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Heat transfer augmentation in rectangular channel using four triangular prisms arrange in staggered manner

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Abstract: The aim of this study is to investigate the heat transfer and fluid flow characteristics in a rectangular channel in the presence of triangular prisms in the laminar and turbulent flow regime. The computations are performed for Reynolds number 50 to 500 for laminar and 5000 to 20000 for turbulent flow. The Navier-Stokes equation and the energy equation are solved by using Fluent [14.0]. The quadrilateral meshing method is used for the computational domain. Four triangular prisms are placed in staggered manner and the direction of flow is perpendicular or parallel to the prism base. The objective of this study is to investigate the effect of the direction of flow with respect to the prism base, on heat transfer and fluid characteristics. The results shows that in the triangular prisms placed parallel to the direction of flow, the average Nusselt number is 4.27 % more as compared to the another orientation in which direction of flow is perpendicular to the prism base. It is further observed that the heat transfer increases with the increase in Reynolds number (Re). The heat transfer enhancement is associated with greater pressure drop.

Keywords: Heat transfer enhancement; staggered arrangement; Triangular Prism, Reynolds Number.

1. Introduction

Heat exchangers are used in a wide range of engineering applications, such as, power generation, auto and aerospace industry, electronics and HVAC. Typical heat exchangers experienced by us in our daily lives include condensers and evaporators used in air conditioning units and refrigerators. Boilers and condensers in thermal power plants are examples of large industrial heat exchangers. There are heat exchangers in our automobiles in the form of radiators and oil coolers. Heat exchangers are also abundant in chemical and process industries. There is a wide variety of heat exchangers for diverse kinds of uses; hence the construction also would differ widely. Thermal performance of heat transfer devices can be improved by heat transfer enhancement techniques. Many techniques based on both active and passive methods are used to enhance heat transfer in these applications. Among these methods one can find systems involving vortex generators such as fins, prisms, turbulence promoters and other cylinders. The geometrical characteristics of vortex generators play a significant role in the rate of heat transfer. Disturbance promoters increase fluid mixing and interrupt the development of the thermal boundary layer, leading to enhancement of heat transfer. The current research work is undertaken to compute the heat transfer enhancement in a channel flow with built-in triangular prisms in staggered manner.

2. Literature Review

Recently, vortex generators have been used by many researchers for the heat transfer enhancement in various thermal systems. For example, [1] numerically studied the effect of longitudinal vortex generator on the heat transfer in a fin-and-tube heat exchanger. The results reveal that the transverse flow of air stream through the punched holes disturbs the air flow in the lower channel, enhancing the heat transfer on the under surface of fin. Reference [2] proved that the use of a triangular prism could enhance significantly the heat transfer in a channel. Reference [3] obtained numerically the rate of heat transfer enhancement in a channel due to the presence of a triangular element. The results indicate that heat transfer in the channel is augmented by around 15%. Turbulent flow and heat transfer in a heated channel with a triangular prism has been investigated, numerically by [4]. The results showed larger heat transfer augmentation. The control of laminar steady forced convection heat transfer in a channel, with three blocks and a triangular adiabatic control element, has been studied numerically by [5]. It has been shown that the heat transfer is enhanced and the best element position determined.

Reference [6] conducted a numerical study to analyze the unsteady flow and heat transfer in a horizontal channel with a built-in heated cylinder. The heat transfer was found to be slightly affected by the blockage ratio and correlations for the Nusselt number were obtained. Heat transfer and fluid flow characteristics in a channel, with the presence of a triangular prism, has been numerically investigated in the laminar flow regime by [7]. It has been found that the average Nusselt number is augmented and the heat transfer increases with the blockage ratio. Heat transfer enhancement for triangular dual prisms has been found to be larger than that for the case of a single triangular prism, for the same blockage ratio. Reference [8] studied the fluid flow and heat transfer across a

long equilateral triangular cylinder set in a horizontal channel for a fixed blockage ratio of 0.25. It has been found that the average Nusselt number increases with the Reynolds number. Simple correlations for Nusselt numbers have also been obtained. Two dimensional laminar forced convection heat transfers around a horizontal triangular cylinder in an air flow have been investigated numerically by [9]. Two orientations of the triangular cylinder have been considered, the first corresponds to the case for which the vertex of the triangle is facing the flow. As for the second case, the base of the triangle is facing the flow. Correlations are obtained and local Nusselt numbers have been found to be in qualitative agreement with corresponding data reported in the literature. Reference [10] analyzed the effect of wall proximity of a triangular cylinder on the heat transfer and flow in a horizontal channel. Results showed that when the triangular element is close to the wall, the vortex shedding is removed and subsequently the heat transfer rate decreases at low Reynolds number.

Experimental investigations have been reported by [11] on steady forced convection heat transfer from the outer surfaces of horizontal triangular cylinders in an air flow. Local Nusselt numbers around the obstacles are observed to decrease, at the beginning, up to the separation points and then increase, in the transition regime, up to the turbulent limit where they decrease again. Reference [12] studied the heat transfer and fluid flow in a channel using an inclined block as an obstacle. By the use of the inclined block, larger vortices were produced and thus heat transfer was augmented considerably. A heat transfer optimization of a channel with three blocks attached to its bottom wall and an inserted triangular cylinder has been carried out by [13]. The goal of the study is to maximize the heat transfer rate as well as achieving heat flux uniformity above the blocks. A genetic algorithm combined with a Gaussian process has been used as an optimization algorithm for that purpose. The results showed that the larger value of the standard deviation multiplier is the more uniform Nusselt numbers are. Moreover, the optimum position of the vortex generator has been found to be above the first block. In this study we present a numerical simulation of flow and heat transfer by forced convection in a rectangular channel. In order to enhance heat transfer, four triangular prisms acting as a vortex generator, arranged in staggered manner are used. The triangular prisms best position, allowing maximal heat dissipation, has been determined. k−ε turbulence model is used to predicting the heat transfer and fluid flow characteristics in turbulent flow.

3. Geometry and Governing Equations

Fig.1 represents a two dimensional computational domain. Two neighboring plates form a rectangular channel of height "H" and length “8.4 H”. The distance between the plates is taken as unity i.e. H = 1 m. The blockage ratio (BR = B/H) is taken as 0.25, where “B” is the base of the prism. The sides of the prism form an equilateral triangle. Four prisms are placed in staggered manner. The computations are performed for two different arrangements of prisms in the Reynolds number range 50-500 in laminar and 5000-20000 in turbulent; is carried out for the analysis of heat enhancement. The four triangular prisms are placed in staggered manner having wall proximity (y) =.25 m. The first triangular prism base is placed at a distance of 1.7233 H from the start of channel and the last (4^{th}) triangular prism is placed at a distance of 1.5068 H from the rear end of the channel. In this arrangement, the direction of flow is perpendicular to base of the prism.

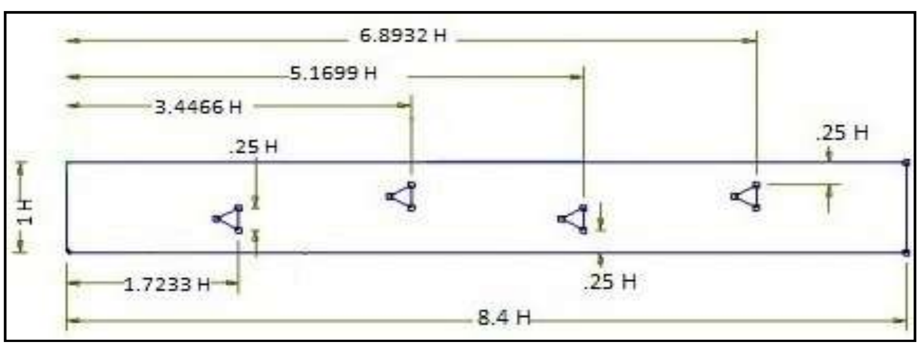

Fig.1: A 2-D rectangular channel having four triangular prisms arrange in staggered manner, y=.25 m, BR=0.25H

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Fig.2: shows a 2-D rectangular channel consists of four triangular prisms arrange in staggered manner with wall proximity (y) .25m. In this, arrangement the direction of flow is parallel to base of the prism. The orientation of the prisms is different from the above orientation.

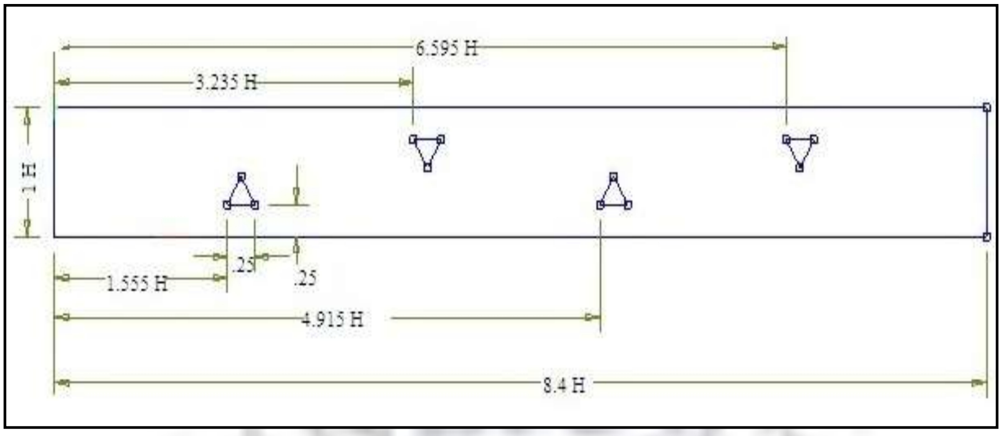

Fig.2: A 2-D rectangular channel having four triangular prisms in staggered manner, y= .25 m, PTF

Governing Equations

The governing two-dimensional equations, in a Cartesian coordinate system, for incompressible, steady, with constant fluid properties, are as follows:

I. Continuity equation

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0$$

II. Momentum equation

$$\frac{\partial U}{\partial \tau}+\frac{\partial (U^2)}{\partial X}+\frac{\partial (UV)}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right)$$

$$\frac{\partial V}{\partial \tau}+\frac{\partial (UV)}{\partial X}+\frac{\partial (V^2)}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)$$

III. Energy equation

$$\frac{\partial \theta}{\partial \tau}+\frac{\partial U\theta}{\partial X}+\frac{\partial V\theta}{\partial Y}=\frac{1}{\mathrm{Re}\,\mathrm{Pr}}\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right)$$

The solution domain of the considered two dimensional flows is geometrically simple, which is a rectangle on the x – y plane, enclosed by the inlet, outlet and wall boundaries. The working fluid is air. The inlet temperature of air is considered to be uniform at 300 K. On walls, no-slip boundary conditions are used for the momentum equations. A constant surface temperature of 400 K is applied to the top and bottom wall of the channel. A uniform one dimensional velocity is applied as the hydraulic boundary condition at the inlet of the computational domain. The pressure at the outlet of the computational domain is set equal to zero gauge. No-slip boundary conditions are taken for the prism. Aluminum is selected as the material for prism.
The properties of air taken are standard.

Density(ρ) kg/m^3	Specific heat(c_p) J/kg-k	Thermal conductivity(k) W/m-k	Viscosity(μ) Kg/m-s
1.225	1.0006.43	.0242	1.7894e-05

4. Turbulence Model

One of the most widely spread models is the standard k-ϵ model proposed by Launder and Spalding. This model implies two transport equations i.e. turbulent kinetic energy and the dissipation of turbulent kinetic, as follows:

Transport Equation for Turbulent Kinetic Energy k

$$\frac{\partial(\rho k)}{\partial t} + div(\rho k\mathbf{U}) = div\left(-\overline{p'\mathbf{u}'} + 2\mu\overline{\mathbf{u}'e_{ij}'} - \rho\frac{1}{2}\overline{u_i'.u_i'u_j'}\right) - 2\mu\overline{e_{ij}'.e_{ij}'} + (-\rho\overline{u_i'u_j'}.E_{ij})$$

Transport Equation for Turbulent Dissipation Rate ε

$$\frac{\partial(\rho\varepsilon)}{\partial t} + div(\rho\varepsilon\mathbf{U}) = div\left[\frac{\mu_t}{\sigma_\varepsilon}grad\ \varepsilon\right] + C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}.E_{ij} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

and the eddy viscosity is define as:

$$\mu_t = \rho c_\mu \frac{k^2}{\varepsilon}$$

The model coefficients are (σ_k; σ_ε; $C_{1\epsilon}$; $C_{2\varepsilon}$; $C\mu$) as follows:

C_μ	$C_{1\varepsilon}$	$C_{2\varepsilon}$	σ_k	σ_ε
0.09	1.44	1.92	1.00	1.30

5. Numerical Procedure

The CFD software (Fluent) is used to simulate the fluid flow and temperature field. The required mesh for computational domain is generated with the help of FLUENT mesh tool. The domain is discretized and equations are formulated using finite volume method. The finite difference governing equations are discretized using the finite volume method. The SIMPLE algorithm is used for the convective terms in the solution equations. The second order up-winding scheme is used to calculate the flow variables. The under relaxation factor is varied between 0.3 and 1.0. The residuals for continuity, momentum and energy equations are all taken as 10-7. The solver iterates the equations till the convergence is obtained for the set residuals.

6. Result and Discussion

6.1 Flow Characteristics

The flow structure in presence of triangular prisms can be discerned by looking at velocity vector plots. The velocity vector plots for both the orientations are shown below. The flow stream divides itself in two streams as it hits the triangular prism and combines after the triangular prism and after that again divides and recombines. The flow passage decreases as the flow moves towards the prism and the flow passage increases as the flow moves away from the prism. The figures 3 and 4 show the velocity contours of the computation domain of the plane channel for both the orientations of triangular prisms.

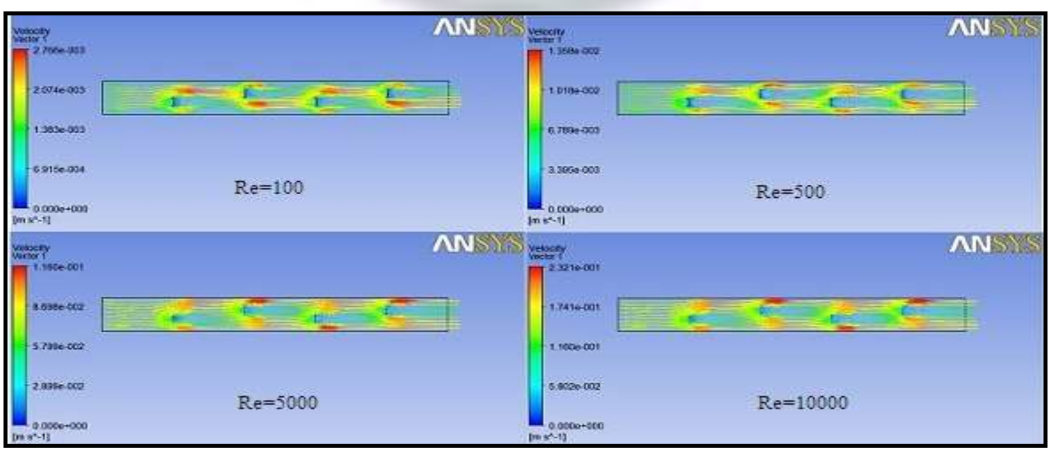

Fig.3: Velocity vector plot for Re=100, 500, 5000 and 10000, y=.25 m, BR=.25 H

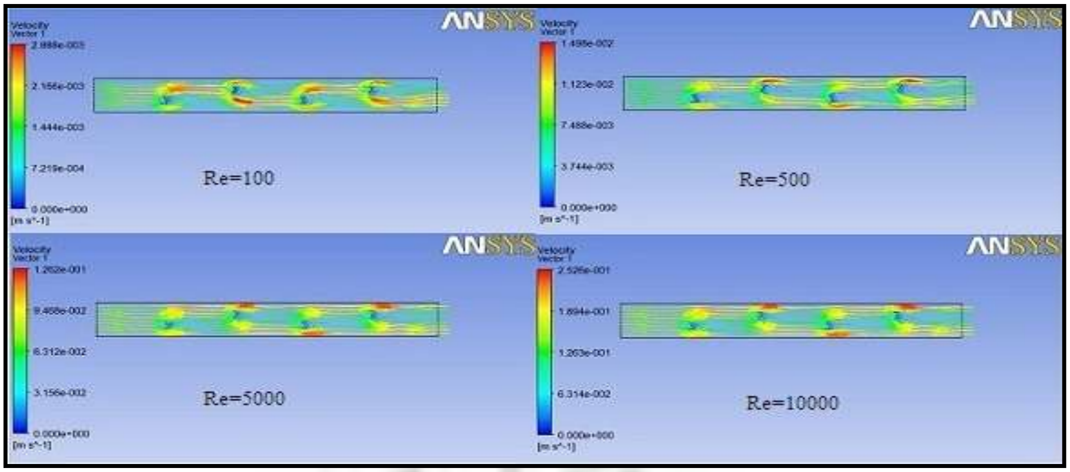

Fig.4: Velocity vector plot for Re=100, 500, 5000 and 10000, y=.25 m, PTF

6.2 Temperature Contours and Heat Transfer Characteristics

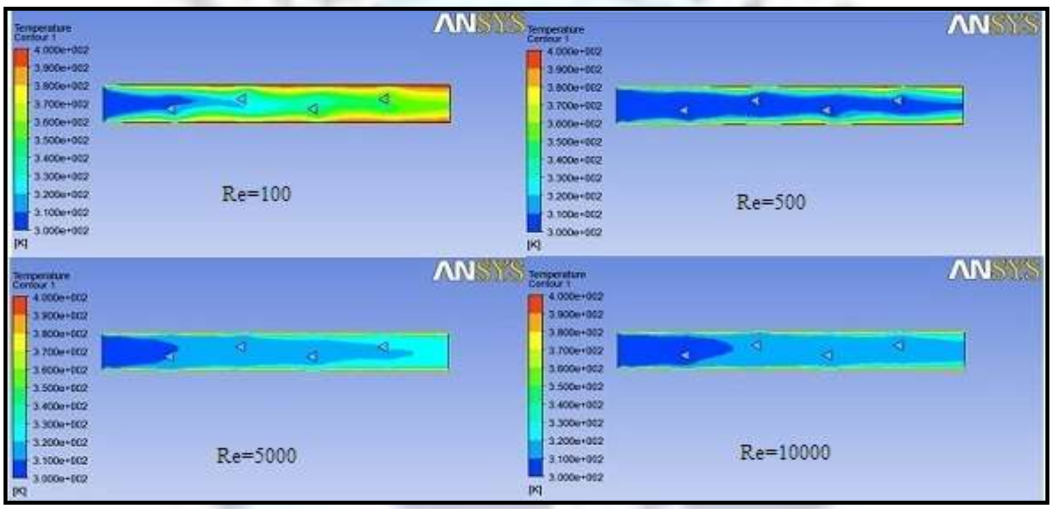

Fig.5: Temperature contours at Re=100, 500, 5000 and 10000, y=.25 m

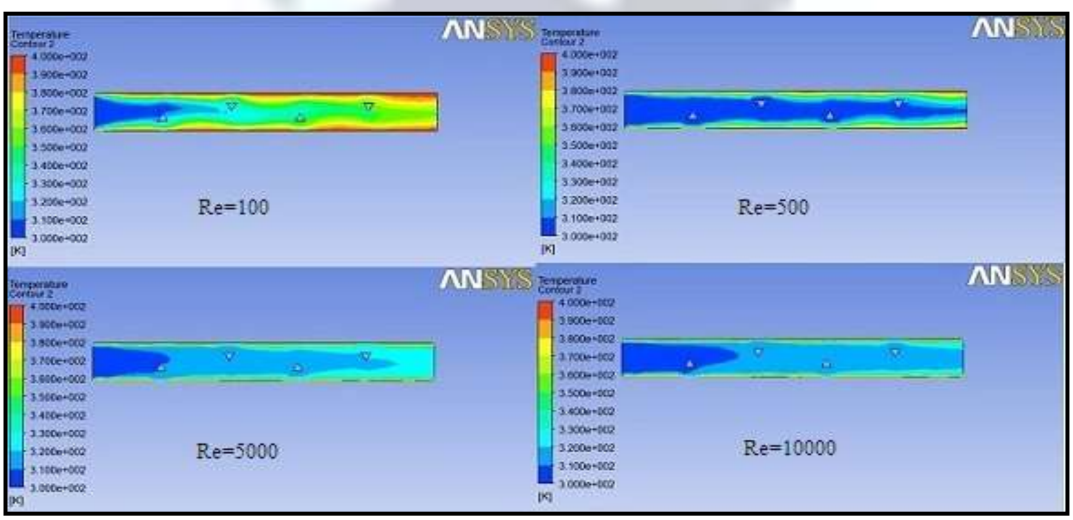

Fig.6: Temperature contours at Re=100, 500, 5000 and 10000, y=.25 m, PTF

The above figures show the temperature contours of the computation domain of the plane channel for both the orientations of triangular prisms. The presence of the obstacle causes the formation of counter rotating vortices which cause the mixing of fluid and hence and increase in the heat transfer coefficient of the fluid and hence the temperature of the fluid increases. The rate of increment in temperature at outlet is more in 2nd orientation as compare to 1st.

Figure 7 and 8 shows the surface Nusselt number ($Nu = h_x H/k$) variation on the top and bottom wall of the channel with triangular prisms. Due to the effect of direction of flow with respect to the prism base, the variation of Nusselt number is more in the arrangement having prisms base parallel to the flow.

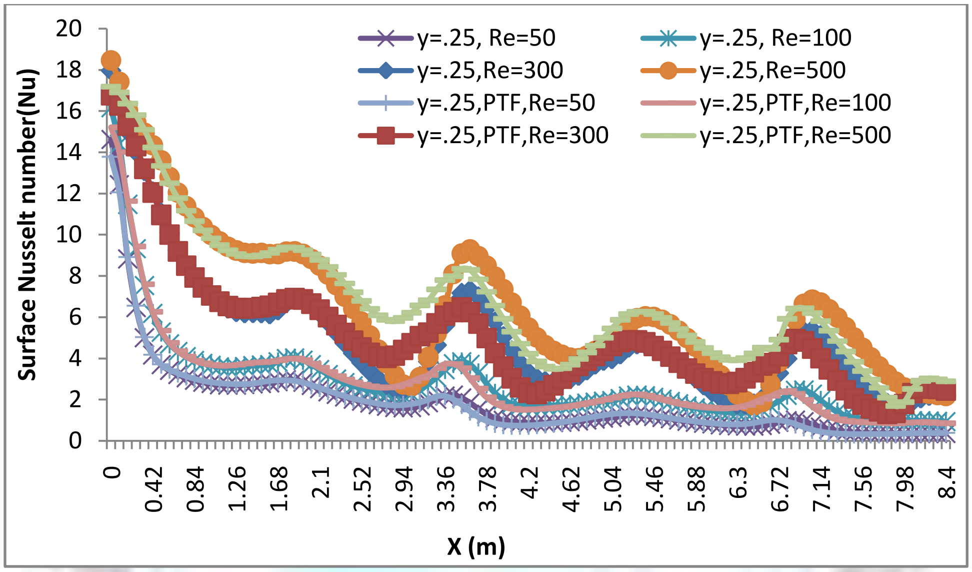

Fig.7: Variation of Nusselt number along the channel length in laminar flow zone

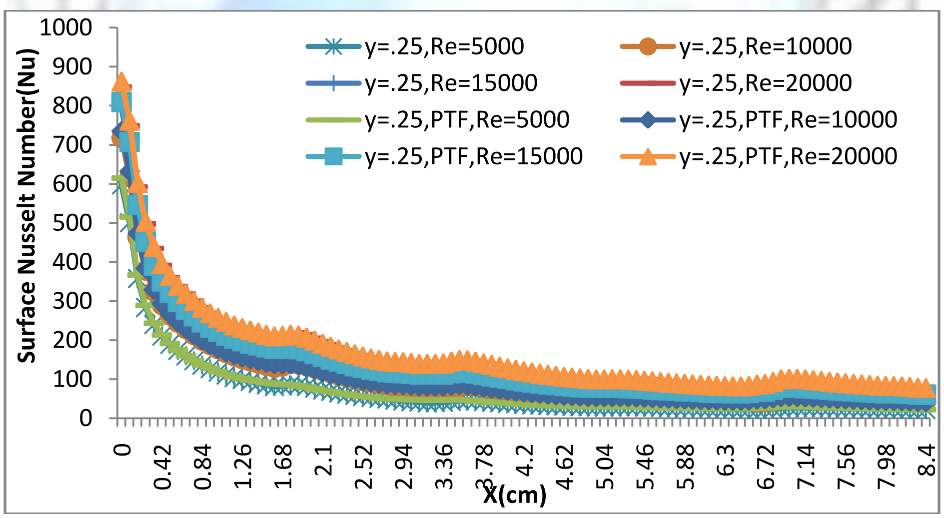

Fig.8: Variation of Nusselt number along the channel length in turbulent flow zone

6.3 Pressure characteristics

The enhancement of heat transfer achieved by using triangular prisms is associated with an increase in the pressure loss. Figure 9 and 10 shows the pressure variation along the channel length with four triangular prisms having the base perpendicular and parallel to the flow. The figures shows that the maximum pressure drop occurs just downstream of the triangular prism because of the form drag and then pressure is recovered and approaches a stabilized value till the end.

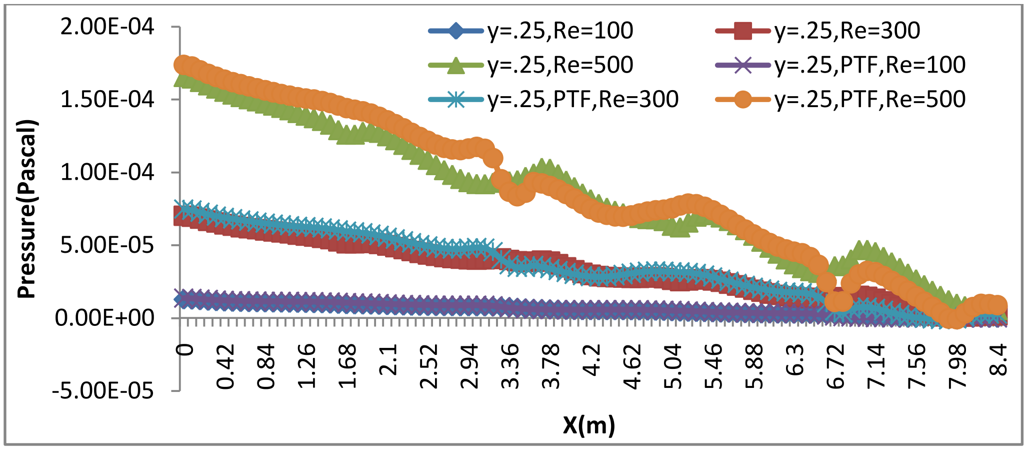

Fig.9: Pressure variations along the channel length in laminar flow zone

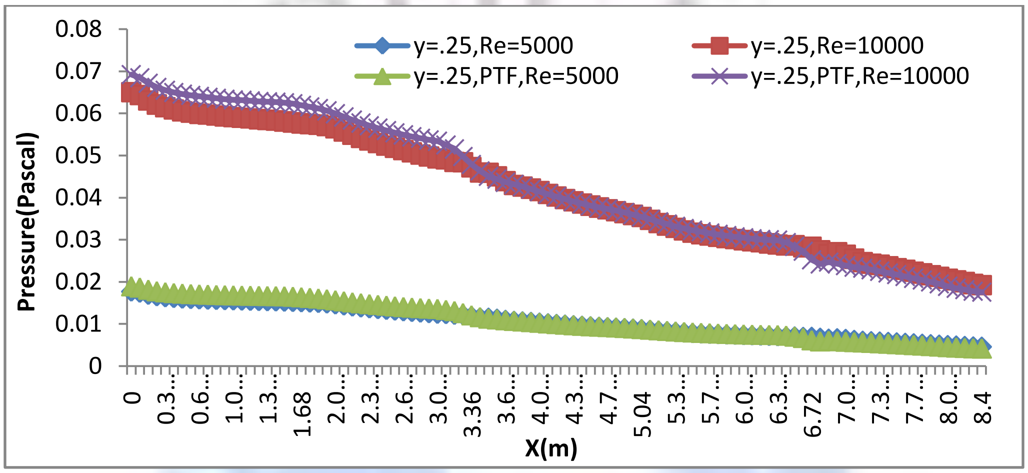

Fig.10: Pressure variations along the channel length in turbulent flow zone

7. Conclusion

In the present problem, the CFD analysis of heat transfer enhancement in 2-D rectangular channel is studied in detail. The flow regimes are laminar and turbulent. The heat transfer characteristics and flow characteristics are studied in detail.

On the basis of the results obtained, the following conclusions are made:

1. The presence of more than single triangular prism significantly improves the heat transfer enhancement. The % increase in heat transfer enhancement in the presence of four triangular prisms at Re no= 500, is 5.34 % more as compare to single prism at Re no = 500.
2. In laminar flow regime up to Reynolds no 100, the prisms arrangement having base perpendicular to flow and wall proximity (y) is .25 m gives better performance as compare to other orientation having base parallel to flow. The % increase in average Nusselt number at Re no 100 is 1.59 % more as compare to other orientations at Re no 100.
3. After Reynolds number 100, the prisms having base parallel to the flow (PTF) and y= .25 m gives better performance as compare to the other orientation.
4. The % increase in average Nusselt number at Re no 300 is 2.64 % more as compare to other orientation having wall proximity (y) is .25 m at Re no 300.
5. In prisms arrangement having base parallel to flow (PTF) and y= .25 m. The % increase in average Nusselt number at Re no 5000 is .156 % more as compare to other arrangement having base perpendicular to flow and wall proximity (y) is .25 m at Re no 5000.

6. Also the % increase in Nusselt number with respect to Reynolds number is more in arrangement having base parallel to flow.
7. The pressure loss is also increased with the increase of Reynolds number due to the presence of four triangular prisms.

Nomenclature

a	area of the rectangular channel, m^2
h	average heat transfer coefficient, W/m^2K
H	characteristic length dimension (distance between the plates), m
L	length of the channel, m
V	mean velocity, m/s
Cp	specific heat capacity of air, J/kg K
k	thermal conductivity of air, W/m K
Nu	Nusselt number
ΔP	pressure drop, Pa
Re	Reynolds number
q	heat flux, W/m^2
T_o	average temperature of outlet
T_i	Inlet temperature
Greek Symbols	
ρ	density of air, kg/m^3
μ	fluid dynamic viscosity, kg/m-s
μ_t	eddy viscosity
Abbreviations	
PTF	parallel to flow
BR	blockage ratio
Subscripts	
y	wall proximity

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