IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

Numerical Analysis of Heat Transfer Augmentation Using Wire Coil Insert in Tube

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Abstract: The need to enhance the thermal performance of heat transfer equipment has driven the development and use of several heat transfer enhancement techniques. Wire-coil insert has been used as one of the passive heat transfer enhancement techniques and are the most widely used in heat transfer applications. The main objective of this work is to study the effect of wire-coil insert on the overall heat transfer rate and the pressure drop characteristics of the tube under constant wall temperature boundary condition. This work presents a numerical study on three wire coils of different pitch (P) (0.0225 m, 0.027 m and 0.03096 m and coil diameter 0.002 m) inserted in a smooth tube in laminar and turbulent regimes. A commercial CFD software tool has been used for this study. The friction factor and Nusselt number for water flowing through the specified pipe (internal diameter (D) = 0.018 m, specimen length = 0.080 m) were obtained first for the smooth pipe and then for the pipe with a wire coil insert in the Reynolds number range of 350 to 4900 and Prandtl number of 6.99. The Nusselt number and friction factor of various insert geometries are higher than that of plain tube. The Nusselt number increases with the rise of Reynolds number and the reduction of pitch of the insert. The friction factor decreases with the increase of Reynolds number. The increase in Nusselt number has been found to be of the order of 1.505 1.47 and 1.225 times with respect to the plain tube for wire coil pitch to diameter ratio of 1.25, 1.50 and 1.72 respectively.

Index Terms - Heat Transfer, Wire Coil Inserts, Nusselt Number

I. INTRODUCTION

Heat Exchangers are the essential parts in industrial applications including steam power plants, nuclear reactors refrigeration and air conditioning systems chemical and food industries or heat recovery systems. To increase the efficiency of these systems it is necessary to emphasis on the design aspects and various enhancement techniques which are easily implement in industries and reducing the maintenance as well as manufacturing cost of these systems. Since design procedure of heat exchanger is quite lengthy and iterative method so it is necessary to have an exact analysis of heat transfer rate, area required and pressure drop which leads to pumping power requirement to maintain the flow of the fluid inside the tube of the heat exchanger [1-2]. Heat augmentation techniques in heat exchanger provide a wide scope for various numerical and experimental investigations in heat transfer enhancement. These augmentation techniques can be categorized as active passive and compound techniques. Active augmentation techniques requires some external power input to maintain the desired flow modification for enhancement by using surface vibration, fluid vibration, electrostatic field, injection of some fluid into the main stream of flowing fluid through a porous heat transfer interface or by using jet impingement whereas passive augmentation techniques are generally implement through surface or geometry modification inside or outside of the tube as per requirement to increase the heat transfer rate by using inserts, incorporating threads inside the tube or using extended surfaces. Passive techniques do not require external power for flow modification. These techniques alter the flow of the fluid and create turbulence which leads to higher heat transfer rates whereas mixed techniques are the hybrid method in which both active and passive methods are used in combination. The Compound techniques are applied in design of complex shapes and hence it has limited applications.

In passive augmentation techniques wire coil insert and twisted tape insert are widely used due to low manufacturing cost, easy installation and removal and preservation of the mechanical strength of the smooth tube in comparison to others enhancement techniques. The effect of heat transfer enhancement inside the tube of heat exchanger is experimentally studied by Garcia et al. [3] in order to characterize their thermo-hydraulic performance in laminar, transition and turbulent region and concluded that wire coil insert do not cause much pressure drop but increases heat transfer rate as well as introduces a flow transition at low Reynolds number around 700 to 1000 and Prandtl number does not have much impact on heat transfer augmentation and he also suggested that wire coil insert offer their best performance within the transition region. Promvonge et al. [4] experimentally studied the wire coil insert with square cross section and with twisted tape wire coil insert and stated that as increase in Reynolds number heat transfer rate decreases rapidly. If wire coil insert is compared with the plain tube while pumping power remain constant an increase in heat transfer rate is observed at low Reynolds number. At Reynolds number 5500 heat transfer enhancement efficiency is of the order of 1.2 to 1.3 but at higher Reynolds number like 25000 it is the order of 1.1 to 1.15. Promvonge et al. [5] experimentally studied the combination of the twisted tape with constant or periodically varying pitch ratio of the wire coil and they found the result that at low Reynolds number combined device provide highest thermal performance which was of the order of 6.3% higher than the wire coil insert alone. Akhavan-Behabadi

[6] experimentally investigated seven coiled wire having pitch ranges from 12mm to 69mm and wire diameter ranges from 2.0mm to 3.5mm. The result of above investigation suggested that fanning friction factor increases as decrease in the pitch of the wire coil and same effect on the fanning friction factor as increase in the thickness of the wire coil insert. Gunes et al. [7] experimentally investigated the equilateral triangular cross section inserted in a tube for turbulent regime. They found that the Nusselt number increases with increase in Reynolds number and wire thickness and decrease in pitch ratios because this introduces turbulence in flow. H.R. Rahai [8] have studied the effect of wire coil and wire matrix turbulators on enhancement in heat transfer augmentation, pumping power requirement and the mineral salt fouling reduction in heat exchanger. Sreenivasulu and Prasad [9] have numerically studied the convective heat transfer and pressure drop in an annulus tube having wire coil insert inside the inner cylinder. They predicted the flow and heat transfer characteristics by k-ω SST turbulence model.

The objective of the present work is numerical study of the circular wire coil insert inside the tube on heat transfer augmentation and pressure drop by varying the pitch of the wire coil insert over the flow ranges from Reynolds number 350 to 10000.The main objective of the present work is to validate CFD model for plain tube and with wire coil insert as well as study the effect of p/d and e/d on heat transfer and pressure drop. For numerical analysis we consider the constant wall temperature condition, velocity inlet and outflow outlet as the boundary conditions.

II. Materials and Methods

a) *PROBLEM FORMULATION*

A smooth Stainless Steel pipe considered for the study whose length is 0.08 meter and its internal diameter is 0.018 meter. The water flows through the pipe and its inlet temperature of water 27˚C and temperature of wall is assumed constant at 100˚C. The overall heat transfers co-efficient, Nusselt number and friction factor values were calculated from empirical equations taking different Reynold’s number values in the laminar and turbulent regions. The analytical results from the empirical relations of the above parameters that have to be validated against numerical or CFD simulation results. Properties of water and wire coil material are taken as for the study which is shown in table 1:

Table 1. Properties of water and wire coil material and dimensions

Density (ρ)	= 998.2kg/m^3
Thermal conductivity (K)	K = 0.6W/m-K
Viscosity (μ)	0.001003 kg/m- s
Specific heat (C_p)	= 4.182 kJ/kg-K
Wire coil insert material	Copper
Wire coil diameter (e)	2 mm

b) *CFD MODELING*

CFD provides the numerical approximation to the partial differential equation which governs the fluid motion. These partial differential equations are discretized to produce numerical analogues of the equations using various techniques of numerical rationalization such as the finite element method, the finite difference method or the finite quantity method. All CFD codes which are used to generate the solutions contains three main elements

- Pre-Processor- In pre-processing we enter our flow problem in CFD software which includes defining the geometry, generation of mesh, selection of phenomena for analysis, definition of fluid properties and boundary conditions.
- Solver- Solver is used to solve the above define parameters which involves approximation and discretization of the governing flow equations.
- Post-Processor-Post-processing of the simulation results is performed in order to obtain the results from the computed flow field.

c) *GOVERNING EQUATIONS*

Equation of continuity:

$$\frac{\partial \rho}{\partial t} + div(\rho u) = 0 \tag{1}$$

where, the fluid density is ρ, time is t, and velocity is u. Above equation is unsteady state 3-D equation of continuity.
Momentum equation:

$$\frac{\partial}{\partial t}(\rho u_i) + div(\rho u_i u) = -\frac{\partial P}{\partial x_i} + div(\mu\, grad\, u_i) \tag{2}$$

where pressure is P, fluid viscosity is μ, x is the coordinate and the subscript i indicates the Cartesian coordinates.
Energy equation:

$$\frac{\partial}{\partial t}(\rho u_i) + div(\rho u_i u) = -P\, div\, u + div(K\, grad\, T) + \phi + S_i \tag{3}$$

where k is the thermal conductivity, T is the temperature, ∅ is the dissipation term and S_i is the source term.

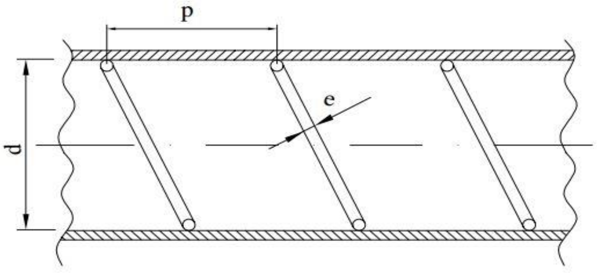

Figure 1: Wire coil insert fitted inside the smooth tube [3]

Table 2: Geometry discretion of different wire coil inserts

S. NO.	WIRE COIL	PITCH OF WIRE COIL INSERT (P) mm	DIAMETER OF TUBE (d) mm	WIRE COIL INSERT DIAMETER (e) mm	P/d
1	WC01	22.50	18	2	1.25
2	WC02	27.00	18	2	1.50
3	WC03	30.96	18	2	1.72

Figure 2: Tube with no wire coil insert

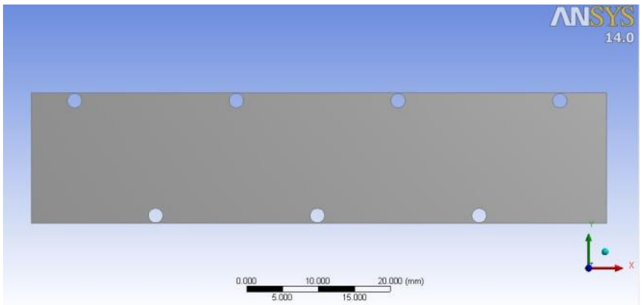

Figure 3: Tube with wire coil insert p/d =1.25

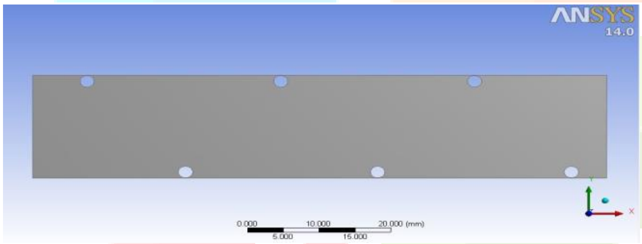

Figure 4: Tube with wire coil insert p/d =1.50

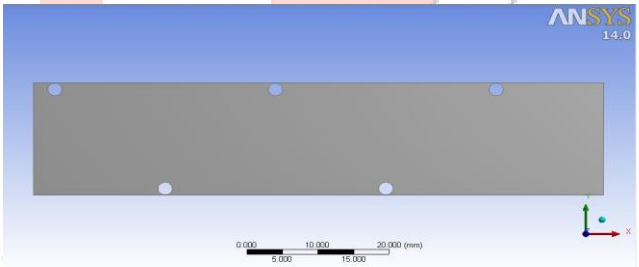

Figure 5: Tube with wire coil insert p/d =1.72

d) *GEOMETRY DISCRIPTION*

Two dimensional numerical simulations are conducted for plain tube having tube diameter 18 mm and its length 80 mm (refer figure 1). The geometry of tube with wire coil insert is tabulated in table 2. Input boundary conditions are velocity inlet outflow outlet and constant wall temperature.

e) *GEOMETRY MODELING*

Geometry of the tube with wire coil insert or without wire coil insert (refer figure 2 to 5) is modeled using ANSYS FLUENT software. Meshing of the tube is done by Face sizing with three-layer refinement at the wall of the tube and over the wire coil insert (refer figure 6 to 8).

f) *SOLUTION SCHEMES-*

For laminar flow, the viscous (laminar) model was used whereas the k-Є turbulence model was used for turbulent flow. The SIMPLE scheme with FIRST ORDER UPWIND method, MOMENTUM AND ENERGY scheme with SECOND ORDER UPWIND used as the solution method. Operating initial conditions are 2-dimension, energy on and steady state condition.

g) *Grid/mesh independent study*

In the grid independence study, find out the optimum grid size and number of elements in the computational domain a grid independent test (GIT) is carried out with three mesh structure having different nodes and elements with varying the face size mesh value from 0.25, 0.50 and 1.

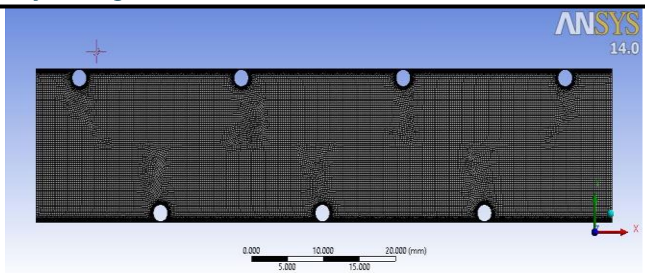

Figure 6: Tube with wire coil insert p/d =1.25 face sizing mesh = 0.25 mm

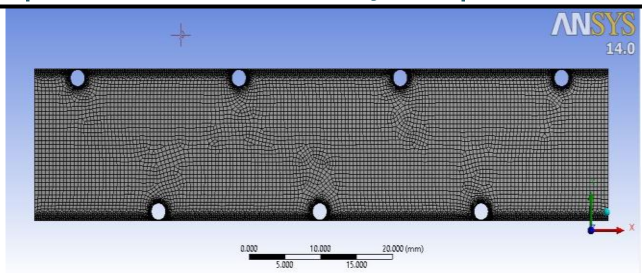

Figure 7: Tube with wire coil insert p/d =1.25 face sizing mesh = 0.50 mm

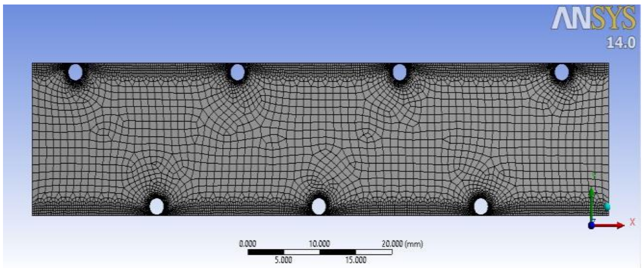

Figure 8: Tube with wire coil insert p/d =1.25 face sizing mesh = 1.00 mm

*h) **Result from grid independent study***

Hence from the figures 9 and 10 it can be seen that; the face sizing mesh size = 0.50 mm have same results as with face sizing mesh size =0.25 mm. It means after face sizing mesh size = 0.50 mm our geometry is independent from mesh nodes and elements. So, it is preferable to choose face sizing mesh size = 0.50 mm for further investigation of wire coil insert's analysis because it takes less time and a smaller number of iterations for converging towards the converging criteria of residuals. Figure 11 and 12 shows the velocity and temperature contour for Reynolds number 250 mesh size = 0.50 mm for p/d = 1.25.

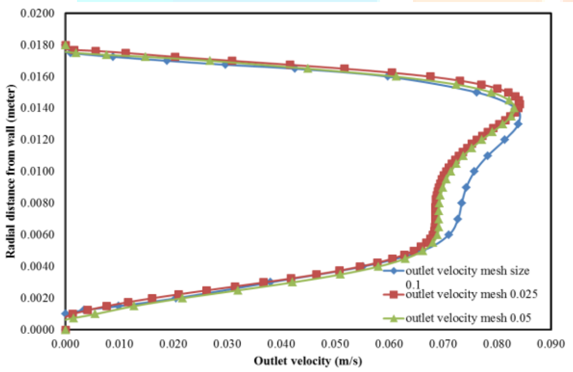

Figure 9: Outlet velocity profile for different mesh size

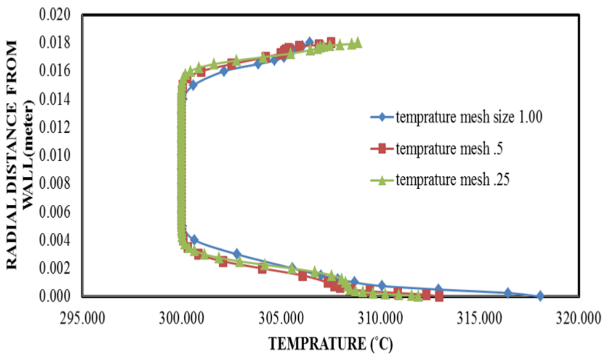

Figure 10: Outlet temperature profile for different mesh size

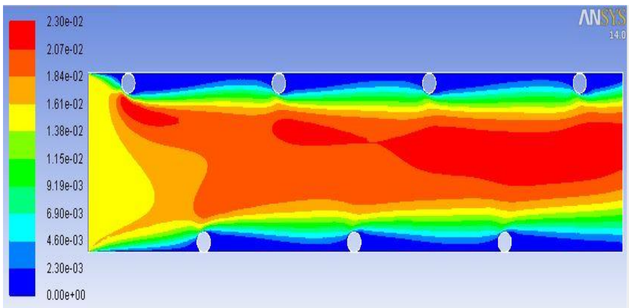

Figure 11: Velocity contour for Reynolds number 250 mesh size = 0.50 mm

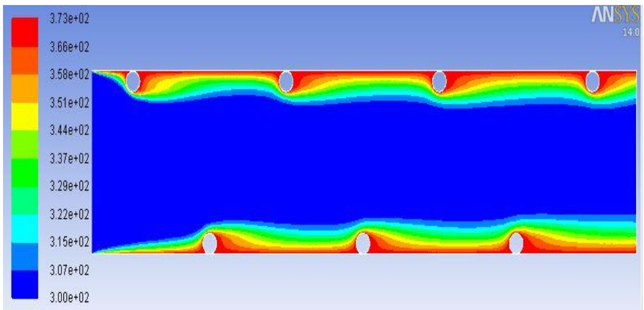

Figure 12: Temperature contour for Reynolds number 250 mesh size = 0.50 mm

*i) **Formula used for calculations***

Reynolds number (Re) $$R_e = \frac{\rho V d}{\mu} \quad (4)$$

Friction factor (f)

Laminar Flow $$f = \frac{16}{R_e} \quad (5)$$

Turbulent Flow $$f = \frac{0.079}{R_e^{0.25}} \quad (6)$$

For CFD calculation $$f = \frac{\pi^2 \times \Delta p \times d^5 \times \rho}{32 l m^2} \quad (7)$$

Mass flow rate $$m = A \times V \quad (8)$$

Area $$A = \pi \times d \times L \quad (9)$$

Temperature difference $$\Delta t = T_{outlet} - T_{inlet} \quad (10)$$

Heat transfer coefficient $$h = \frac{m \times C_p \times \Delta t}{A \times \ln(\Delta t)} \quad (11)$$

Nusselt Number $$N_u = \frac{h \times d}{K} \quad (12)$$

Where, Δp is the pressure difference between inlet and outlet, K is the thermal conductivity of water (0.6 W/m-K), μ is viscosity of water (0.001003 kg/m-s), C_p is the specific heat of water (4.182 kJ/kg-K), ρ is the density of water (998.2 kg/m^3), Δt is the temperature difference.

I. Results and Discussion

a) **Effect of wire coil insert on flow velocity**

From the figure 13 it can observe that with insert the wire coil in tube obviously reduces the cross-sectional area of tube which causes the average flow velocity is increases. The average flow velocity increment is order of 1.45 at Reynolds number 1350 in the inserted tube with respect to velocity in the smooth tube without wire coils. Therefore, it can be said that the wire coil geometry produces a significant flux variation even in the laminar regime.

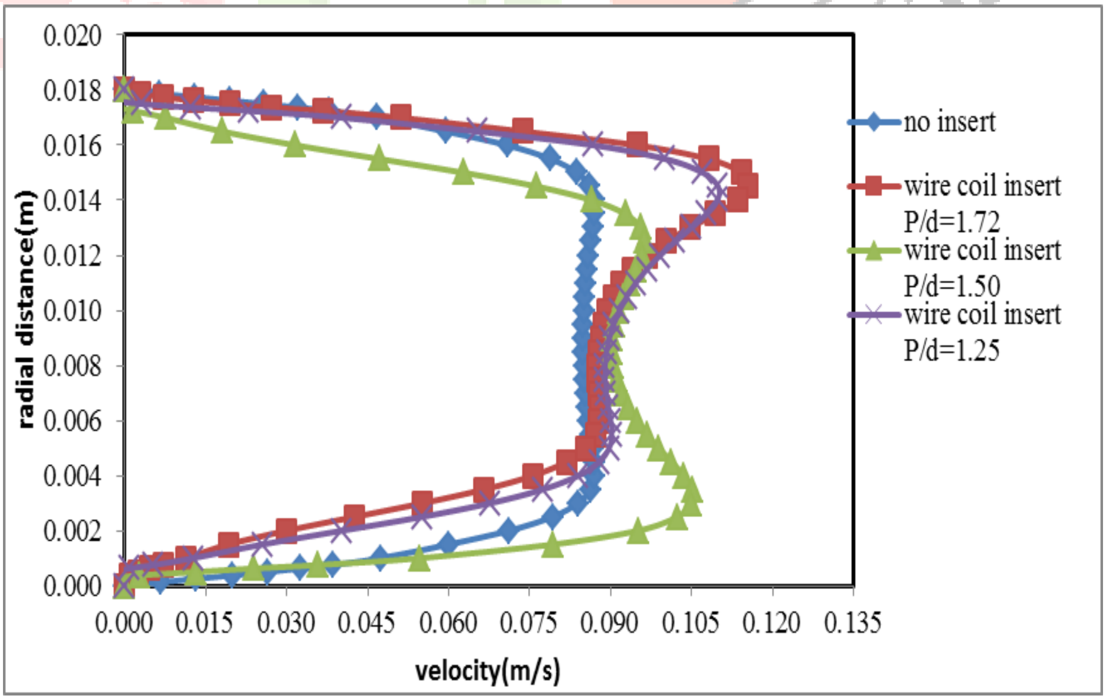

Figure 13: Comparison of velocity profile at outlet of the tube for different geometries

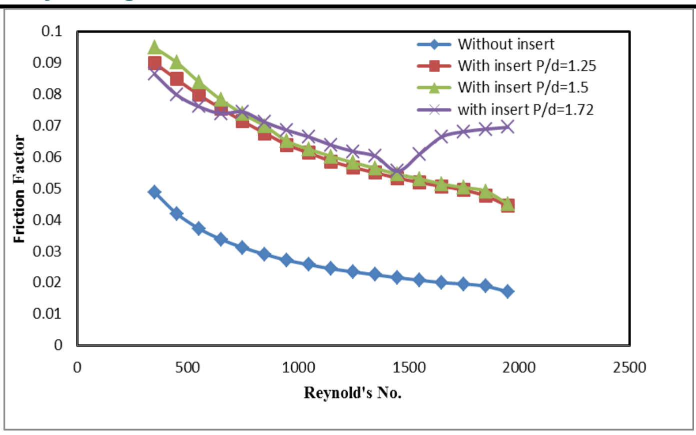

Figure 14: Reynolds number vs. Friction factor for laminar flow

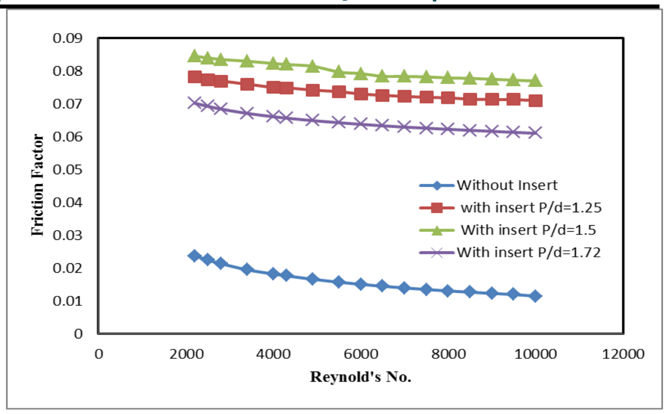

Figure 15: Reynolds number vs. Friction factor for turbulent flow

b) Effect of wire coil insert over friction factor

The friction factor decreases with increasing Reynolds number for different pitches. It can be seen from Figures 14 and 15 that the friction factor for a tube equipped with a coil wire insert is much higher than for a plain tube for a given Reynolds number It indicates that friction factor for a given Reynolds number increases with decreasing pitch due to swirl flow generated by coil wire inserts. The wire coil is an inserted element which reduces the tube cross section and increases the average flow velocity. The increase in friction factor for copper wire coil insert for WC01 ranges 1.84 to 6.2, for WC02 is 1.94 to 6.7 and for WC03 is 1.77 to 5.33 times with respect to plane tube. It can be concluded from the trend followed by the graphs that friction factor changes drastically for lower values of Reynolds number but as Reynolds number approaches towards its upper limits a gradual stability in friction factor can be observed.

c) Effect of wire coil insert over Nusselt Number

From figure 16 for a given pitch, as Reynolds number increases the Nusselt number also increases, indicating enhanced heat transfer coefficient. It is also observed that Nusselt number for a given Reynolds number increases with decreasing pitch of the coil. As the pitch of the coil decreases, the intensity of swirl flow increases leading to higher heat transfer rate and it is order of 1.505, 1.47 and 1.225 for WC01, WC02 and WC03 respectively with respect to tube having no insert. It has also been observed that the wire coil insert introduce turbulence inside the tube at Reynolds number ranges from 1000 to 1350.

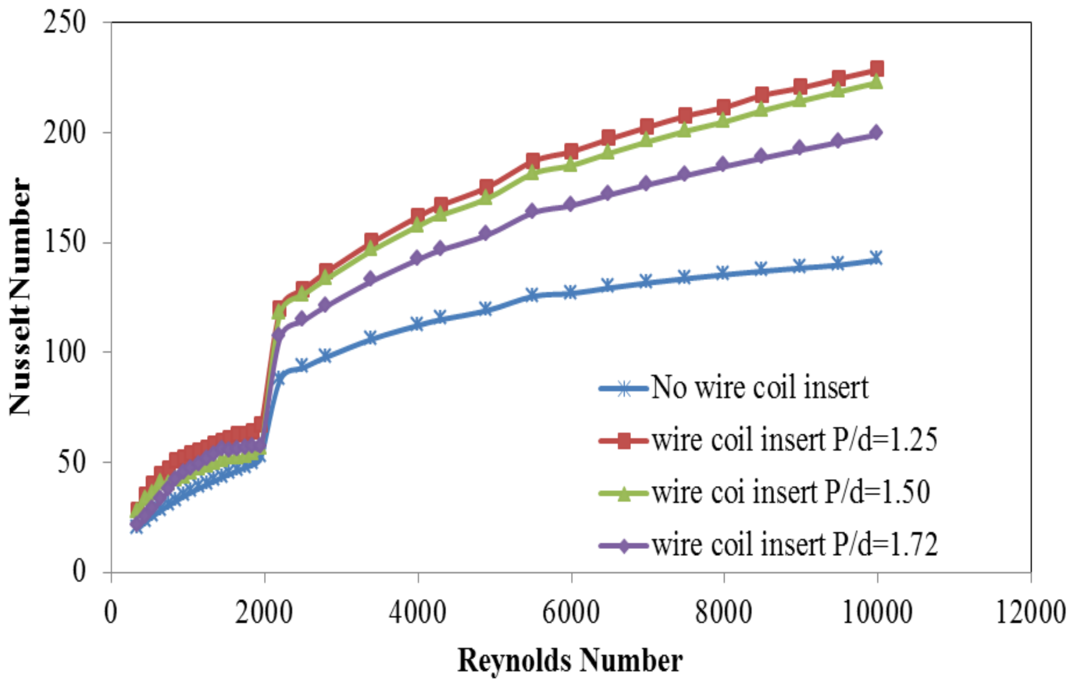

Figure 16: Reynolds number vs Nusselt number

II. CONCLUSIONS

A numerical study on three wires of different pitch inserted in a smooth tube, has been carried out in ANSYS FLUENT software and calculations for friction factor and Nusselt number at the specified conditions using the empirical equations available in literature. The following results are obtained from the above numerical investigation

1- The wire coil insert causes a high pressure drop which depends mainly on pitch of wire coil and wire thickness, but provides considerable enhancement in heat transfer.
2- The increase in friction factor for copper wire coil insert for WC01 ranges 1.84 to 6.2 for WC02 is 1.94 to 6.7 and for WC03 is 1.77 to 5.33 times with respect to plane smooth tube.
3- The enhancement efficiency or Nusselt number increases with the decreasing pitches and is the order of 1.505, 1.47 and 1.225 for WC01, WC02 and WC03 respectively.
4- The wire coil is an inserted element which reduces the tube cross section and increases the average flow velocity and flow velocity increment is the order of 1.45 at Reynolds number 1350 for coiled tube in comparison to smooth tube having no coil insert.
5- Increase in flow velocity inside the tube introduces turbulence inside the tube with respect to tube having no wire coil insert at Reynolds number ranges from 1000 to 1350.

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