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Research Article

The Effects of Physical Parameters on the Forced Convective Heat Transfer and Fluid Flow in Corrugated Channel

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Abstract. The laminar fluid flow and convective heat transfer are numerically investigated for single phase flow in corrugated duct. The governing equations of fluid flow are discretized using finite volume method based on SIMPLE algorithm and solved using CFD code. Also, the considered computational domain is two dimensional channel which corrugated angles, heat transfer and Reynolds numbers are used as design variables. The obtained results show that the Nusselt number increase with an increase in the Reynolds numbers, angles of corrugation and heat flux. However, the friction factor decreases versus the Reynolds numbers. Numerical results are compared with those of straight channel and there is a good agreement.

Keywords. Numerical Modeling; Corrugation Angle; CFD code; Correlations; Finite volume method

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1. Introduction

In the context of energy management, 90% of this energy passes through a heat exchanger, in application areas such as climate engineering; the chemical or petrochemical industry; the food industry; etc. The heat exchanger is a device that ensures the transfer of heat from a hot to cold fluid without direct contact between the two fluids. The same fluid can maintain its liquid or gaseous physical state, or appear successively under the two phases; this is the case of condensers, evaporators, boilers or cooling towers. The field of intensification of heat exchangers has for many years beyond the laboratory stage and was widely considered in industrial applications. Many heat exchangers in a variety of processes are equipped with heat exchange surfaces (tubes or plates) specially designed to have high exchange coefficients and in particular higher than smooth exchange surfaces. The concern to manufacture heat exchangers more compact led to a search of intensification of these heat exchangers processes. Among the passive techniques used in the design of tubular heat exchangers or plate, the use of corrugations allows to promote the reduction of the boundary layer and increase the turbulence in this layer. The corrugated flat surfaces are typically used in heat exchangers plate and in industrial heat exchangers. In this industrial context, plate exchangers play an important role, offering many advantages; compactness, cost, modularity, easy removal and cleaning, etc.

In recent decades, many experimental and theoretical studies on the heat transfer and the pressure were made to improve the thermal performance of the heat exchanger and to find the effective heat transfer surface which does not induced a lot of loss. Using the corrugated plate is an appropriate method to increase the thermal performance and provide higher compactness. Several researchers have studied the effects of certain geometrical parameters on the characteristics of heat transfer and pressure drop.

A numerical study was performed in a channel with different angles of corrugations 30°, 45° and 60° for Reynolds numbers ranging from laminar to turbulent regime. The author noted an improvement of heat transfer and an increase in pressure loss when there is a transition from a laminar to a turbulent flow. The author has also shown that the turbulent flow is preferred for tilt angles steeper (Hessami [4]).

Numerical and experimental studies are performed in a corrugated channel with a constant heat flux imposed on the walls from 0.5 to 1.2 kW/m^2, with three corrugations angles of 20°, 40° and 60° and flow rates for a Reynolds number $400 \le Re \le 1600$. The flow and heat transfer was simulated by the k-ε model and the finite volume method was used for the discretization of the equations governing the flow. The author found from these studies that the Nusselt number increases with the increase of the Reynolds number and the chevron angle (Naphon [7]).

Abdulbasit and Abdulsayid [1] numerically studied the effect of the triangular shape of the two-dimensional channel, sinusoidal and square on the thermal and hydraulic behavior with different Reynolds numbers ranging from 400 to 1400, with the incoming water with a hot temperature. These authors noted that an increase in Reynolds number causes an increase in the Nusselt number. Moreover, the Nusselt numbers corresponding to the square shaped channel are significantly higher than those of the triangular or sinusoidal channel.

The study of Zonouz and Salmanpour [8] is based on the thermal and hydraulic performance of a two-dimensional corrugated channel for laminar flow regime of the air. A constant temperature condition is imposed on the corrugated channel walls. This analysis is devoted to study the effect of the Reynolds number and the wave width on the thermal-hydraulic behavior. Distributions of the velocity and the heat transfer coefficient were obtained for different cases. The authors noted an increase in the Nusselt number with increasing Reynolds number and the wave height; they also noted that these results are higher compared to those of smooth channel.

Amala and Velu [2] conducted an experimental study to measure the condensation heat transfer coefficient and the pressure drop in a plate heat exchanger using a refrigerant, R134A. Three chevron angles were tested 45°, 35° and 20° by varying the mass flow. The authors found that the heat transfer coefficient and the pressure drop increases proportionately with the mass flow and steam quality and are inversely proportional with the condensing temperature and the angle rafter. Correlations of the Nusselt number and the friction coefficient with the geometric parameters are suggested for the tested exchanger.

A numerical study of flow and heat transfer of the air in both sinusoidal and rectangular channels with a hot temperature imposed on corrugated walls and a range of Reynolds number between 100 and 1000 is given in Ozbolat et al. [9]. The authors found that increasing the Reynolds and the channel height results in an increase of heat transfer in the channel.

A numerical study was conducted by Falahat [3] to study the effect of the Reynolds number and volume fractions of nanoparticles on heat transfer and pressure drop across a wavy channel with a constant heat flux imposed on the sides, using a laminar flow. The results were obtained for Reynolds numbers and a volume fraction in the range 50 to 500 and 0 to 0.1 respectively. The author noted an increase in the Nusselt number with increasing Reynolds number and volume fractions of nanoparticles, also an increase of the pressure drop with the Reynolds number.

Majdi and Abed [5] have numerically investigated the effect of the Reynolds number and the volume fraction of nanofluid used in the heat transfer and pressure drop for a range of Reynolds number varying from 5,000 to 20,000 in a corrugated channel with a chevron angle of 60°. A two-equation model was adopted for modeling turbulence. The authors found that the heat transfer is better using nanofluids as the working fluid and the Nusselt numbers are superior to those of a base fluid. The authors also found that the average Nusselt number increased with increasing volume fraction of the nanoparticles and the Reynolds number. In addition, these authors have also noted a slight increase of the pressure drop with the Reynolds number.

An experimental study was conducted by Murugesan and Akilamudhan [6] to measure the heat transfer coefficient and the pressure drop across a heat exchanger used in the pasteurization of milk. Different chevron angles have been tested 35°, 30°, 25° with flow variation. This experience has shown a proportionality of the heat transfer coefficients and pressure drop with flow rate. The authors concluded that the heat transfer is better than the smooth channel. Furthermore, correlations of the Nusselt number and the friction coefficient on the geometric parameters have been suggested for the test plate.

Rao, Varun, Murali Krishna and Sastry [10] conducted an experimental study of a heat exchanger sinusoidal corrugated plate with water as test fluid. Three channels have been tested with corrugations angles 30°, 40° and 50° and a height channel equal to 5 mm. The authors observed that the corrugation angle has a major effect on the pressure drop and the friction coefficient.

An experimental study was conducted to investigate the effect of the corrugation angle and the Reynolds number of the heat transfer in a sinusoidal channel height of 5 mm. Three different angles of corrugation are used in this study 30°, 40° and 50°. The water at hot temperature is taken as the test fluid. The wall temperatures are measured along the length of the exchanger. The authors observed that the pressure drop and the friction coefficient are affected by the corrugation angle and that the increase in the angle leads to a decrease of the friction coefficient (Rao, Varun, Surywanshi and Sastry [11]).

Our work is focused on the numerical simulation of two-dimensional incompressible steady flow with heat transfer in a channel which upper and lower walls are corrugated and triangular. The resolution method of the equations governing the flow is given by the FLUENT CFD code. The objective of this study is also to describe the flow and heat transfer and to determine the influence of certain parameters related to the geometry of the exchange and friction laws.

2. Mathematical Formulation

2.1 Introduction

Forced convection in complex geometries is important in many industrial applications, especially in heat exchangers. Considerable work has been done in recent years on the flow and heat transfer in plate heat exchangers.

In this work, we present the physical problem of stationary forced convection within a horizontal channel in the presence of transverse corrugations and the equations governing the flow in the corrugated channel. The mathematical equations on which this study is based and which govern the laminar flow are the continuity equation, the equations of motion and the energy equation. These equations are obtained from the fundamental laws of mechanics and thermodynamics. These principles are expressed in terms of partial differential equations. The major advantage of the mathematical formulation is that conservation equations can be expressed in the same form.

2.2 Equations Governing the Flow

In the present work, the flow considered is two dimensional, steady, laminar with heat transfer of a fluid with constant physical properties. The equations governing the flow are as follows:

- The Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{2.1}$$

- The momentum equation following x

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu}{\rho}\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right] \tag{2.2}$$

- The momentum equation following y

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\mu}{\rho}\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right] \tag{2.3}$$

- The energy Equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{K}{\rho c p}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{2.4}$$

2.3 Configuration Problem

The considered physical model is a channel where the upper and lower walls are corrugated. The dimensions of the channel are based on experimental data [7]. The total length of the channel is $L = 0.675$ m; those of the corrugations are $l = 0.3$ m and the channel height is $H = 0.125$ m.

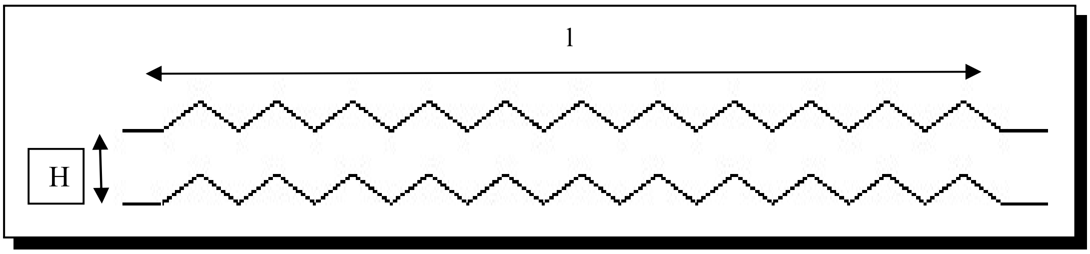

Figure 1. Studied configuration

2.4 Boundary Conditions

- *At the entrance of the channel*: The heat transfer fluid is air heated to room temperature between the channel with flow rates derived from the Reynolds number in the range 730-1400.
- *On the corrugated walls*: a steady flow of heat in the range of 0.5 to 1.2 kW/m^2 and no slip condition are imposed.

3. Results and Discussions

3.1 Mesh effect

The numerical results are obtained for a two-dimensional air flow in a corrugated channel using the Fluent CFD code. They are presented as curves for the thermal and dynamic field. The mesh effect on the numerical results was considered to obtain satisfactory solutions. To show the effect of the mesh on the solution, three grids were tested 360531; 457639 and 560853 in flow regime for a Reynolds number $Re = 400$. We found that the solution was independent of the number of nodes. Therefore, our choice was focused on 457639 mesh nodes for Reynolds numbers between 730 and 1400.

3.2 Validation of results

The validation of numerical simulation is needed to verify the accuracy of numerical results obtained by the Fluent CFD software. A comparison of our results was made with those of the experimental study of Naphon [7]. The author has considered a corrugated channel using an angle of 20° and a constant flow applied to the corrugated walls.

Figure 2 shows the variation of the average Nusselt number depending on the Reynolds number for a corrugated channel with an aspect ratio $h/w = 0.458$. We see that an increase in the Reynolds number leads to an increase of Nusselt number and they are significantly higher than those of the smooth channel, as we note that the values of Nusselt number for a refined mesh is closer to the experimental values than those of the uniform mesh. We also note that there is a good agreement with the experimental results of Naphon [7]. The results are obtained for a refined mesh near the wall.

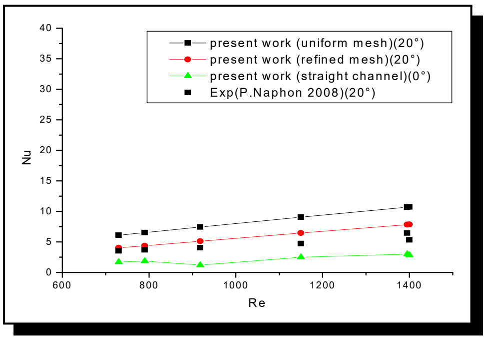

Figure 2. Variation of average Nusselt number as function of Reynolds with $h/w = 0.458$

3.3 Results and discussion

The numerical results are obtained for different Reynolds numbers which vary between 730 and 1400, different angles and different corrugation heat flux.

3.3.1 Effect of the Reynolds number

The dynamic and thermal fields are presented for different Reynolds numbers with a corrugation angle of 20° and a heat flow of 580 W/m^2. The velocity profiles for different Reynolds numbers at stations $x = 81.81$ mm and $x = 95.445$ mm are represented by Figure 3. It is noted the appearance of negative velocities, this is due to the recirculation zones and they are becoming larger with increasing Reynolds number.

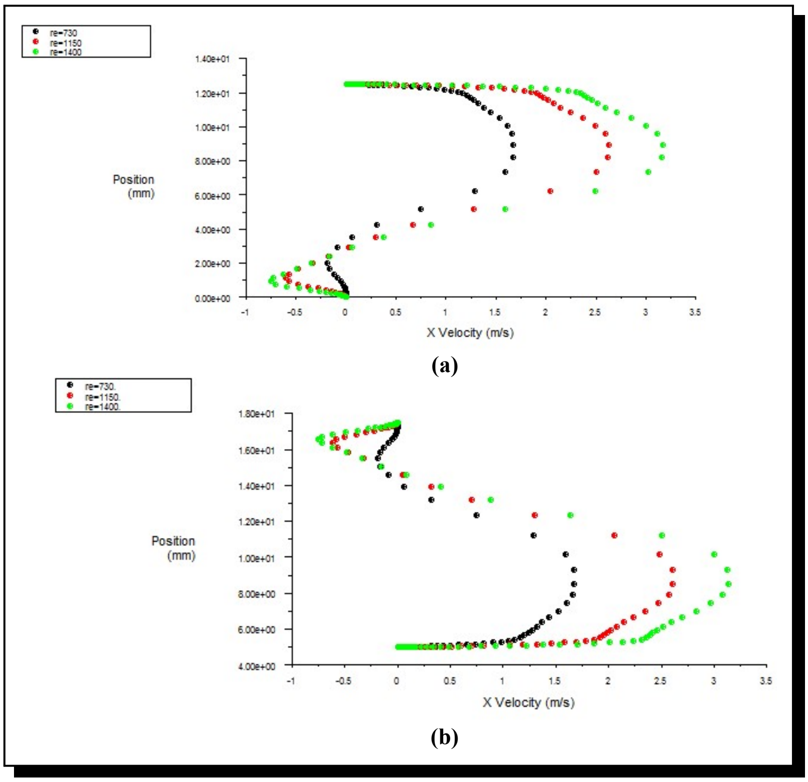

Figure 3. Profiles of the horizontal velocity with $h/w = 0.458$ for different Reynolds (a) $x = 81.81$ mm (b) $x = 95.445$ mm

The distribution of the local friction coefficient versus Reynolds number is represented by Figure 4. It is noted that the friction coefficient is influenced by the Reynolds number. It is also observed that most the Reynolds number increases and most the friction decreases.

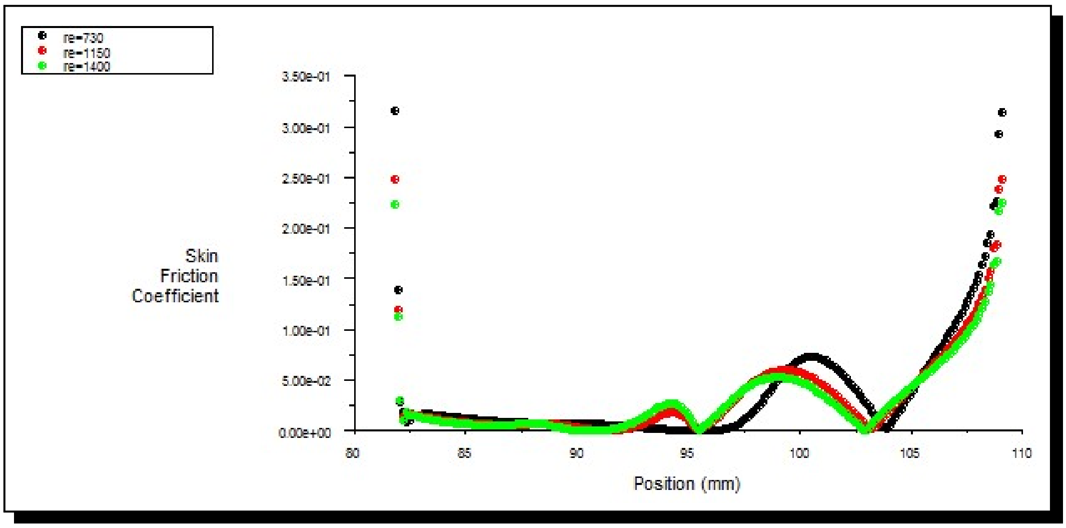

Figure 4. Distribution of the local friction coefficient for different Reynolds number with $h/w = 0.458$ for periodic corrugation (upper wall)

3.3.2 Effect of the corrugation angle

The dynamic and thermal fields are presented for different corrugation angles with a heat flux equal to 580 W/m^2 and to a Reynolds number of 1400.

Dynamic Field

Figure 5 shows the contours of the average velocity for a Reynolds number $Re = 1400$ and for different angles of corrugation. It is found that the flow velocity at the channel center increases with increasing in the corrugation angle. Dynamic boundary layers are observed along the upper and lower wall where fluid velocities are low (presence of recirculation zones). Moreover, it is noted that the thickening rate of the boundary layer increases with increasing angle.

The velocity vectors for different angles of corrugation with a heat flow of 580 W/m^2 and for $Re = 1400$ are shown in Figure 6. Note the appearance of recirculation zones whose size increases with increasing in angle.

Figure 7 illustrates the influence of the corrugation angle versus the friction coefficient. It is seen that the latter depends on the Reynolds number and the increase in angle tends to increase the friction coefficient.

Thermal field

Figure 8 shows the temperature contours for different angles with a heat flow of 580 W/m^2 and a Reynolds number $Re = 1400$. It is noted that the maximum temperatures are located near the corrugated walls and there is a heat transfer from the hot walls to the cold fluid and heat transfer increases with increasing angle.

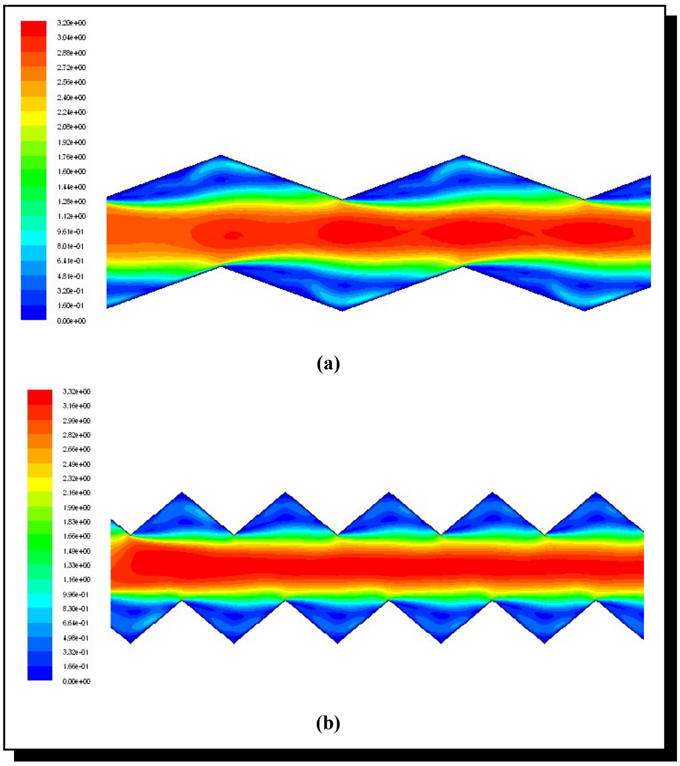

Figure 5. Contours of the average velocity for $Re = 1400$ (a) $\alpha = 20°$ (b) $\alpha = 40°$

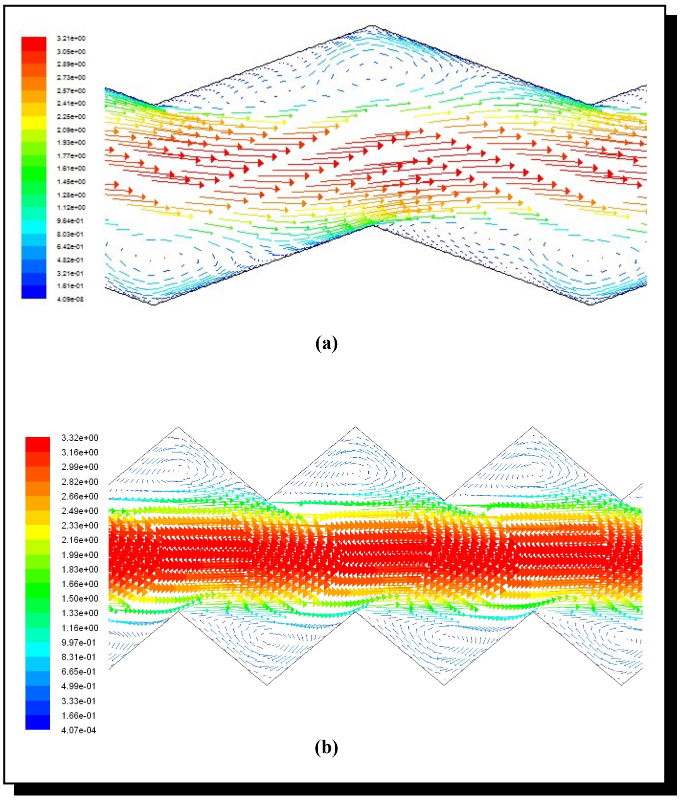

Figure 6. Contours velocity vector for $Re = 1400$ (a) $\alpha = 20°$ (b) $\alpha = 40°$

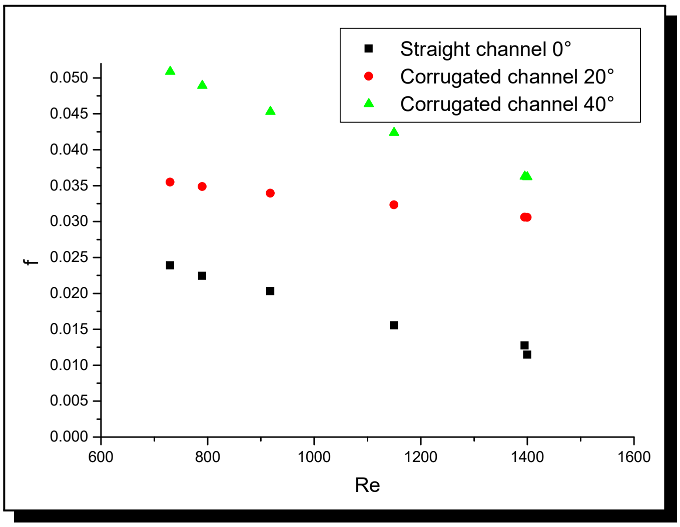

Figure 7. Effect of corrugation angles on friction coefficient

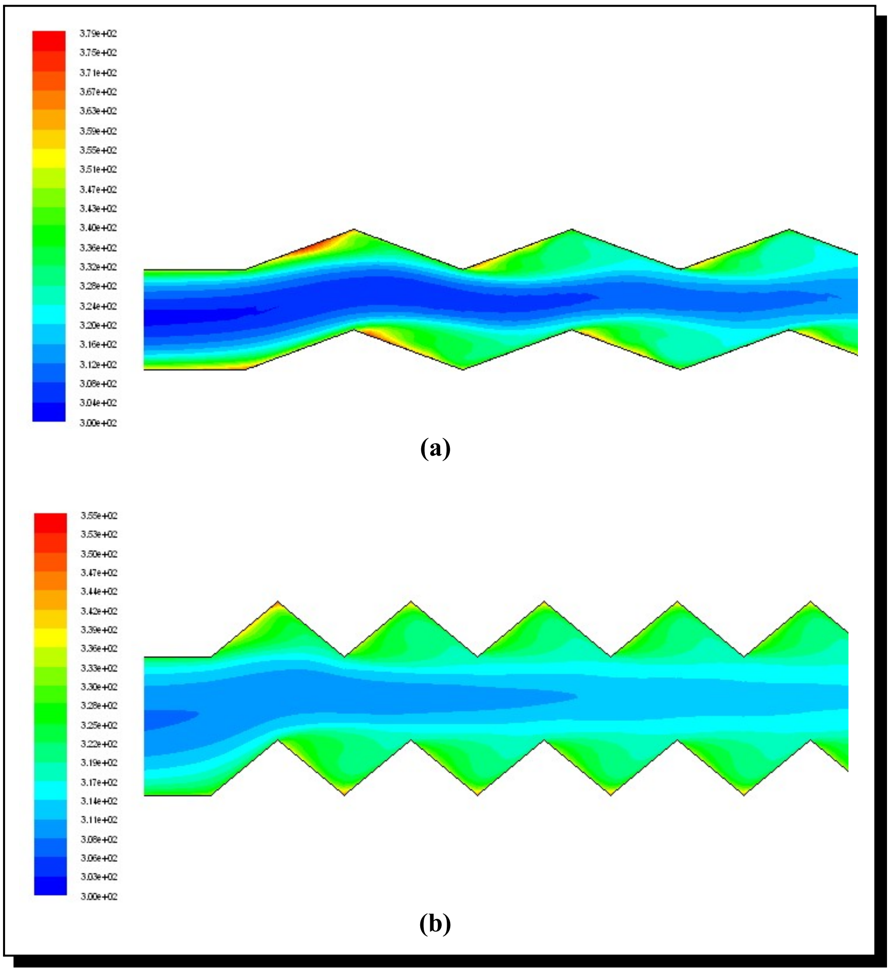

Figure 8. Contours of static temperature for $Re = 1400$ (a) $\alpha = 20°$ (b) $\alpha = 40°$

The effect of the corrugation angle on the Nusselt numbers is shown in Figure 9. It is seen that the latter increases with increase in the corrugation angle and that the Nusselt numbers of the corrugated channel are higher than those of the smooth ones.

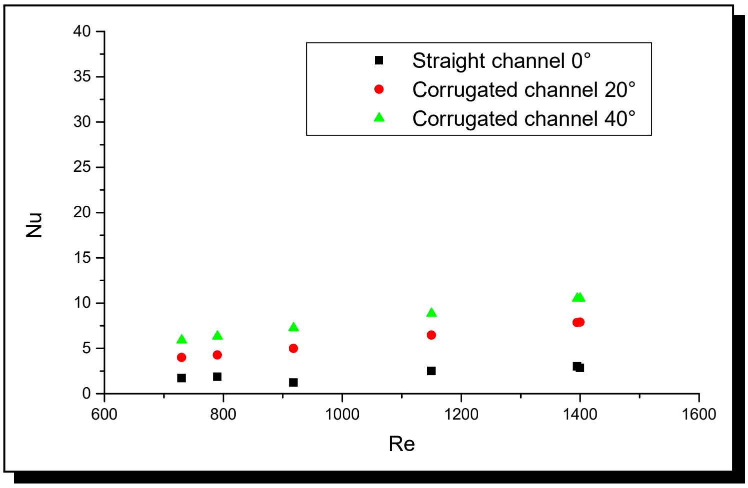

Figure 9. Variation of the average Nusselt number for different corrugation angles

3.3.3 Effect of heat flux

The thermal field is given for different heat flux with a corrugation angle of 20° and for a Reynolds number varying from 730 to 1400. The variation of the Nusselt number for different heat flow is shown in Figure 10. An increase in the Nusselt number is observed with increasing heat flux.

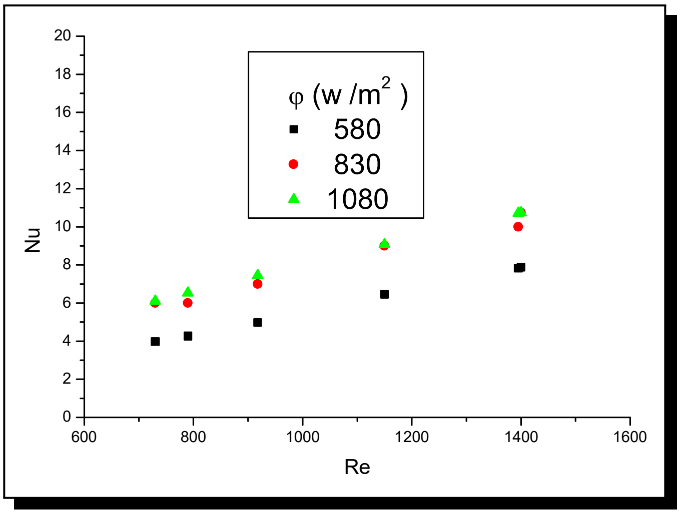

Figure 10. Variation in average Nusselt number for different heat flux

The variation in the average temperature of the wall with Reynolds for different heat flux is shown in Figure 11. There is a decrease of the temperature of the corrugated wall with increasing Reynolds number and increases with increasing heat flux.

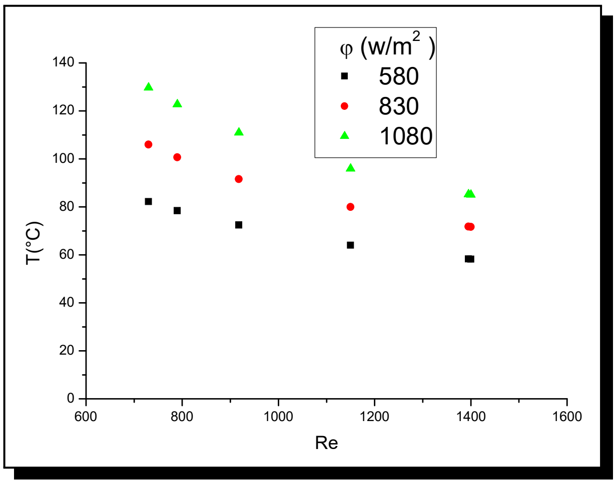

Figure 11. Variation of average surface plate temperature versus Reynolds number for different heat flux

Figure 12 shows the variation of the outlet air temperature with the Reynolds number for different heat flux. It is noticed that the outlet air temperature decreases with increasing mass flow rate (Reynolds number).

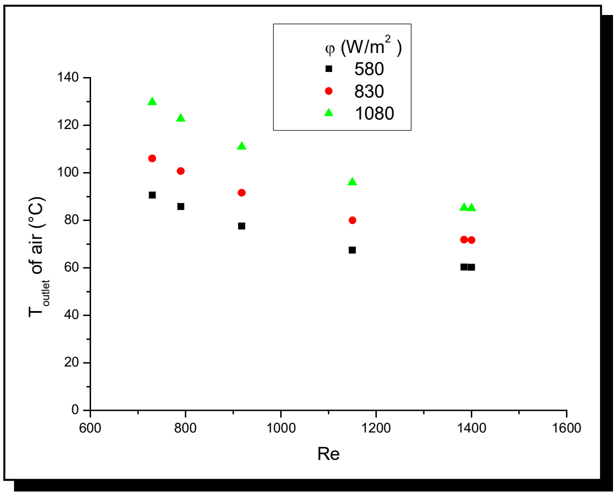

Figure 12. Variation of the outlet air temperature versus Reynolds number for different heat flux

4. Conclusion

A numerical study of flow and heat transfer by forced convection through a corrugated channel was performed using the Fluent CFD code. The equations developed by the mathematical model were solved numerically using the finite volume method. From this study which is devoted to analyze the effect of the Reynolds number; corrugation angle and heat flux on the thermal and hydraulic behavior in the channel, were deduced the following results.

An increase in the Reynolds number results in an increase of the recirculation zones. The effect of Reynolds number on the heat transfer is important. Also, there is an increase in the Nusselt with increasing proportional Reynolds number. Increasing the Reynolds number causes a reduction in the friction coefficient. In addition, the Nusselt number and the friction coefficient are influenced by the corrugation angle. An increase in angle tends to increase both numbers. Note that the obtained numerical results are in good agreement with the experimental results.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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