Analysis of Heat Transfer Enhancement in Tube-in-tube Helical Coil Heat Exchangers

Ruchal G. Humbare, Suraj R. Gurav, S. B. Trimbake

Abstract— The heat exchangers most widely used are shell and tube heat exchangers which are larger in size and offer lesser heat transfer rate. Also, in shell and tube heat exchanger dead zone is produced which further reduces heat transfer rate and in order to improve heat transfer rate some active techniques are required. Helical heat exchanger is more compact, offer better heat transfer rates and heat transfer rate can be further improved by passive techniques. Its shape offers advantages such as more fluid contact, elimination of dead zones, and secondary turbulence. An experimental test rig was developed for evaluation of tube-in-tube helical coil heat exchanger. This paper deals with parametric analysis and its effect on performance of tube-in-tube helical coil heat exchanger.

Index Terms— Tube-in-tube helical coil, Dean Number, Dimensionless pitch, Curvature ratio, Effectiveness, Secondary turbulence, Heat transfer coefficient, Nusselt number.

I. INTRODUCTION

Helical coil heat exchangers consist of long, small diameter tubes wound or bent in helix. Helical Coil heat exchanger is an excellent heat exchanger because of far compact and high heat transfer efficiency. Helical Coil Heat exchanger is different from Coiled or Spiral heat exchangers. Experimental investigations have shown that the flow patterns in curved tubes are significantly different than in straight tubes. Dean was the first person to study flow patterns in curved tubes using Toroidal Co-ordinate System. The secondary flow which divides itself along the diameter of tube to constitute two sets of distinct re-circulating vortices was established [4]. Several studies have indicated that helically coiled tubes are superior to straight tubes when employed in heat transfer applications. The centrifugal force due to the curvature of the tube results in the secondary flow development which enhances the heat transfer rate.

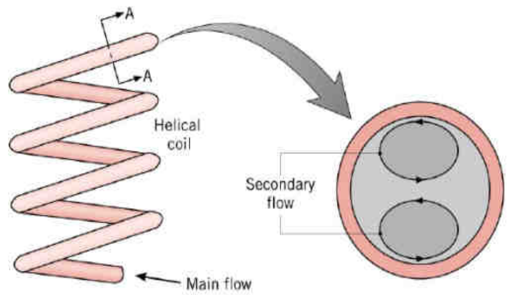

Fig.1. Secondary flow developed due to curvature

Various researches are being carried out to study different parameters of helical coil heat exchangers. Purandare et al. [12] carried out parametric analysis of Helical Coil Heat Exchanger. The range of *Re* considered for the analysis is about 100 to 6000 and the analysis is carried out for laminar and turbulent region separately for tube side heat transfer coefficient (*hi*) and *Nu*. Four different correlations of *Nu* are selected from the literature for the analysis modified by M.R. Salimpour, Kalb et al, Roger et al and Xin et al. The analysis also shows that, as tube diameter with constant coil diameter (*D*), the curvature ratio (δ) increases, which increases the intensity of secondary's developed in fluid flow. The increase in the intensity of secondary's developed in fluid flow increases, *Nu* increases. Kshirsagar et al. [10] studied with the pitch variation of the internal wounded wire and its result on the heat transfer rate. It was observed that when wire coils are compared with a smooth tube, the overall heat transfer coefficient increases with minimum pitch distance of wire coils. Ankanna et al. [1] focused on an increase in the effectiveness of a heat exchanger and analysis of various parameters affecting it. Shirgire et al. [11] considered the fluid to fluid heat exchange. Wilson plot method was used to calculate inner heat transfer coefficient. The result proved that heat transfer coefficient is affected by the geometry of the heat exchangers. Patil et al. [15] described the procedure of designing helical coil heat exchanger and discussed some of its advantages. Jayakumar [6] continued to study a number of numerical experiments to find the influence of coil parameters, viz., pitch circle diameter, coil pitch and pipe diameter on heat transfer. Lines [7] enlisted various advantages of helical coil heat exchangers and summarized them through applications such as sample cooling, condensers, seal coolers, etc. Rennie [21] studied the heat transfer characteristics of a double pipe helical heat exchanger for both counter and parallel flow. For dean numbers ranging from 38 to 350 (fig 4.7, page 82) the overall heat transfer coefficients were determined. The results showed that the overall heat transfer coefficients varied directly with the inner dean number but the fluid flow conditions in the outer pipe had a major contribution on the overall heat transfer coefficient. The study showed that during the design of a double pipe helical heat exchanger the design of the outer pipe should get the highest priority in order to get a higher overall heat transfer coefficient.

II. MATERIALS

Selection of materials involves the thorough understanding of their availability, source, lead time, product forums, and size. It is necessary for the selected material to be moderately ductile for bending process and smooth formation of helical coil. Material must possess low relative roughness in order to have low friction factor resulting in minimum Depending upon the relative roughness values from Moody's chart, materials like copper, mild steel, stainless steel and others can

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be used.

III. PROTOTYPE DEVELOPMENT

The proposed model of Tube-in-tube Helical Coil Heat Exchanger is as further. Two concentric tubes are used, bent in helical shape where, one fluid can pass through inner tube and other fluid through the annular space between two tubes. This arrangement provides compact heat exchanger which is compared with the same length, tube-in-tube straight heat exchanger. Proposed model was manufactured without any bent in it throughout its structure and to keep proper alignment and spacing in between two tubes. Two properly designed copper tubes with dimensions 6 mm and 12 mm as inner and outer tubes respectively were selected. Firstly, rectangular small plate with 6mm hole is drilled in it. Another hole of 12mm diameter is marked concentric to 6mm diameter hole. Smaller tube is then passed through 6mm diameter hole up to length of 2 inch and rectangular plate is brazed around its periphery. Two holes are drilled on two ends of bigger tube on its periphery for the flow of fluid through it. This tube is placed on concentrically marked 12mm diameter hole on rectangular plate and rectangular plate is brazed to outer tube at that point. Molding sand which is capable of withstanding high temperature is used to maintain spacing between two pipes. This sand is filled in inner tube then in the space between inner and outer tube. Sand is filled so tightly that there should not be any space left in between tubes. Other end of both tubes is brazed with similar kind of rectangular plate. Rectangular plates are provided to support the tubes. Then, these two tubes are heated to sufficient temperature to make bending easier. These heated tubes are bent along outer surface area of cylinder having same diameter as desired coil diameter of test rig. Constant pitch is maintained while bending. After temperature of tubes goes down, sand is removed from holes on outer tubes to clear the path for fluid.

IV. EXPERIMENTATION

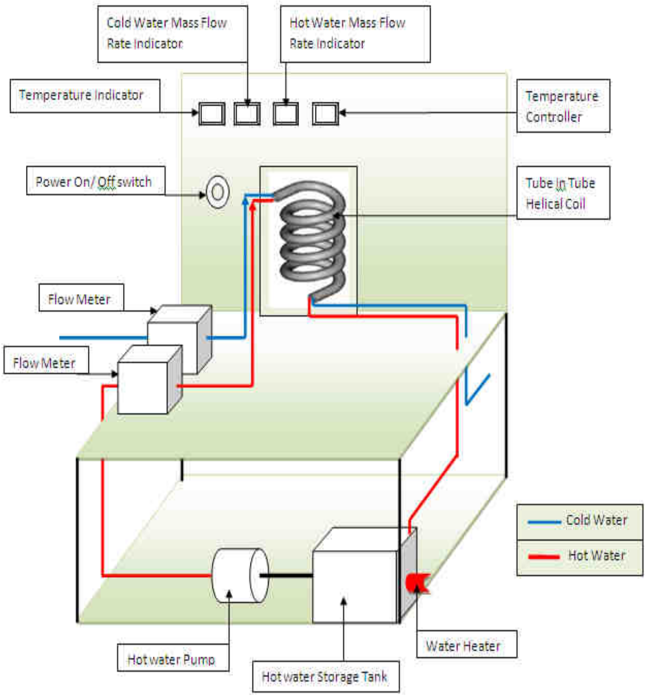

Fig.2. Schematic diagram of tube-in-tube helical coil heat exchanger experimental set-up

The experiment is performed to analyze the performance of our Tube-in-tube Helical Coil Heat Exchanger and compare it with Straight Tube-in-tube Heat Exchanger having same dimensions of tubes and same flow arrangement. Water is used as working fluid. Experimental set up easily provides an arrangement to change and control temperature of water, flow of water, flow arrangement. Flow arrangement from parallel flow to counter flow and vice versa can be changed easily. Two flow meters and flow indicators are fitted in setup to measure the flow of water. One temperature indicator is also fitted on setup to indicate the temperature of hot and cold water at inlet and outlet. Also, there is one temperature controller to limit the temperature of water in storage tank up to preset temperature in controller.

The experimentation was broadly classified as parallel flow and counter flow configuration. Moreover, it was sub-divided as hot water inside or cold water inside. Thus, four sets of flow configurations. For each flow configuration flow rate and inlet temperature was varied. The flow rate was varied between 100 LPH to 250 LPH.

Fig. 3: Actual tube-in-tube helical coil used

Specifications of helical coil

I. Specifications of helical coil

Parameters	Dimensions
Inner tube diameter, d_i	6 mm
Outer tube diameter, d_o	12 mm
Coil diameter, D	165.2 mm
Length of coil, L	3260 mm
Pitch, b	25 mm

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Fig. 4: Actual experimental set up

V. DATA REDUCTION

We assumed temperatures of hot and cold fluid at inlet and outlet as T_{hi}, T_{ho}, T_{ci} and T_{co}. Also, we assumed hot fluid mass flow rate as $\dot{m}_h$.

From [9], various constants like Specific Heat (C_p), Dynamic Viscosity (μ), Thermal Conductivity (k), Prandtl Number (Pr) are obtained.

1. Finding mass flow rate of cold water, $\dot{m}_c$

   Heat lost by hot fluid = Heat gained by cold fluid

$$Q = \dot{m} C p \Delta T \tag{1}$$

2. Dimensionless pitch, γ

$$\gamma = \frac{b}{\pi D} \tag{2}$$

3. Curvature Ratio, δ

$$\delta = \frac{r}{R} \tag{3}$$

4. Reynolds number, Re

$$Re = \frac{\rho V d}{\mu} \tag{4}$$

   Where, $V = \frac{\dot{m}}{\rho A}$ m/s (5)

5. Dean number, De [5]

$$De = Re\left(\frac{d}{D}\right)^{0.5} \tag{6}$$

6. Nusselt number, Nu[12]

   Nu is calculated by various correlations at specified conditions:

   a) M. R. Salimpour,

$$Nu = 0.152 De^{0.431} Pr^{1.06} \gamma^{-0.277}$$

$$\text{for } De < 3000 \tag{7}$$

   b) Kalb et al.,

$$Nu = 0.836 De^{0.5} Pr^{0.1}$$

$$\text{for } De \geq 80 \text{ and } 0.7 < Pr < 5 \tag{8}$$

   c) Xin et al.,

$$Nu = (2.153 + 0.318 De^{0.643}) Pr^{0.177}$$

$$\text{for } 20 < De < 2000;\ 0.7 < Pr < 175 \text{ and } \frac{d}{D} < 0.0884 \tag{9}$$

   d) Roger et al.,

$$Nu = 0.023 Re^{0.85} Pr^{0.4} \delta^{0.1}$$

$$\text{for } Re > 2000 \tag{10}$$

7. Heat transfer coefficient, h

$$h = \frac{Nu * k}{d}, \text{ W/m}^2\text{K} \tag{11}$$

8. Pressure drop, Δp

$$\Delta p = \frac{2 f_c L \rho V^2}{d} \tag{12}$$

   Correlation proposed by White [2],

$$f_c = f_s\left(1 + 0.033 (\log_{10} De)^{4.0}\right)$$

$$\text{for } De > 1 \tag{13}$$

9. Effectiveness, ε

   a. $C = \frac{C_{min}}{C_{max}}$ (14)

   b. $\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$ (15)

   c. $(UA) = \frac{C_{min} \Delta T_{max}}{\Delta T_{lm}}$ (16)

   d. $N = NTU = \frac{UA}{C_{min}}$ (17)

   e. For parallel flow,[21]

$$\varepsilon = \frac{1 - e^{-NTU(1+C)}}{1 + C} \tag{18}$$

   f. For counter flow,[21]

$$\varepsilon = \frac{1 - e^{-NTU(1-C)}}{1 - C e^{-NTU(1-C)}} \tag{19}$$

10. Overall heat transfer coefficient, U_o

$$R_{th} = \frac{1}{h_1 A_1} + F_1 + \frac{\ln\left(r_2/r_1\right)}{2\pi K_2 L} + \frac{1}{h_2 A_2} + F_2 + \frac{\ln\left(r_4/r_3\right)}{2\pi K_2 L} \tag{20}$$

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$$U_o = \frac{1}{R_{th}} \qquad (21)$$

VI. RESULTS AND DISCUSSION

Parametric analysis performed on tube-in-tube helical coil heat exchanger in comparison with straight tube-in-tube heat exchanger for same dimensions. Four different correlations of Nu are selected for tube-in-tube helical coil heat exchanger from the literature for the analysis, as these correlations fulfill the conditional requirements of the data selected for the analysis [12]. The range of mass flow rate considered for analysis pertains to turbulence range.

6.1. Effect on Nusselt number:

Following fig. 5(a) and 5(b) indicates graph between Nusselt numbers (Nu) versus Reynolds number (Re) for counter flow with cold water in inner tube.

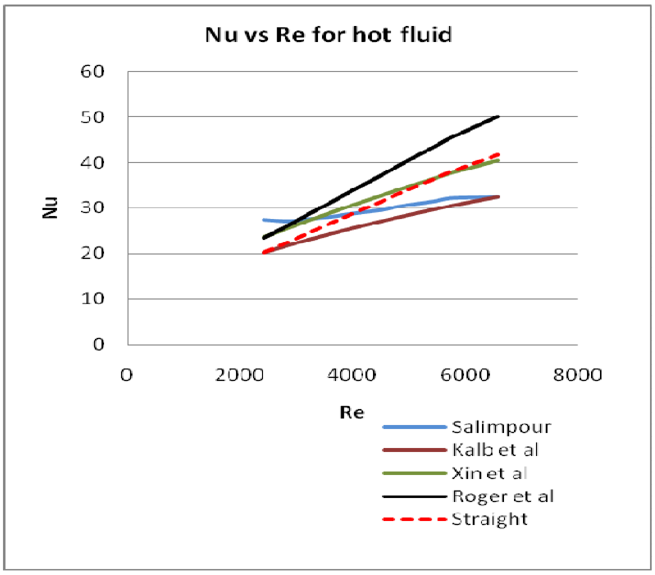

Fig. 5(a): Nusselt number vs. Reynolds number for hot fluid

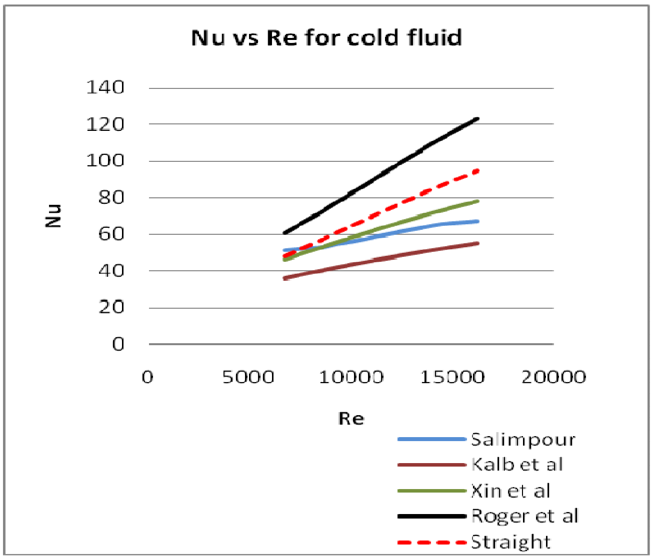

Fig. 5(b): Nusselt number vs. Reynolds number for cold fluid

The increase in secondary turbulence allows proper mixing of fluid flow, which enhances the Nu and h. The above graphs not only represent comparison of Nusselt numbers used in the analysis but also compare straight tube-in-tube heat exchanger. It shows that Nusselt number given by Roger et al is highest. Moreover, Nusselt number by Xin et al, Salimpour and Kalb et al are in their descending order. Thus, the highest Nusselt number given by Roger et al is used for further analysis. The heat transfer for same mass flow rate is higher for tube-in-tube helical coil heat exchanger. The present analysis also confirms a similar trend for other flow configurations.

6.2. Effect of Dean Number:

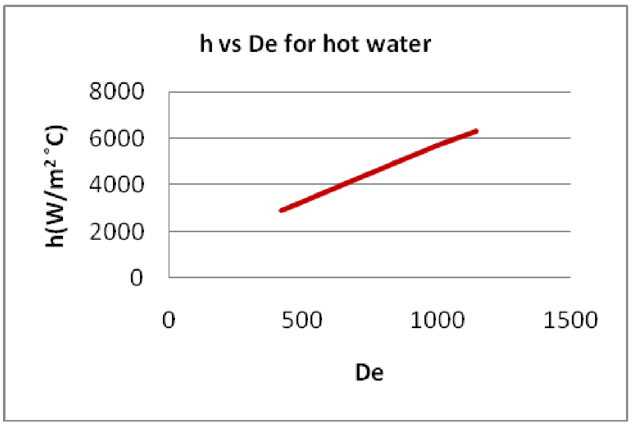

Fig. 6(a): heat transfer coefficient vs. Dean Number for hot fluid

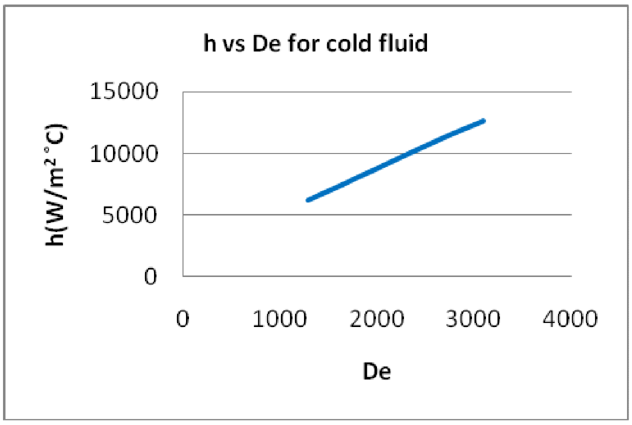

Fig. 6(b): heat transfer coefficient vs. Dean Number for cold fluid

Dean Number is the most significant term in tube-in-tube helical coil heat exchangers. It is observed that as Dean Number increases centrifugal force acting on fluid increases. Due to this, there is a rise in secondary turbulence which leads in enhanced heat transfer.

6.3. Experimental matrix:

II. A comparisons of Nusselt Numbers for all the four configurations

Operating condition: Mass flow rate : 210 LPH				
	Parallel Flow Configuration			
	Inner tube – hot fluid	Annular space – cold fluid	Inner tube – cold fluid	Annular space – hot fluid
Tube-in-tube Helical Heat Exchanger	129.842	42.9265	131.36	43.28

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Tube-in-tube Straight Heat Exchanger	100.33	35.52	101.57	35.84

Operating condition: Mass flow rate : 210 LPH				
	Counter Flow Configuration			
	Inner tube – hot fluid	Annular space – cold fluid	Inner tube – cold fluid	Annular space – hot fluid
Tube-in-tube Helical Heat Exchanger	129.83	43.47	117.94	47.72
Tube-in-tube Straight Heat Exchanger	100.32	36.00	90.54	39.77

Experimental matrix describes a comparison between all Nusselt numbers for different configurations used. When the mass flow rate is kept constant for all four flow configuration, it is found that Nusselt number for tube-in-tube helical coil are higher than straight tube-in-tube heat exchanger.

6.4. Effect of pressure drop:

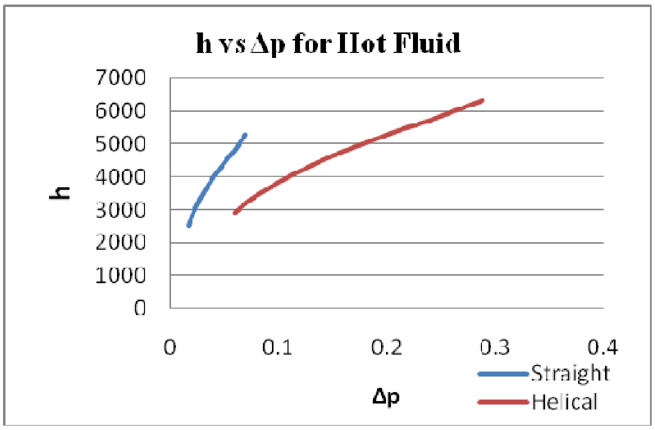

Fig. 7(a): heat transfer coefficient vs. pressure drop for hot fluid

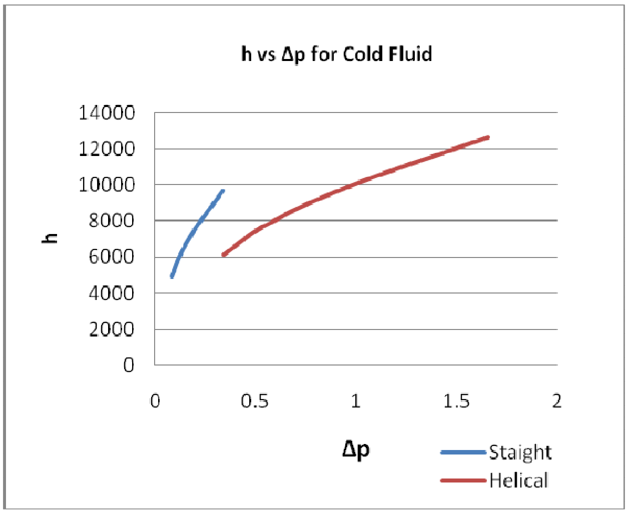

Fig. 7(b): heat transfer coefficient vs. pressure drop for cold fluid

Pressure drop is driving force for heat transfer. As per correlation given by White [2], friction factor for helical tube is high as compared to straight tube of same material. A similar trend is observed in the analysis. With gradual increase in mass flow rate, pressure drop increases more rapidly in helical coil heat exchangers comparatively. This is within permissible limit for compact heat exchangers.

6.5. Effect of curvature ratio

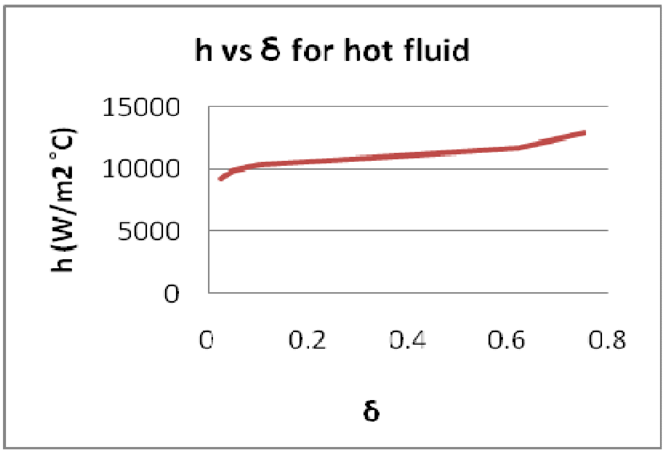

Fig. 8(a): heat transfer coefficient vs. curvature ratio for hot fluid

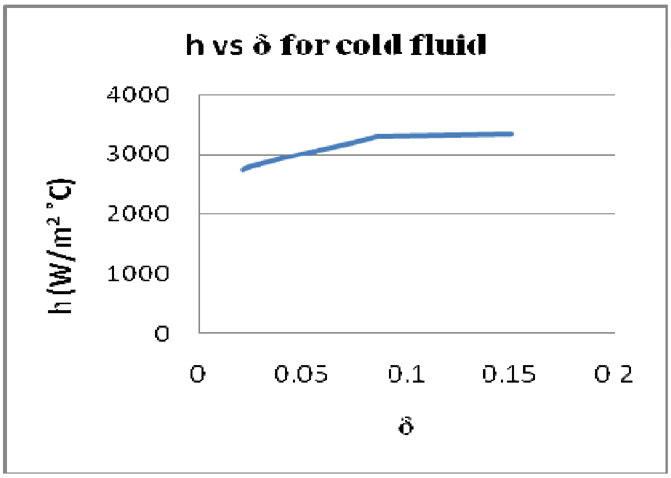

Fig. 8(b): heat transfer coefficient vs. curvature ratio for cold fluid

Curvature ratio is one of the most important parameters in tube-in-tube helical coil heat exchanger. The Dean number includes the curvature ratio and it has to be noted that both parameters of d and D can change the curvature ratio. Above graphs i.e. fig. 5(a) and 5(b) shows the effect of curvature ratio on heat transfer coefficient. The coil diameter was varied to obtain different curvature ratios. It is seen that the slope of the curve has gradually increased. Henceforth it is concluded that there is increase in heat transfer with increasing curvature ratio.

6.6. Effectiveness

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III. Effectiveness and heat transfer coefficients for different flow configurations Operating conditions – 210 LPH

Serial No.	Configuration	Effectiveness	h(hot) $W/m^2\ ^\circ C$	h(cold) $W/m^2\ ^\circ C$
1	Parallel flow with hot water inside tube	0.4954	13664.7	5258.49
2	Parallel flow with cold water inside tube	0.4959	5316.35	13874.9
3	Counter flow with hot water inside tube	0.6666	13664.5	5345.81
4	Counter flow with cold water inside tube	0.6757	6021.14	12086.2

Above table represents effectiveness for all four flow configurations. Effectiveness is more in case of counter than parallel configuration. Moreover, it is seen that counter flow with cold water in inside tube is the most effective case.

VII. CONCLUSION

Comparative study is carried out between helical coil heat exchanger and straight tube heat exchanger. The results of this analysis shows that previously published correlations yield similar results to the one obtained by this method. Based on the results obtained by conducting the experiments on helical (parallel and counter flow) and straight (parallel and counter flow) tube, the following conclusions are drawn:

- For same heat transfer rate of these heat exchangers, straight tube-in-tube heat exchanger is large in size and thus bulky. Thus compact size provides a distinct benefit of helical coil heat exchanger. Conversely, it also implies that for the same surface area, the heat energy absorbed by helical tube is more than that of straight copper tube.
- As curvature ratio increases, heat transfer coefficient enhances. Intensity of secondary flow developed goes on increasing with increase in curvature ratio. This increase in turbulence allows proper mixing of fluid inside the tube and further that increases Nu and h.
- The overall heat transfer coefficient in helical heat exchanger increased with flow rate and approached a maximum value at higher flow rates. It is observed that the overall heat transfer coefficient for helical tube is approximately 10 to 20% times that of straight tubes.
- Pressure drop in case of tube-in-tube helical coil heat exchanger is more than tube-in-tube straight heat exchanger, but heat transferred is significantly more in helical coil. The enhancement in heat transfer is obtained at the expense of pressure drop within permissible limit.
- Overall heat transfer coefficient decreases with increase in pitch of the helical coil. But the effect is comparably negligible. Hence pitch doesn't show a great influence on the performance.
- In tube-in-tube helical coil heat exchanger counter flow with cold fluid inside shows overall better results than other flow configurations.

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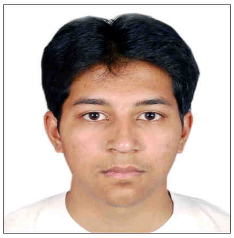

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