

Heat Transfer Augmentation in Rectangular Channel using Three Triangular Prisms

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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. By using three triangular prisms attached with channel wall, the heat transfer is augmented considerably. This is due to the large vortices produced by the prisms as compared to the plane channel. The results show that in the presence of the triangular prism with circle at their edges, the average Nusselt number is 9.72 % more as compared to presence of triangular prism without circle. It is further observed that the heat transfer increases with the increase in Reynolds number (Re). The enhancement is due to the formation of vortices which travels long way in the downstream direction. However the heat transfer enhancement is associated with greater pressure drop.

Keyword: Heat transfer enhancement, Triangular Prism, Reynolds Number, Nusselt Number

I. 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 three triangular prisms.

II. 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 the 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. $k-\epsilon$ turbulence model is used to predicting the heat transfer and fluid flow characteristics in turbulent flow.

III. 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. 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 first triangular prism base is placed at a distance of 2 H from the start of channel and the last triangular prism is placed at a distance of 2 H from the rear end of the channel.

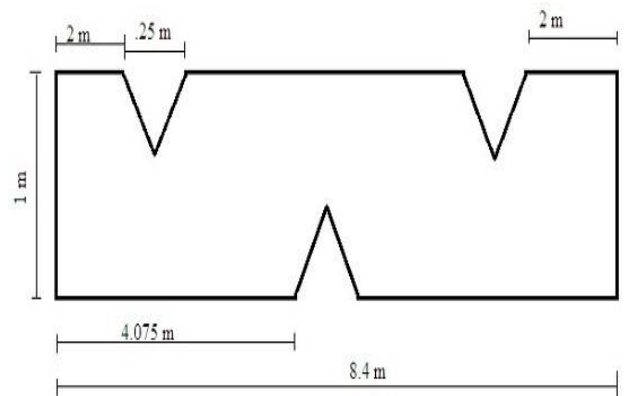


Fig.1: A 2-D rectangular channel having three triangular prisms, without circle at their edges

Fig.2: shows a 2-D rectangular channel consists of three triangular prisms with built-in circles at their edges. The diameter of circle is .15 m

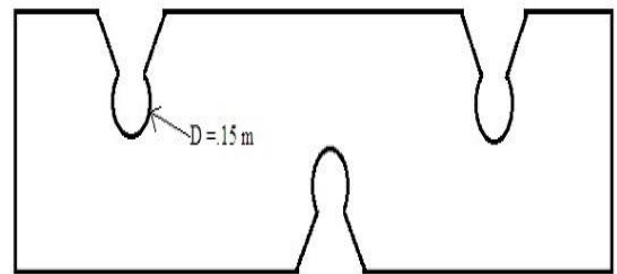


Fig.2: A 2-D rectangular channel having three triangular prisms, with circle at their edges

A. Governing Equations

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

- 1) Continuity equation

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

- 2) Momenum equation

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

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

- 3) Energy equation

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

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	1006.43	0.0242	1.7894e-5

IV. 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

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

Transport Equation for Turbulent Dissipation Rate ϵ

$$\frac{\partial(\rho \epsilon)}{\partial t} + \text{div}(\rho \epsilon \mathbf{U}) = \text{div}\left[\frac{\mu_t}{\sigma_\epsilon} \text{grad } \epsilon\right] +$$

and the eddy viscosity is define as:

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

The model coefficients are (σ_k ; σ_ϵ ; $C1\epsilon$; $C2\epsilon$; C_μ) as follows:

C_μ	$C1\epsilon$	$C2\epsilon$	σ_k	σ_ϵ
0.09	1.44	1.92	1.00	1.30

V. 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.

VI. RESULT AND DISCUSSION

A. 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 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 arrangements of triangular prisms.

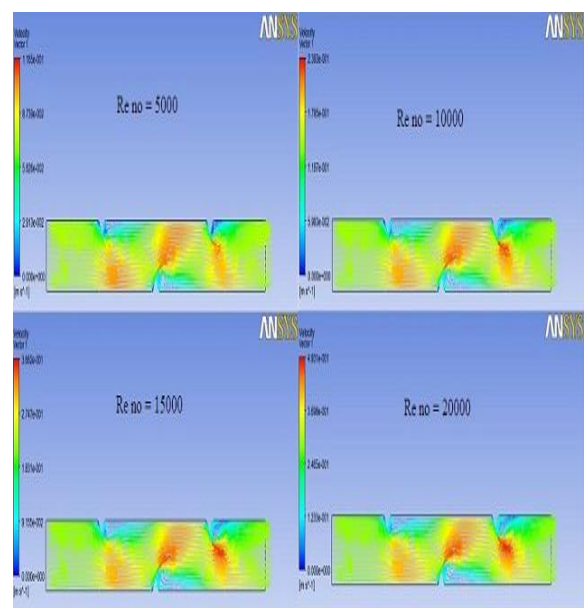


Fig: 3 Velocity vector plot for Re no 5000 to 20000, triangular prism without circle

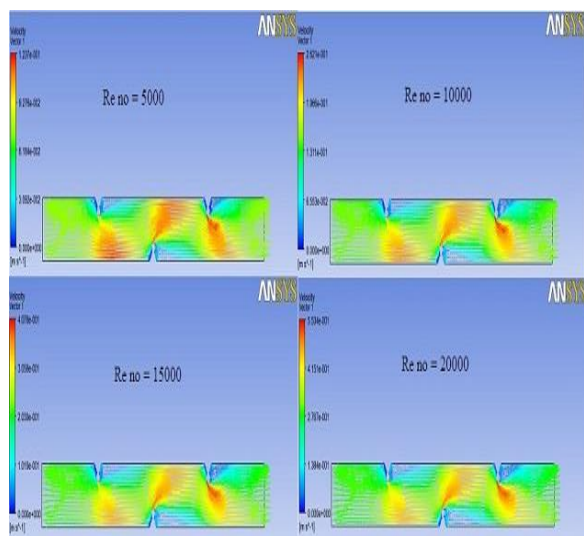


Fig: 4 Velocity vector plot for Re no 5000 to 20000, triangular prism with circle

B. Temperature Contours and Heat Transfer Characteristics

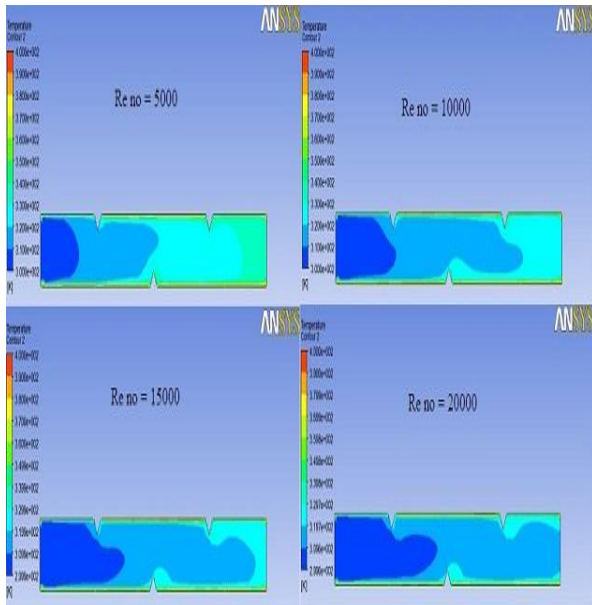


Fig: 5 Temperature contours for Re no 5000 to 20000, triangular prism without circle

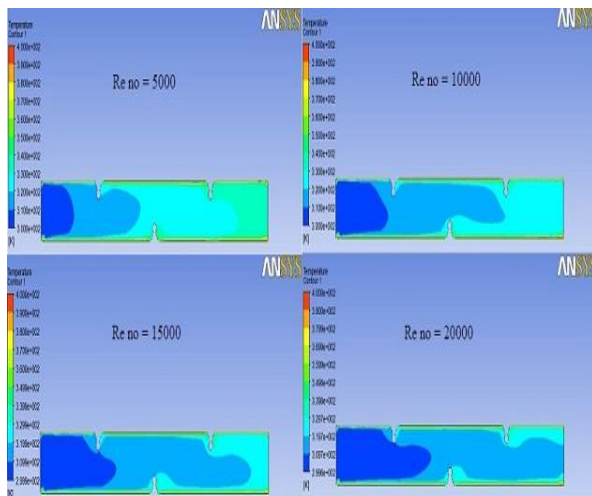


Fig: 6 Temperature contours for Re no 5000 to 20000, triangular prism with circle

The above figures show the temperature contours of the computation domain of the plane channel for both the arrangements of triangular prisms with or without circle at their edges. The presence of the obstacle causes the formation of counter rotating vortices which cause the mixing of fluid and hence an 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 arrangements having triangular prisms with circle at their edges.

C. Pressure contours and characteristics

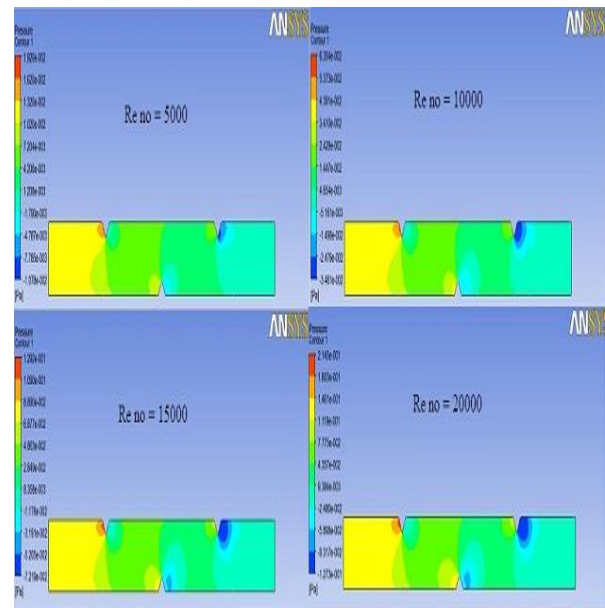


Fig: 7 Pressure contours for Re no 5000 to 20000, triangular prism without circle

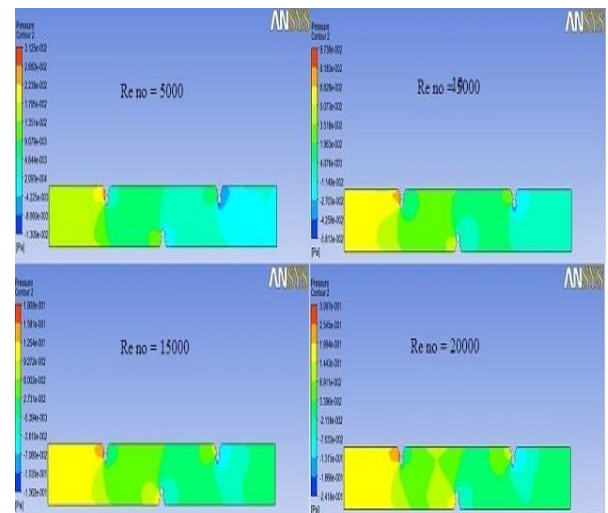


Fig:8 Pressure contours for Re no 5000 to 20000, triangular prism with circle

Pressure contours show the pressure drop across the channel length and heat transfer through the channel walls. The heat enhancement is due to the more pressure drop in the channel.

The enhancement of heat transfer achieved by using triangular prisms is associated with an increase in the pressure loss. Figure 9 and 10 show the pressure variation along the channel length. The figures show 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.

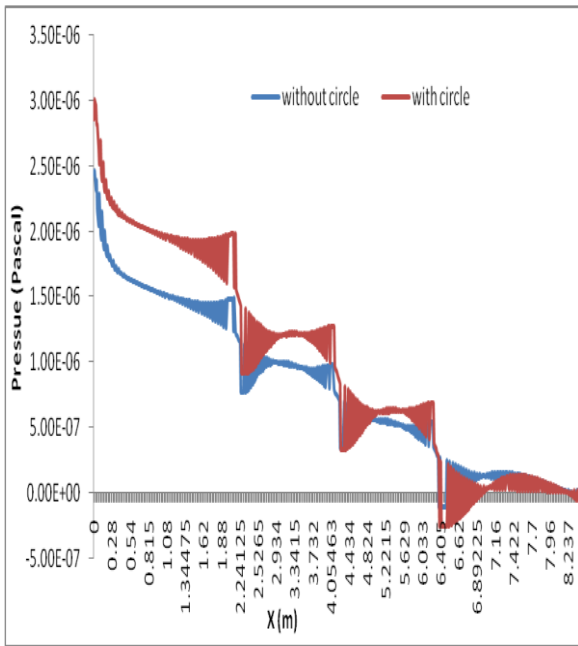


Fig. 9: Pressure variations along the channel length in laminar flow zone
 D. *Nusselt number (Nu) vs. Reynolds number (Re)*
 E.

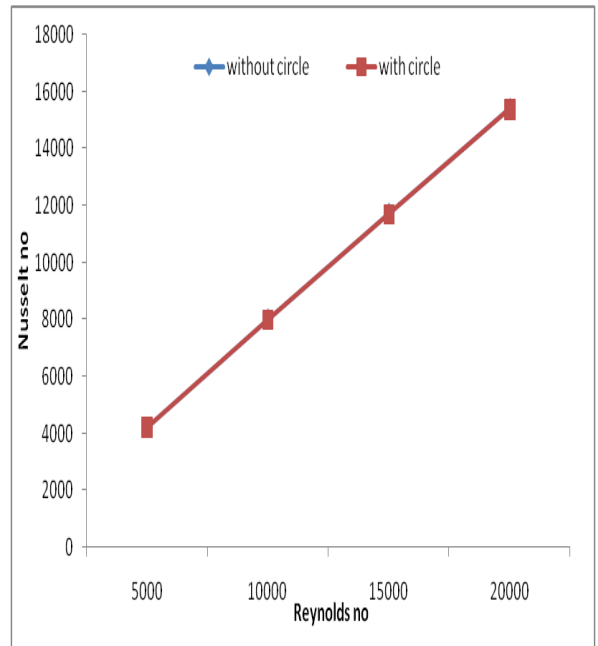


Fig 11 : Nusselt number (Nu) vs. Reynolds number (Re) in turbulent flow
 F. *Pressure vs. Reynolds number (Re)*

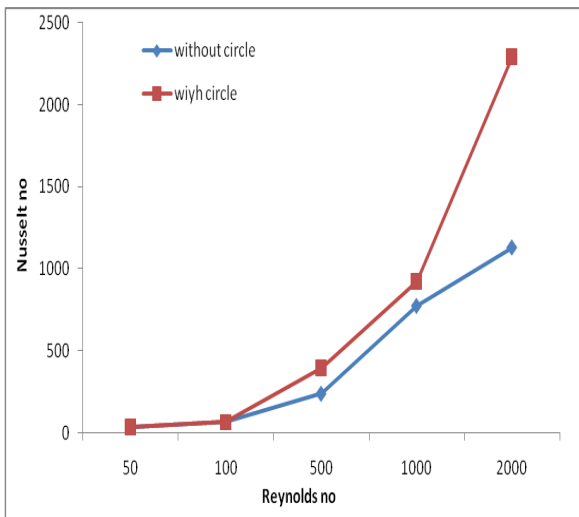


Fig. 10: Nusselt number (Nu) vs. Reynolds number (Re) in laminar flow

The above figures show the variation of Nusselt number vs. Reynolds number. Figures clearly define the value of Nusselt number with the increase of Reynolds number.

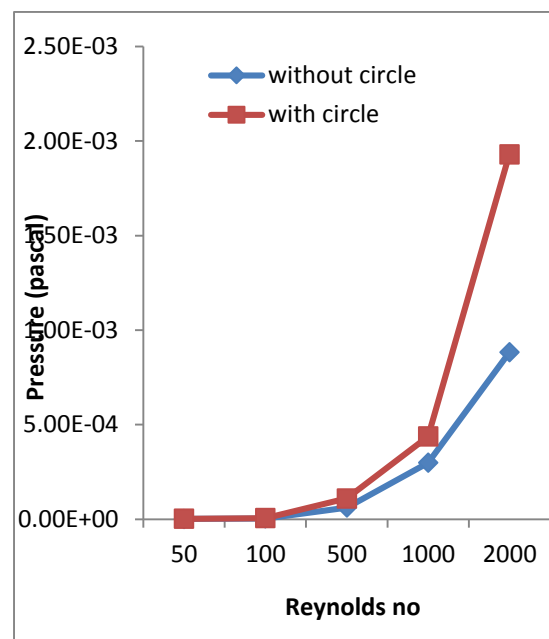


Fig.12: Pressure vs. Reynolds number (Re) in laminar flow

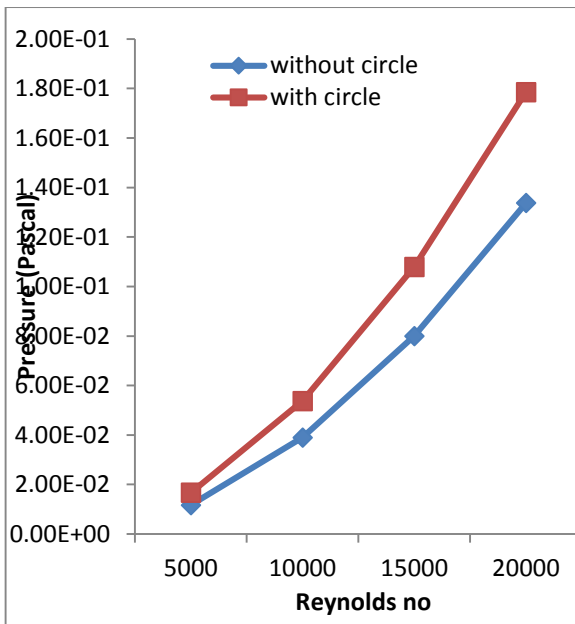


Fig 13: Pressure vs. Reynolds number (Re) in turbulent flow

These are the pressure vs. Reynolds number plots which gives the value of pressure difference between the inlet to outlet. The value of pressure difference is clearly shown in plots. There is more pressure drop when prism with circular edge is used in the channel flow.

VII. 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 three 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 without circle at their edges gives better performance as compare to other arrangement. The % increase in average Nusselt number at Re no 100 is 1.59 % more as compare to other at Re no 100.
- 3) After Reynolds number 100, the prisms having circles at their edges gives better performance as compare to the other. The % increase in average Nusselt number at Re no 1000 is 16.08 % more as compare to other arrangements having prisms without circle at their edges at Re no 1000.
- 4) Also the % increase in Nusselt number with respect to Reynolds number is more in arrangement having prisms with circle at their edges.

- 5) The pressure loss is also increased with the increase of Reynolds number due to the presence of three triangular prisms.

VIII. NOMENCLATURE

a	area of the rectangular channel, m ²
h	average heat transfer coefficient, W/m ² K
H	characteristic length dimension (distance between the plates), m
L	length of the channel, m
V	mean velocity, m/s
C _p	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

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