Experimental Study of Free Convection in Coiled Tube Heat Exchanger with Vertical Orientation

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Abstract
An experimental study has been conducted on steady-state natural convection heat transfer from helical coil tubes in vertical orientation. Water was used as a bath liquid without any mixing and cold water was used as a coolant fluid. A straight copper tube of 6 mm ID, 8 mm OD and 3 m length was bend to fabricate the helical coil. Four coils are used in this experiment has different curvature ratios and pitches. The data were correlated using tube diameter as the characteristic length. The results show that the overall heat transfer coefficient and Nusselt number increase when the flow rate of coolant and curvature ratio increase. The effect of coil pitch was investigated and the results show that when of the coil pitch (angle of inclination) increases Nusselt number increase. A correlation was presented to calculate the outside average Nusselt number of coil.
Keywords: Coil, free convection, heat transfer, orientation

دراسة عملية لانتقال الحرارة بالحمل الحر في مبادل الأنبوب الحلزوني الموضوع بشكل عمودي

الخلاصة
إن الغرض من هذا البحث هو دراسة خصائص انتقال الحرارة بالشكل الحر في الحالة المستقرة من أنبوب حلزوني موضوع بشكل عمودي حيث تمت الدراسة عمليا . تم وضع الأنبوب الحلزوني في حمام مائي وبدرجات حرارة مختلفة وقد ادخل ماء) مائع التبريد (داخل الحلزون .استخدم في التجارب أربعة حلزونات ذات نسب تقوس ومسافات بين ألفات مختلفة حيث تم تشكيل هذه الحلزونات باستخدام أنبوب نحاسي قطره الداخلي 6 ملم وقطره الخارجي 8 ملم ويبلغ طوله 3 متر .تم استخدام قطر الانبوب الخارجي في الحسابات.بيّنت التجارب العملية أن معامل انتقال الحرارة الكلي و يزيدان بزيادة معدل جريان مائع التبريد داخل الانبوب الحلزوني وكذلك بزيادة نسبة التقوس .تم دراسة تأثير Nu يزداد بزيادة هذه المسافات .تم ايجاد معادلة Nu المسافات بين لفة وأخرى) زاوية الانحناء (حيث بيّنت التجارب أن على سطح الحلزون الخارجيNu .
الكلمات الدالة: ملف، الحمل الحر، انتقال الحرارة، اتجاه

Nomenclature
D helix coil diameter, m
d tube diameter, m
P coil pitch, m
T temperature, ^oC
Q heat transfer rate, W
m. mass flow rate, kg/s
Cp specific heat, kJ/kg ^oC
U overall heat transfer coefficient,W/m^2 ^oC
A surface area, m^2
ΔT_{lm} log mean temperature difference, ^oC
h heat transfer coefficient, W/m^2 ^oC
k thermal conductivity, W/m ^oC
L coil length, m
Nu Nusselt number, hi di/k
Re Reynolds number, ρ di u/μ
Ra Rayleigh number, g β (Tw - T∞) do 3 ν-1 α-1
Gr Grashof number, g β (Tw - T∞) do 3 ν-2

Greek Symbols

ν kinematic viscosity, $m^2 s^{-1}$
α thermal diffusivity, $m^2 s^{-1}$
β coefficient for thermal expansion, K^{-1}
ρ density, kg/m^3
μ viscosity, kg/m.s
∞ ambient medium

Subscripts

i inner
b bulk
o outer
w wall

Introduction

Coiled tubes are used in many engineering applications, such as heating, refrigeration, (HVAC) systems (heat, ventilation and air conditioning). They are used also in steam generator and condenser design in power plant because of their large surface area per unit volume. In the present study, four coils of various curvature ratios and pitches were used to predict the effect of these ratios and pitches on the natural convection heat transfer from the outer surface of vertically oriented coiled tube.

(Prabhanjan et.al 2004)[1] reported an experimental investigation of the natural convection heat transfer from helical coil in water. Their experiments were conducted in helical heat exchangers with four coils. The outside Nusselt number was correlated to the Rayleigh number using different characteristic lengths as the following:

For tube length:

$Nu_o = 9.759\times10^{-3} (Ra)^{0.3972}$
$5\times10^{14}\leq Ra\leq 3\times10^{15}$ …………………..(1)

For coil length:

$Nu_o=0.0749(Ra)^{0.3421}$
$9\times10^{9}\leq Ra\leq 4\times10^{11}$ …………..…..…..(2)

For normalized length:

$Nuo=2.0487 (Ra)^{0.1768}$
$2\times10^{6}\leq Ra\leq 3\times10^{9}$ ……………….……..(3)

They concluded that the best correlation is when using the total height of the coil as the characteristic length and they developed model to predict the outlet temperature of the fluid flowing through a helical coiled heat exchanger, given the inlet temperature, bath temperature, coil dimensions, and fluid flow rate. (Ali 2006)[2] reported an experimental study on steady-state natural convection heat transfer from vertical helical coil tubes in Petromin heat transfer oil of a Prandtl number range of 250-400. Fifteen coils were used in this work. These coils were classified into five groups; each group has a specified coil diameter-to-tube diameter ratio of two, five, and ten turns. The helix coil to tube diameter ratio were 30, 20.83, 17.5, 13.33, and 10. The results showed that the average heat transfer coefficient increased as the coil number of turns decreased for a fixed diameter ratio, three overall empirical correlations were developed: for oil with 250≤Pr≤400, the correlation between the Nusselt and Rayleigh number was:

$Nu_L=0.619 (Ra_L)^{0.3}$
$4.37\times10^{10}\leq Ra_L\leq 5.5\times10^{14}, 10\leq Ddo\leq 30$
………………………………………(4)

For oil data and water, the correlation between Nusselt and Grashof numbers using Prandtl number as a parameter was reported as:

$Nu_L=0.555 (Gr_L)^{0.301}(Pr)^{0.314}$
$1\times10^{8}\leq Gr_L\leq 5\times10^{14}, 4.4\leq Pr\leq 345$ ……(5)

An alternative correlation of oil and water using Nusselt number as a function of Rayleigh number only was reported as:

$Nu_L=0.714(Ra_L)^{0.294}$ $4.35\times10^{10}\leq Ra_L\leq 8\times 10^{14}$ $4.4\leq Pr\leq 345$ …………………….(6)

(Ali 2004)[3] reported an experimental investigation of laminar-and transition-free convection heat transfer from the outer surface of helical pipes with a finite pitch oriented vertically in a 57% glycerol-water solution by mass. His experiments were carried out for three coil diameter to tube diameter ratios, D/do, and for five and ten coil turns. The results showed that the heat transfer coefficient is enhanced either by reducing the diameter ratio or the number of coil turns. The overall correlations covering all the data are reported as:

$Nu_L=1.535\times10^{-5}$ $(Ra_L)0.671($ D do$)0.7027\times10^{12}\leq Ra_L\leq 8\times10^{14}$……......(7)
$Nu_L=2.53\times10^{-5}(Ra_L)^{0.739}$ $(Ddo)^{-1.313}$
$1\times10^{12}\leq Ra_L\leq 1\times10^{14}$………………...(8)

(Ali 1998)[4] reported an experimental investigation of a steady state natural convection from uniform heated helical coiled tubes oriented horizontally in air. These experiments have been carried out for four coils and for various values of heat fluxes of 500-5000 W m^{-2}. Average heat transfer coefficients are obtained for laminar natural convection. It was shown that the average heat transfer coefficient decreases with increasing the number of coil turns up to (or close to) the middle turn where a transition to turbulent begins. Correlation for all heat fluxes for all coils using the horizontal coil axis distance-x corresponding to each turn as a characteristic length is given by:

$Nu_x=0.9125(Ra_x)^{0.301}$…………..……(9)

Experimental Setup and Procedure

The coil shown in table (1) used in the present work was fabricated by bending a copper pipe of 6 mm ID and 3 m long. The coil length was measured before forming it, and the outer diameter (D) of the coil is measured using a vernier caliper. The test of coils were curried out in a different ambient temperatures bath (40×40×35 cm), which serves as a heating medium. The ambient temperature bath was constant in each run which controlled with sensitive mercury temperature controller connected to electrical heater of 3000 W as shown in figure (1-A). Water was pumped in the tube coil as a coolant with different volumetric flow rates (0.55-3.5 l/min) which were measured by a flow meter having a range of (0.5-20 l/min). The bath temperature, inlet and outlet temperatures were measured by mercury thermometers having a range of (0-200 $_o$C).The schematic diagram of experimental set-up is shown in Figure (1-B).In each test the bath was filled with water at 30 cm of height submerging the coil completely. Heating was done by immersion coil and simultaneously cooling water was entered through one end of the coil. At steady state conditions, bath temperature and water temperature (both at inlet and outlet sections) were measured. The experiments were conducted for six different flow rates.

Analysis of Experiment

The physical properties of water flowing inside the tube coil test section are assumed constant along the coil length and evaluated at the average bulk temperature for each run. The overall heat transfer rate through the coil can be evaluated from:

$Q= m.\ Cp\ (Tb_2-Tb_1)$…………….(10)

Where Q is the overall heat transfer rate through the coil, m. is the mass flow rate of water, Tb_1 is the coil inlet temperature, Tb_2 is the coil outlet temperature, and Cp is the water specific heat. Having obtained a value for the heat transfer rate Q, the overall heat transfer coefficient is calculated from:

$$U_o = \frac{Q}{A_o\,\Delta T_{lm}}$$

$$\text{where } \Delta T_{lm} = \frac{T_{b2} - T_{b1}}{\ln\left[\frac{T_\infty - T_{b1}}{T_\infty - T_{b2}}\right]} \quad \text{.......(11)}$$

Where U_o is the overall heat transfer coefficient, A_o is the outside surface area of the coil, ΔT_{lm} is the log mean temperature and T_∞ the ambient temperature bath. The overall heat transfer coefficient is defined as:

$$U_o = \left[\frac{1}{\frac{A_o}{A_i h_i} + \frac{A_o \ln(\frac{d_o}{d_i})}{2\pi k L} + \frac{1}{h_o}}\right]. \quad \text{......(12)}$$

The diameter for inner wall and the outer wall of the tube are d_i and d_o respectively, A_i is the inside surface area of coil, and the thermal conductivity of the coil is k. It was necessary to determine the inside heat transfer coefficient, h_i, to proceed with the calculations for h_o. the relationship of (Rogers and Mayhew 1964)[5] based on the film temperature was used to determine the inner Nusselt number, Nu_i, of the coil (this is similar to the method of (Prabhanjan et.a 2004)[1] and (Ali 2006)[2]:

$$Nu_i = 0.021\,(Re)^{0.85}\,(Pr)^{0.4}\,(\frac{r_i}{R})^{0.1} \quad \text{...(13)}$$

Since the wall temperature was not known, the film temperature used to evaluate Reynolds number, Re, and Prandtl number, Pr, was also unknown. Therefore an iterative approach was used to determine the wall temperature and the inner Nusselt number simultaneously. A first approximation was made for the average wall temperature and was used to calculate the film temperature. All properties for Reynolds number and Prandtl number were evaluated at the film temperature and Nusselt number was calculated using Eq. (13). The inside heat transfer coefficient was then determined from:

$$hi = \frac{Nu_i.k}{d_i} \quad \text{...........................(14)}$$

The wall temperature, T_w, was then determined from :

$$T_w = \frac{Q}{h_i.A_i} + T_b \quad \text{.........................(15)}$$

Where Tb is the average bulk temperature (average of the inlet and outlet temperatures) of the processing fluid. The newly calculated wall temperature was used as a second approximation of the temperature and the iteration was repeated until convergence was obtained. The outside heat transfer coefficient, h_o, was then calculated from the thermal resistance equation (Eq. 12). The physical properties of water are evaluated from (Holman 1981)[6]

Results and Discussion.

The behavior of the overall heat transfer coefficient for two curvature ratios can be seen in figure (2). As expected the overall heat transfer coefficient is directly proportional to the volumetric flow rate of the fluid inside the coil at a constant bath temperature, and the coil of a higher curvature ratio has higher values of overall heat transfer coefficient. Figure (3) shows the variation of the average inner Nusselt number calculated from the present experiment with Reynolds number. It illustrates that when the increase in Reynolds number leads to an increase in

Nusselt number. This is because Nusselt number depends directly on the heat removal capacity of the cold water. In addition the curvature ratio (di/D = 0.048) gives higher values of Nusselt number than the ratio (di/D = 0.027). This is because that the centrifugal force increases when the curvature ratio increased. The behavior of the outer heat transfer coefficient can has be seen in a nondimensional form of Nu_{do} and Ra_{do} in Figure (4) for two curvature ratios of coils. It can be seen from this figure that Nusselt number increases as Rayleigh number increases, and the coil of high curvature ratio has higher values of Nusselt number. Figures (5-A and 5-B) show significant effect of the coil pitch on the outer Nusselt number. They show that increasing in coil pitch, leads to an increase in outer Nusselt number. This result has a good agreement with experimental results of the flow characteristic of water falling film in spiral tube which investigated by (Abdel- Rahman and Abdulla 2007)[7]. They concluded that the ratio of the surface film velocity to average film velocity increases as the angle of inclination increases. The correlation covering the experimental data point outside the coil with correlation coefficient R^2 =0.987 is:

$$Nu_{do} = 0.2183(Ra)^{4.01}\left(\frac{di}{D}\right)^{2.79}\left(\frac{P}{L}\right)^{7.281} \quad ....(16)$$

Where P is the coil pitch and L is tube length. Figures (6-A and 6-B) show a good agreement of experimental and correlated results of the average Nusselt number vs. Rayleigh number.

Conclusions

1- The over all heat transfer coefficient and Nusselt number increases as the flow rate of coolant is increased.

2- The curvature ratio (d_i/D = 0.048) gives higher values of overall heat transfer coefficient than the ratio (d_i/D = 0.027), in addition, when the curvature ratio of coil increases Nusselt number values increase also.

3- The coil pitch has a significant effect on the convection heat transfer in coiled tube i.e. when increasing in coil pitch, outer Nusselt number will increase.

4- Empirical correlation was developed for outer Nusselt number as a function of Rayleigh number, curvature ratio, and coil pitch reported by Eq. (16).

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Table (1) Coils Dimensions Used in the Experiments

Coil	d_i (mm)	d_o (mm)	D (cm)	d_i/D	P (cm)
1	6	8	12.5	0.048	1.8
2	6	8	12.5	0.048	3
3	6	8	22.5	0.027	2
4	6	8	22.5	0.027	5.5

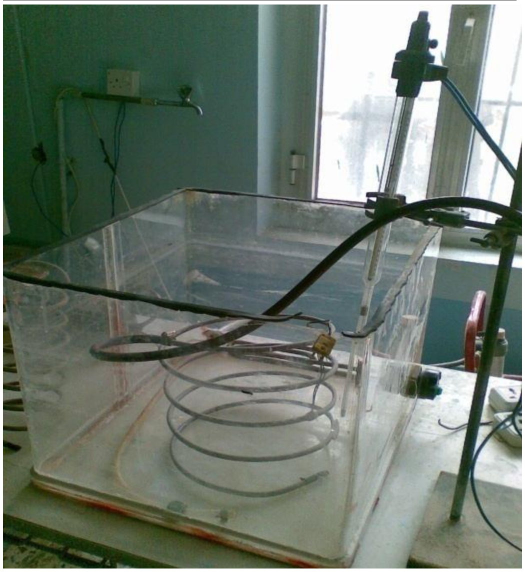

Fig.(1-A) Photograph of vertical coiled tube used in the present study

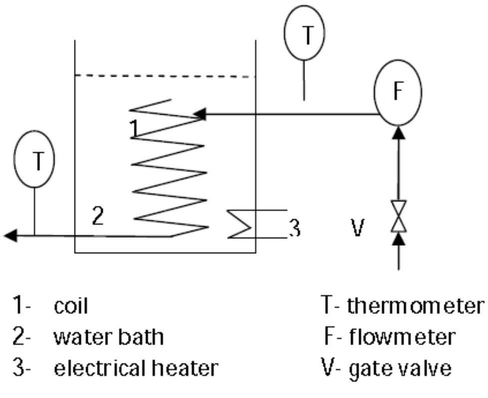

Fig.(1-B) Flow diagram of the experimental set-up

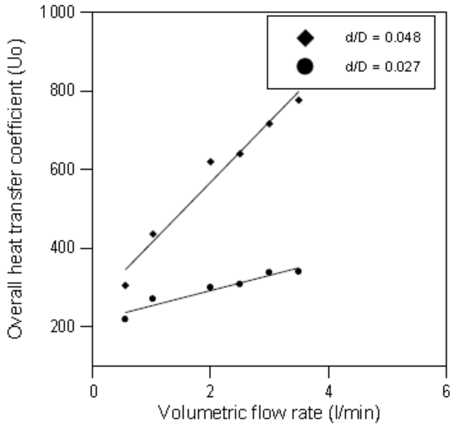

Fig. (2) The effect of the curvature ratio of coil on the overall heat transfer coefficient

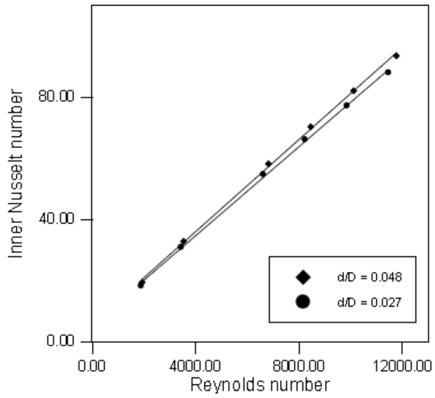

Fig.(3) The variation of inner Nusselt number with Reynolds number .

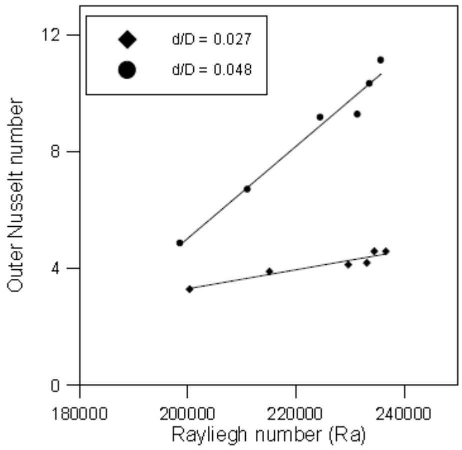

Fig.(4) The effect of curvature ration on the behavior of Nusselt and Rayleigh numbers.

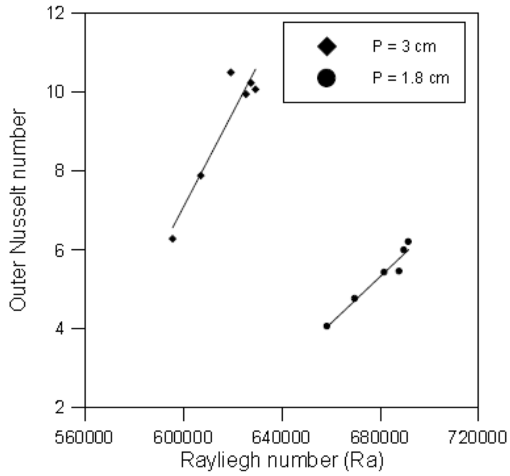

Fig. (5-A) The effect of coil pitch of Nusselt and Rayleigh numbers behavior for coil of (d/D = 0.048).

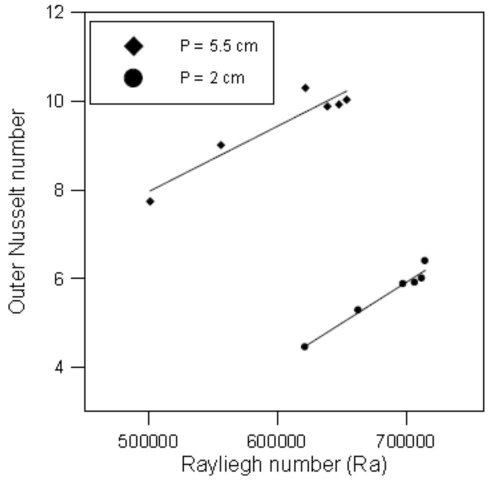

Fig. (5-B) The effect of coil pitch of Nusselt and Rayleigh numbers behavior for coil of (d/D = 0.027).

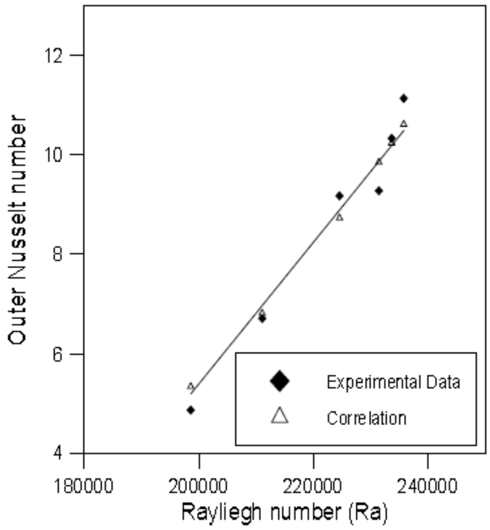

Fig. (6-A) Experimental and correlation average outer Nusselt number for coil of (d/D = 0.048).

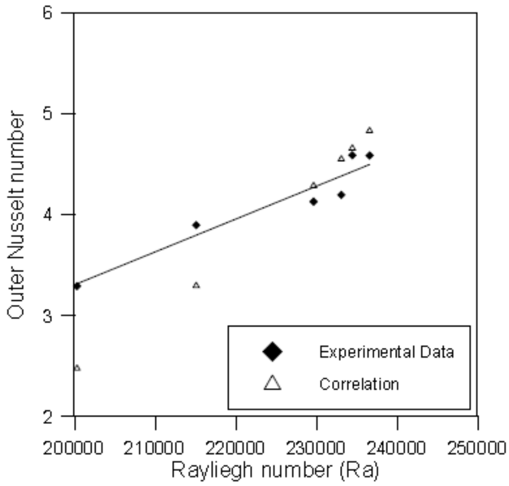

Fig. (6-B) Experimental and correlation average outer Nusselt number for coil of (d/D = 0.027).