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NUMERICAL ANALYSIS OF HEAT TRANSFER CHARACTERISTICS IN ROUND TUBE WITH CONVERGENT CONICAL RING INSERTS

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Abstract: A numerical analysis of heat transfer characteristics of fluid flow through heat exchanger tubes are inserted with perforated conical rings. Conical rings are used as a turbulence promoter for creating turbulences and enhancing heat transfer efficiency. This paper suggests that the incorporation of conical rings can significantly improve heat exchange performance within a double pipe heat exchanger, making it a promising solution for various industrial applications requiring efficient heat transfer. In the present study, the heat transfer of plain tube, conical rings and perforated conical rings are studied. The conical rings and the perforated conical rings (PCR) turbulators were located in plain tube. The perforated conical-rings (PCRs) used are four different numbers of perforated holes N= 4, 6, 8and 10 holes. The simulation was carried out by air with the inlet temperature of 300 K was selected as the working fluid, while the tube wall temperature was kept constant at 350 K. The mass flow rate of air in the tube is 0.004, 0.008, 0.012, 0.016, 0.02 kg/s. The fluid moves through the tube and is heated at the outlet of the tube. The results showed that the heat transfer coefficient, Nusselt number and pressure drop increased with increase of Reynolds number, friction factor and thermal performance factor values decreased as the Reynolds number increase. From this work, it is shown that the utilization of conical rings without holes has more advantage than regular tube heat exchanger to improve the heat transfer rate in less area.

Keywords - Plain tube, Conical Ring Inserts, Heat Transfer calculations and CFD.

Nomenclature

A	area, m^2
D	diameter of the tube, mm
D_1	inlet diameter of conical ring, mm
D_2	outlet diameter of conical ring, mm
d	diameter of conical ring holes, mm

f	friction factor
h	heat transfer coefficient (W/m^2-K)
k	thermal conductivity (W/m-K)
K	kelvin
kg	kilograms
L	length, mm
l	length of the conical ring, mm
m_a	mass flow rate of air, kg/s
m	length (meter)
mm	millimetre
Nu	Nusselt number
N	number of perforated holes
ΔP	pressure drop (Pa), N/m^2
p	pitch, m
PR	pitch ratio
Pr	Prandtl number
Re	Reynolds number
Ra	Rayleigh number
s	seconds
T	temperature
V	velocity of fluid (m/s)
Greek letters	
Δ	delta
η	thermal performance factor
µ	dynamic viscosity (Ns/m^2)
ρ	density (kg/m^3)

1. INTRODUCTION

Heat exchangers are widely used in different processes ranging from conversion, utilisation & recovery of thermal energy in various industrial, commercial & domestic applications. Some common examples include steam generation & condensation in power & cogeneration plants; etc. Omidi et al. [1] theoretically studied comprehensive review on DPHE. some advantages of DPHE are, the simplest geometry, facility of installation, and low installation and maintenance costs. Use of Heat transfer enhancement techniques lead to increase in heat transfer coefficient but at the cost of increase in pressure drop. So, while designing a heat exchanger using any of these techniques, analysis of heat transfer rate & pressure drop has to be done. Turbulators are the most important and effective passive method of enhancing heat transfer rate techniques. These devices can indirectly promote energy transfer via heat exchange surfaces by flowing the stream over the hot or cold channel walls, producing more swirl flows. Turbulators are mainly used to promote fluid turbulence and rotation and eventually raise the heat transfer rate. Yakut et al. [2] investigated experimentally flow-induced vibration characteristics of conical-ring turbulators used for heat transfer enhancement in heat exchangers. The conical-rings, having 10, 20 and 30 mm pitches, are inserted in a pipe through which air is passed as the working fluid. He found that the Nusselt number increases with the increasing Reynolds number and the maximum heat transfer is obtained for the smallest pitch arrangement. Kishore [3] theoretically predictions for friction factors and convective heat transfer coefficients using twisted tapes within a tube. This prediction spanned a wide range of Reynolds numbers and Prandtl numbers. The physical presence of the tape in the flow was seen to potentially lead to a gradual transition from laminar to turbulent flow. A combined friction coefficient correlation applicable across a wide Reynolds number range was extended to according to theoretically predict convective heat transfer coefficients, with the idea that a distinct laminar-to-turbulent flow transition might not be evident. Promvonge et al. [4] investigated experimentally the heat transfer enhancement characteristics in a uniform heat flux circular tube fitted with conical nozzles and swirl generator. Three different pitch ratios (PR) = 2.0, 4.0 and 7.0 He found that the conical nozzle and the snail can help to increase the heat transfer rate over that of the plain tube by about 278% and 206%, respectively. The use of the conical nozzle in common with the snail leads to a maximum heat transfer rate that is up by 316%. Sarma et al. [5] theoretically predicted wall friction coefficients and Nusselt numbers that showed reasonable agreement with established solutions such as the Blasius wall friction coefficient and Dittus and Boelter heat transfer correlation. The predictions of Nusselt numbers using eddy diffusivity expressions also agreed satisfactorily with the Dittus and Boelter correlation. Furthermore, the analysis could be adapted by adjusting the correction factor to align with predictions from the Petukhov–Gnielinski correlation. Promvonge et al. [6] experimentally investigated heat transfer, friction factor and enhancement efficiency characteristics in a circular tube fitted with conical-ring turbulators and a twisted-tape swirl generator. Reynolds number range of 6000 to 26,000. Two twisted-tapes of different twist ratios are Y= 3.75, and 7.5. The results reveal that the Nusselt number values of around 4 to 10% and enhancement efficiency of 4 to 8% higher than that with the conical-ring alone. A maximum heat transfer rate of 367% and enhancement efficiency of around 1.96 is found for using the conical-ring and the twisted-tape of Y= 3.75. Kongkaitpaiboon et al. [7] investigated experimentally perforated conical-ring (PCR) is one of the turbulator devices for enhancing the heat transfer rate in a heat exchanger system. The PCRs three different pitch ratios (PR=p/D= 4, 6 and 12) and three different numbers of perforated holes (N= 4, 6 and 8 holes). The range of Reynolds number between 4000 and 20,000. He found that the heat transfer rate up to about 137% over that in the plain tube. Evidently, the PCRs can enhance heat transfer more efficient than the typical CR on the basis of thermal performance factor of around 0.92 at the same pumping power. Sarma et al. [8] performed an experiment to predict momentum and thermal diffusivities with Al_2O_3 nano fluid to develop the Nusselt number and friction factor correlations. The enhancement of the convective heat transfer occurs due to presence of nanoparticles in water. An improvised method for the evaluation of both eddy momentum and thermal diffusivities as a function of dimensionless velocity and distance is presented. Nakhchi et al. [9] numerically investigated entropy generation analysis for the Cu–water nanofluid flow through a heat exchanger tube equipped with perforated conical rings. Frictional and thermal entropy generation rates are defined as functions of velocity and temperature gradients. Reynolds number is in the range of 5000–15,000. The results indicate that the frictional entropy generation reduces with increasing the number of holes from 4 to 10. This is because of stronger velocity gradient near the perforated holes. Bejan number decreases with augment of Reynolds number.

2. DESCRIPTION OF PERFORATED CONICAL RINGS

In this work, all the perforated conical rings (PCR) turbulators were located in plain tube. The length of the plain tube, L is 1440 mm and diameter of the tube, D is 64 mm. The length of the PCRs, l is 60 mm, PCR inlet diameter, D_1 is 50 mm, PCR thickness, δ is 2 mm, PCR outlet diameter, , D_2 is 20 mm and hole diameter, d is 3 mm. The number of holes varied from 0 to 10. The holes are mounted on the middle of the conical surface. The Pitch length is 240 mm and pitch ratio, p/D_1 = 4 was selected in this analysis. The simulation was carried out by air with the inlet temperature of 300 K was selected as the working fluid, while the tube wall temperature was kept constant at 350 K. The fluid moves through the tube and is heated at the outlet of the tube.

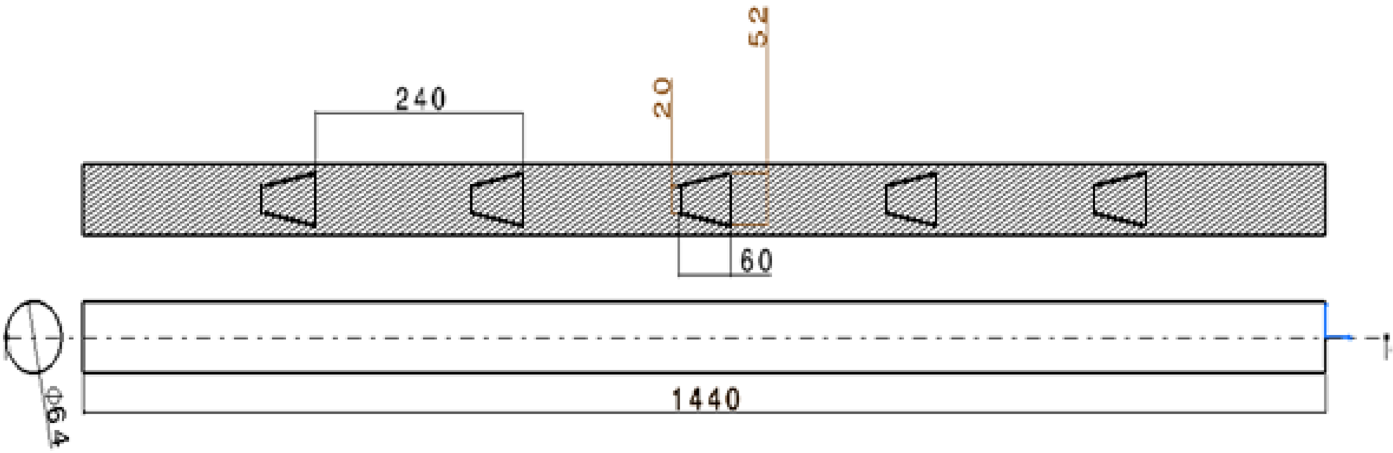

Fig.1: Conical rings in plain tube with dimensions

3. THEORETICAL ANALYSIS

Here is a simple procedure for the evaluation of heat transfer enhancement

1.For plain tube

Velocity of the air, $v_a = m_a / \rho_a A$

For calculating the Nusselt number, the dittus-boelter correlation is used

Nusselt Number, $Nu = 0.023\ Re^{0.8}\ Pr^{0.4}$

Reynolds Number, $Re = v_a D \rho_a / \mu$

Heat transfer coefficient, $h = Nu\ K / D$

The correlation of friction factor for the plain tube is recommended by Kongkaitpaiboon

Friction factor, $f = 0.458\ Re^{-0.284}$

2.For conical rings without holes

Promvonge has developed the following empirical relations for calculating Nusselt number, friction factor and thermal performance factor

Nusselt number, $Nu = 0.096\ Re^{0.789}\ PR^{0.02}\ Pr^{0.333}$

Friction factor, $f = 1490\ Re^{-0.5}\ PR^{-0.835}$

Thermal performance factor, $\eta = 1.87\ Re^{-0.081}\ PR^{-0.153}$

3. For conical ring with holes

Kongkaitpaiboon has developed the following empirical relations for calculating Nusselt number, friction factor and thermal performance factor

Nusselt number, $Nu = 1.258\ Re^{0.606}\ PR^{-0.39}\ N^{-0.32}\ Pr^{0.4}$

Friction factor, $f = 985.48\ Re^{-0.368}\ PR^{-0.747}\ N^{-1.253}$

Thermal performance factor, $\eta = 1.596\ Re^{-0.067}\ PR^{-0.142}\ N^{-0.095}$

4. GEOMETRIC MODEL

The three-dimensional fluid flow and heat transfer characteristics are studied through a round tube with a set of conical rings installed in it such that they create vortices and because of turbulence created it results in increasing in heat transfer coefficient.

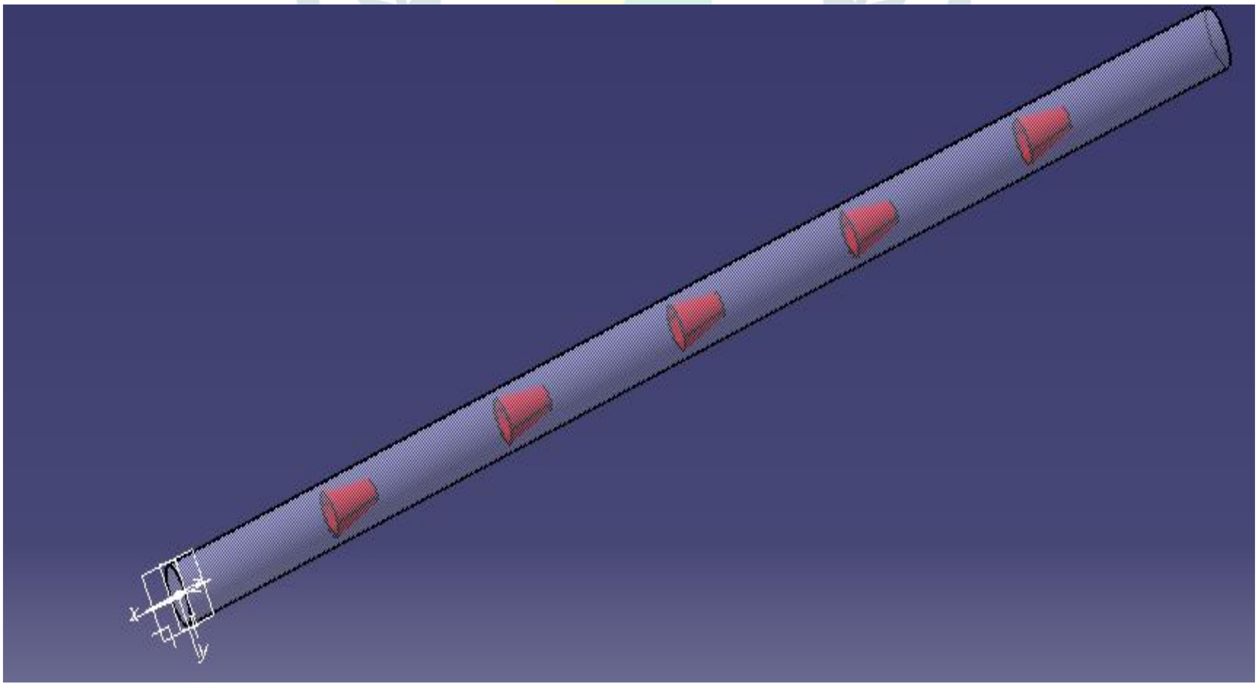

Fig.2: conical rings inserted in a plain tube

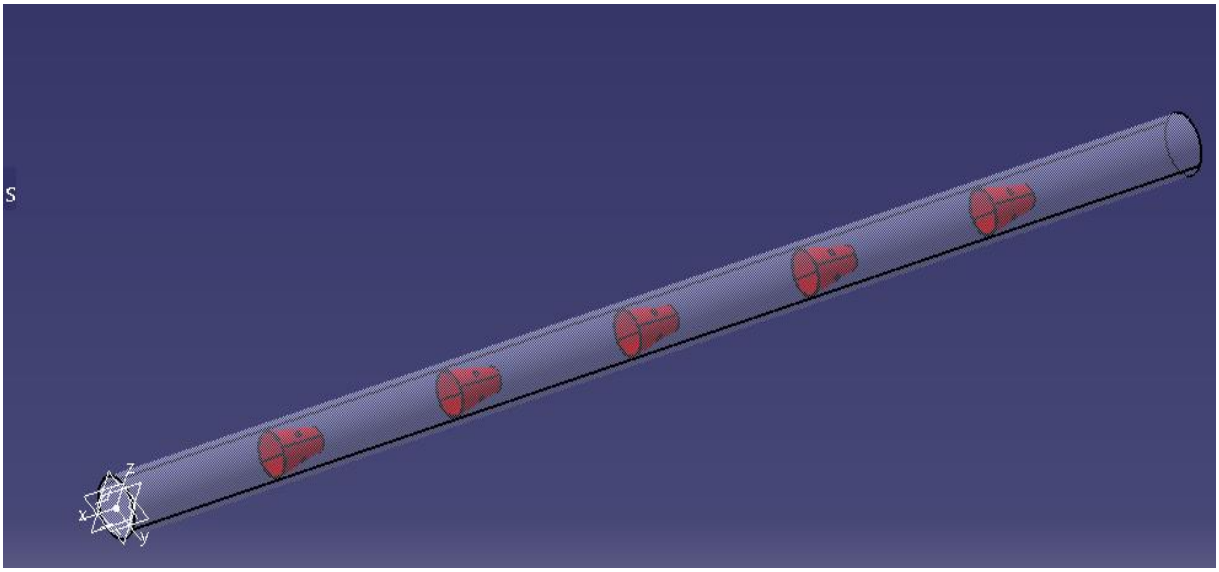

Fig.3: conical ring with 4 holes

5. NUMERICAL METHOD

The problem is solved using the commercial software ANSYS Fluent 19.0 based on the finite volume method. The discretization of the mass, momentum, turbulence kinetic energy, turbulence dissipation rate, and energy equations are performed by the second-order upwind scheme. The velocity–pressure coupling is overcome by the SIMPLE algorithm.

Governing equations

The governing equations of the turbulent flow and heat transfer for the model may be written as:

Continuity Equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0$$

Momentum Equation:

$$\frac{\partial}{\partial x_i}(\rho_f u_i u_j) = -\frac{\partial \rho}{\partial x_j} + \frac{\partial}{\partial x_i}\left[\mu_f\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right)\right]$$

Energy Equation:

$$\frac{\partial}{\partial x_i}(\rho_f u_i c_{pf} \mathrm{T}) = \frac{\partial}{\partial x_i}\left(k_f \frac{\partial \mathrm{T}}{\partial x_i}\right) + \mu_f\left[2\left(\frac{\partial u_i}{\partial x_i}\right)^2 + \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_i}\right)^2\right]$$

For the solid:

$$\frac{\partial}{\partial x_i}\left(k_f \frac{\partial \mathrm{T}}{\partial x_i}\right) = 0$$

6. ANSYS MODELING

The CATIA model is established and can be seamlessly imported into the ANSYS simulation software using the IGES file format.

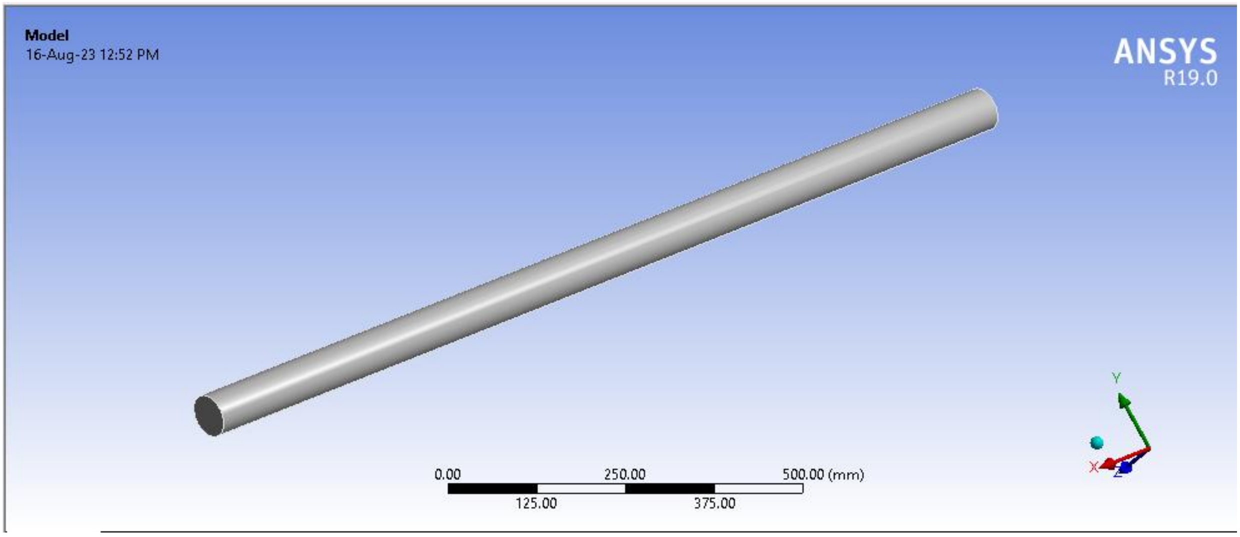

Fig.4: Geometry model of Plain tube

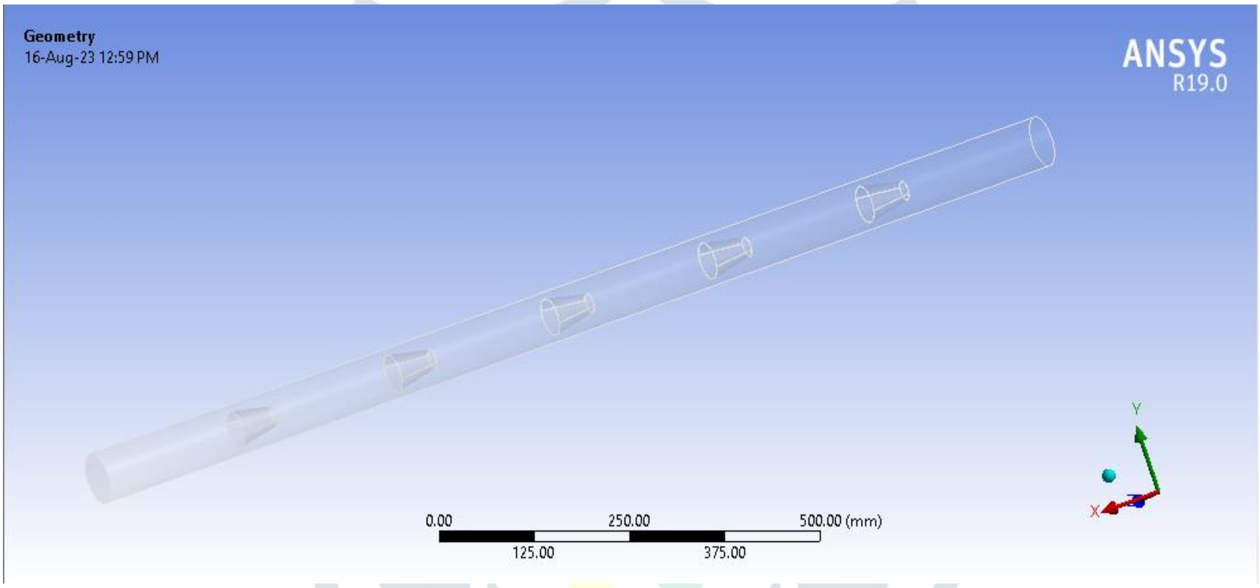

Fig.5: Geometry model of conical ring with tube

Meshing is a next concept once the model is prepared. The entire domain material is assigned as FLUENT, every edge of domain is planned to divide to gain hexagonal meshing. If right clicked on mesh, we get generate option and using this option meshing is performed.

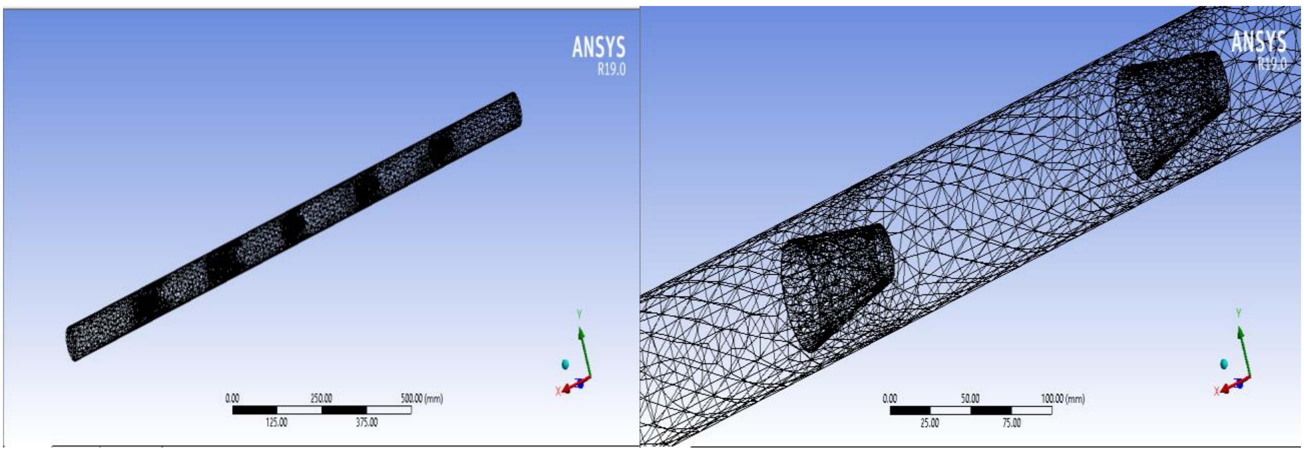

Fig.6 (a) & (b): Finite Volume model of conical ring with tube.

The primary objective of this study revolves around investigating the variation in heat transfer coefficient resulting from changes in inlet velocity. Standard initialization is employed for every analysis, facilitating the estimation of initial values for pertinent variables. This initialization prompts the entire setup, including x and y velocities, temperature, and pressure. All other parameters are held as constant across the entire domain.

7. RESULTS AND DISCUSSIONS

Following the completion of both analytical and numerical analyses, outcomes including heat transfer coefficients, Nusselt numbers, pressure drops, and friction factors are graphically displayed for comparative purposes. These results are subsequently discussed in the following section.

Heat transfer coefficient

The heat transfer coefficient is an important metric in heat transport and thermodynamics. From the graph it is seen that the maximum heat transfer coefficient is seen in N=0 (theoretical) which is high heat transfer coefficient which is 79.51 W/m^2K at Reynolds number 20699. For all the n values, when the Reynolds number increases the heat transfer coefficient will increase.

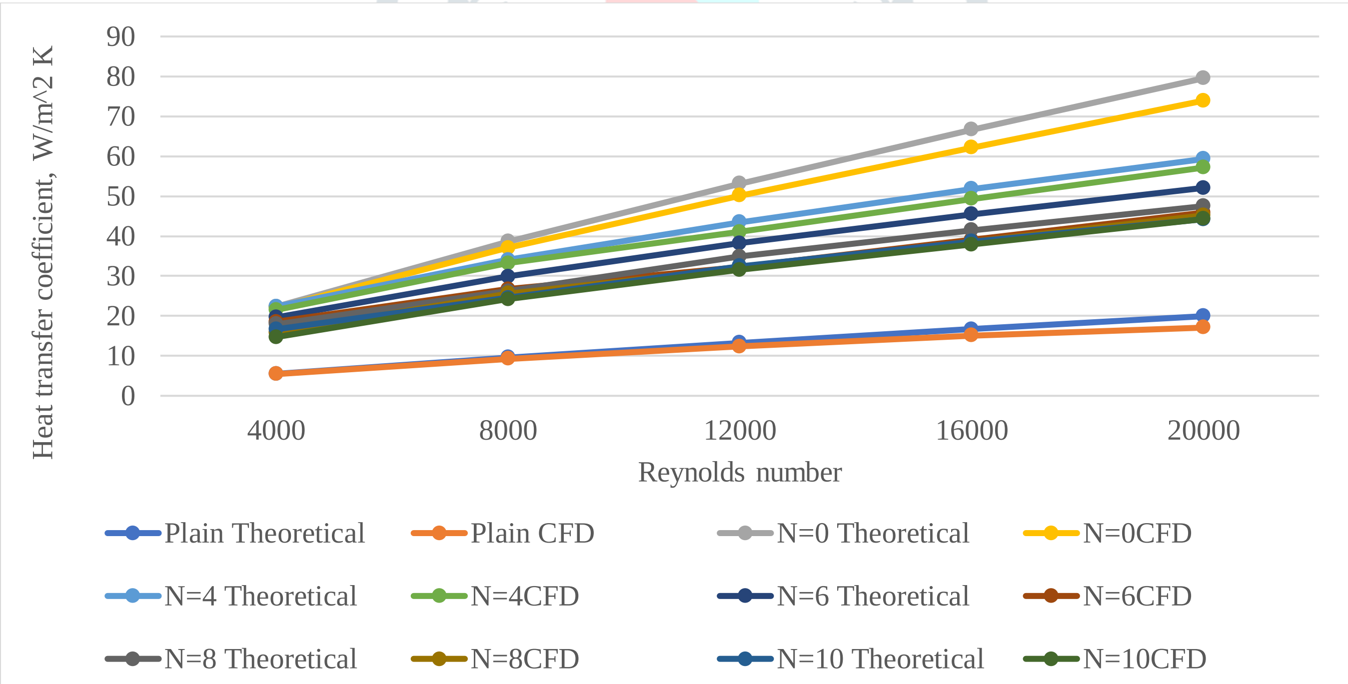

Fig.7: Variation of Heat transfer with Reynolds number

Nusselt number

The Nusselt number (Nu) is a dimensionless quantity used in fluid dynamics to describe the heat transfer that occurs between a solid surface and a fluid that flows over it. The graph reveals that the maximum Nusselt number is achieved at N=0 (theoretical), registering a high value of 220 at a Reynolds number of 20,699. Across all N values, an increase in Reynolds number correlates with an elevation in the Nusselt number.

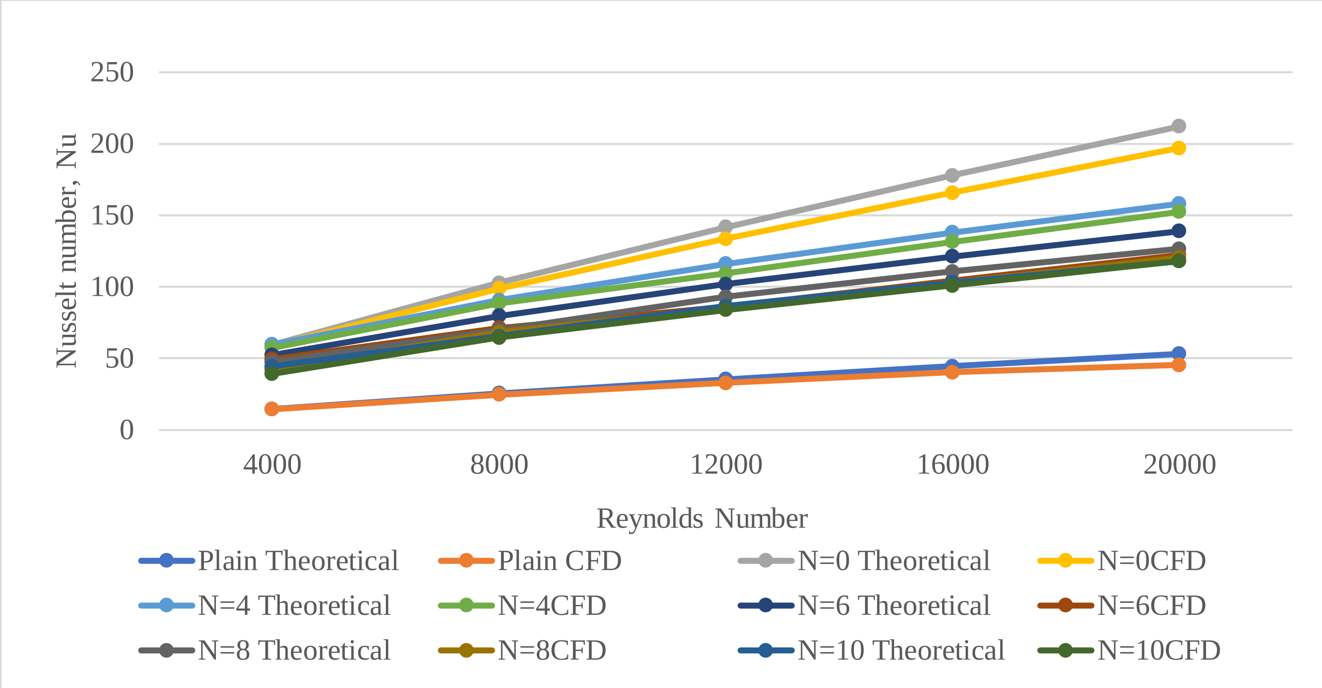

Fig.8: Variation of Nusselt number with Reynolds number

Pressure drop

Pressure drop is the difference in pressure between two points in a fluid-carrying network. From the graph shown above the pressure drop for all values of N will increases with respect to increase in Reynolds number. When comparing with all N values, the N=0 in CFD has maximum pressure drop which is 1300 Pa for maximum Reynolds number of 20699.

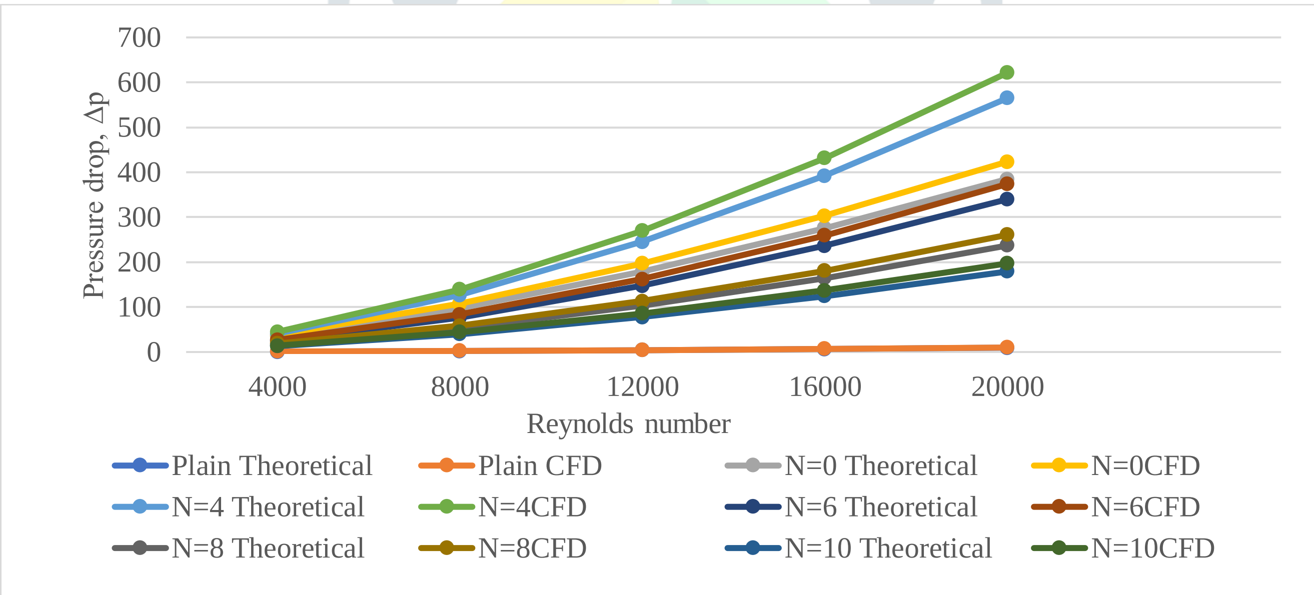

Fig.9: Variation with pressure drop with Reynolds number

Friction factor

The friction factor is a dimensionless quantity that characterizes the frictional resistance to flow in a pipe. It is seen that when there is an increase in Reynolds number, there will be decrease factor for all values of N. The maximum friction value is seen in N=0 which has friction value of 0.77 when compared to others.

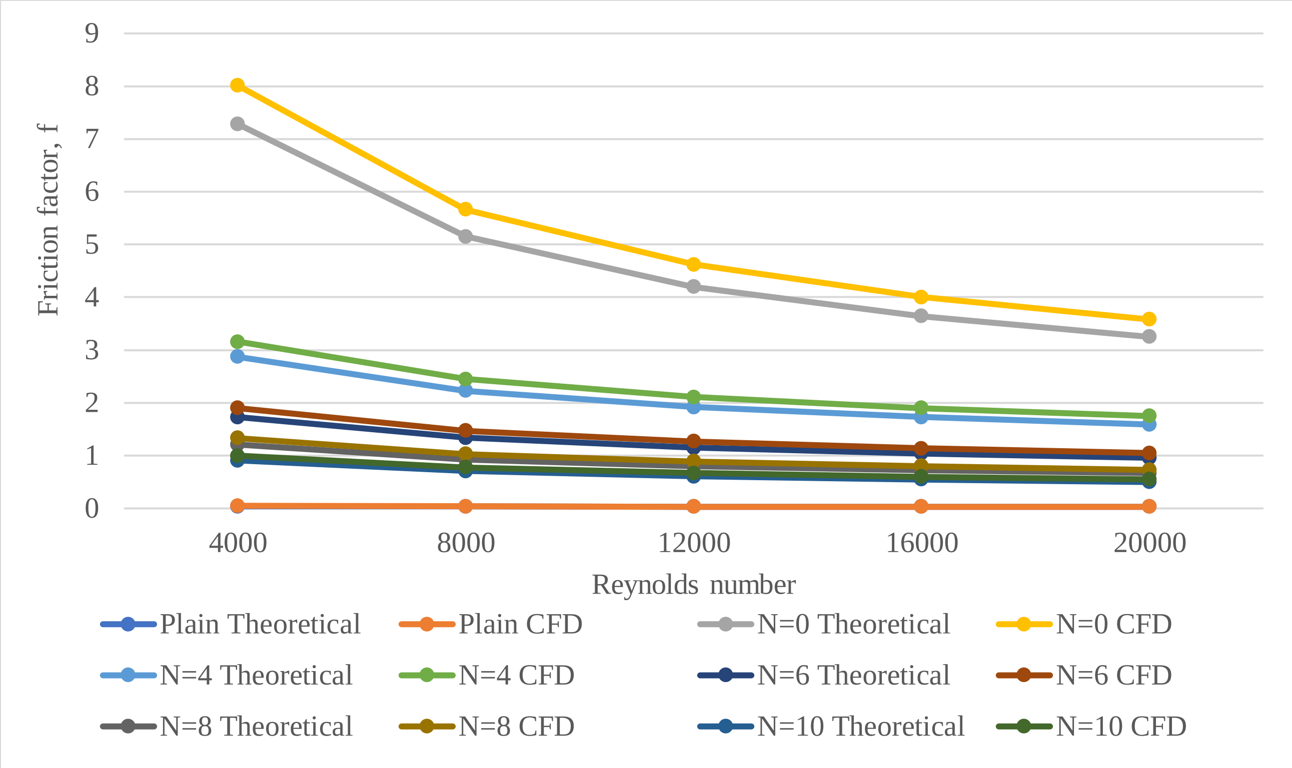

Fig.10: Variation of Friction factor with Reynolds number

Thermal Performance Factor

Comparisons between the thermal performance factor and Reynolds number values obtained from the present work. The enhancement efficiency tends to reduce at high Reynolds number for all cases. Thermal performance enhancement for N = 4 is found to be 41.29% more than that the tube fitted with typical conical rings, while at N=10, it is found to be approximately 16.76%. The maximum thermal performance factor of 0.7704 is obtained which is occurred for N = 10, at Reynolds number of 4140.

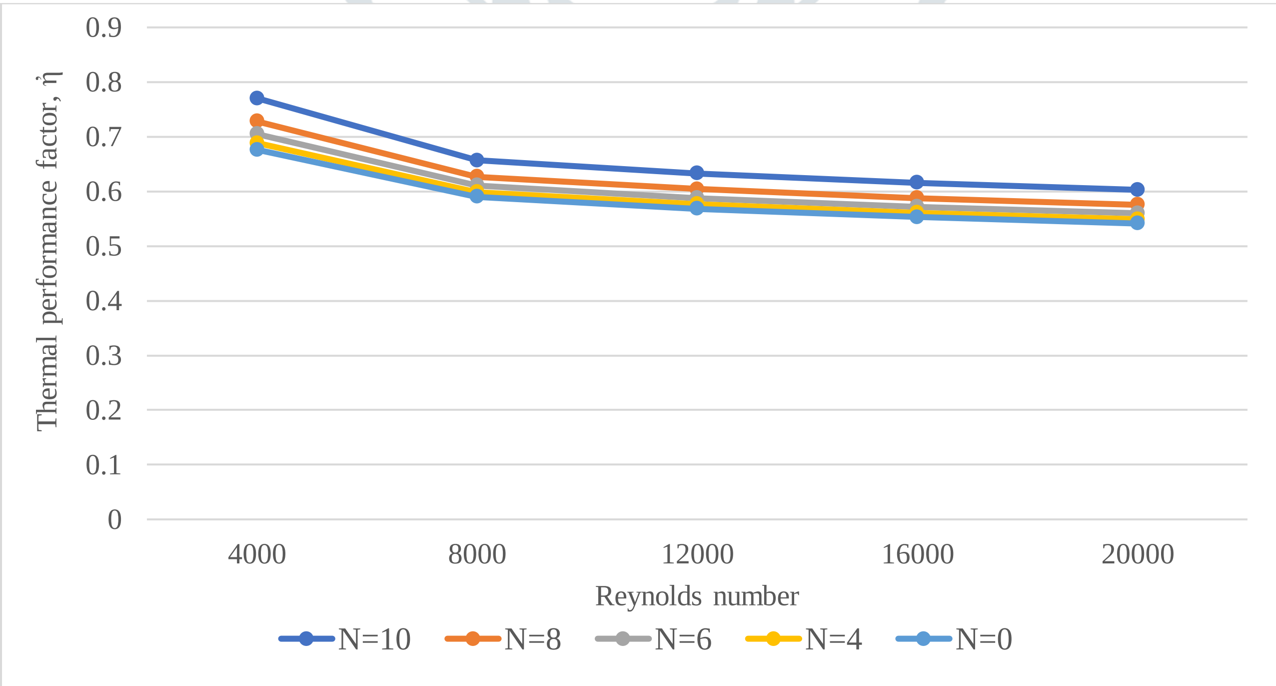

Fig.11: Variation of thermal performance factor with Reynolds number

8. CONCLUSIONS

1. The maximum heat transfer coefficient is seen in N=0 (theoretical) which is high heat transfer coefficient, which is 79.51 $W/m^2 K$ at Reynolds number 20699. It is decreased up
2. The Nusselt number of PCRs decreases up to 34.76% with increasing the number of holes from 4 to 10.
3. Friction factor shows decrement of 58.31%, 79.54%, 82.56%, and 89.79% in comparison with typical conical ring (N=0) for N = 4, 6, 8 and 10 respectively.
4. Thermal performance enhancement for N=4 is found to be 41.29% more than that the tube fitted with typical conical rings, while at N=10, it is found to be approximately 16.76%.

From this work, it is shown that the utilization of conical rings without holes plate has more advantage than regular tube heat exchanger to improve the heat transfer rate in less area.

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