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The Pipe Diameter Effect on Heat Transfer of Helical Coil Heat Exchanger in the Solar Water Heater Storage Tank

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ABSTRACT

Solar thermal collectors are widely applied in various areas; one of them is solar water heating system. Inside the solar water heating system, there is a heat exchanger system located on thermal storage tank. It needs to develop the most efficient heat exchanger with some limited installation area. Helical coil heat exchanger is chosen as an alternative for saving the installation space by the coil helix geometry. The main difference between the helical heat exchanger and shell and tube heat exchanger is the geometry. This geometry causes differences in heat transfer process, as a result of the secondary flow in the fluid. This study analyzed the effect of the pipe diameter variance to heat transfer of helical coil heat exchanger, applied to solar water heating systems, performed by using three helical coils with pipe diameters variation, with an outer diameter of 6.4; 4.9; 2.95 mm. The heat transfer performance was analyzed by dimensionless number relationship with Wilson Plot technique. The experiment showed that, the performance of helical coil heat exchanger is better at bigger diameter. Forced convection inside the pipe obeyed $\boldsymbol{Nu_i = C_i . Re^{0.7}}$ with various $\boldsymbol{C_i}$ number. The values of $\boldsymbol{C_i}$ are bigger at bigger pipe diameter and higher hot water temperature.

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INTRODUCTION

The solar energy has been utilized for some activities. Some technologies were developed related to the application of solar energy, one of them is solar collector (Murugan et al., 2022). The solar collector is an equipment to capture solar energy and convert it to heat to be transferred into working fluid. The solar collectors have been applied for some aspects, i.e., solar water heater, solar cooling and heating system, solar water desalination, industrial system, power system, etc (Saxena et al., 2020).

The solar water heater itself is a device which utilize solar radiation as an energy source (Missaoui et al., 2021). This device consisted by solar collector, storage tank, pump, heat exchanger, auxiliary heating system (can be in the form of electric heater), and heating control panel (Prabhanjan et al., 2004). There are some principles of solar collectors type, one of them is indirect heating which apply heat exchanger in the storage tank (Langerova et al., 2023). This indirect system works with collecting solar energy and circulate the heat through working fluid (Najafabadi et al., 2022). In some system, there are 2 heat exchangers with different principle, called them as HE I and HE II. The HE I working as heat supplier located in the solar collector to absorb heat from solar collector to distribute into working fluid, while the HE II work as heat absorber located in the storage tank to absorb heat from working fluid. The water collected from HE II then will be used as hot water for domestic and household supply.

Heat exchanger collector configuration can be in the form of shell and tube, double-pipe, shell and frame, coil helix, and etc (Yuan et al., 2024). Some studies stated that the helical coil heat exchanger has more advantages than the other type of heat exchangers due to its geometrical configuration. There is a secondary flow from a centrifugal force due to its curvature shape which contribute to more heat transfer performed in heat exchanger (Prabhanjan et al., 2002). This flow produces higher efficiency of heat transfer process. The performance analysis needs to determine the effect of geometrical variation, such as pipe diameter, curvature diameter, and pitch ratio to the heat transfer efficiency. More efficient heat transfer process will produce the optimal heat exchanger design, which probably produce less production and operational cost (Duan et al., 2024).

The previous studies had determined some performance analysis based on curvature variation in high temperature application. The curvature itself is a pipe to coil diameter ratio. The domestic solar water heater aims to produce the warm water which is comfortable for domestic use, e.g. around 40 ºC. Therefore, it needs to study the performance analysis when it is applied on medium temperature application (50 – 90 °C inlet water temperature). This research aims to identify the performance analysis based on pipe diameter variation, by determining some dimensionless number parameter. The relationship between Nusselt and Reynolds number inside the pipe was identified to define the heat transfer characteristic (Hozien et al., 2021). Karima E. Amori (Amori & Sherza, 2013) has been studied the heat transfer rate, pressure difference, heat transfer effectiveness, friction factor, and collector efficiency with different flow rate as 1.8, 3, 6, and 9L/minutes. The result showed that the heat transfer inside the coil pipe was increasing following the increment of flow rate; therefore, the collector efficiency was also increased

The other correlation between Nusselt and other dimensionless number for heat transfer inside the pipe was also experimented by Jayakumar. The equation (1) showed the relationship among Nusselt, Reynolds, Prandtl, and curvature ratio (Jayakumar, 2012).

$$Nu = 0{,}116\, Re^{0,71} Pr^{0,4} \delta^{0,11} \tag{1}$$

Comparison of heat transfer performance between helical coil heat exchanger and shell and straight pipe heat exchanger had been studied by some researchers. While Prabhanjan had also studied about a natural convection of helical coil pipe surface and its water bath. The heat transfer coefficient outside the pipe is not only affected by heat exchanger geometry, but also the water bath temperature of heat exchanger. However, the flow rate inside the pipe coil does not have impact to the natural convection process of heat exchanger (Prabhanjan et al., 2002).

METHOD

This research considered the heat exchanger system by using helical coil on storage tank of solar water heater. The heat circulation from solar collector was out of scope. Helical coil was located on the hot water bath, with the cold fluid was flowing through the coil pipe. The experiment was performed by prototype, laboratory scale with the scheme shown by Figure 1. The temperature measurement was performed on 4 locations, e.g. cold-water inlet, cold water outlet, the top side of hot water bath, and bottom side of hot water bath. This temperature data would be used to calculate the logarithmic mean temperature difference or LMTD.

The experiment performed three different coils with pipe diameter variation, but the same heat transfer area. The specification of each helical coil is shown by Table I. The data collection had been performed each 5 minutes range, with the period was 50 ms. The data should be recorded from the transient to steady state. The boundary condition of the research is shown by Table II. Each coil was tested by three different fluid flow rate and three different hot water bath starting temperature. Each experiment was repeated for three times.

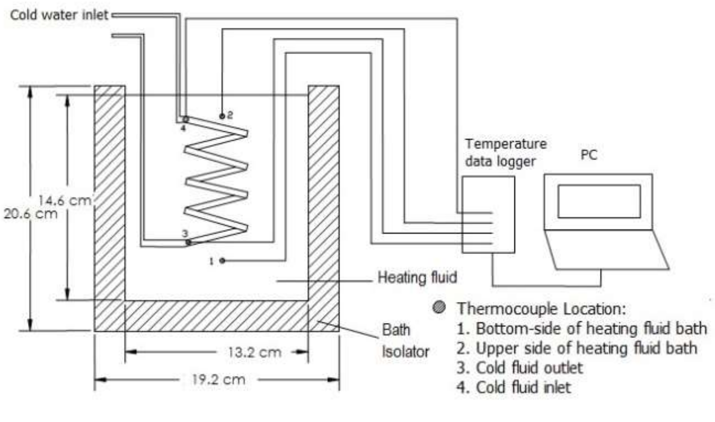

Figure 1. Experimental Scheme

Table 1. Coil Specification

Coil	Dimension						
	d_o (mm)	d_i (mm)	*Pitch* (mm)	D (mm)	N	H (mm)	A_o (m^2)
Coil I	6.4	4.05	10	90	7	55.4	0.038
Coil II	4.9	3.05	10	90	9	67.9	0.038
Coil III	2.95	1.45	10	90	15	107.95	0.038

d_o: Pipe outside diameter
d_i : Pipe inside diameter

D: Coil diameter
N: Number of coil winding
H: Helical coil height
A_o:Heat transfer area (by outside diameter)

Table 2. Experimental Scope

Coil I		**Coil II**		**Coil III**	
V **(m/s)**	***Re***	***v*** **(m/s)**	***Re***	***v*** **(m/s)**	***Re***
0.39	2698.75	0.68	3583.58	1.44	3354.54
0.25	1741.13	0.44	2311.99	1.01	2348.18
0.18	1285.12	0.33	1706.47	0.68	1583.04

v: Fluid velocity
Re: Reynolds Number

From the measured temperature, analyzed the heat received by cold fluid Q_c and logarithmic mean temperature difference (LMTD). Based on energy balance of helical coil heat exchanger on storage tank, the received heat of cold fluid was equal with the heat transferred from hot fluid. The equation for Q_c and $LMTD$is shown by equation (2), (3), and (4).

$$Q_c = \dot{m}_c \times c_{p_c} \times \left(T_{c_o} - T_{c_i}\right) \tag{2}$$

$$LMTD = \frac{\left(T_{h_i} - T_{c_o}\right) - \left(T_{h_o} - T_{c_i}\right)}{\ln\left(\frac{T_{h_i} - T_{c_o}}{T_{h_o} - T_{c_i}}\right)} \tag{3}$$

$$Q_c = Q_h \tag{4}$$

While $Q_h$was the transferred heat from hot fluid. The value of Q_c and LMTD was analyzed by Wilson Plot to get the heat transfer coefficient (Seara, 2007).

Overall thermal resistance is shown by equation (5) to equation (8).

$$R_{ov} = \frac{LMTD}{Q_c} \tag{5}$$

$$R_{ov} = \frac{1}{h_i.A_i} + \frac{\ln\left({d_o}/{d_i}\right)}{2.\pi.k_w.L_w} + \frac{1}{h_o.A_o} \tag{6}$$

$$R_{ov} = R_i + R_w + R_o \tag{7}$$

$$R_{ov} = \frac{1}{U.A} \tag{8}$$

The inside and outside heat transfer coefficient was calculated by original Wilson Plot as shown by Figure 2, equation (9) to (12).

$$C_1 = R_w + R_o \tag{9}$$

$$R_{ov} = R_i + C_1 \tag{10}$$

$$R_i = \frac{1}{h_i.A_i} \tag{11}$$

$$h_i = C_2 . v^n \tag{12}$$

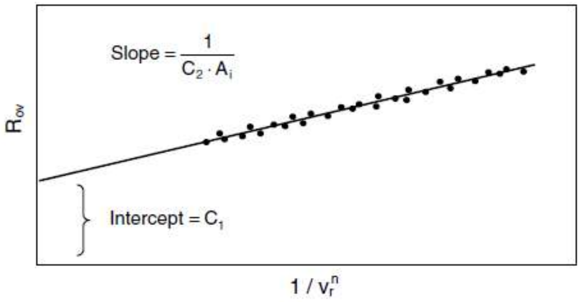

Figure 2. Original Wilson Plot (Seara, 2007)

The dimensionless number correlation was used to reflect the fluid flow characteristic, helical coil geometry (helix curvature), and heat transfer characteristic. Dimensionless number equation of heat transfer used the calculated heat transfer coefficient. Heat transfer inside the pipe obeyed equation (13).

$$Nu_i = f(Re) \tag{13}$$

RESULTS AND DISCUSSION

The measured temperature showed the transient state at initial, then steady state after some time. The measured temperature of the bottom of water bath was lower than the upper side due to the natural convection. The temperature difference led density change of the water. Density on the upper side of water bath was lower than the bottom side. The experiment used quasi-steady assumption on the analysis, therefore the sampling data used after transient state, e.g. approximately after 50s. The data to be analysed was random sampled from overall process data.

Wall resistance from coil I, II, and III, were 9.48×10^{-5}; 7.52×10^{-5}; and 6.78×10^{-5} respectively. Since the wall resistance was very small compare with other resistance, this value was neglected. The convection phenomenon led more significant impact to the heat transfer process, therefore some other research studies only focused on convection process. The convection coefficients were analysed from Wilson Plot.

The analysis differentiated the Wilson Plot for the coils with its each hot water bath temperature. The convection inside the pipe was categorized as forced convection due to the cold fluid flow, therefore we used Nusselt and Reynolds correlation on each curvature ratio. Nusselt number was used for characterizing the convection and conduction through the pipe, while Reynolds number was reflecting the turbulent or laminer the flow was. Equation (18) shows the correlation between Nusselt and Reynolds number.

$$Nu_i = C_i . Re^{0.7} \tag{14}$$

The C_i was a constant used for coefficient of Reynolds number exponential equation. The thermal properties were assumed constant, e.g. c_p, ρ, and μ; therefore, constant Prandtl number. Constant curvature ratio was used for all experiment. The exponent for Reynolds number ($n = 0.7$) came from the value given by Wilson plot by least square method. The C_i value for each coil and hot water bath temperature T_w **(ºC)** is shown by Table III, varies in the range 0.018 to 0.325.

Table 3. C_i constanst value

Coil I		**Coil II**		**Coil III**	
T_w **(ºC)**	C_i	T_w **(ºC)**	C_i	T_w **(ºC)**	C_i
50	0.061	50	0.141	50	0.018
70	0.325	70	0.036	70	0.019
90	0.056	90	0.058		

The figure 3, 4, and 5 shows the Nu_i and Re correlation for each coil, by hot water bath temperature 50, 70, and 90 ºC respectively.

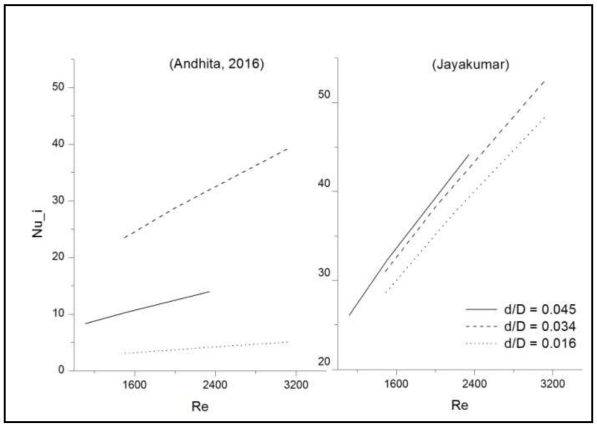

Figure 3. Comparison with the previous research for Nu_i and Re correlation for hot water bath temperature 50 ºC

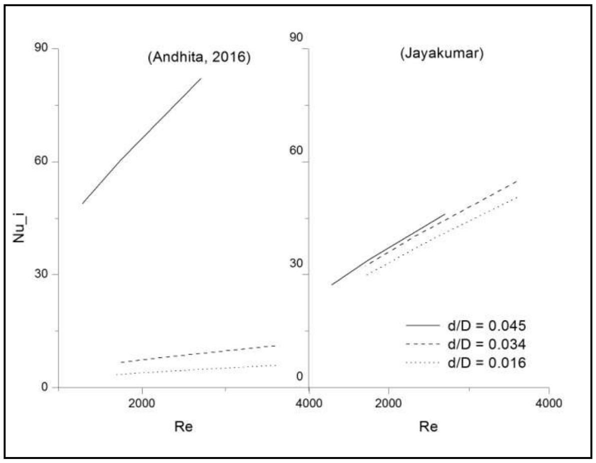

Figure 4. Comparison with the previous research for Nu_i and Re correlation for hot water bath temperature 70 ºC

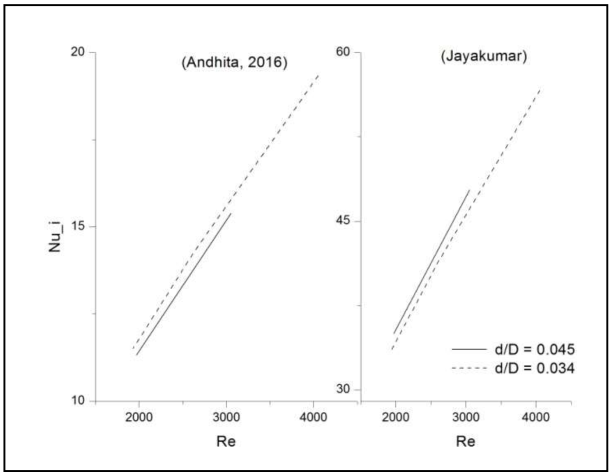

Figure 5. Comparison with the previous research for $\boldsymbol{Nu_i}$ and $\boldsymbol{Re}$ correlation for hot water bath temperature 90 ºC

From Figure 3, the highest heat transfer was occurred in Coil II when on hot water bath temperature $T_w = 50$ ℃. Coil I and Coil III on the second and third position respectively. Coil I, Coil II, and Coil III pipe diameters got smaller respectively. The slope gradient in Wilson's plot for Coil II was too small so the convection coefficient in the resulting pipe was too high. The slope gradient was inversely proportional to the value of h_i, so the smaller the slope gradient the greater the value of h_i. The value of h_i was used in the calculation of the Nu_i number.

As for the equation of the study results by Jayakumar, 2012, it showed that the higher the curvature ratio, the higher the Nusselt number, even though the difference was not too significant. The three curvature ratios (d/D) in the research results showed a similar trend. The overall results of the study were lower than the results obtained by Jayakumar. In this study, the value of Nu_i obtained was at 2.97 $< Nu_i <$ 39.12; while, the experiments by Jayakumar were collected in the range of values 26.08 $< Nu_i <$ 52.36. In addition, the range of experimental conditions used by Jayakumar was higher than the range of experimental conditions carried out in this study. Jayakumar experimental conditions using fluid flow with Reynolds numbers was included in the turbulent regime, while the experimental conditions in this study used laminar flow and transition. In addition, the curvature ratio used by Jayakumar is 0.05 $< d / D <$ 0.2. From Figure 3, it is also found that the higher the Reynolds number, the higher the Nusselt number (Nu_i).

For the experimental conditions at heating water temperature of 70 ºC is shown in Figure 4. The values of Nu_i from high to low respectively occurred in Coil I, Coil II, and Coil III. Coil II and Coil III had Nusselt numbers which were not much different. In the Wilson plot, the slope gradient of Coil III was relatively the same compared to the slope gradient of Coil II at the same heating water temperature. The convection coefficient on Coil I differed too much when compared to the other two coils. This was because the Wilson Coil I plot in the temperature range was too steep and had a high enough deviation of more than 20%. The value of Nu_i Coil I was also higher than the research by Jayakumar.

Coil II and Coil III had almost the same trend, but Coil I had a trend that was too steep as a result of the cooling water flow rate that was not in accordance with the specified value. In Coil II and Coil III, the data collected in the range $3.49 < Nu_i < 11.14$, but Coil I is at a value of $48.82 < Nu_i < 82.07$. In contrast to research by Jayakumar, all coils were at a value of $27.23 < Nu_i < 54.66$.

Under experimental conditions with heating water temperature of 90ºC, the Nusselt numbers in the pipes for Coil I and Coil II did not differ greatly and showed a similar trend. The yield of Nusselt numbers in both coils was at $11.31 < Nu_i < 19.33$, lower than the Nusselt number in Jayakumar research which was $33.45 < Nu_i < 55.66$. The heat transfer of convection in the pipe at that temperature is shown in Figure 5. From Figure 5, all the numbers Nu_i produced in this study are lower than previous studies, because the flow regime used is different.

This research had some limitation regarding water flowrate variation. It needs to perform the wider flowrate range to get the more accurate correlation among dimensionless numbers. The flow controller is also required to be applied to maintain the flow consistency; therefore, the result will be more accurate.

CONCLUSION

Increased fluid velocity caused an increase in the value of the performance of heat transfer inside the pipe of the helical coil heat exchanger. This was evidenced by the increase in the value of Nu_i with an increase in the value of Reynolds numbers in all coils. In addition, the greater the value of the diameter of the pipe on the helical coil, the heat transfer that occurred was faster because the higher the heat transfer value.

The relationship between the transfer coefficient of convection in the pipe with the diameter of the pipe is shown by the equation $Nu_i = C_i . Re^{0.7}$, with the value of varied C_i. The higher the diameter of the pipe increases the value of the constant C_i. The higher the temperature of the heating water, the higher the $C_i$constant value.

When applied to solar water heating systems, water heaters were more effective using large diameter coils, because they were faster at delivering heat.

As for heat transfer outside the pipe, the large diameter of the pipe did not have a significant effect on the performance of the heat exchanger. The higher the Rayleigh number, the higher the value of the dimensionless number Nu_o. The relationship between the transfer coefficient of convection outside the pipe with the pipe diameter is shown by the equation $Nu_o = C_o . Ra^{0.1768}$, with the C_o value varying for each coil on the difference in heating water temperature. The higher the heating water temperature, the greater the C_o constant value.

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