Experimental Investigation of Coil Curvature Effect on Heat Transfer and Pressure Drop Characteristics of Shell and Coil Heat Exchanger

The present work experimentally investigates the characteristics of convective heat transfer in horizontal shell and coil heat exchangers in addition to friction factor for fully developed flow through the helically coiled tube (HCT). The majority of previous studies were performed on HCTs with isothermal and isoflux boundary conditions or shell and coil heat exchangers with small ranges of HCT configurations and fluid operating conditions. Here, five heat exchangers of counter-flow configuration were constructed with different HCT-curvature ratios (δ) and tested at different mass flow rates and inlet temperatures of the two sides of the heat exchangers. Totally, 295 test runs were performed from which the HCT-side and shell-side heat transfer coefficients were calculated. Results showed that the average Nusselt numbers of the two sides of the heat exchangers and the overall heat transfer coefficients increased by increasing coil curvature ratio. The average increase in the average Nusselt number is of 160.3–80.6% for the HCT side and of 224.3–92.6% for the shell side when δ increases from 0.0392 to 0.1194 within the investigated ranges of different parameters. Also, for the same flow rate in both heat exchanger sides, the effect of coil pitch and number of turns with the same coil torsion and tube length is remarkable on shell average Nusselt number while it is insignificance on HCT-average Nusselt number. In addition, a significant increase of 33.2–7.7% is obtained in the HCT-Fanning friction factor (f_c) when δ increases from 0.0392 to 0.1194. Correlations for the average Nusselt numbers for both heat exchanger sides and the HCT Fanning friction factor as a function of the investigated parameters are obtained. [DOI: 10.1115/1.4028612]

Keywords: heat exchanger, experimental, helically coiled tube, curvature, friction

1 Introduction

In most of the industrial applications, increasing the thermal performance of heat exchangers affects directly on energy, material, and cost savings. The major challenge in designing heat exchangers is to make the equipment compact and achieve a high heat transfer rate with minimum pumping power [1]. Coiled tubes of helical shape are one of the enhancement techniques that are widely used as heat exchangers and have applications in various industries: chemical, biological, petrochemical, mechanical, biomedical, etc.

This wide use of HCTs is because they are compact and promote good mixing of the fluids that increase the heat transfer coefficients. In addition, this equipment is low cost and of easy construction and maintenance [2–16]. Due to the extensive application of the HCTs in these fields, knowledge about the heat transfer and pressure drop characteristics is very important.

Topakoglu [17] studied the flow pattern for steady incompressible viscous laminar flow in curved pipes. Results showed that the flow rate depends on two independent variables, Reynolds number and δ. McConalogue and Srivastava [18] performed numerical studies to determine the characteristics of the secondary flow for fully developed laminar flow. Their results showed that as the axial velocity increases, the maximum value of the axial velocity moves toward the outer wall and the secondary vortices migrate closer to the outer wall. Hüttl and Friedrich [19,20] numerically studied the effects of coil curvature and torsion, λ, on the characteristics of turbulent incompressible fluid flow in HCTs. They demonstrated that the effect of torsion on the axial velocity is much lower than the curvature effect but it could not be neglected. Gammack and Hydon [21] presented analytic and numerical solutions for flows in pipes with nonuniform curvature and torsion. They found that as δ increases, the axial velocity is forced toward the outer wall and the secondary velocity field is increased in strength. In addition, increasing torsion skews the components of velocity in the direction of increasing torsion. This was confirmed numerically by Masud et al. [22] for incompressible viscous steady flow through a curved pipe with circular cross section. Yu et al. [23] experimentally performed three-dimensional laser Doppler anemometry measurements on developed laminar flow in three HCTs (0.0734 ≤ δ ≤ 0.1374 and 0.0793 ≤ λ ≤ 0.193). The authors reported that δ and λ are the key parameters to affect the centrifugal force on fluid in a HCT.

There are several studies in the literature concerning the friction losses in HCTs. Eustice [24,25] experimentally noted an increase in resistance to flow for the curved tube compared to the straight tube and this increase in resistance could be correlated to δ. Dean [26] explained the higher pressure gradient in a curved pipe by that some of the fluid is in continual oscillation between the central part of the pipe, where the velocity is high, and the outer portion of the pipe, where the velocity is low. This movement is due to the centrifugal forces caused by the pipe curvature and results
in a loss of energy. White [27,28] experimentally studied the resistance of an isothermal flow of water and mineral oil through curved pipes. It was shown that, for De < 11.6, there is no difference in flow resistance compared to straight tubes.

Ito [29] performed experiments on smooth curved pipes with δ from 0.1 to 0.6. Results showed that for turbulent flow, f, is equivalent to that of a straight pipe for values of Re, δ/δ below 0.034. A correlation was proposed for 0.034 < Re< 300 and 15,000 < Re< 150,000. Mori and Nakayama [30–32] theoretically studied the pressure drop in curved pipes with laminar and turbulent isothermal flow. A correlation was proposed for 13.5 < De < 2000. Schmidt [33] studied the pressure drop for laminar flow inside HCTs for isothermal and nonisothermal flow conditions under constant wall temperature. The author concluded that the physical properties should be determined at the film temperature. The effect of δ and pd on f, for Newtonian fluids flowing through HCTs was studied by Mishra and Gupta [90]. Pressure drop data in the turbulent regions were reported and a correlation was obtained for 4500 < Re< 100,000, 0.00289 < δ < 0.1493, and 0 < pd/Dd < 25.4.

Prasad et al. [34] experimentally studied the pressure drop in a HCT in shell heat exchanger. The experimental setup consisted of copper HCTs with δ of 0.0254 and 0.0575 for two separate tests. A correlation for f, was developed for turbulent flow in the range of Re< 59,500. Ali [35] experimentally studied the pressure drop for steady isothermal flow of Newtonian fluids in HCTs. Generalized pressure drop correlations were developed in terms of the Euler and Reynolds numbers and geometrical parameters. Pimenta and Campos [36] determined f, experimentally with simultaneous heat transfer for Newtonian and non-Newtonian fluids at constant wall temperature as boundary condition for fully developed laminar flow inside vertical HCT. It was concluded that f, for non-Newtonian fluids was similar to those for Newtonian fluids when De < 80.

There is a significant amount of experimental and numerical studies in the literature regarding the convective heat transfer in isothermal and isoflux heated HCTs. Kirpikov [37] experimentally studied the heat transfer for turbulent flow of water in HCTs having δ of 0.1, 0.0769, and 0.0556. Heat transfer coefficients were obtained using the wall to bulk temperature difference and a correlation was proposed for the average Nusselt number of HCT flow (Nu) for 10,000 < Re< 45,000 and Pr ≈ 7. Seban and McLaughlin [38] experimentally studied the heat transfer for oil laminar flow and water turbulent flow in uniformly heated HCTs (0.0096 < δ < 0.0588). They concluded that the outer periphery has higher local Nusselt number than the inner with both being substantially higher than values for a straight pipe under the same conditions.

Experimental results for forced convection heat transfer for turbulent flow of water through steam heated coiled tubes were reported by Rogers and Mayhew [39]. Three coils with δ of 0.0926, 0.075, and 0.05 were used during experiments. They proposed a correlation for Re, between 10,000 and 100,000. Theoretical and experimental studies on forced convective heat transfer in HCTs were carried out by Mori and Nakayama [30–32] with laminar and turbulent flow under isoflux and isothermal conditions. Results indicated that the heat transfer coefficient is improved by a factor related to De.

Numerical studies for uniform wall heat flux with peripherally uniform wall temperature, with 1 < De < 1200, 0.005 < Pr < 1600, and 0.01 < δ < 0.1, were performed by Kalb and Seader [40]. For Pr > 0.7, it was shown that the local Nusselt number in the area of the inner wall was always less than that of a straight tube. The local Nusselt number on the outer wall continued to increase with increasing De. Correlations were developed to estimate Nu. Janssen and Hoogendoorn [41] studied experimentally and numerically the laminar convective heat transfer for both isoflux and isothermal heated HCTs. The effect of the different kinds of boundary conditions is shown to be small. Fully developed laminar flow and heat transfer was studied numerically by Zapryanov et al. [42]. Their work focused on the case of constant wall temperature and showed that Nu increased with increasing Pr, even for cases at the same De.

Xin and Ebadian [43] experimentally studied the effect of Pr and geometric parameters on the convective heat transfer characteristics in uniformly heated HCTs. Empirical correlations were proposed for the fully developed flow 1200 < Pr < 0.884 and 0.0637 < δ < 0.8149. Bai et al. [6] experimentally studied the turbulent heat transfer in horizontal HCTs under constant heat flux. They concluded that the local heat transfer coefficient on the outer wall could be 3–4 times that of the inner wall, and it is observed that Nu for horizontal HCT is less than that for vertical one for the same conditions. Prabhajnan et al. [44] compared experimentally the heat transfer coefficient for HCT versus straight tube heat exchangers. They found that the HCT had a heat transfer coefficient 1.16 and 1.43 times larger than for the straight tube heat exchanger for 40 and 50 °C, respectively.

Rennie and Raghavan [45,46] performed experimental and numerical studies on a double-pipe helical heat exchanger. Results showed that the overall heat transfer coefficients increase with higher inner Dean number. Jayakumar et al. [47] performed an experimental and numerical estimation of heat transfer in vertical shell and coil heat exchangers for turbulent regime (2000 < De < 12,000 and 1 < Pr < 3.5). A correlation was proposed numerically and validated against experiments. Jayakumar et al. [48] numerically analyzed the characteristics of heat transfer under turbulent flow of water through HCTs for constant temperature and constant wall heat flux boundary conditions. Results showed that local Nusselt number on the outer side of the HCT is higher than that at the inner side. The authors developed correlations to estimate Nu for 14,000 < Re< 70,000, 1000 < De< 22,000, 3 < Pr < 5, and 0.05 < δ < 0.2.

Shokouhmand et al. [49] carried out an experimental study of shell and coil heat exchangers using Wilson plots for both parallel and counter flow configurations. Salimpour [50,51] experimentally studied the heat transfer characteristics for laminar flow of oil and water inside HCT counter flow configuration. Empirical correlations were developed to predict the heat transfer coefficients of both fluids inside the HCT as a function of De, Pr, and δ. Purandare et al. [52] presented a comparative analysis of the different correlations given by the different researchers for helical coil heat exchanger. The analysis showed that for low Re, the graphs of Nu versus Re are steeper than that at high Re. In addition, HCTs are efficient in low Re. The analysis also showed that increasing δ enhances the intensity of secondary flow and consequently increases Nu.

The aforementioned literature survey indicates that the majority of studies were performed on HCT with isothermal and isoflux boundary conditions or shell and coil heat exchangers with small ranges of HCT configurations and fluid operating conditions. So, the present study aims to investigate experimentally the effect of coil curvature on characteristics of convective heat transfer in horizontal shell and coil heat exchangers with same torsion over a wide range of fluid operating conditions. Present measurements were utilized to introduce experimental correlations for the average Nusselt numbers and the HCT-Fanning friction factor as a function of Reynolds number, coil curvature ratio, and Prandtl number.

2 Experimental Apparatus

The experimental facility employed in the present investigation consists of heating and cooling units, shell and coil heat exchanger, pumps, measuring devices, valves, and the connecting pipes. Figure 1 is a schematic diagram of the experimental apparatus. In addition, Fig. 2 represents photo for the present setup. Two cylindrical containers of 50 l made of stainless steel (2 mm wall thickness) were employed for hot and cold fluid tanks. Each tank was installed inside 2 mm thick galvanized steel tanks with 20 mm gap, which was injected by spray foam insulation to minimize the
heat loss or gain. An electric heater of 6 kW rated power was fixed horizontally on the bottom of the heating tank and performed the function of heating the water to the required temperature. The heat was removed from the cooling tank by two refrigeration units of 10.5 kW cooling capacity. The electric heater and the refrigeration cooling units operate based on pre-adjusted digital thermostats, which were used to keep constant temperatures of the liquids directed to the heat exchanger.

As illustrated in Fig. 1, each circuit contains bypass line and ball valve to control the mass flow rate directed to the heat exchanger. Two identical flow meters (1.7–18 l/min) were used to measure the volume flow rates directed to the test section. Twenty eight k-type thermocouples of 0.1 mm diameter were installed within each test section to measure the temperatures. Four thermocouples were inserted into the flow streams, at approximately 60 mm from the heat exchanger ports, to measure the inlet and exit temperatures of the shell and HCT fluids.

Twenty thermocouples were used to measure the HCT wall surface temperatures. They were mounted at ten equally distanced (441.5 mm) positions on the HCT surface, with installing two thermocouples at each position on the outer and inner diameter of the coil. To achieve higher accuracy in calculation of flow rate, four thermocouples were installed at inlet and exit of flow meters to record the flow temperature. All thermocouples were connected to a digital thermometer indicator with resolution of 0.1 °C to display the thermocouples outputs. A digital differential pressure transducer was employed for measuring the pressure drop of water across the HCT. Two identical 1.5 hp rated power centrifugal pumps were installed to circulate the hot and cold water. Flexible nylon and polyvinyl chloride (PVC) tubes were used for all connections.

Five configurations shell and coil heat exchanger were constructed with different HCT curvature ratios. Due to the variation of curvature ratio ($\delta = d_1/d_t$), the coil pitch ($p_r$) and consequently number of turns ($N$) are varied to sustain constant coil torsion ratio ($\lambda = p_r/nD_t$) of 0.0895. The dimensions of the copper tube used in each coil are 4.415 m lengths, 9.52 mm outer diameter, and 8.3 mm inner diameter. The characteristic dimensions of
the different configurations are revealed in Table 1. A photo and schematic layout of the shell and coil heat exchanger are shown in Fig. 3.

The shell of the heat exchangers was made of mild steel (2 mm wall thickness) and was formed as cylindrical shape with the aid of rolling machine in addition to welding. Two nipples of same material and 4 mm wall thickness were welded on both ends of the shell. The distance between the nozzles centers and the neighboring shell end was 50 mm, which made the HCT partially block the opening as recommended by Kupprn [53]. Ten holes of 1 mm diameter were made in the shell wall to pass the thermocouples to their positions on the HCT surface. The holes were drilled directly facing the positions of the thermocouples to provide the smallest length of the thermocouples in the shell to minimize their effects on the shell flow. The outer surface of the shell was thermally insulated using a layer of each ceramic fiber, asbestos rope, and glass wool. Finally, all equipments were assembled: the shell and coil heat exchanger, heating and cooling units, pumps, ball valves, connecting lines, and the measuring devices.

3 Experimental Procedures and Data Reduction

The first step in collecting data from the system was to fill the heating and cooling tanks with water from the local water supply. Then, the heater, the cooling units, and the pumps were operated. Inlet temperatures of the water in both sides were adjusted by regulating the temperatures of the heating and cooling tanks through their thermostats. The flow rates were adjusted through the flow meters and the installed valves, which were regulated to obtain the required flow rates in the primary lines and the remainder is bypassed to the tanks. The range of the operating conditions is given in Table 2.

During the operation, the steady state condition is conducted when the maximum variation of 0.5°C for each thermocouple reading is within 20 min. It should be noted that for heat transfer calculations, the fluid properties of the shell, and HCT sides were calculated at the bulk temperatures, $T_{sh,m}$ and $T_{i,m}$, respectively. While for pressure drop calculations, the HCT water properties were calculated at the film temperature, $T_f$, as recommended by Schmidt [33]. The bulk and film temperatures are calculated as follows:

$$T_{sh,m} = \frac{(T_{sh,i} + T_{sh,o})}{2} \quad (1)$$

$$T_{i,m} = \frac{(T_{i,i} + T_{i,o})}{2} \quad (2)$$

$$T_{f} = \frac{\sum t_{f,s}}{20} \quad (3)$$

$$T_i = \frac{(T_{i,m} + T_{i,s})}{2} \quad (4)$$

The inner surface temperature of the HCT wall was taken equal to the outer surface due to very low conduction resistance of the tube wall. The water thermophysical properties were evaluated from Remsburg [54].

The measurements of the flow rates and inlet and outlet temperatures of both streams of the heat exchanger were used to calculate heat transfer rates on the HCT and shell sides ($Q_i$ and $Q_{sh}$) as

$$Q_i = \dot{m}C_p(T_{i,i} - T_{i,o}) \quad (5)$$

Without heat gain or loss from the heat exchanger, there is an energy balance between the two streams ($Q_i = Q_{sh}$). In the real experiments, due to measurement errors or heat gain/loss, there would always be some discrepancy between the two heat transfer rates. Therefore, the arithmetical average of the two, $Q_{ave}$, can be used as the heat load of the exchanger. For all experimental tests, the heating and cooling loads calculated from the hot and cold experiments, due to measurement errors or heat gain/loss, there would always be some discrepancy between the two heat transfer rates. Therefore, the arithmetical average of the two, $Q_{ave}$, can be used as the heat load of the exchanger. For all experimental tests, the heating and cooling loads calculated from the hot and cold sides did not differ by more than ±1.78%.

Table 1 Characteristic dimensions of the used shell and coil heat exchangers

<table>
<thead>
<tr>
<th>HCT No.</th>
<th>$D_h$ (mm)</th>
<th>$\delta$</th>
<th>$d_c$ (mm)</th>
<th>$\lambda$</th>
<th>$L_h$ (mm)</th>
<th>$L_{sh}$ (mm)</th>
<th>$D_{sh,i}$ (mm)</th>
<th>$D_{sh,b}$ (mm)</th>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>69.5</td>
<td>0.1194</td>
<td>19.52</td>
<td>0.0895</td>
<td>405</td>
<td>505</td>
<td>271</td>
<td>205.1</td>
<td>20.21</td>
</tr>
<tr>
<td>2</td>
<td>105.0</td>
<td>0.0796</td>
<td>29.52</td>
<td>10</td>
<td>62.085</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>140.5</td>
<td>0.0591</td>
<td>39.52</td>
<td>54</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>176.0</td>
<td>0.0472</td>
<td>49.52</td>
<td>7.98</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>211.5</td>
<td>0.0392</td>
<td>59.52</td>
<td>6.64</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
\[ Q_{ave} = \frac{|Q_i| + |Q_h|}{2} \]  

(7)

The heat load of the heat exchanger, \( Q_{ave} \), was used to calculate the average heat transfer coefficient for the HCT side fluid, \( \hat{h}_{sh} \), and then the average Nusselt number for the HCT side fluid, \( \bar{N}_{th} \), as follows:

\[ Q_{ave} = \hat{h}_{sh} A_{t,i} (T_{i,m} - T_{i,s}) \]  

(8)

\[ \bar{N}_{th} = \frac{\hat{h}_{sh} d_{i,i}}{k_i} \]  

(9)

The overall thermal conductance was calculated from the temperature data and flow rates using Eq. (10) as

\[ U_{oA,i} = \frac{Q_{ave}}{\Delta T_{LM}} \]  

(10)

\[ \Delta T_{LM} = \frac{(T_{i,m} - T_{sh}) - (T_{i,o} - T_{sh,i})}{\ln \left( \frac{T_{i,m} - T_{sh}}{T_{i,o} - T_{sh,i}} \right)} \]  

(11)

Neglecting the thermal resistances of the tube wall and fouling, the overall thermal conductance can be expressed in terms of convection thermal resistances. The average heat transfer coefficient for the shell side fluid, \( \hat{h}_{sh} \), and then the average Nusselt number for the shell-side fluid, \( \bar{N}_{th,h} \), can be obtained as follows:

\[ \frac{1}{U_{oA,h}} = \frac{1}{\hat{h}_{sh} A_{t,h}} + \frac{1}{\hat{h}_{sh} A_{h,i}} \]  

(12)

\[ \bar{N}_{th,h} = \frac{\hat{h}_{sh} D_{sh,h}}{k_h} \]  

(13)

The more general definition of the hydraulic diameter of the shell side, \( D_{sh,h} \), described in Shah and Sekulic [55] was used in the present work

\[ D_{sh,h} = \frac{4V_h}{A_{h,c}} = \frac{4(V_{sh,i} - V_{o,c})}{A_{h,c}} = \frac{D_{sh,i} L_{sh} - d_{i,i}^2 L_i}{D_{sh,h} L_{sh} + d_{i,i}^2 L_i} \]  

(14)

HCT and shell Reynolds number can be written as follows:

\[ Re_i = \frac{4d_{i,i}}{\pi \hat{h}_{sh} \mu_i} \]  

(15)

\[ Re_{sh} = \frac{4d_{sh,h}}{\pi \hat{h}_{sh} \mu_{sh}} \]  

(16)

The Fanning friction factor for the fluid in circulation inside the HCT, \( f_c \), was calculated with the following equation:

\[ f_c = \frac{\Delta P_c \frac{d_{i,i}}{2 L_i \rho_i u_i^2}}{\frac{\Delta P_c}{2 L_i \rho_i u_i^2} = \frac{\pi^2 \rho_i d_{i,i}^2}{32 L_i m_i^2}} \]  

(17)

Daily and Harleman [56] reported that the developed region in HCTs may be along a distance equal to 50 diameters of the HCT. Also, Nigam et al. [57] presented that the fully developed region in HCTs is formed after a distance equal to 30 diameters of the HCT. These values represent 5.64–9.4% of the total length of the HCTs used in the present study, which can be neglected and the fully developed profiles are confirmed.

4 Uncertainty Analyses

In general, the accuracy of the experimental results depends on the accuracy of the individual measuring instruments and techniques. It should be noted that according to the manufacturer, uncertainty (\( \omega \)) in the HCT outer and inner diameters is ±0.01 mm, which can be neglected. The uncertainty in the measured coil and shell dimensions was assumed to be ±0.5 mm; this was guessed quantity from meter scale. In addition, the uncertainty applied to the thermal properties of water was assumed to be ±0.1%. The uncertainty is calculated based upon the root sum square combination of the effects of each of the individual inputs as introduced by Kline and McClintock [58]. For all experimental runs, the uncertainty in \( Re_i \) and \( Re_{sh} \) was ±1.67%. Also, the average uncertainty was ±4.96% in \( \bar{N}_{th} \), ±2.57% in \( \bar{N}_{th,h} \), ±2.16% in \( U_o \), and ±3.66% in \( f_c \).

5 Results and Discussion

First, the experimental apparatus and procedures were validated by comparing the results of \( \bar{N}_{th} \) for water flowing through the HCT with \( \bar{N}_{th} \) reported from literature. From the literature review, it is obvious that there is lack in the correlations required to calculate the heat transfer coefficient for applied shell and coil heat exchangers. On the contrary, there are a number of correlations in the literature for the \( \bar{N}_{th} \) for water flowing through the HCT with isoflux and isothermal wall boundary conditions.

Here, the present experimental data for \( \bar{N}_{th} \) were validated with the experimental data obtained by Xin and Ebadian [43], and Rogers and Mayhew [39] as they were used by Purandare et al. [52]. In addition, another comparison of the experimental data for HCT-Fanning friction factor with the results of White [28] and Prasad et al. [34] was performed. The results of these comparisons are shown in Fig. 4. From this figure, it can be seen that the experimental results for both heat transfer and friction factor calculations are in good agreement with previous studies.

A series of 295 experiments were carried out on five heat exchangers shown in Table 1, which were constructed with different coil curvature ratios. These configurations were tested at different mass flow rates and inlet temperatures for the two sides of heat exchanger as presented in Table 2. The corresponding dimensionless parameters are 6471 ≤ \( Re_i \) ≤ 62085, 2.86 ≤ \( Pr_i \) ≤ 4.43, 129 ≤ \( De_l \) ≤ 20927, 179 ≤ \( Re_{sh} \) ≤ 1384, 3.25 ≤ \( Pr_{sh} \) ≤ 7.54, and 0.0392 ≤ \( \delta \) ≤ 0.1194.

5.1 Heat Transfer Results. Results of heat transfer in terms of HCT and shell Nusselt numbers are presented for the different governing parameters. First, the operating conditions are hold constant in the shell side at \( T_{sh} = 20^\circ C \) and \( V_{sh} = 6.0181/\text{min} \), while the HCT operating conditions are varied according to
Table 2. Figure 5 illustrates the effect of coil curvature ratio on HCT average Nusselt number versus HCT Reynolds number for 0.0392 < δ < 0.1194 at $T_{i, sh} = 55^\circ C$.

From Fig. 5, it is clear that increasing coil curvature ratio increases HCT-average Nusselt number. The average increase in the HCT-average Nusselt number is of 160.3–80.6%, and the average increase in the overall heat transfer coefficient is of 116.9–110.8% when the coil curvature ratio increases from 0.0392 to 0.1194 for 6471 ≤ Re < 62085. This can be attributed to increasing the centrifugal force with higher coil curvature ratio, which induces more effective secondary flow. Also, it is clear that increasing HCT-Reynolds number increases the HCT-average Nusselt number at the same coil curvature ratio. This can be returned to the effective secondary flow due to centrifugal force, which increases at higher Reynolds number.

The thermal performance of the shell side is introduced for 179 < Re < 1384, 5.25 ≤ Pr < 7.54, and 0.0392 ≤ δ ≤ 0.1194. The inlet flow rate and temperature at HCT fluid remain constant at 6.018 l/min and 55°C, respectively. Figure 6 shows the shell average Nusselt number versus shell side Reynolds number at $T_{i, sh} = 20^\circ C$.

From Fig. 6, it is clear that increasing coil curvature ratio leads to increase $Nu_{sh}$ even at same $Re_{sh}$. The average increase is of 224.3–92.6% in shell Nusselt number and 210.8–93.2% in the overall heat transfer coefficient when the coil curvature ratio increases from 0.0392 to 0.1194 for 179 ≤ $Re_{sh} ≤ 1384$. This is because of increasing number of HCT turns and decreasing coil pitch associated with increasing δ provides more sequential fluid impingement with the coil surface, and consequently enhances $Nu_{sh}$ and $U_d$. Also, it is clear that increasing $Re_d$ increases $Nu_{sh}$ and $U_d$ at same δ and $T_{i, sh}$. This can be attributed to increasing the fluctuations and fluid layers mixing around the coil turns by increasing $Re_{sh}$.

The influence of the coil form ($p_c$ and $N$) with the same tube length and the same coil torsion on the HCT average Nusselt number and the overall heat transfer coefficient for the five configurations at $T_{i, sh} = 55^\circ C$, $T_{i, d} = 20^\circ C$ and $V_{sh} = 6.018 l/min$ are shown in Figs. 7 and 8. The results are presented as a function of Dean number ($De = Re_d \delta^{-1/2}$) instead of $Re_d$ to compare the obtained values of $Nu_{sh}$ and $U_d$ at the same centrifugal force inside the HCT.

From Fig. 7, it is clear that the effect of coil form ($p_c$ and $N$) on HCT average Nusselt number is almost insignificant for a specific $De_d$. This can be returned to the same fabricated coil ratio and the same driving centrifugal force inside HCT for a specific Dean number. However, the coil form effect on the overall heat transfer coefficient is noticeable at the same $De_d$ with shell flow rate remains constant as shown in Fig. 8. This can be attributed to higher turns number and small pitch provides more turbulence level as a result of sequential fluid impingement on the external surface of the coil which enhances shell side convection heat coefficient and consequently the overall heat transfer coefficient.

The influence of coil and shell inlet temperatures on the thermal performance of the heat exchanger ($Nu_{sh}$ and $Nu_{dh}$) is studied for 0.0392 < δ < 0.1194. The influence of fluid inlet temperature inside coil on the HCT average Nusselt number at δ = 0.0591 is shown in Fig. 9. The experimental runs were performed for coil inlet fluid temperature at $T_{i, sh} = 45, 55$ and 65°C corresponding to 2.86 ≤ Pr ≤ 4.43.

The effect of shell fluid inlet temperature at δ = 0.0591, $T_{i, sh} = 15, 20$, and 25°C is shown in Fig. 10.

For all tested heat exchangers, it is clear that as the inlet temperature at both sides increases, $Nu_{sh}$ and $Nu_{dh}$ decrease at same Reynolds number. This can be attributed to the decrease in Prandtl number with increasing the fluid temperature.

5.2 HCT Friction Factor. Experimental runs were carried out to study the effects of coil curvature and HCT fluid inlet temperature on friction factor inside HCT. The mass flow rate is varied from 1.7 to 11.158 l/min and coil inlet fluid temperature of
T = 45, 55, and 65°C. The corresponding dimensionless parameters are 6389 ≤ Re ≤ 60, 227 and 0.0392 ≤ δ ≤ 0.1194. Figure 11 presents the effect of coil curvature ratio for three different inlet temperatures at T_{in} = 20°C and V_{in} = 6.018 l/min.

From Fig. 11, it is seen that Fanning friction factor increases noticeably when coil curvature ratio increases at the same Re_t. The average increase in HCT-friction factor is of 33.2–7.7% when the coil curvature ratio increases from 0.0392 to 0.1194. This can be attributed to the higher centrifugal force that induces more secondary flow and consequently the friction factor inside the HCT.

Figure 12 shows the effect of HCT fluid inlet temperature on the Fanning friction factor at δ = 0.1194 and 0.0392. It is clear that the effect of T_{in} on f_c is nearly insignificant especially at higher Ret. This may be returned to the low effect of viscous force compared with the higher centrifugal force, which is the dominant at HCT Reynolds number.

6 Correlations for Average Nusselt Numbers and Fanning Friction Factor

Using the present experimental data, correlations were developed to predict the average Nusselt number of both sides of shell and coil heat exchanger and the Fanning friction factor inside the HCT.

The HCT average Nusselt number is correlated as a function of HCT Reynolds and Prandtl numbers and coil curvature ratio

\[ \text{Nu}_{ht} = 0.00241 \ Re^{0.09293} \ Pr^{0.0177} \ \delta^{0.556} \]  \hspace{1cm} (18)

Equation (18) is applicable for 6471 ≤ Re ≤ 62,085, 2.86 ≤ Pr ≤ 4.43, 1329 ≤ De ≤ 20,927, and 0.0392 ≤ δ ≤ 0.1194 with maximum deviation of 13.8%.

From the test runs that were performed for the shell-side, a correlation to estimate \( \text{Nu}_{sh} \) was obtained as follows:

\[ \text{Nu}_{sh} = 4.4275 \ Re^{0.4922} \ Pr^{1.5676} \ \delta^{0.6964} \]  \hspace{1cm} (19)

Fig. 10 Shell Nusselt number versus shell Reynolds number at different shell inlet temperatures

Fig. 11 Variation of HCT-Fanning friction factor with HCT-side Reynolds number at different HCT-curvature ratios: (a) \( T_{in} = 65°C \), (b) \( T_{in} = 55°C \), and (c) \( T_{in} = 45°C \)

Fig. 12 Effect of HCT inlet temperature on the HCT Fanning friction factor: (a) δ = 0.1194 and (b) δ = 0.0392

Fig. 13 Comparison of experimental values for HCT average Nusselt number with that correlated by Eq. (18)

Fig. 14 Comparison of experimental values for shell average Nusselt number with that correlated by Eq. (19)
Equation (19) is applicable for $179 \leq \text{Re}_{\text{sh}} \leq 1384$, $5.25 \leq \text{Pr}_{\text{sh}} \leq 7.54$, and $0.0392 \leq \delta \leq 0.1194$ with maximum deviation of 15%.

Additionally, a correlation for Fanning friction factor in the HCT was obtained within $6389 \leq \text{Re}_t \leq 60,227$, $1286 \leq \text{De}_t \leq 20,284$, and $0.0392 \leq \delta \leq 0.1194$ with maximum deviation 4.6%.

\[
f_c = 0.04883 \text{Re}^{-0.1372} \delta^{0.105} \tag{20}
\]

From these figures, it is evident that the proposed correlations are in good agreement with the present experimental data (Figs. 13–15).

7 Conclusions

The present work was carried out to investigate the heat transfer characteristics in shell and coil heat exchanger, in addition to the pressure drop inside the HCTs. The influence of coil curvature and HCT and shell Reynolds numbers for the same coil torsion were discussed. The investigated ranges are $6471/20$ and $HCT$ and shell Reynolds numbers for the same coil torsion characteristics in shell and coil heat exchanger, in addition to the torsion characteristics.

From these figures, it is evident that the proposed correlations are in good agreement with the present experimental data (Figs. 13–15).

8 Acronyms and Abbreviations

<table>
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<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>HCT</td>
<td>helically coiled tube</td>
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<tr>
<td>PVC</td>
<td>polyvinyl chloride</td>
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</table>

9 References

10. Rennie, T. J., 2004, Numerical and Experimental Studies of a Double-Pipe Helical Heat Exchanger, Department of Bioresource Engineering, McGill University, Montreal, Canada.