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EXPERIMENTAL HEAT TRANSFER ANALYSIS FROM HELICAL COILED TUBES WITH THE SAME SURFACE AREA

Summary

Helical coiled tubes are commonly used in water storage tanks. In this study, an experimental investigation was carried out to obtain the heat transfer characteristics of different geometric dimensions of helical tubes under steady state conditions. Helical coiled tubes of different geometric dimensions with the same overall length and total surface area were fabricated from the same copper tubes. The helical coiled tubes were placed in a hot water tank which could be adjusted to different water temperatures. Cold water was pumped into the helical coiled tubes at different flow rates at 20 °C. The experiments were carried out for laminar flow in the range of *Re* numbers between 3394 and 8332. The helical coiled tube *Nu* number was determined and compared with the literature. Then, the effectiveness of the helical coiled tubes was calculated using the *ε-NTU* method.

Key words: *Heat exchanger, helical coiled tube, ε-NTU, Nu number*

1. Introduction

Heat exchangers of various kinds have been developed for a wide variety of applications such as air conditioning and refrigeration systems [1,2], power plants [3], the food industry [4] and heat recovery systems [5]. Helical coiled heat exchangers are used in many engineering fields due to their remarkable heat transfer performance, compact structure, and low production costs. As fluid passes through a tube with a helical coil structure, the curvature of the helix creates a centrifugal force, giving rise to a secondary flow [6]. Secondary flow increases the mixing of fluids, which in turn increases heat transfer.

Many researchers have conducted heat transfer studies on helical coiled heat exchangers. Ali [7] carried out an experimental study to investigate heat transfer in horizontal helical coiled tubes under steady state conditions. Helical coiled tubes were uniformly heated in the air. Average heat transfer coefficients were obtained under laminar natural convection conditions. A comparison was carried out between straight tubes and helical coiled tubes with similar dimensions by Prabhanjan et al. [8] who found that the heat transfer coefficient is increased by using helical coiled heat exchangers. Prabhanjan et al. [9] experimentally investigated natural convection heat transfer in helical coiled heat exchangers in water. They also developed a model to predict the water outlet temperature from the heat exchanger. The results of the developed prediction model were compared with the experimental results and the authors reported that the results were consistent. Pawar and Sunnapwar [10] experimentally investigated convection heat transfer in helical heat exchangers placed in water under steady state conditions. They used three heat exchangers with different geometrical properties. The water in the tank was maintained at a constant temperature of 60 °C throughout the experiments and cold water flowed through the tube. A total of 30 tests were performed on three different heat exchangers for 10 different cold water flow rates. At first, the Nusselt number was correlated with a dimensionless number 'M'. According to their reports, the developed correlations are in very close agreement with the findings of earlier researchers. Neshat et al. [11] carried out experimental and numerical research to investigate natural convection occurring on the outer surface of helically coiled heat exchangers. A total of four helical heat exchangers with two different curvature ratios were used in the experimental study. Each heat exchanger was placed both horizontally and vertically in the tank. The study showed that the vertically placed heat exchanger is more beneficial than the horizontal one when L/d (the total tube length/tube diameter) > 90.546. In addition, the Nusselt number increased with the increase in the heat exchanger length. Amori [12] experimentally investigated the thermal and hydraulic properties of heat exchangers consisting of helical tubes immersed in cold water. Two types of heat exchangers were tested: a vertical single tube helical coil and three vertical helical coils with parallel connections. In the experimental tests, the pressure drop and cold and hot water temperatures were measured at different hot water flow rates. Comparing the single tube configuration, the triple heat exchanger exhibited a notable enhancement in heat transfer. According to the *ε-NTU* method, the efficiency of the triple heat exchanger was found to be higher than that of the single tube. Fernandez-Seare et al. [13] developed a numerical model to predict heat transfer and pressure drop in a helical coiled heat exchanger placed inside a water tank. Sheeba et al. [14] conducted a study to determine the heat transfer characteristics of tubes in tube helical coiled heat exchangers. They reported that higher Nu numbers are obtained with the use of helical coiled heat exchangers compared to the straight tube. In addition, it was found that the Nu number will increase with the increase in the Dean number. Missaoui et al. [15] investigated a variable pitch helical coiled heat exchanger which, compared to the use of a typical helical coil, increased the average heat transfer. Gilbile et al. [16] numerically analysed helical, spiral, and conical tube heat exchangers of similar diameters and lengths and, as a result, were able to obtain the heat transfer coefficients and heat transfer rates of these heat exchanger models.

According to the literature review, it can be seen that various studies have been carried out to increase heat transfer in helical coils. The application of corrugated and finned tubes is also used to improve heat transfer. In addition, investigating coils of different sizes and the effect of coil geometry on performance is another issue of interest. In the studies carried out on this subject, the effects of coil diameter or pitch values on heat transfer were investigated. However, it was observed that in addition to these geometrical features, another feature such as tube length (hence the surface area) or tube diameter varied. In the present study, coil models with the same tube length and same tube surface area were designed and fabricated with different geometrical properties (coil diameter and pitch) using the same copper tube. All the experimental models were investigated under the same desired conditions. Firstly, the Nu numbers obtained from the experimental results were compared with the literature and then the effect of the geometrical feature on the heat transfer characteristics were demonstrated in comparison using the *ε-NTU* method.

2. Materials and Methods

2.1 Experimental Apparatus

Four different heat exchangers were examined to explore the impact of the coil diameter and pitch on heat transfer in helically coiled tubes. Figure 1 illustrates the schematic view and the dimensions of the helically coiled tubes used.

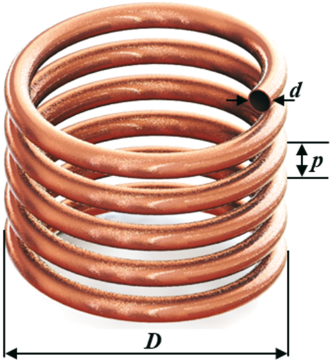

Fig. 1 Schematic view and dimensions of a helical coil

The wall thickness of the copper tubes is 1 mm (14 mm inside diameter and 16 mm outside diameter). The dimensions of the used coil configurations are given in Table 1. The total tube lengths and surface areas are also shown in Table 1 and those properties (lengths and surface areas) are almost equal for each model used in this study.

Table 1 Dimensional properties of the coil used in the experiments

Coil No	d , mm	D , mm	p , mm	N	L (m)	A_s (m^2)
1	16	210	25	4.5	2.74	0.138
2	16	170	25	5.5	2.66	0.134
3	16	145	25	6.5	2.64	0.133
4	16	170	32	5.5	2.67	0.134

Approximately 80 litres of hot water were stored in a water tank with a diameter of 35 cm and a height of 80 cm. Fernandez-Seare et al. [17] stated that if the coils are placed at the top of the tank, an almost constant temperature is maintained around the coil. Therefore, in the present study, the coils were placed 10 cm below the top of the tank to ensure steady state conditions. Two electric heaters with a total power of 7500 W were placed at the bottom of the hot water tank and controlled by a PID temperature controller. Thus, the temperature of the water in the tank was kept constant at the desired test temperatures (50-60-70-80 °C) with an accuracy of ± 0.8 °C. The cold water tank dimensions used for the experiments were 40 cm x 45 cm x 45 cm. An electric heater of 3750 W and a PID temperature controller were used to heat the water to the desired test temperature. Both the hot water and cold water tanks were fabricated from galvanised steel with a thickness of 2 mm and were insulated using 10 cm thick glass wool. Figure 2 shows the laboratory view of the experimental setup, while Figure 3 shows a schematic drawing of it.

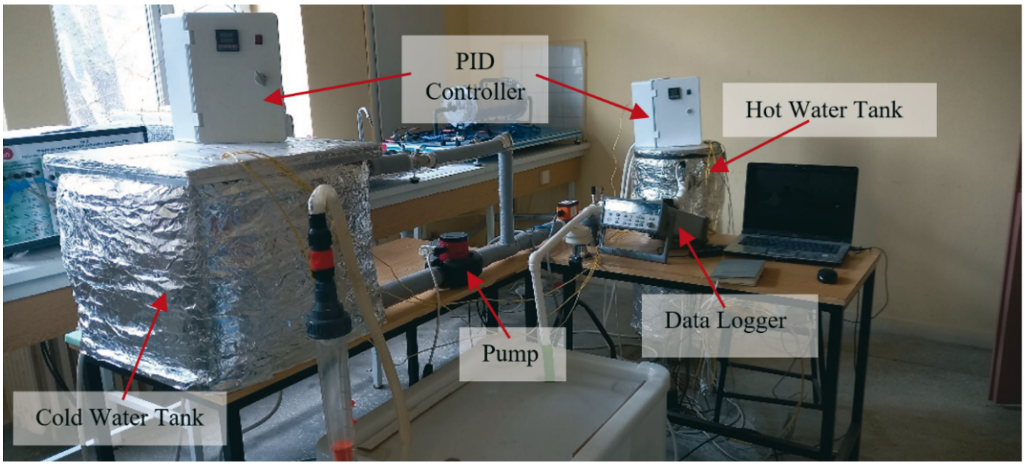

Fig. 2 Photo of the experimental setup

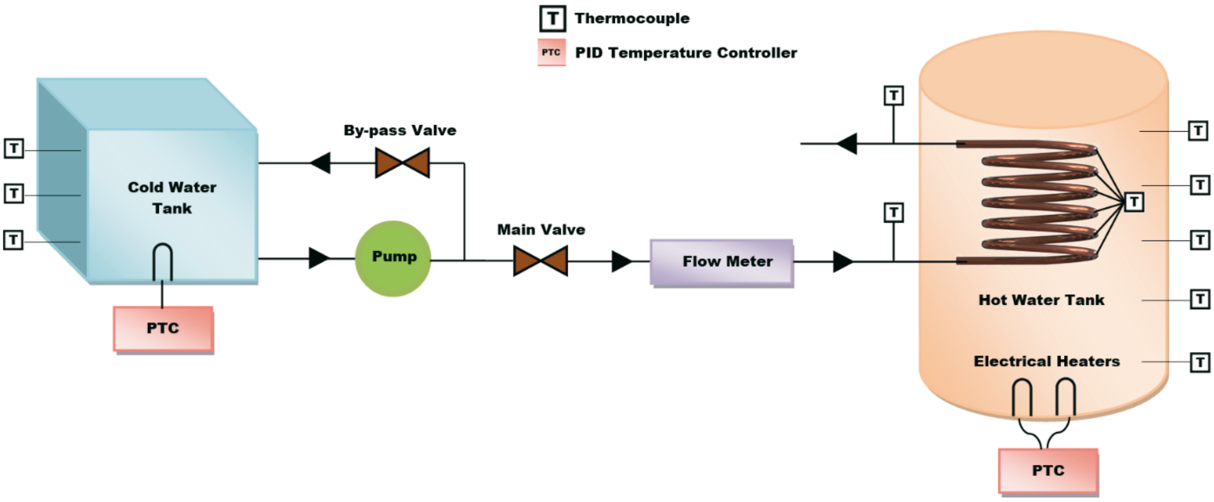

Fig. 3 Schematic drawing of the test system

Three thermocouples were placed in the cold water tank at intervals of 10 cm. Five thermocouples were used at 15 cm intervals in the hot water tank. Immersion-type thermocouples were installed in line to determine the inlet and outlet temperatures of the water in the coil. Surface-type thermocouples were used to obtain the surface temperature of the tube. The surface temperatures were measured at each turn of the coils to obtain the average surface temperature. In order to prevent the thermocouples from being affected by the temperature of the hot water, thermal insulators were placed on top of the thermocouples and covered with waterproof tape (Figure 4). To demonstrate the efficiency of the insulator, a thermocouple without an insulator was placed next to the insulated thermocouple and tested. There was a temperature difference of 5.1 °C between the insulated and uninsulated thermocouple at conditions of 50 °C and 2 l/min. This temperature difference shows that it is essential to do this insulation process and it should be done by researchers.

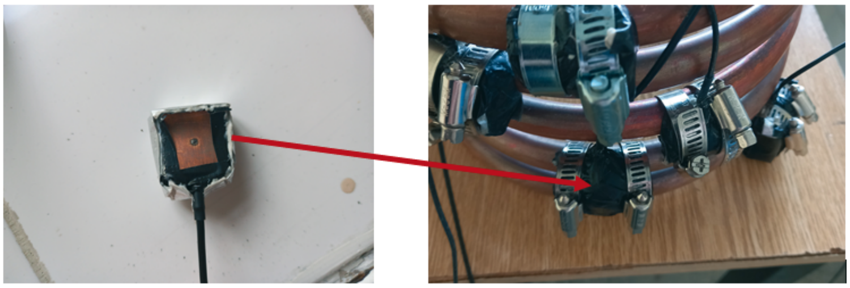

Fig. 4 Surface type thermocouples

J (Iron-Constantan) and K (Chromel–Alumel) types of thermocouples were used for temperature measurements. All the thermocouples were calibrated to meet the limits of error ±0.1 °C. Temperature measurements were recorded using an Agilent Technologies 34970A Data Logger. Cold water was pumped to the coil through a frequency converter circulation pump (Grundfos Alpha2 25-60 180). A bypass line was established to adjust the flow rate of the cold water to be sent to the coil. A Kobold MIK-5VA30KE14R flow meter was used to measure the cold water volume flow rate. This flow meter has a precision of 0.01 l/min and an accuracy of ±2%.

2.2 Experimental Procedure

Experiments were carried out for four different hot water temperatures (50-60-70-80 °C) with different cold water volume flow rate conditions (2 - 3 - 4 and 5 l/min). Thus, a total of 64 tests were performed for four different cold water volume flow rates, four different hot water temperatures, and four different helical coiled heat exchangers. In all the experiments, the cold water inlet temperature was kept constant at 20 °C. After reaching the steady state conditions, data were recorded at 15 s intervals (which means that the last 12 items of data were used for the calculation). All tests were repeated a second time to check the precision of the experimental results.

The *Re* number was calculated within the range of 3394 to 8332 in the specified experimental conditions. The critical *Re* number calculations with known correlations that were given in the literature can be seen in Table 2. The laminar flow condition in the present study is seen according to Table 2.

Table 2 Critical *Re* numbers calculated according to the literature

	Coil 1	**Coil 2**	**Coil 3**
Schmidt [18]	10829	11483	12018
Srinivasan et al. [19]	8870	9698	10402
Mishra and Gupta [20]	8624	9285	9827
El Genk and Schriener [21]	8807	9470	10013

2.3 Heat Transfer Analysis

The thermophysical properties (*ρ, cp, μ, k*) of the water passing through the helical coils were assumed to be constant and were determined based on the average of the fluid's inlet and outlet temperatures.

The heat transfer from hot to cold water can be calculated from the following relations:

$$\dot{Q} = \rho \dot{V} c_p (T_\mathrm{o} - T_\mathrm{i}) = \dot{m} c_p (T_\mathrm{o} - T_\mathrm{i}) \tag{1}$$

$$\dot{Q} = UA\Delta T_\mathrm{lm}. \tag{2}$$

The logarithmic mean temperature difference can be calculated with Equation (3):

$$\Delta T_\mathrm{lm} = \frac{(T_\mathrm{t}-T_\mathrm{o})-(T_\mathrm{t}-T_\mathrm{i})}{\ln\frac{(T_\mathrm{t}-T_\mathrm{o})}{(T_\mathrm{t}-T_\mathrm{i})}}, \tag{3}$$

where T_i and T_o represent the inlet and outlet temperatures of cold water, respectively, and T_t denotes the temperature of the hot water within the tank.

The inside heat transfer coefficient was calculated with Equation (4):

$$h_\mathrm{in} = \frac{\dot{Q}}{A_\mathrm{in}\Delta T_\mathrm{in}}, \tag{4}$$

where ΔT_in is defined as the difference between the average temperature of the bulk fluid (average of the inlet and outlet temperatures) and the average temperature of the inner surface of the tube, and A_in is the inside surface area of the coil. The inner surface temperatures were calculated by using the thermal resistance R_th.

The inside *Nu* number can be calculated as follows:

$$Nu_\mathrm{in} = \frac{h_\mathrm{in} d_\mathrm{i}}{k}, \tag{5}$$

$$\dot{Q} = \frac{\Delta T_\mathrm{wall}}{R_\mathrm{th,wall}}. \tag{6}$$

The effectiveness of the heat exchanger was determined by using:

$$\varepsilon = \frac{T_\mathrm{i}-T_\mathrm{o}}{T_\mathrm{i}-T_\mathrm{t}}. \tag{7}$$

The *NTU* number can be calculated as follows:

$$NTU = \frac{UA}{(\dot{m}c_p)_{\min}} \ . \tag{8}$$

By using Equations (1)-(2) and (8), the *NTU* number is obtained as:

$$NTU = \frac{T_\text{o} - T_\text{i}}{\Delta T_\text{lm}} \, . \tag{9}$$

3. Results

In the present study, the heat transfer performance of helical coiled tubes was evaluated using models made from the same copper tube with the same overall tube length. The experiments were carried out at different cold water flow rates and different hot water temperatures. Based on the measured data, the heat transfer rate, the *Nu* number in the tube, the temperature difference of the cold water, the effectiveness, and the *NTU* values were calculated and presented in graphical form.

3.1 Nusselt Number Comparison with Previous Experimental Studies

In previous studies, some experimental correlations were proposed for determining the *Nu* number under laminar flow conditions in helical coiled tubes. In the present experimental study, the inside *Nu* number was calculated for coil no. 2 using the measured data at a 20 °C inlet temperature and at an 80 °C tank bulk temperature. The determined *Nu* numbers were compared with the previous studies [10,22,23] and the results compare well and are in agreement, as shown in Figure 5. As the volume fluid flow rate increases, there is a noticeable increment in the inside *Nu* number.

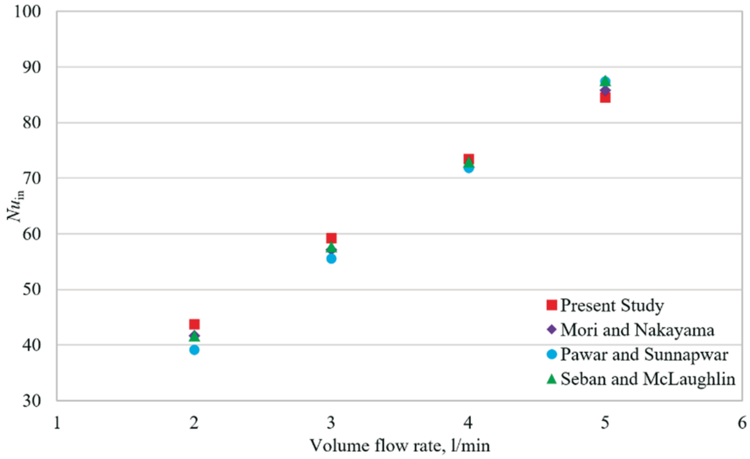

Fig. 5 Comparison of the Nu number with previous experimental studies (for coil no. 2)

3.2 Temperature Difference Results for Cold Fluid

Cold water temperature differences at different hot water temperatures and different cold water volume flow rates are illustrated in Figure 6 for coil no. 1. Cold water was pumped into the helical coiled tube at a temperature of 20 °C during the experiments. As expected, when the hot water temperature was increased, then the temperature difference increased for inlet and outlet cold water. The temperature difference also decreased when the cold water volume flow rate was increased. The highest temperature difference was 31.87 °C at a temperature of 80 °C hot water and a 2 l/min cold water volume flow rate. The lowest temperature difference was 7.80 °C at 5 l/min and a 50 °C hot water temperature.

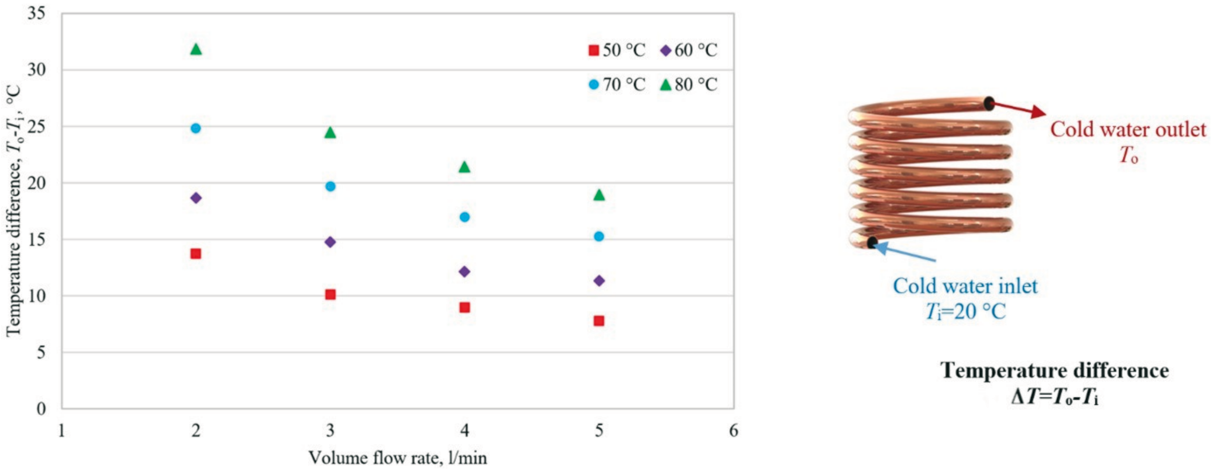

Fig. 6 Temperature difference in cold water at different hot water temperatures and different cold water volume flow rates (for coil no. 1)

3.3 Effect of the Helical Coil Diameter on Effectiveness

Figure 7 shows the effect of the fluid volume flow rate on the effectiveness of helical coiled tubes with different coil diameters placed in a hot water tank at different temperatures. As can be seen, increasing the volume flow rate decreases the effectiveness, while increasing the temperature increases the effectiveness in each model. In addition, effectiveness decreased as the coil diameter increased. This is because, as the coil diameter increases, the effect of the secondary flow caused by the centrifugal forces decreases. The highest effectiveness value was obtained in coil no. 3 which has the lowest diameter at a volume flow rate of 2 l/min at 80 °C. As a result of the tests, the effectiveness values were calculated between 0.25 - 0.56 for the three coil models.

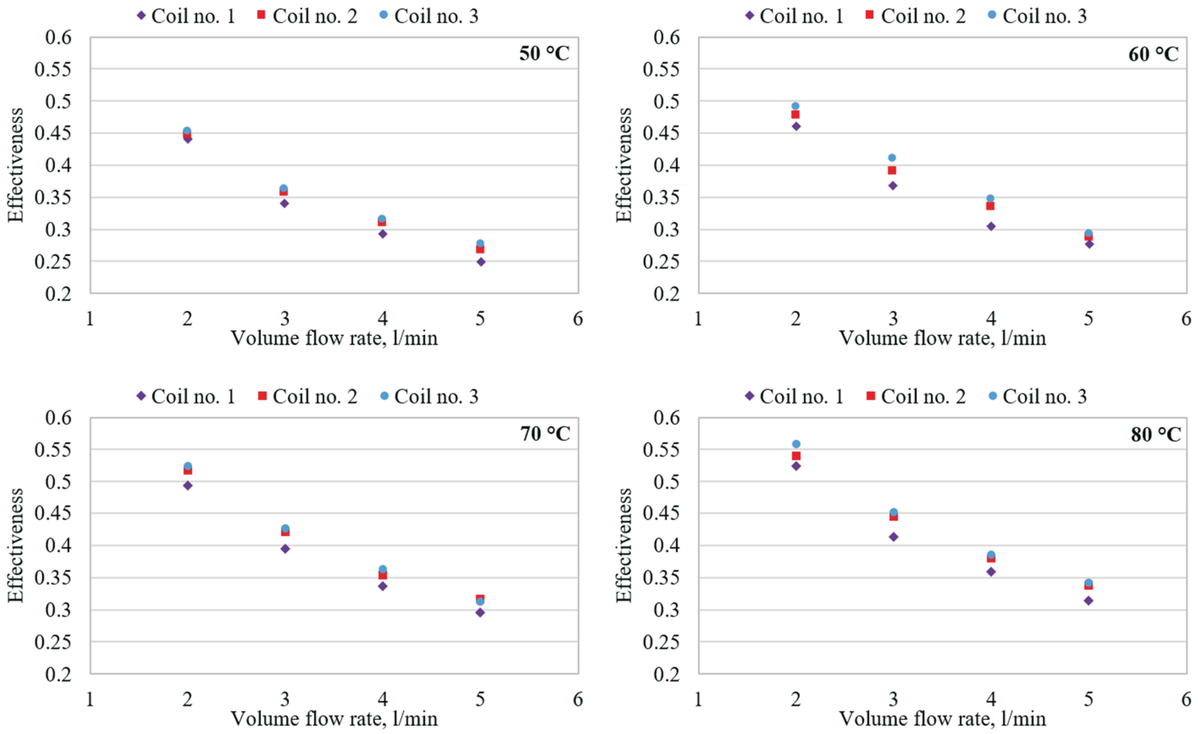

Fig. 7 Effect of fluid volume flow rate on effectiveness

When the cold water inlet and average hot water temperatures are kept constant, an increase in the cold water volume flow rate causes the outlet temperature of the cold water to decrease, as can be seen in Figure 6. This is because the heat transfer rate increases as the cold water volume flow rate rises. However, the increase in heat transfer is not as much as the growth in the cold water volume flow rate. This causes the outlet temperature of cold water to tend to fall as the flow rate of cold water increases. Accordingly, the effectiveness value decreases with the increase in the cold volume flow rate.

3.4 Effect of the Coil Diameter on the Heat Transfer Flow Rate

The heat transfer flow rates calculated at 50 °C and 4 l/min are given in Figure 8. The highest heat transfer flow rate occurred in coil no. 3 due to the higher secondary flow effect.

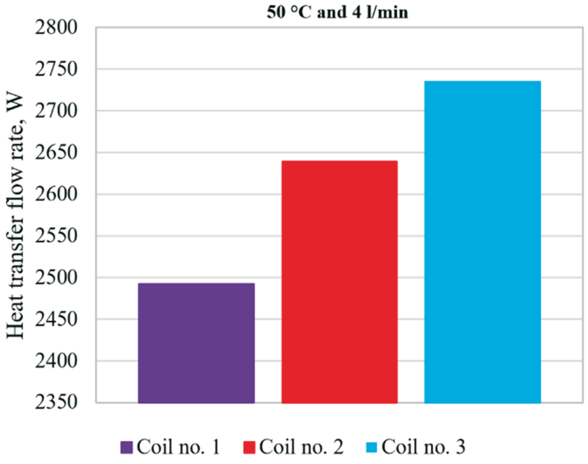

Fig. 8 Heat transfer flow rate of coiled tubes at 50 °C and 4 l/min

3.5 Effectiveness - *NTU* Comparison

The ε - *NTU* relationships for helical coiled tubes at different volume flow rates at a 60 °C constant tank bulk temperature are shown in Figure 9. As expected, the ε and *NTU* values are higher at low volume flow rates.

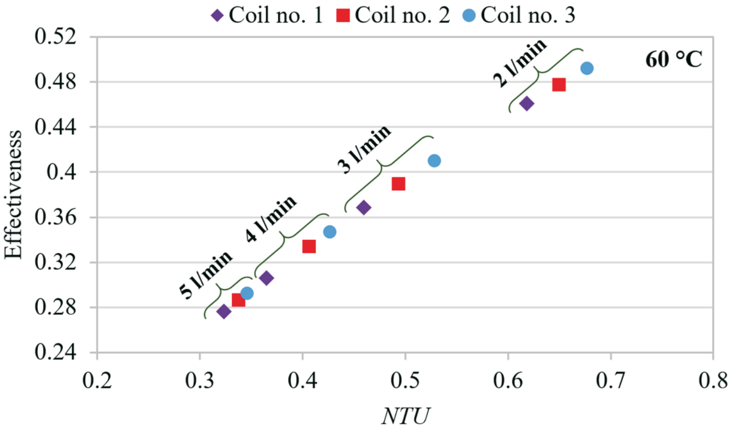

Fig. 9 Effectiveness – *NTU* relationship at 60 °C

3.6 Effect of Pitch on Effectiveness

A comparison was made between helically coiled tube nos 2 and 4 to investigate the effect of pitch. Looking at the dimensions of these coils from Table 1, it can be seen that only the pitch is different, while the length of the tubes and the surface areas of the tubes were almost the same. The calculated effectiveness values for different volume flow rates at an 80 °C hot water temperature are shown in Table 3. When the values are analysed, it is observed that augmenting the pitch increases the effectiveness. At the same time, this increment is not so significant for small pitch changes. Therefore, the effect of pitch on the effectiveness results are not given in detail.

Table 3 Effect of Pitch on Effectiveness

Volume flow rate	ε % (Coil 2)	ε % (Coil 4)
2 l/min	54.03	54.17
3 l/min	44.50	45.35
4 l/min	38.07	38.78
5 l/min	33.78	33.99

4. Conclusion

This study conducted experimental investigations to explore the effects of coil dimensions on the heat transfer characteristics in helical coiled tubes designed with an almost equal surface area. For this purpose, four different helical coiled tubes of different sizes were constructed. The coils were placed inside a hot water tank and cold water was pumped through the tubes. Experiments were carried out for four different hot water temperatures and four different cold water flow rates. The present study has some significant results for helical coiled tubes of the same length and surface area, which can be summarised as follows:

1. As the volume flow rate increases, there is a noticeable increment in the inside *Nu* number.
2. As the hot water temperature increases, the temperature of the cold water also grows. When the volume flow rate of cold water rises, the temperature difference of the cold water falls.
3. As the coil diameter of the helical coiled tube decreases, the effectiveness value increases. There was an average 7.8% difference in the effectiveness value between 210 mm and 145 mm coil diameters. It should particularly be pointed out here that the length and surface area of the helical coiled tubes were the same.
4. Increasing the pitch increases effectiveness. However, this increment is not significant for small changes in pitch.

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