HEAT TRANSFER STUDIES ON SPIRAL PLATE HEAT EXCHANGER

by

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In this paper, the heat transfer coefficients in a spiral plate heat exchanger are investigated. The test section consists of a plate of width 0.3150 m, thickness 0.001 m and mean hydraulic diameter of 0.01 m. The mass flow rate of hot water (hot fluid) is varying from 0.5 to 0.8 kg/s and the mass flow rate of cold water (cold fluid) varies from 0.4 to 0.7 kg/s. Experiments have been conducted by varying the mass flow rate, temperature, and pressure of cold fluid, keeping the mass flow rate of hot fluid constant. The effects of relevant parameters on spiral plate heat exchanger are investigated. The data obtained from the experimental study are compared with the theoretical data. Besides, a new correlation for the Nusselt number which can be used for practical applications is proposed.

Key words: *spiral plate heat exchanger, Reynolds number, Nusselt number, heat transfer coefficient, mass flow rate*

Introduction

Heat exchanger is a device in which energy is transferred from one fluid to another across a solid surface. Compact heat exchangers are characterized with its large amount of surface area in a given volume compared to traditional heat exchangers, in particular the shell-and-tube type. The most basic compact heat exchangers have a volume less than 50% of that of a comparable shell-and-tube heat exchanger, for a given duty. The development and investigation of compact heat exchangers, has become an important requirement during the last few years. The interest stems from various reasons *viz*. decreasing raw material and energy resources, the increasing environmental pollution and increasing costs for manufacturing and operation of heat exchangers. Compact heat exchangers are of two types, spiral and plate type heat exchangers. Spiral heat exchanger is self cleaning equipment with low fouling tendencies, easily accessible for inspection or mechanical cleaning and with minimum space requirements.

Seban *et al*. [1] calculated heat transfer in coiled tubes for both laminar and turbulent flows. Plot of Nusselt *vs*. Graetz numbers were presented for coils with curvature ratios of 17 and 104 with Reynolds numbers ranging from 12 to 5600 for the laminar flow region. Prandtl numbers ranged from 100 to 657. Heat transfer and pressure loss in steam heated helically coiled tubes were studied by Rogers *et al.* [2]. They observed that even for a steam heated apparatus, uniform wall temperature was not obtained, mainly due to the distribution of the steam condensate over the coil surface. Mori *et al.* [3] studied the fully developed flow in a curved pipe with a uniform heat flux for large Dean numbers. Flow and temperature fields were studied both theoretically and experimentally. They assumed that the flow was divided into two sections, a small boundary layer near the pipe wall, and a large core region making up the remaining flow. Pressure drop and heat transfer for laminar flow of glycerol was presented by Kubair *et al.* [4] for different types of coiled pipes, including helical and spiral configurations. Reynolds numbers were in the range of 80 to 6000 with curvature ratios in the range of 10.3 to 27. The number of turns varies from 7 to 12. The results of Kubair *et al*. [4] match with those of Seban *et al*. [1] at low Graetz numbers, but deviated at higher Graetz numbers.

Outside-film and inside-film heat transfer coefficients in an agitated vessel were studied by Jha *et al*. [5]. Five different coils were studied, along with different speeds and locations of the agitator. They derived an equation to predict the Nusselt number based on the geometry of the helical coil and the location of the agitator. Numerical studies for uniform wall heat flux with peripherally uniform wall temperature for Dean numbers in the range of 1-1200, Prandtl numbers of 0.005-1600, and curvature ratios of 10 to 100 for fully developed velocity and temperature fields were performed by Kalb *et al*. [6]. They found that the curvature ratio parameter had insignificant effect on the average Nusselt number for any given Prandtl number. Kalb *et al*. [7] furthered this work by applying the method to the case of a uniform wall-temperature boundary condition with Dean numbers up to 1200, Prandtl numbers and curvature ratios in the ranges of 0.05 to 1600 and 10 to 100, respectively. Their results illustrate that there is a slight effect of curvature on the peripheral variation of the Nusselt number. However, it did not affect the average Nusselt number. The effects of buoyancy forces on fully developed laminar flow with constant heat flux were studied analytically by Yao *et al.* [8]. Their studies were based on the Boussinesq approximation for the buoyancy forces and analyzed for both horizontally and vertically orientated curved pipes. Nusselt number relationships based on the Reynolds number, Rayleigh number and Dean number were presented for both orientations.

Laminar flow and heat transfer were studied numerically by Zapryanov *et al.* [9] using a method of fractional steps for a wide range of Dean (10 to 7000) and Prandtl (0.005 to 2000) numbers. Their work focused on the case of constant wall temperature and showed that the Nusselt number increased with increasing Prandtl numbers, even for cases at the same Dean number. They also presented a series of isotherms and streamlines for different Dean and Prandtl numbers. The effect of buoyancy on the flow field and heat transfer was studied numerically by Lee *et al*. [10], for the case of fully developed laminar flow and axially steady heat flux with a peripherally constant wall temperature. They found that buoyancy effects resulted in an increase in the average Nusselt number, as well as modifying of the local Nusselt number allocation. It was also found that the buoyancy forces result in a rotation of the orientation of the secondary flow patterns. The heat transfer to a helical coil in an agitated vessel studied by Havas *et al*. [11] and a correlation was developed for the outer Nusselt number based on a modified Reynolds number, Prandtl number, viscosity ratio, and the ratio of the diameter of the tube to the diameter of the vessel. Heat transfer enhancements due to chaotic particle paths were studied by Acharya *et al*. [12, 13] for coiled tubes and alternating axis coils. They developed two correlations of the Nusselt number (Re_m), for Prandtl numbers less than and greater than one, respectively. Lemenand *et al.* [14] developed a Nusselt number correlation based on the Reynolds number, Prandtl number and the number of bends in the pipe. For the same Reynolds and Prandtl numbers, their work showed that the Nusselt number slightly drops off with increasing number of bends.

Heat transfer for pulsating flow in a curved pipe was numerically studied by Guo *et al.* [15] for fully developed turbulent flow in a helical coiled tube. In their work they examined both the pulsating flow and the steady-state flow. They developed the following correlation (1) for steady turbulent flow for the Reynolds number range of 6000 to 180000:

$$\mathrm{Nu} = 0.328\mathrm{Re}^{0.58}\mathrm{Pr}^{0.4} \tag{1}$$

They found that the Reynolds number was increased to very large values (>140,000), the heat transfer coefficient for coils began to match the heat transfer coefficient for straight tubes. They also presented correlations of the peripheral local heat transfer coefficients as a function of the average heat transfer coefficients, Reynolds number, Prandtl number, and the location on the tube wall. Inagaki *et al.* [16] studied the outside heat transfer coefficient for helically coiled bundles for Reynolds numbers in the range of 6000 to 22,000 and determined that the outside Nusselt number described by the following relationship (2) for their particular setup.

$$\mathrm{Nu} = 0.78\mathrm{Re}^{0.51}\mathrm{Pr}^{0.3} \tag{2}$$

Heat transfer and flow characteristics in the curved tubes have been studied by a number of researchers. Although some information is currently available to calculate the performance of the spiral plate heat exchanger, there is still room to discuss whether it gives reliable prediction of the performance. This is because the heat transfer and flow characteristics of spiral plate heat exchanger has been studied. In the present study, the heat transfer and flow characteristics of water for spiral plate heat exchanger have been experimentally studied, in addition to the development of a new correlation for Nusselt number.

Experimental setup

Table 1. Dimensions of the spiral plate heat exchanger

Parameters	Dimensions
Plate width, [m]	0.3150
Plate thickness, [m]	0.0010
Mean channel spacing, [m]	0.0050
Mean hydraulic diameter, [m]	0.0100
Heat transfer area, [m^2]	2.2400

The experimental setup consists of spiral heat exchanger, thermometer, and steam purging coil, manometers, pumps and tanks as shown in fig. 1. The parameters of heat exchanger are shown in the tab. 1. The hot fluid inlet pipe is connected at the center core of the spiral heat exchanger and the outlet pipe is taken from periphery of the heat exchanger. The hot fluid is heated by

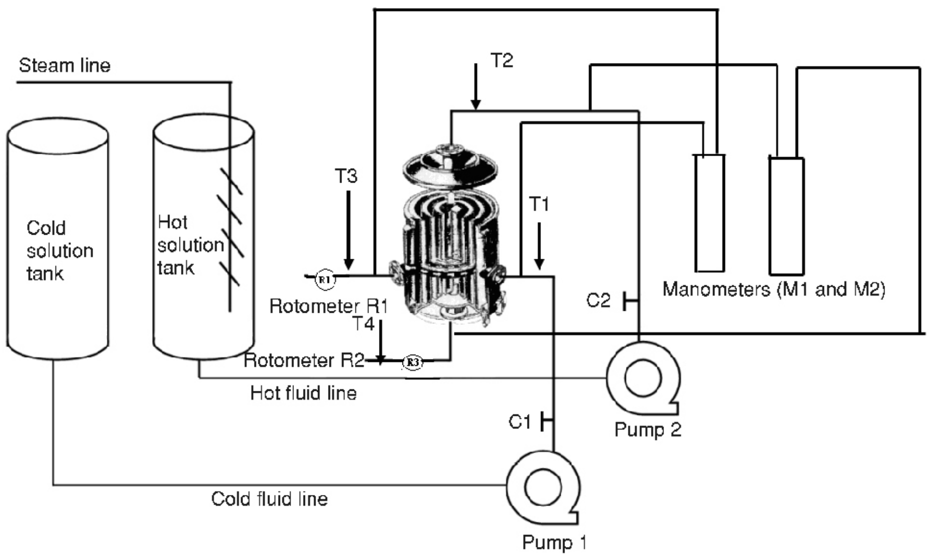

Figure 1. Schematic diagram of experimental apparatus

pumping the steam from the boiler to a temperature of about 60-70 °C and connected to hot fluid tank having a capacity of 1000 liters then the hot solution is pumped to heat exchanger using a 367.75 watts pump. Thus the counter flow of the fluid is achieved. The cold fluid inlet pipe is connected to the periphery of the exchanger and the outlet is taken from the centre of the heat exchanger. The cold fluid is supplied at room temperature from cold solution tank and is pumped to the heat exchanger using a 367.75 watts pump.

Experimental procedure

The heat transfer and flow characteristic of water is tested using spiral plate heat exchanger as shown in fig. 1. Water is used as the working fluid. The inlet hot fluid flow rate is kept constant and the inlet cold fluid flow rate is varied using a control valve. The flow of hot and cold fluid is varied using control valves C1 and C2, respectively. Hot and cold fluid flow paths of heat exchanger is shown in fig. 2. Thermometers T1 and T2 are used to measure inlet temperature of cold and hot fluids, respectively; T3 and T4 are used to measure the outlet temperature of cold and hot fluids, respectively. For different cold fluid flow rate the temperatures at the inlet and outlet of hot and cold fluids are recorded, after achieving the steady-state. The same procedure is repeated for different hot fluid flow rates and the data related to temperatures, the corresponding temperatures and mass flow rates are recorded. The mass flow rate is determined by using the rotometer fitted at the outlet of the corresponding fluids. The range of experimental conditions in this study is given in tab. 2.

Table 2. Experimental conditions

Variables	Range
Hot water temperature	65-50 °C
Cold water temperature	30-50 °C
Mass flow rate of hot water	0.5-0.8 kg/s
Mass flow rate of cold water	0.4-0.7 kg/s

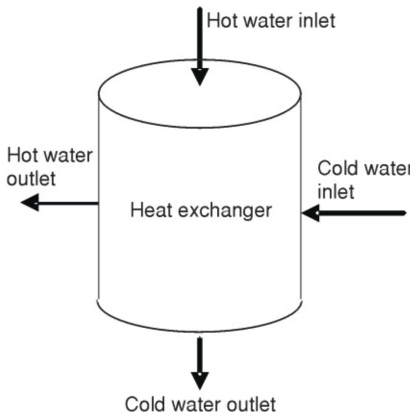

Figure 2. Hot and cold fluid flow paths of exchanger

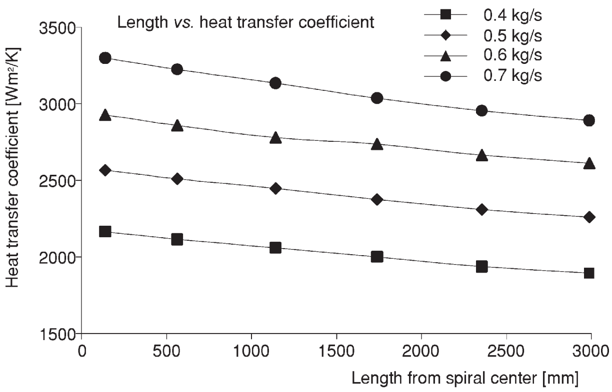

Figure 3. Variation of *L* with *h* for different water mass flow rates

Results and discussion

Figure 3 shows the variation of the length from spiral center and heat transfer coefficient of cold water for different mass flow rates. It is clear that the heat transfer coefficient is varying with mass flow rates. When the mass flow rate is increased the heat transfer coefficient is also increased. On the other hand, the heat transfer coefficient is decreased when the length of spiral plate is increased.

Figure 4 shows the comparisons of the Nusselt numbers obtained from the experiment conducted with those calculated from theoretically. It can be noted that the experimental and predicted Nusselt numbers fall within ±8%. The major discrepancy between the measured data and calculated results may be due to the difference in the configuration of test sections and uncertainty of the correlation.

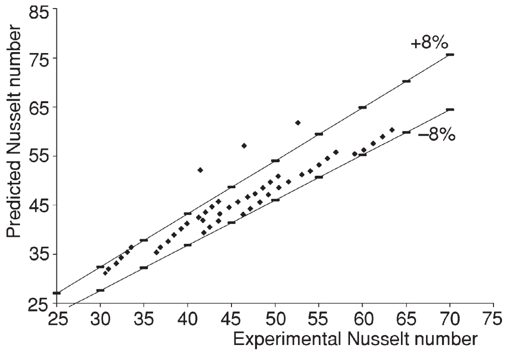

Figure 4. Comparison of Nusselt number (experimental) with Nusselt number (predicted)

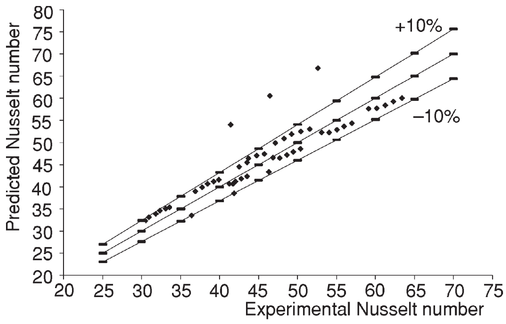

Figure 5. Comparison of experimental data with Holger Martin correlation

The proposed Nusselt number correlation (3) for spiral plate heat exchanger is expressed as:

$$Nu = 0.242Re^{0.591}Pr^{0.1325} \tag{3}$$

The Holger Martin correlation (4) [17]:

$$Nu = 0.04Re^{0.74}Pr^{0.4} \qquad 4\cdot10^2 < Re < 3\cdot10^4 \tag{4}$$

Comparisons of the Nusselt numbers obtained from the present experiment with those calculated from the existing correlation are shown in fig . 5. It can be noted that the values obtained from the correlation are slightly consistent with the experimental data and lie within ±10% for the Holger Martin correlation.

Conclusions

This paper presents new experimental data from the measurement of the heat transfer coefficient of water flows in a spiral plate heat exchanger. The effects of relevant parameters are investigated. The data obtained from the present study are compared with the theoretical data. In addition, a new correlation based on the experimental data is given for practical applications.

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Nomenclature

C	– control valve	Nu	– Nusselt number (= hd/k), [–]
c	– constant	Pr	– Prandtl number (= $\mu C_p/k$), [–]
h	– heat transfer coefficient, [$Wm^{-2}K^{-1}$]	Re	– Reynolds number (= $\rho vd/\mu$), [–]
L	– length of spiral plate, [mm]	Re_m	– modified Reynolds number (= Re/c), [–]
M	– manometer	T	– thermocouple

References

[1] Seban, R. A., McLaughlin, E. F., Heat Transfer in Tube Coils with Laminar and Turbulent Flow, *International Journal of Heat and Mass Transfer, 6* (1963), 5, pp. 387-395

[2] Rogers, G. F. C., Mayhew, Y. R., Heat Transfer and Pressure Loss in Helically Coiled Tubes with Turbulent Flow, *International Journal of Heat and Mass Transfer, 7* (1964), 11, pp.1207-1216

[3] Mori, Y., Nakayama, W., Study on Forced Convective Heat Transfer in Curved Pipes, *International Journal of Heat and Mass Transfer, 8* (1965), 1, pp. 67-82

[4] Kubair, V., Kuloor, N. R., Heat Transfer to Newtonian Fluids in Coiled Pipes in Laminar Flow, *International Journal of Heat and Mass Transfer, 9* (1966), 1, pp. 63-75

[5] Jha, R. K., Rao, M. R., Heat Transfer through Coiled Tubes in Agitated Vessels, *International Journal of Heat and Mass Transfer, 10* (1967), 3, pp. 395-397

[6] Kalb, C. E., Seader, J. D., Heat and Mass Transfer Phenomena for Viscous Flow in Curved Circular Tubes, *International Journal of Heat and Mass Transfer, 15* (1972), 4, pp. 801-817

[7] Kalb, C. E., Seader, J. D., Fully Developed Viscous-Flow Heat Transfer in Curved Circular Tubes with Uniform Wall Temperature, *AIChE Journal, 20* (1974), 2, pp.340-346

[8] Yao, L. S., Berger, S. A., Flow in Heated Curved Pipes, *Journal of Fluid Mechanics, 88* (1978), 2, pp. 339-354

[9] Zapryanov, Z., Christov, C., Toshev, E., Fully Developed Laminar Flow and Heat Transfer in Curved Tubes, *International Journal of Heat and Mass Transfer, 23* (1980), 6, pp. 873-880

[10] Lee, J. B., Simon, H. A., Chow, J. C. F., Buoyancy in Developed Laminar Curved Tube Flows, *International Journal of Heat and Mass Transfer, 28* (1985), 2, pp. 631-640

[11] Havas, G. A.,Deak., Sawinsky, J., Heat Transfer to Helical Coils in Agitated Vessels, *The Chemical Engineering Journal, 35* (1987), 1, pp. 61-64

[12] Acharya, N., Sen, M.,Chang, H. C., Heat Transfer Enhancement in Coiled Tubes by Chaotic Mixing, *International Journal of Heat and Mass Transfer, 35* (1992), 10, pp. 2475-2489

[13] Acharya, N., Sen, M., Chang, H. C., Analysis of Heat Transfer Enhancement in Coiled-Tube Heat Exchangers, *International Journal of Heat and Mass Transfer, 44* (2001), 17, pp. 3189-3199

[14] Lemenand, T., Peerhossaini. H., A Thermal Model for Prediction of the Nusselt Number in a Pipe with Chaotic Flow, *Applied Thermal Engineering, 22* (2002), 15, pp. 1717-1730

[15] Guo, L., *et al.*, Transient Convective Heat Transfer in a Helical Coiled Tube with Pulsating Fully Developed Turbulent Flow, *International Journal of Heat and Mass Transfer, 41* (1998), 19, pp. 2867-2875

[16] Inagaki, Y., *et al.*, Thermal Hydraulic Study on a High-Temperature Gas-Gas Heat Exchanger with Helically Coiled Tube Bundles, *Nuclear Engineering and Design, 185* (1998), 2, pp. 141-151

[17] Martin, H., Heat Exchangers, Hemisphere Publishing Corporation, London, 1992

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