extensively in many articles (for example [4–8]).

Corrugated channels are widely utilized in industrial applications as they are the major components in plate heat exchangers. Naphon [9] conducted experiments to show the performance of a turbulent flow inside a two-sided corrugated channel with an in-line and staggered arrangements. He showed the important effect of corrugation on the augmentation of heat transfer and pressure loss. Eiamsa-ard and Promvonge [10] experimentally examined the thermal-hydrodynamic performance of the three types of ribbed-grooved ducts. They reported that the maximum rate of heat exchange and pressure drop exist in the ducts with a rectangular rib and a triangular groove. Elshafei et al. [11] conducted experiments to examine the thermal-hydraulic performance of corrugated channels under the influence of variations of phase shift and channel spacing. The corrugated channels exhibit a compound increase in heat transfer and pressure loss. Mohammed et al. [12] performed a computational model to investigate the effects of wavy tilt angle, channel height, and channel height on the flow-thermal fields in a corrugated channel. A three-dimensional numerical model to investigate the employing baffles on the heat transfer-flow in the corrugated channels was presented by Li and Gao [13]. Increasing the baffle height enhances heat transfer effectively but leads to dramatic penalty in pressure drop. Pehlivan et al. [14] experimentally investigated the rate of heat exchange for sharp corrugation peak fins of corrugated channel for three different types and sinusoidal converging–diverging channels. It is reported that the rate of heat transfer increases with the corrugated angle. The numerical results showed that the wavy channel is an efficient method to increase the heat transfer. Ravi et al. [15] numerically studied the impact of different rib configurations on the heat transfer-flow characteristics of the turbulent flow inside corrugated channels. Shubham et al. [16] numerically investigated the thermal-hydrodynamic transport characteristics of non-Newtonian fluids in corrugated channels. It was found that using of shear thinning fluids is more convenient for maximum augmentation of thermal performance with a minimum penalty in pressure drop.

The present study offers a numerical model to investigate the thermal flow attributes of turbulent flow in corrugated channels. The performance of corrugated channels are examined under the effects of corrugation arrangement (inward, outward, and inward-outward rib distribution), corrugation configuration, corrugation roughness parameters (rib pitch, rib width, and rib height), and rib shapes (rectangular, trapezoidal, and semicircular). The comparisons between the predicted thermal flow performance of corrugated channels and that of smooth ones are fulfilled under a large range of Reynolds number (5000–60,000).

2. Numerical model

The two-dimensional corrugated channel with a width (b) of 10 mm is described schematically in **Figure 1**. The water as heat transfer fluid enters the computational domain at a temperature of 27°C and intensity of turbulent of 5%. Also, 5% of turbulent intensity is considered at the exit. The end effects and viscous dissipation terms are ignored. The constant heat flux of 600 W/cm^2 is applied on the channel wall. The consideration of an axisymmetric situation reduces the size of the numerical domain for saving computational time.

The flow-thermal behavior is modeled by the governing conservation equations (continuity, momentum, and energy) in a RANS technique as

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

$$\frac{\partial}{\partial x_j}\left(\rho\, u_i u_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_j}{\partial x_j}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\, \overline{u_i' u_j'}\right) \tag{2}$$

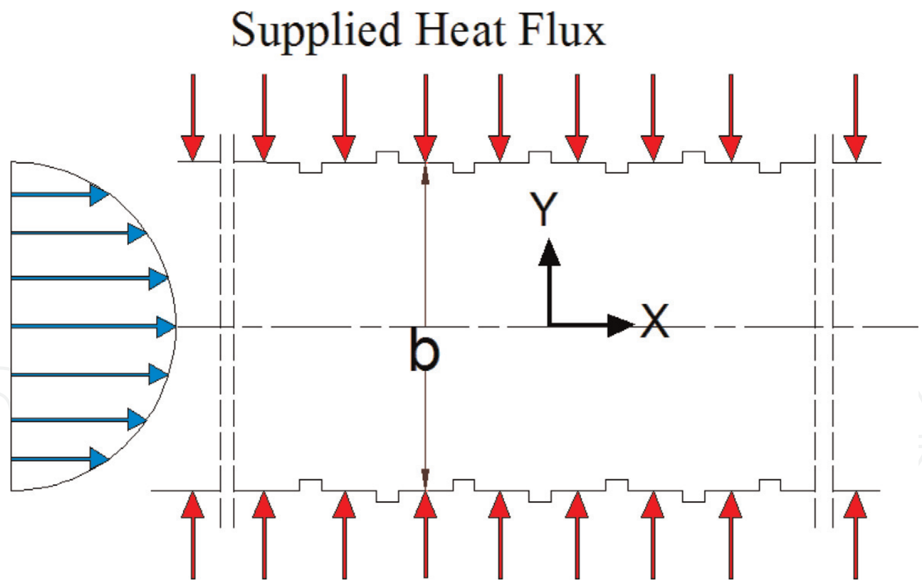

Figure 1.
Schematic representation of the computational domain.

in which ρ, μ, u', and $\rho\overline{u_i'u_j'}$ are density, viscosity, fluctuated velocity, and turbulent shear stress, respectively.

$$\frac{\partial}{\partial x_i}\left[u_i(\rho E + P)\right] = \frac{\partial}{\partial x_j}\left[\frac{\partial T}{\partial x_j}\left(kt + \frac{C_p \mu_t}{\mathrm{Pr}_t}\right) + u_i\left(\tau_{ij}\right)_{eff}\right] \tag{3}$$

where Pr_t is the turbulent Prandtl number and $(\tau_{ij})_{eff}$ is the deviatoric stress tensor which is evaluated as

$$\left(\tau_{ij}\right)_{eff} = \mu_{eff}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu_{eff}\frac{\partial u_i}{\partial x_j}\delta_{ij} \tag{4}$$

The transport equations in k-e model are presented as [17]

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon \tag{5}$$

$$\frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}(\varepsilon/k)G_k - C_{2\varepsilon}\rho\left(\varepsilon^2/k\right) \tag{6}$$

and μ_t is the eddy viscosity which is modeled as

$$\mu_t = \frac{\rho\, C_\mu\, k^2}{\varepsilon} \tag{7}$$

The model constants C_μ, $C_{1\varepsilon}$, $C_{2\varepsilon}$, σ_k, and σ_ε are 0.09, 1.44, 1.92, 1.0, and 1.3, respectively.

No-slip condition and constant wall heat flux are assumed as boundary conditions.

The thermal-hydrodynamic performance of the corrugated channels is assessed by dimensionless parameters which are the Nusselt number, friction factor, and performance evaluation criterion (*PEC*).

The average Nusselt number is presented as

$$Nu = \frac{q''d}{kt}\int_0^x \frac{1}{T_w(x) - T_b(x)}dx \tag{8}$$

where q'' and $T_w(x)$ and $T_b(x)$ act as the supplied heat flux and wall and local bulk temperatures, respectively.

The friction factor is defined as

$$f = \frac{2\,\Delta P\, d}{L\,\rho\, {u_m}^2} \tag{9}$$

The comparison between the enhancement in thermal performance and a penalty in the pressure drop is assessed by introducing the performance evaluation criteria (PEC) of corrugated channels with different roughness dimensions. The PEC can be calculated as

$$PEC = \frac{Nu/Nu_s}{\left(f/f_s\right)^{1/3}} \tag{10}$$

where f_s and Nu_s are the friction factor and the Nusselt number of smooth channel, respectively.

The performance of corrugated channels is estimated according to different values of the Reynolds number which is introduced as

$$\mathrm{Re} = \frac{\rho\, u_m\, d_h}{\mu} \tag{11}$$

where μ, ρ, d_h, and u_m are dynamic viscosity, density, hydrodynamic diameter, and mean fluid velocity.

The ANSYS Fluent CFD package-based control volume method is adopted to discretize the governing equations and simulate thermal flow behavior of corrugated channels. The SIMPLE algorithm is utilized for solving the flow field. The diffusion terms and other resulting terms are discretized by employing the first-order upwind scheme. The residuals lower than 10^{-6} is chosen to achieve the convergence criterion for all variables. A fine grid discretization close to the wall is adopted. Also, the meshing system of 23,964 grids is sufficient for solution accuracy. On the other hand, the numerical code that is validated through a reasonable agreement is shown (**Figure 2a**) between the Nusselt number of the present work and the same number which is obtained from the well-known Gnielinski correlation [18]. Furthermore, good agreement is indicated for the friction factor (**Figure 2b**) between the present work and the work of San and Huang [5].

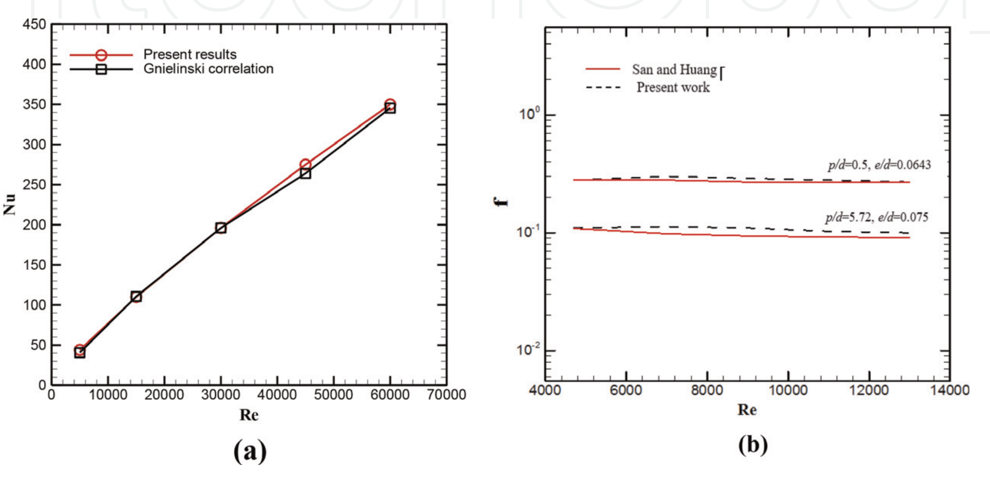

Figure 2.
(a) Numerical Nu of the present work and that obtained from Gnielinski's correlation [17] and (b) Numerical f and that of San and Huang [5].

3. Results and discussion

The flow-thermal features of turbulent flow in corrugated channels are evaluated numerically. The enhanced heat transfer and an accompanied pressure loss are assessed for corrugated channels under the influences of rib arrangement, rib configuration, rib roughness parameters, and rib shapes. The dimensionless parameters Nu, f, and PEC through a wide range of Re are presented to assess the performance of corrugated channels.

3.1 The effect of rib arrangements

Corrugated channels exist in three layouts depending on rib arrangements, IOCC, ICC, and OCC, as described in **Figure 1a**. The variations of Nu and f with the Re number of all rectangular rib arrangements of corrugated channels and smooth one are presented in **Figure 3a** and **b**, respectively. The rate of heat that is transferred in corrugated channels is higher than that of the smooth channel. The heat transfer varies insignificantly with the rib distribution at the low Re. The rib distribution experiences a pronounced influence on the Nusselt number when Re increases. The ICC shows a maximum ability to exchange the heat, while the OCC has a lower thermal performance. On the other hand, there is an additional pressure loss associated with corrugated channels compared with smooth ones as exhibited in **Figure 3b**. The friction factor decreases slightly with the Re. Also, the OCC has a

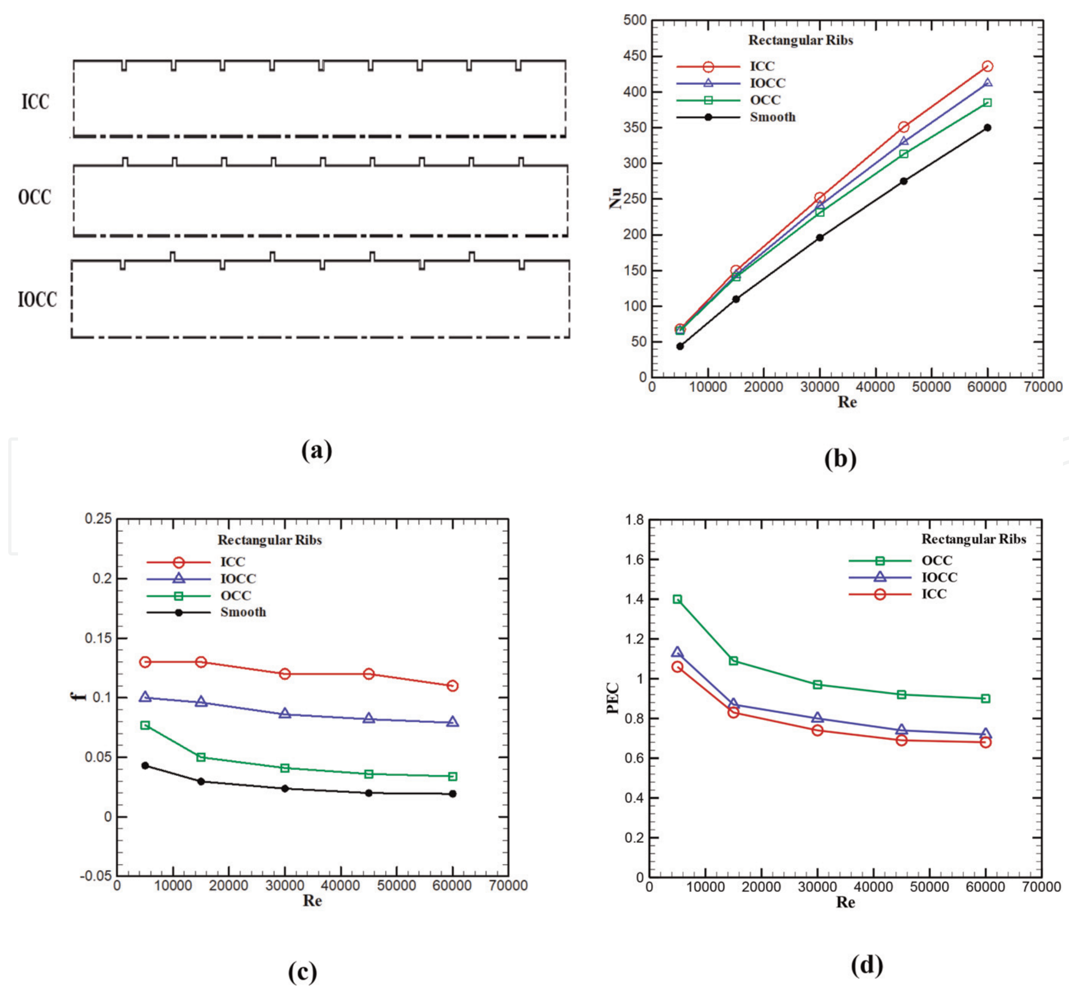

Figure 3.
(a) Different rib arrangements of corrugated channels and the influence of rib configuration on Nu, f, and PEC as described in (b), (c), and (d), respectively, for the different values of Re.

minimum friction factor, while the ICC owns a maximum pressure loss. Moreover, the performance evaluation criterion (PEC) varies inversely with the Re as exhibited in **Figure 3c**. The increase in pressure loss exceeds the enhancement in the heat transfer for all corrugated channel layouts. Also, OCC has higher PEC than both IOCC and ICC channels. This is due to the increase in *f* of OCC is lower than that of ICC and IOCC. Even though, both ICC and IOCC have higher *Nu* than IOCC.

3.2 The influence of rib configurations

Seven configurations of rib trapezoidal corrugated channels are denoted (B1, B2, C1, C2, C3, D1, and D2) which are presented in **Figure 4a**. Also, the smooth channel is indicated by A. The variation of the Nusselt number for all channels is depicted in **Figure 4b**. The increase in *Re* and flow velocity causes enhancement in mixing the

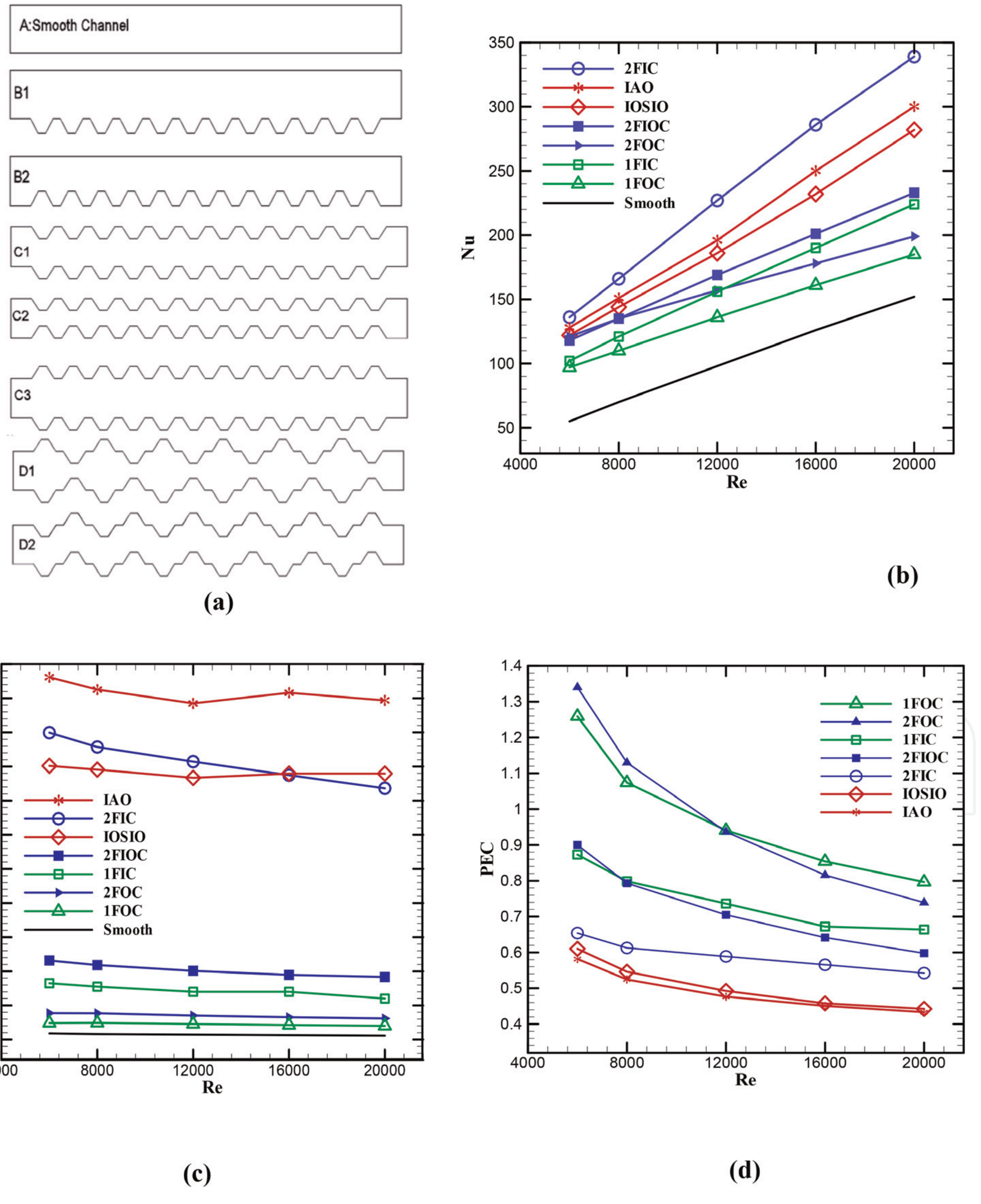

Figure 4.
(a) Different configurations of corrugated channels and the influence of rib configuration on Nu, f, and PEC as depicted in (a), (b), and (c), respectively, for the different values of Re.

rate between the core flow and recirculating flow. Thus, the heat exchange between the heating wall and the flow is enhanced. On the other hand, f is higher for corrugated channels than the smooth one as revealed in **Figure 4c**. In one side, the results revealed that the heat is transferred more effectively in the corrugated channel than the smooth one due to the additional surface area, suppressing the boundary layer thickness associated with corrugated channels. On the other side, the corrugation results in a substantial flow recirculation and separation and an extra surface area, and thus it creates higher pressure drop. The corrugated channel C1 registers the highest *Nu*, while the minimum *Nu* is achieved for corrugated channel B1. Conversely, the results exhibit that the minimum pressure drop is registered for B1 configuration channel among other corrugated channels. Moreover, the influence of rib configuration of corrugated channels on the *PEC* is presented in **Figure 4d**. The results reveal that there is a monotonic decrease of *PEC* with the *Re*. The optimum performance is accomplished at the lower *Re*. As *Re* increases the conflict between the augmentation in thermal performance and degradation in pressure drop is initiated. The higher values of *PEC* are obtained for C3 and B1 corrugated channels, whereas D1 and D2 configurations have the minimum values of *PEC*.

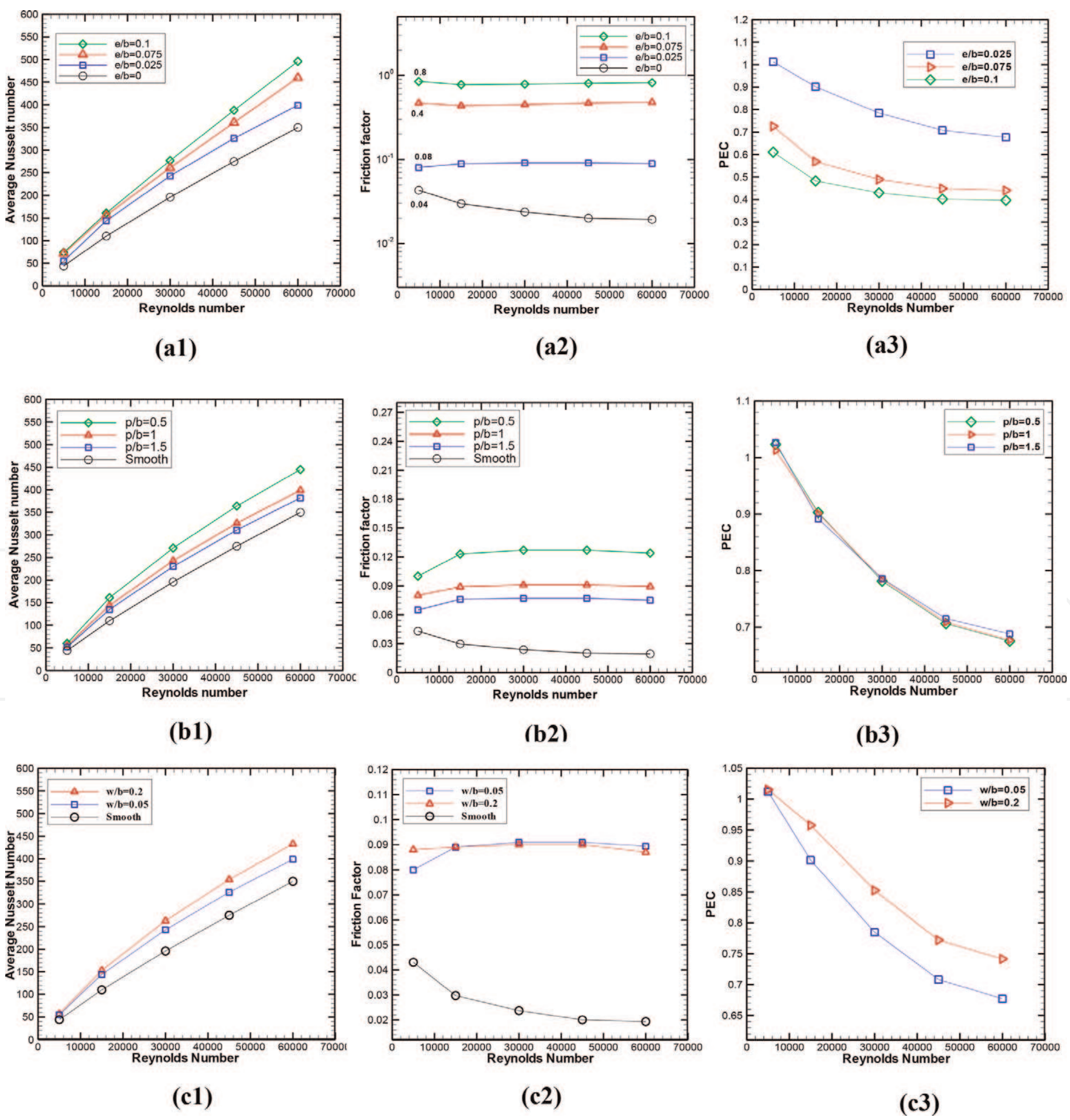

Figure 5.
Nu, f, and PEC for different (a) rib heights, (b) rib pitches, and (c) rib widths.

3.3 The impact of rib roughness parameters

The roughness parameters of corrugated channels involve relative rib height (e/b), relative rib pitch (p/b), and relative rib width (w/b) as illustrated later in **Figure 6a**. The impact of roughness parameters on the thermal-flow behavior of corrugated channels is presented in **Figure 5**. The computed *Nu*, f, and PEC are tested for different relative roughness heights which are presented in **Figure 5a1, 5a2**, and **5a3**, respectively, with constant values of p/b and w/b. Generally, corrugated channels have higher *Nu* than a smooth channel. It is observed that the Nusselt number increases monotonically with both rib height and *Re*. But there is a relatively small effect of rib height on the *Nu* at lower values of *Re*. At the same time, the friction factor varies positively with the relative rib height. While, there is an insignificant effect of *Re* on *f*, the variation of *PEC* (**Figure 5a3**) confirms that the diverse effect of friction factor exceeds the enhancement in transferred heat especially with an increase of *Re*. The influence of rib pitch of corrugation on *Nu*, *f*, and *PEC* of corrugated channels is illustrated in **Figure 5b1, 5b2**, and **5b3**, respectively, for constant corrugation height and width. Decreasing the pitch results in an increase in the number of ribs for unit length and excites the secondary flow. Therefore, the thickness of boundary layer is decreased, and the rate of heat transfer is augmented. However, the flow impedance is increased due to the increase in the number of roughness elements which add extra friction to the flow stream. It appears that the influence of corrugation pitch is insignificant on the *PEC* as

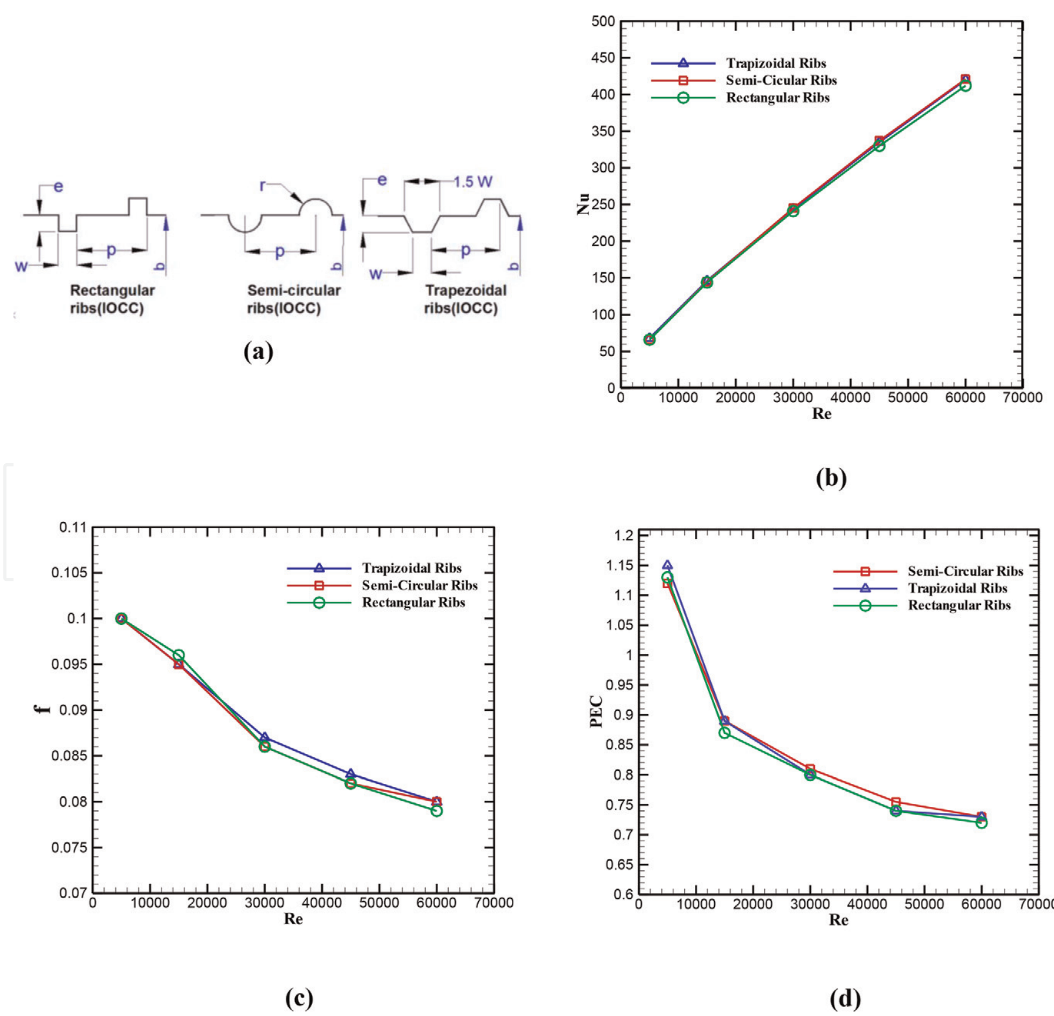

Figure 6.
(a) Different rib shapes of IOCC channels and the influence of rib shapes on the Nu, f, and PEC as presented in (b), (c), and (d), respectively, for the different values of the Re.

presented in **Figure 5b3**. In a similar way, the influences of two values of rib width on the performance of corrugated channel are shown in **Figure 5c**. As the rib width increases, the secondary flow becomes more intense. Therefore, there is a mutual increase in *Nu* and *f* as depicted in **Figure 5c1** and **5c2**, respectively. Furthermore, the *PEC* shows a monotonic decrease with the rib width and *Re* as described by **Figure 5c3**.

3.4 The influence of rib shape

The heat transfer-flow behavior of IOCC channel, for example, is examined for rectangular, semicircular, and trapezoidal rib shapes. The different shapes of the rib are illustrated in **Figure 6a**, while the *Nu*, f, and *PEC* for various rib shapes are presented in **Figure 6b, c** and **d**, respectively, for (p/b = 1, e/b = 0.025, and w/b = 0.05). It is found that the influence of the roughness shape is small on the performance of corrugated channels.

4. Conclusion

The computational investigation of thermal-flow performance of turbulent flow in corrugated channels is carried out for the Reynolds number from 5000 to 60,000. The effects of rib arrangements, rib configurations, rib roughness parameters, and rib shapes are investigated. All layouts of corrugated channels showed a superior ability of exchange heat than that experienced by smooth channel. However, the pressure loss associated with corrugated channels is higher than that of the smooth ones. Furthermore, it is inferred that the arrangement of rib distribution, rib configuration, and rib roughness parameters has a pronounced effect on the thermal-flow performance of corrugated channels, while the influence of rib shapes seems to be small.

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References

[1] Léal L, Miscevic M, Lavieille P, Amokrane M, Pigache F, Topin F, et al. An overview of heat transfer enhancement methods and new perspectives: Focus on active methods using electroactive materials. International Journal of Heat and Mass Transfer. 2013;**61**:505-524. DOI: 10.1016/j.ijheatmasstransfer.2013.01.083

[2] Liu S, Sakr M. A comprehensive review on passive heat transfer enhancements in pipe exchangers. Renewable and Sustainable Energy Reviews. 2013;**19**:64-81. DOI: 10.1016/j.rser.2012.11.021

[3] Alamgholilou A, Esmaeilzadeh E. Experimental investigation on hydrodynamics and heat transfer of fluid flow into channel for cooling of rectangular ribs by passive and EHD active enhancement method. Experimental Thermal and Fluid Science. 2012;**38**:61-73. DOI: 10.1016/j.expthermflusci.2011.11.008

[4] Vicente PG, Garcia A, Viedma A. Experimental investigation on heat transfer and frictional characteristics of spirally corrugated tubes in turbulent flow at different Prandtl numbers. International Journal of Heat and Mass Transfer. 2004;**47**:671-681. DOI: 10.1016/j.ijheatmasstransfer.2003.08.005

[5] San JY, Huang WC. Heat transfer enhancement of transverse ribs in circular tubes with consideration of entrance effect. International Journal of Heat and Mass Transfer. 2006;**49**: 2965-2971. DOI: 10.1016/j.ijheatmasstransfer.2006.01.046

[6] Li XW, Meng JA, Li ZX. Roughness enhanced mechanism for turbulent convective heat transfer. International Journal of Heat and Mass Transfer. 2011; **54**:1775-1781. DOI: 10.1016/j.ijheatmasstransfer.2010.12.039

[7] Dizaji HS, Jafarmadar S, Mobadersani F. Experimental studies on heat transfer and pressure drop characteristics for new arrangements of corrugated tubes in a double pipe heat exchanger. International Journal of Thermal Sciences. 2015;**6**:211-220. DOI: 10.1016/j.ijthermalsci.2015.05.009

[8] Dhaidan NS, Abbas AR. Turbulent forced convection flow inside inward-outward rib corrugated tubes with different rib-shapes. Heat Transfer - Asian Research. 2018:1-13. DOI: 10.1002/htj.21365

[9] Naphon P. Heat transfer characteristics and pressure drop in the channel with V corrugated upper and lower plates. Energy Conversion and Management. 2007;**48**:1516-1524. DOI: 10.1016/j.enconman.2006.11.020

[10] Eiamsa-ard S, Promvonge P. Thermal characteristics of turbulent rib–grooved channel flows. International Communications in Heat and Mass Transfer. 2009;**36**:705-711. DOI: 10.1016/j.icheatmasstransfer.2009.03.025

[11] Elshafei EAM, Awad MM, El-Negiry E, Ali AG. Heat transfer and pressure drop in corrugated channels. Energy. 2010;**35**:101-110. DOI: 10.1016/j.energy.2009.08.031

[12] Mohammed HA, Abed AM, Wahid MA. The effects of geometrical parameters of a corrugated channel within out-of-phase arrangement. International Communications in Heat and Mass Transfer. 2013;**40**:47-57. DOI: 10.1016/j.icheatmasstransfer.2012.10.022

[13] Li Z, Gao Y. Numerical study of turbulent flow and heat transfer in cross-corrugated triangular ducts with delta-shaped baffles. International Journal of Heat and Mass Transfer. 2017;

108:658-670. DOI: 10.1016/j.ijheatmasstransfer.2016.12.054

[14] Pehlivan H, Taymaz I, İslamoğlu Y. Experimental study of forced convective heat transfer in a different arranged corrugated channel. International Communications in Heat and Mass Transfer. 2013;**46**:106-111. DOI: 10.1016/j.icheatmasstransfer.2013.05.016

[15] Ravi BV, Singh P, Ekkad SV. Numerical investigation of turbulent flow and heat transfer in two-pass ribbed channels. International Journal of Thermal Sciences. 2017;**112**:31-43. DOI: 10.1016/j.ijthermalsci.2016.09.034

[16] Shubham SA, Dalala A, Pati S. Thermo-hydraulic transport characteristics of non-Newtonian fluid flows through corrugated channels. International Journal of Thermal Sciences. 2018;**129**:201-208. DOI: 10.1016/j.ijthermalsci.2018.02.005

[17] Launder BE, Spalding DB. Mathematical Models of Turbulence. New York: Academic Press; 1972

[18] Gnielinski V. New equations for heat and mass transfer in turbulent pipe and channel flow. International Chemical Engineering. 1976;**16**:359-368