

Parametric Analysis of Helical Coil Heat Exchanger

Pramod S. Purandare^a, Mandar M. Lele^b, Rajkumar Gupta^c

^aDepartment of Mechanical Engineering, Thapar University, Patiala, India

^bDepartment of Mechanical Engineering, Maharashtra Institute of Technology, Pune, India

^cDepartment of Chemical Engineering, Thapar University, Patiala, India

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 coil (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°C |
| 6 | Average cold water temperature | 30°C |

The following four important dimensionless numbers are considered in analysis

Table 2. Dimensionless Numbers

| Sr. No. | Dimensionless Number | Details |
|---------|----------------------|--------------------------------------|
| 1 | Reynolds Number | $Re = \rho V d / \mu$ |
| 2 | Nusselt Number | $Nu = h d / k$ |
| 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°C (for the values of ρ and μ).

$$\bar{v} = \frac{(Re \times \mu)}{(\rho \times d)} \quad 3.1$$

3. Mass flow rate is calculated as.

$$\dot{m} = \rho \times A \times \bar{v} \quad 3.2$$

4. Dean Number (De) is calculated as

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

5. Helix Number (He) is calculated as

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

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

- a. M.R. Salimpour [19],

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

- b. Kalb et al. [20]

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

- c. Xin et al. [8]

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

- d. Roger et al. [21]

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

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

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

4. Results and Discussion

The analysis is carried out for laminar and turbulent region separately for tube side heat transfer coefficient (h_i) 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

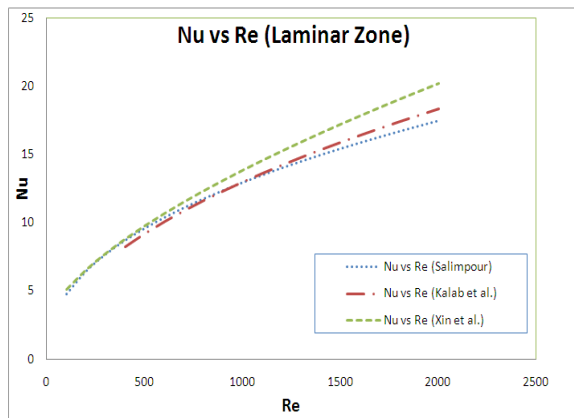
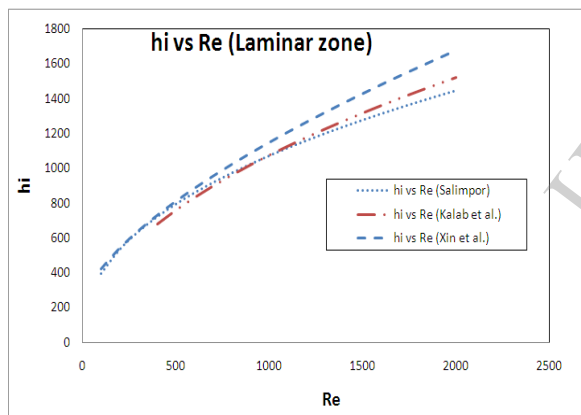


Fig.4.1 Variation of Nu Vs Re (Laminar Region)

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 hi 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 hi . The present analysis also confirms similar

trend for Nu and hi with respect to Re for different tube diameters ($d = 10\text{ mm}$ 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.

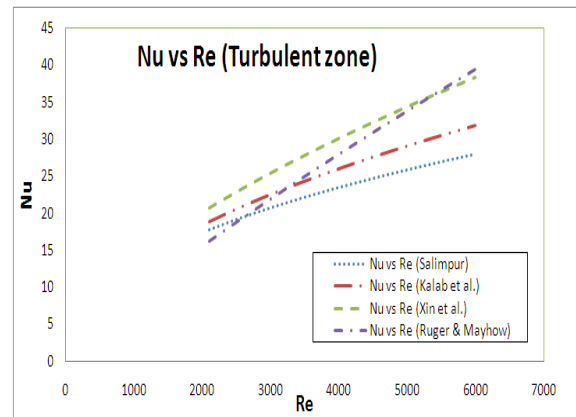


Fig.4.3 Effect of Re on Nu (Turbulent Region)

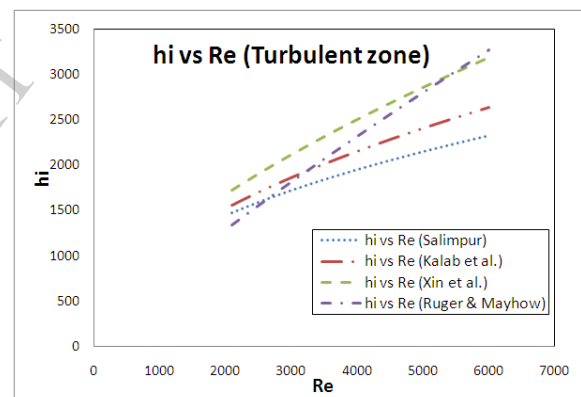


Fig. 4.4 Effect of Re on hi (Turbulent Region)

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 hi 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.

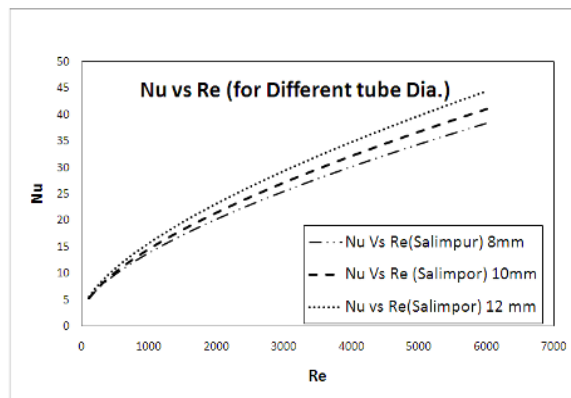


Fig. 4.5 The variation of Nu Vs Re with different tube diameters (d) and constant coil diameters (D).

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 h_i is presented in this paper. The analysis shows that, for low Re , the graphs of Nu Vs Re and h_i 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 secondaries 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, $b/(\pi*D)$ |

References

- [1] Dravid, A. N., Smith, K. A., Merrill, E.A., and Brian, P.L.T., (1971) "Effect of secondary fluid motion on laminar flow heat transfer in helically coiled tubes", *AIChE Journal*, Vol. 17(5):1114-1122.
- [2] Naphon, P., (2007) "Thermal performance and pressure drop of the helical-coil heat exchangers with and without helically crimped fins", *Int. Communication of Heat Mass Tran.*, Vol. 34 (3), pp. 321-330.
- [3] Naphon, P., and Wongwises, S., (2006) "A review of flow and heat transfer characteristics in curved tubes", *Renew. Sust. Energ.*, Rev. 10, pp. 463-490.
- [4] Dean, W. R., (1927) "Note on the motion of fluid in a curved pipe", *Philosophical Magazine*, Series 7, Vol. 4(20), pp. 208-23.
- [5] Dean, W. R., (1928) "The streamline motion of fluid in a curved pipe", *Philosophical Magazine*, Series 7, Vol. 5(30), pp. 673-95.
- [6] White, C. M., (1929) "Streamline flow through curved pipes", *Proceedings of the Royal Society of London*, Series A, Vol. 123(792), pp. 645-663.
- [7] Zapryanov, Z., Christov, C. and E. Toshev., (1980) "Fully developed laminar flow and heat transfer in curved tubes", *International Journal of Heat and Mass Transfer*, Vol.23, pp. 873-880.
- [8] Xin, R.C., and Ebdadian, M.A., (1997) "The effects of Prandtl numbers on local and average convective heat transfer characteristic in helical pipes", *Journal of Heat Transfer*, Vol. 119, pp. 467-473.

- [9] Li, L.J., Lin, C.X., and Ebadian, M.A., (1999) "Turbulent heat transfer to near-critical water in a heated curved pipe under the conditions of mixed convection", *International Journal of Heat and Mass Transfer*, Vol. 42(16), pp. 3147-3158.
- [10] Acharya, N., Sen, M., and H. C. Chang, (1992) "Heat transfer enhancement in coiled tubes by chaotic mixing", *International Journal of Heat and Mass Transfer*, Vol. 35(10), pp. 2475-2489.
- [11] Acharya, N., Sen, M., and H. C. Chang, (2001) "Analysis of heat transfer enhancement in coiled-tube heat exchangers", *International Journal of Heat and Mass Transfer*, Vol. 44, pp. 3189-3199.
- [12] Guo, L., Chen, X., Feng, Z., and Bai, B., (1998) "Transient convective heat transfer in a helical coiled tube with pulsating fully developed turbulent flow", *International Journal of Heat and Mass Transfer*, Vol. 41, pp. 2867-2875.
- [13] Guo, L., Feng, Z., and X., Chen, (2002) "Transient convective heat transfer of steam-water two-phase flow in a helical tube under pressure drop type oscillations", *International Journal of Heat and Mass Transfer*, Vol. 45, pp. 533-542.
- [14] Inagaki, Koiso, Y., Takumi, H., Ioka, H., and Y. Miyamoto, (1998) "Thermal hydraulic study on a high-temperature gas-gas heat exchanger with helically coiled tube bundles", *Nuclear Engineering and Design*, Vol. 185, pp. 141-151.
- [15] Prabhanjan, D. G., T. J. Rennie, and G. S. V. Raghavan, (2004) "Natural convective heat transfer from helical coiled tubes.", *International Journal of Thermal Sciences*, Vol. 43(4):359-365.
- [16] Yamamoto, K., Akita, T., Ikeuchi, H., and Kita, Y., (1995) "Experimental study of the flow in a helical circular tube", *Fluid Dynamics Research*, Vol. 16, pp. 237-249.
- [17] Aravind, G.S., Arun, Y, Sunder, R S, Subrahmaniyam S, (2003) "Natural Convective Heat Transfer in Helical Coiled Heat Exchanger", *IE (I) Journal CH*, Vol. 84.
- [18] Shokouhmand, H., Salimpour, M.R., Akhavan-Behabadi, M.A., (2007) "Optimal Reynolds number of laminar forced convection in a helical tube subjected to uniform wall temperature", *International Communications in Heat and Mass Transfer*, Vol. 34, pp. 753-761.
- [19] Salimpour, M.R.,(2009) "Heat transfer coefficients of shell and coiled tube heat exchangers", *Experimental Thermal and Fluid Science*, Vol. 33, pp. 203-207.
- [20] Kalb, C.E., and Seader, J.D., (1974) "Fully developed viscous-flow heat transfer in curved circular tubes with uniform wall temperature", *AIChE Journal*, Vol. 20, pp. 340-346.
- [21] Rogers, G. F. C., and Y. R., Mayhew, (1964) "Heat transfer and pressure loss in helically coiled tubes with turbulent flow", *International Journal of Heat and Mass Transfer*, Vol. 7, pp. 1207-1216.

Authors Information



P.S. Purandare is a Ph.D student in the Department of Mechanical Engineering, Thapar University Patiala, India. His research interests lie in the areas of thermal engineering, heat transfer, and energy conservation.
(purandareps@gmail.com)



conservation.

Mandar M. Lele is a faculty member in the Department of Mechanical Engineering of Maharashtra Institute of Technology, Pune, India. He received his Ph. D. in 2006 from the Indian Institute of Technology, Bombay, India. His teaching and research interests lie in the areas of thermodynamics, heat transfer, refrigeration and air conditioning, cryogenics, energy



Raj Kumar Gupta is a faculty member in the Department of Chemical Engineering of Thapar University Patiala, India. He received his Ph. D. in 2006 from the Thapar University Patiala. His teaching and research interests lie in areas of Modelling and Simulation, Multiphase reacting flow incorporating heat and mass transfer, CFD modelling.

(rkgupta@thapar.edu)