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Numerical Simulation of Heat Transfer and Fluid Flow Characteristics of Triangular Corrugated Wavy Channel

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The present numerical simulation has been performed with the objective to study the fluid flow and heat transfer characteristics of a corrugated wavy channel. The considered channel has a rectangular cross-section and triangular corrugations with a corrugation angle of 21.8°. The flow was assumed to be Laminar through the channel with Reynolds number (Re) varying from 500 to 1500 and the analysis was performed under steady state and constant heat flux (10 kW/m^2) conditions. For quantitatively analyzing the heat transfer enhancement rate, Nusselt number (Nu) was estimated along the top front corrugated line (tfcl) and it was found that Nu values increased with increasing Re. Also, the triangular corrugated channel was found to outperform the plain rectangular channel with regards to its high Nu values. The increased Nu values upon the incorporation of corrugation were thought to be due to the formation of recirculation zones and high-intensity swirl flow near the vicinity of corrugations zone. The only analyzed disadvantage of such a channel was found to be its rise in pressure loss value with increasing Re.

***Keywords*:** Corrugated wavy channel, laminar flow, Nusselt number, recirculation flow.

1. Introduction

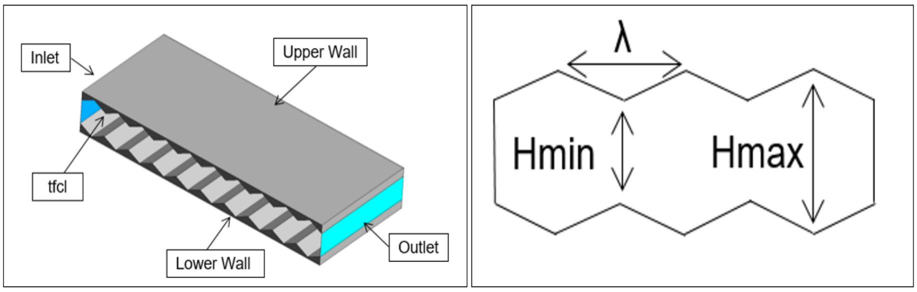
The increasing need for compact, effective and efficient heat exchangers for several industrial applications have aggravated the demand for the development of advanced heat transfer enhancement techniques. Several methods are incorporated to intensify this enhancement rate [1], and among the various methods employed, corrugated surfaces on account of its capability to promote the formation of recirculation zones, increase the effective fluid flow path [2], etc. is widely used for electronic cooling, solar collectors, electrochemical and catalytic reactors [3], etc.

In order to gain a comprehensive insight into the various heat transfer enhancement techniques, this domain has been extensively studied and investigated. Analytically and numerically, the heat transfer enhancement mechanism in both two-dimensional, as well as three-dimensional sinusoidal channel, was examined which was subjected to different temperature conditions on the lower and upper wall. The flow was predominantly steady and laminar. The presence of stagnation points and asymmetry of flow was found to be the reason behind heat transfer enhancement in the case of 2-D corrugations. Though the primary mechanism behind heat transfer enhancement is essentially the same in the case of 3-D corrugations as well, yet advection due to transverse flow was also attributed as one of the additional causes [4]. Also, the use of corrugation leads to a complex flow pattern which promotes better momentum transfer, swirling and recirculation of the flow which results in enhanced heat transfer rate [5]. Additionally, it leads to a significant pressure drop due to friction in the channel which is higher in comparison to the conventional straight channels [6-7]. The heat transfer rate between a plain channel and three different types of corrugated channel of two different heights (5 mm and 10 mm) were experimentally examined and the channel with the maximum corrugation angle (50°), minimum pitch (10 mm) and height (5cmm) was found to outperform the other channels as it exhibited the highest Nu values at Re ranging from 2000 to 5000 [8]. Heat transfer enhancement is generally quantified by estimating the value of Nu and it has been noticed that the value of Nu increases with increase in the value of Re and it strongly depends upon the corrugation angle and height of the channel as well [9]. Quite recently, a unique method of applying a non-uniform axial magnetic field upon a Ferro nanofluid flow through a corrugated channel was examined. The Re value was considered as 100 and the volume fraction of the Nanofluid was taken as 3%. Due to an applied magnetic field, recirculation zone near the corrugation cavities vanished which led to a reduction in the fluid temperature near the wall and increment in heat transfer coefficient value [10].

2. Numerical Analysis

2.1 Geometry (Computational Domain)

In the present problem, the considered geometry as shown in Fig.1 is a rectangular channel with triangular corrugation profiles with corrugation angle approximately 21.8 °. The length, width and height of the total channel are 300 mm, 130 mm and 35 mm respectively whereas the maximum (Hmax) and the minimum height (Hmin) of the triangular corrugations employed are 32 mm and 20 mm respectively. There are a total of 10 corrugation cycles in the channel and the length of the pitch (λ) is 30 mm.

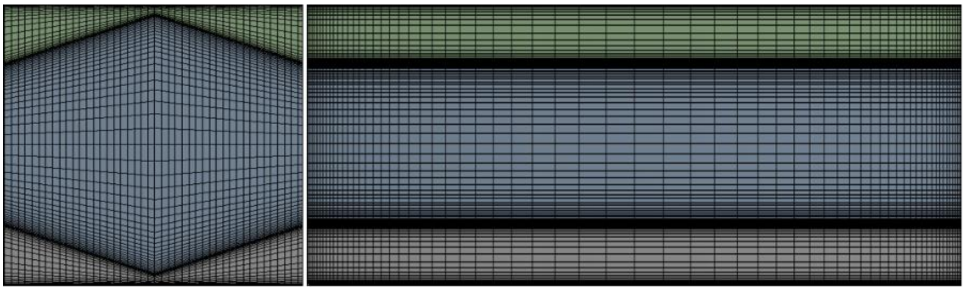


a) b)

Fig 1. a) Geometry of the channel and b) Schematic of a portion of the corrugation.

2.2 Mesh Generation

The partial differential equations that govern any fluid flow and heat transfer problems are analytically unsolvable except for a very few simple cases. Therefore, in order to analyse such problems, the computational domain is split into smaller subdomains (made up of geometric primitives like hexahedral and tetrahedral shapes in 3D and quadrilaterals and triangles in 2D). The governing equations are then discretized and solved inside each of these subdomains. These subdomains are created by the Mesh option in Ansys Fluent. The mesh of the computational domain was generated using the edge sizing method with finer mesh near the solid-fluid interface to better capture the boundary effects and coarser mesh near the centre to reduce the total computational time. Fig.2. a) and b) depicts the mesh employed in one corrugation section and in the side walls respectively.



a) b)

Fig. 2. a) Mesh pattern employed in the corrugation and b) in the side wall of the channel.

2.3 Simulation Methodology and Governing Equations solved

In order to understand and examine the fluid flow and heat transfer characteristics of the triangular corrugated wavy channel, the commercial code, Fluent, was used. Reynolds number considered was varied from 500 to 1500 and the flow was assumed to be steady throughout the channel. For simulating the same, viscous laminar model was chosen with water as the working fluid and pipe material as aluminium. During simulation, the following governing equations were solved:

1. Mass Conservation equation

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{v}) = 0 \tag{1}$$

2. Momentum Conservation equation

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla.(\rho \vec{v}\vec{v}) = -\nabla p + \nabla.(\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \tag{2}$$

3. Energy equation

$$\frac{\partial}{\partial t}(\rho E) + \nabla.\left(\vec{v}(\rho E + p)\right) = \nabla.\left(k\nabla T + (\bar{\bar{\tau}}.\vec{v})\right) \tag{3}$$

where ρ = density, $\vec{v}$ = velocity, $p = static\ pressure$, k = thermal conductivity, T = temperature, $\bar{\bar{\tau}} = stress\ tensor$. Here, $\rho\vec{g}$ and $\vec{F}$ are the gravitational body force and external body forces respectively. The first term in the right hand side of equation (3) represents energy transfer due to conduction and the second term represent energy transfer due to viscous dissipation. The term 'E' used in equation (3) (total energy) can be expressed as:

$$E = h - \frac{p}{\rho} + \frac{v^2}{2} \tag{4}$$

In order to simulate the flow characteristics and thermal behaviour of the channel, it was subjected to specific boundary conditions as illustrated in table.1.

Table.1 Boundary Conditions.

Domain	**Boundary Conditions**
Inlet	Velocity inlet (Re dependent)
Upper Wall	Constant heat flux (10 kW/m^{-2})
Lower Wall	Constant heat flux (10 kW/m^{-2})
Outlet	Pressure outlet (Atmospheric)
Rest of the walls	At adiabatic conditions

For the purpose of solving the pressure-velocity coupled equation, the SIMPLE scheme was adopted and for the spatial discretization of Pressure, Momentum and Energy, Second Order Upwind interpolation scheme was employed. To ensure convergence in the continuity and momentum equations, the scaled residuals were set to 10^{-8}, whereas for energy, it was set to10^{-9}.

2.4 Grid Independence Test

The results obtained from the numerical simulation was mesh independent as shown in fig. 3. Two different cases were made, viz. case 2 and case 3 with around 22% and 27 % decrease in the number of elements and the results were compared with the original case (case 1). The results were found to vary approximately by around 5% (average)

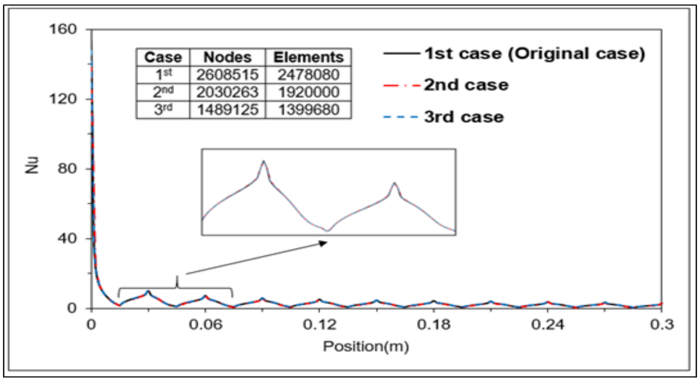


Fig 3. The mesh independent test graph between Nu and Position (m).

2.5 Results and Discussions

To examine the heat transfer characteristics, Nu values were estimated along the tfcl of the rectangular channel for five different values of Reynolds number (Re=500, 750, 1000, 1250, 1500) as shown in figure 4. By carefully analysing the obtained graph, it was concluded that the value of Nu increased with the increase in the value of Re, which can be attributed to the formation of recirculation zones and enhanced swirl flow intensity near the corrugations. Since Nu increases, the augmentation of heat transfer rate takes place with increase in Re. Also, the Nu values of corrugated channel significantly increased in comparison to the straight channel as shown in figure 5. The streamlines obtained from the simulation as shown in figure 6. further confirmed the presence of recirculation zones (blue region) near the corrugations. Additionally, due to the presence of corrugations used in the channel, the pressure drop along the tfcl at different Re values was observed as shown in figure 7.

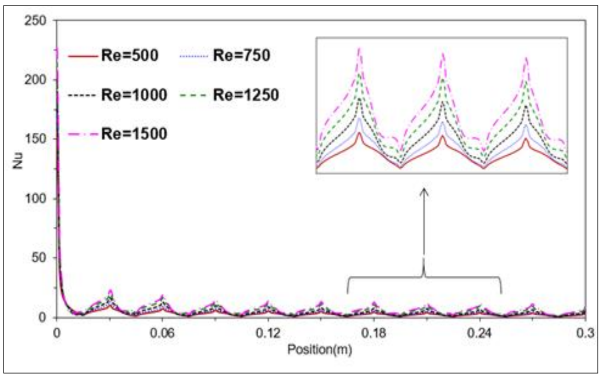


Fig. 4. The graph of Nu Vs Position (m) along the tfcl Re at five different Re.

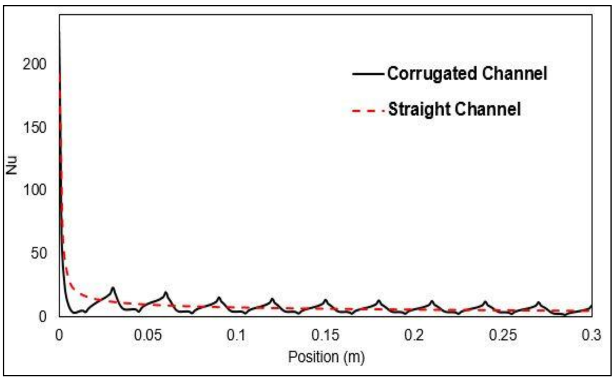


Fig. 5. The graph of Nu Vs Position (m) at 1500 comparing channel behaviour.

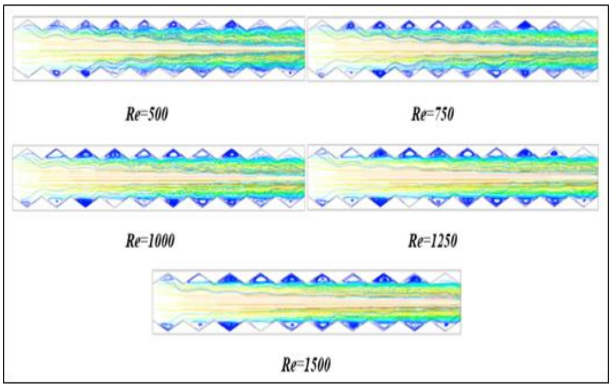


Fig. 6. Streamlines at different Re showing the formation of recirculation zones.

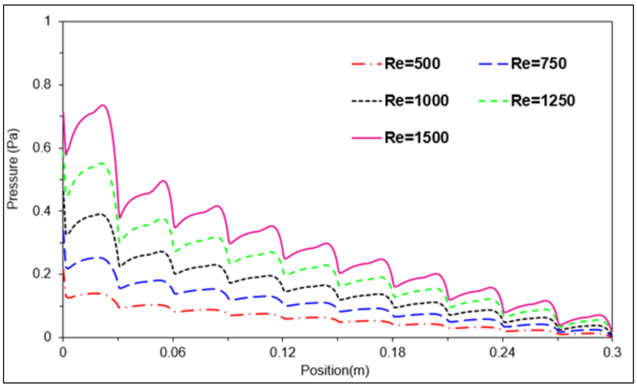


Fig. 7. The graph of Pressure (Pa)Vs Position (m) along tfcl zones tfcl at five different Re

4. Conclusion

Corrugated channel profiles can be used as a potential alternative to straight channels in heat exchanger tubes on account of its enhanced heat transfer performance. But its study still requires further investigation to develop optimized corrugated channel dimensions which will have a superior thermal behaviour as compared to straight channels.

In the present study, fluid flow and heat transfer characteristics of a triangular corrugated channel were simulated by using the finite volume method by employing a commercial numerical code (ANSYS fluent). By varying the Re values the subsequent effect in the Nu, pressure drop and streamlines were analysed which were as follows:

1. The value of Nu was found to increase with the increasing Re.
2. On the contrary, with increase in Re, rise in pressure drop was noticed.
3. With the rise in Re values, the occurrence of flow recirculation and swirling near the corrugations were found to increase substantially and it was thought to be the reason behind enhancement in Nu values
4. Enhanced Nu values augmented the heat transfer rate of the channel.

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