Parametric Analysis of Helical Coil Heat Exchanger

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Abstract: *Heat exchangers are the important engineering systems with wide variety of applications including power plants, nuclear reactors, refrigeration and air-conditioning systems, heat recovery systems, chemical processing and food industries. Helical coil configuration is very effective for heat exchangers and chemical reactors because they can accommodate a large heat transfer area in a small space, with high heat transfer coefficients. This paper deals with the parametric analysis of the helical coiled heat exchanger with various correlations given by different researchers for specific conditions. The parametric analysis of these various correlations with specific data is presented in this paper.*

Keywords: *Shell and coiled tube, Heat exchanger, Experimental, Laminar, Turbulent, Heat transfer coefficient*

1. Introduction:

The flow through a curved pipe has been attracting much attention because helical coiled pipes are widely used in practice as heat exchangers and chemical reactors. The fluid flowing through curved tubes induces secondary flow in the tubes. This secondary flow in the tube has significant ability to enhance the heat transfer due to mixing of fluid. The intensity of secondary flow [1, 2] developed in the tube is the function of tube diameter (d) and coil diameter (D). Due to enhanced heat transfer in helical coiled configuration the study of flow and heat transfer characteristics in the curved tube is of prime important.

The several studies have indicated that helical 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.

This phenomenon can be beneficial especially in laminar flow regime. Naphon [2] investigated the thermal performance and pressure drop of a shell and helical coiled tube heat exchanger with and without helical crimped fins. Naphon et al. [3] summarized the phenomenon of heat transfer and flow characteristics of single-phase and two-phase flow in curved tubes including helically coiled tubes and spirally coiled tubes.

The first attempt has been made by Dean [4, 5] to describe mathematically the flow in a coiled tube. A first approximation of the steady motion of incompressible fluid flowing through a coiled pipe with a circular cross-section is considered in his analysis. It was observed that the reduction in the rate of flow due to curvature depends on a single variable, K, which is equal to $2(Re)^2 r/R$, for low velocities and small r/R ratio. White [6] has continued the study of Dean for the laminar flow of fluids with different viscosities through curved pipes with different curvature ratios (δ). The result shows that the onset of turbulence did not depend on the value of the Re or the De. He concluded that the flow in curved pipes is more stable than flow in straight pipes. White also studied the resistance to flow as a function of De and Re. There was no difference in flow resistance compared to a straight pipe for values of De less than 11.6.

The fully developed laminar flow and heat transfer, studied numerically, by Zapryanov et al. [7] by using a method of fractional steps for a wide range of De (10 to 7000) and Pr (0.005 to 2000). The effect of the Pr on the heat transfer in helical pipes was studied by Xin et al. [8]. They studied the effect of Pr on both the average and local Nu. Li et al. [9] numerically investigated turbulent heat transfer in curved pipe for developing flow with water near the critical point. The heat transfer enhancements due to chaotic particle paths were studied by Acharya et al. [10, 11] for coiled tubes and alternating axis coils. The work on pulsating curved tube flow was performed by Guo et al. [11] for fully developed turbulent flow in a helical coiled tube. The two-phase flow of a steam-water mixture in a helical coil was studied experimentally by Guo et al. [12]. Inagaki et al. [14] studied the outside heat transfer coefficient for helically coiled bundle for Re in the range of 6000 to 22,000. The heat transfer studies of a helical coil immersed in a water bath was studied by Prabhanjan et al. [15]. The experimental study of the flow in a helical circular tube was performed by Yamamoto et al. [16]. Arvind et al. [17] studied heat transfer experimentally in the helical coil with the coolants of different viscosity. An analytical and experimental study has carried out by Shokouhmand et al. [18] to optimize the *Re* of laminar viscous flow in a helically coiled tube subjected to constant wall temperature by minimizing entropy generation. Thermal performance and pressure drop *(Δp)* of the helical-coil heat exchangers with and without helically crimped fins was analyzed by Naphon et al. [2]. The heat transfer characteristics of a temperature-dependent-property of fluid in shell and coiled tube heat exchangers has studied by Salimpour [19].

2. Geometry and parameters of helical coils

The major geometric dimensions include the diameter of the tube *(d)*, the curvature radius of the oil *(D)* and the coil pitch (increase of height per rotation, *b*). The following four important dimensionless numbers are considered

The present analysis considers the following dimensional and operating parameters.

Table 1. Dimensional and operating parameters

Sr. No.	**Dimensional parameters**	**Dimension**
1	Average coil diameter (*D*)	*200 mm*
2	Tubes of internal diameter (*d*)	*8,10,12 mm*
3	Tube length (*L*)	*2m*
4	Working fluid	Water
5	Average hot water temperature	60^{O}C
6	Average cold water temperature	30^{O}C

The following four important dimensionless numbers are considered in analysis

Table 2. Dimensionless Numbers

Sr. No.	**Dimensionless Number**	**Details**
1	Reynolds Number	$Re = \rho Vd / \mu$
2	Nusselt Number	$Nu = hd / k$
3	Dean Number	$De = Re\ (d / D)^{1/2}$
4	Helix Number	$He = De / [1+ (b/2\pi a)^2\ ]^{1/2}$

3. Data Reduction

The analysis of the helical coil heat exchanger is carried out through following procedure:

1. The range of *Re* considered for the analysis is about 100 to 6000.
2. The velocity of the fluid flowing through the tube is calculated by considering the tube diameter (*d*) as 8mm, 10mm and 12 mm. The properties of the fluid flowing through the tube are taken at average temperature of 60^{O}C (for the values of ρ and μ).

$$\bar{V} = \frac{(Re \times \mu)}{(\rho \times d)} \qquad 3.1$$

3. Mass flow rate is calculated as.

$$\dot{m} = \rho \times A \times \bar{V} \qquad 3.2$$

4. Dean Number (*De*) is calculated as

$$De = Re \times \left(\frac{d}{D}\right)^{0.5} \qquad 3.3$$

5. Helix Number (*He*) is calculated as

$$He = \left(\frac{De}{(1+\gamma^2)^{0.5}}\right) \qquad 3.4$$

6. Nu is calculated by various correlations at specified conditions:

a. M.R. Salimpour [19],

$$Nu = 0.152 De^{0.431} Pr^{1.06} \gamma^{-0.277} \quad \text{for } De<3000 \qquad 3.5$$

b. Kalb et al. [20]

$$Nu = 0.836 De^{0.5} Pr^{0.1} \quad \text{for } De \geq 80 \text{ and } 0.7<Pr<5 \qquad 3.6$$

c. Xin et al. [8]

$$Nu = (2.153+0.318 De^{0.643})\ Pr^{0.177} \quad \text{for } 20<De<2000;\ 0.7<Pr<175 \text{ and } d/D<0.0884 \qquad 3.7$$

d. . Roger et al. [21]

$$Nu = 0.023\ Re^{0.85} Pr^{0.4} \delta^{0.1} \quad \text{for } Re>2000 \qquad 3.8$$

7. Calculate h_i (Heat Transfer coefficient inside the Tube)

$$h_i = \frac{Nu \times k}{d} \qquad 3.9$$

4. Results and Discussion

The analysis is carried out for laminar and turbulent region separately for tube side heat transfer coefficient (*hi*) and *Nu*. The calculations are performed as per the data reduction procedure for helical coil configuration and the results are tabulated for heat transfer analysis. Four different correlations of *Nu* are selected from the literature for the analysis, as these correlations fulfil the conditional requirements of the data selected for the analysis.

The variation of *Nu* Vs *Re* in laminar region is presented in Fig. 4.1, whereas the variation of *hi* Vs *Re* in laminar region is given in Fig. 4.2

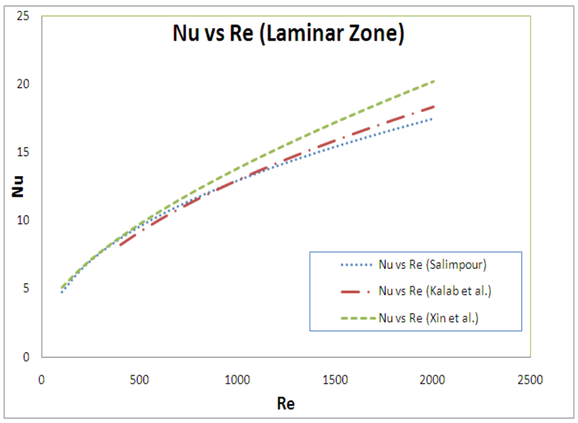
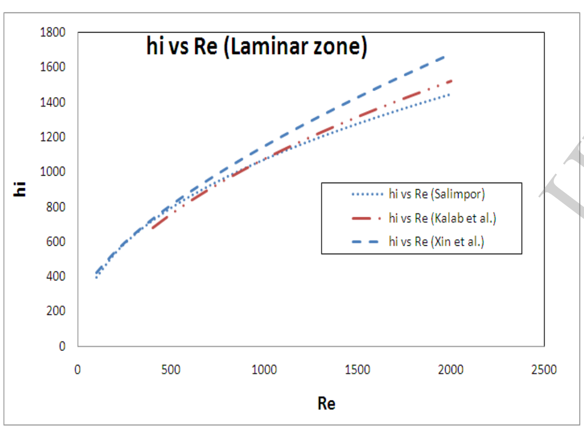


Fig.4.1 Variation of *Nu* Vs *Re* (Laminar Region)

Fig.4.2 Variation of *hi* Vs *Re* (Laminar Region)



In laminar region, it is observed that *Nu* and *hi* increases with increase in *Re*. The *Nu* obtained by Eq. 3.5 is having lowest values as compared to the other two correlations (Eq.3.6 and Eq. 3.7), which may be due to the direct effect of dimensionless pitch considered in the equation. Equation 3.5 and Eq.3.6 gives close agreement for *Nu* and *hi*, whereas *Nu* and *hi* given by Eq.3.7 correlation are on higher side. Equation 3.5 and Eq.3.7 shows the variation of about 15 to 20% for the *Nu* and h_i values, for same *Re*.

This shows that in laminar region the secondaries developed in the fluid flow goes on increasing, as *Re* increases, which increases the turbulence in the fluid flow. The increase in turbulence allows proper mixing of the fluid, which enhances the *Nu* and h_i. The present analysis also confirms similar trend for *Nu* and h_i with respect to *Re* for different tube diameters (*d =10 mm* and *12 mm*).

Figure 4.3 shows the effect of *Re* on *Nu* and Fig. 4.4 shows the effect of *Re* on *hi* in turbulent region.

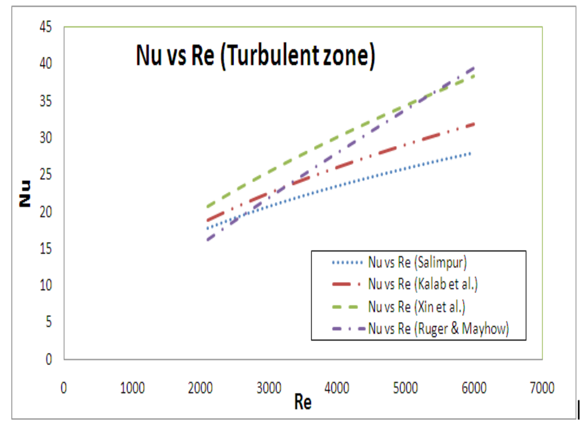


Fig.4.3 Effect of *Re* on *Nu* (Turbulent Region)

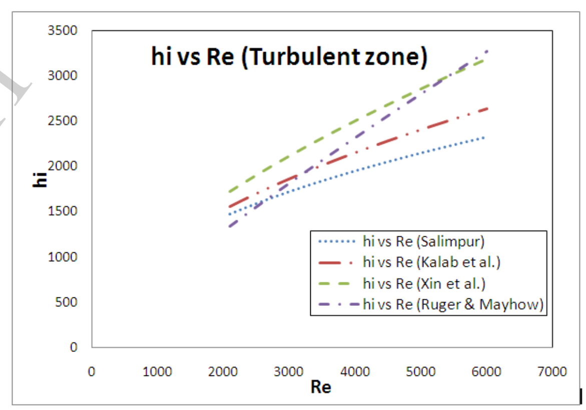


Fig. 4.4 Effect of *Re* on h_i (Turbulent Region)

Figure 4.3 and 4.4 shows that the trend present in laminar zone is continued further in turbulent region. As *Re* increases the *Nu* and *hi* also increases. In turbulent region four correlations (Eq.3.5 to 3.8) are applicable. In the range of *Re* between 2000 to 4500 the values of *Nu* and h_i with Eq. 3.5, Eq.3.6 and Eq.3.8 shows close agreement, whereas the values predicted by Eq.3.7 correlation are slightly overestimated. This may be due to the fitting the data in power equation for given range of values. The analysis for Eq.3.8, with *Re* the greater than 4500, shows the overestimation for the *Nu* and *hi*. This may be due to the development of the equation with the base equation as straight tube. This shows that the intensity of secondaries developed goes on increasing which increases mixing of the fluid inside the tube and further that increases *Nu* and *hi*. The similar trend for *Nu* and h_i with respect to *Re* is observed for the given range of tube diameters.

Figure 4.5 shows the variation of *Nu* Vs *Re* with different tube diameters (*d*) and constant coil diameters (*D*). The curvature ratio (δ) is the function of tube diameter (*d*) and coil diameter (*D*). The curvature ratio increases with increase in tube diameter. The analysis presented in Fig. 4.5 is with mean coil diameter (*D*) of 200 mm and tubes of diameters (*d*) 8mm, 10mm and 12 mm based on Eq. 3.5.

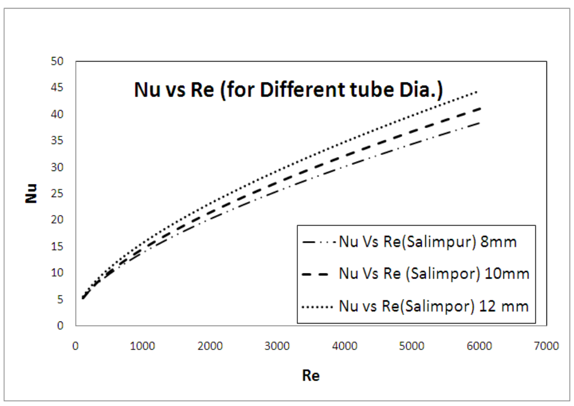


Fig. 4.5 The variation of *Nu* Vs *Re* with different tube diameters (*d*) and constant coil diameters (*D*).

Figure 4.5 show that, *Nu* increases with increase in curvature ratio (δ) for the same *Re*. This is because *Nu* is the function of *De*, which is directly proportional to curvature ratio (δ). It is also observed that *Nu* increases with *Re*.

The analysis in Fig. 4.5 also shows that the slope of the curves at low *Re* is greater than that of high *Re* and after words the slope remains linear. This shows that at low *Re* there is a major enhancement in heat transfer due to more secondaries developed. The slope is more or less steady for higher *Re*. Hence it is noted that for very high *Re* the effect of secondaries are not much predominant. The similar trend is shown by other correlations for the selected data.

5. Conclusion

This paper presents a comparative analysis of the different correlations given by the different researchers for helical coil heat exchanger. The various equations use different parameters for the analysis. The overall effect of these parameters on *Nu* and *hi* is presented in this paper. The analysis shows that, for low *Re*, the graphs of *Nu* Vs *Re* and *hi* Vs *Re* is steeper than that at high *Re*. It indicates that helical coils are efficient in low *Re*. The analysis also shows that, as tube diameter (*d*) increases with constant coil diameter (*D*), the curvature ratio (δ) increases, which increases the intensity of secondaries developed in fluid flow. The increase in the intensity of secondaries developed in fluid flow increases *Nu*. Hence, it is desirable to have small coil diameter (*D*) and large tube diameter (*d*) in helical coil heat exchanger, for large intensities of seconderies in tube.

Nomenclature

d	Tube Diameter, *m*
D	Coil Diameter, *m*
h	Heat Transfer Coefficient, W/m^2K
L	Tube Length, *m*
r	Tube Radius, *m*
R	Radius of Curvature, *m*

Subscripts

i	Inside Condition
o	Outside Condition

Greek Letters

ρ	Density, kg/m^3
δ	Curvature Ratio, *r/R*
μ	Viscosity, Ns/m^2
γ	Dimensionless Pitch, $b/(\pi * D)$

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