CSCanada
Energy Science and Technology
Vol. 3, No. 2, 2012, pp. 1-9
DOI:10.3968/j.est.1923847920120302.378

ISSN 1923-8460[PRINT]
ISSN 1923-8479[ONLINE]
www.cscanada.net
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Experimental Study of Forced Convection over Equilateral Triangle Helical Coiled Tubes

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Received 12 March 2012; accepted 14 May 2012

Abstract

This study presents an experimental investigation of an equilateral triangular cross-sectioned helical tube under uniform heat flux boundary condition. The experiments are carried out for nine helical coiled-tubes of different parameters. Different diameter ratio (D/a) ranged from 6.77 to 15.43 and pitch ratio (P/a) ranged from 1.127 to 3.062 are employed in the present study, The experiments covered a range of Reynolds number from 5.3×10^2 to 2.2×10^3. Uniform heat flux is applied to the inside surface of the helical coil and air is selected as tested fluid. The experimental results obtained from the equilateral triangular cross-sectioned helical tube indicated that the parameters of the coil diameter and pitch of helical coil have important effects on the heat transfer coefficient. The Nusselt number increases with the increase of Reynolds number and coil diameter at constant pitch of the helical coil. Also, Nusselt number increases with the increase of Reynolds number and Pitch of helical coil at constant coil diameter tube. A comparison between the present experimental data with a previous work with circular cross-sectioned helical tubes have the same test conditions was achieved. From this comparison, it is clear that the average enhancement of Nusselt number for equilateral triangular cross-sectioned helical is about 1.12~1.25 times the circular cross-sectioned helical for all tested conditions. A general correlation of the average Nusselt number as a function in Re, D/a and P/a ratios is obtained to describe the forced convection from the equilateral triangle cross sectioned coiled tube.

Key words: Forced convection; Helical coiled tubes; Coil diameter ratio; Pitch ratio

Ibrahim, E., & El-Kashif, E. (2012). Experimental Study of Forced Convection over Equilateral Triangle Helical Coiled Tubes. *Energy Science and Technology, 3*(2), 1-9. Available from: URL: http://www.cscanada.net/index.php/est/article/view/j.est.1923847920120302.378
DOI: http://dx.doi.org/10.3968/j.est.1923847920120302.378

NOMENCLATUR

A: Surface area of the equilateral triangular helically coiled-tubes, m^2
a: The length of equilateral triangular helically coiled-tubes, m
C_p: specific heat, kJ/kg k
D: Coil diameter, m
H: Coil height, m
h_m: Average heat transfer coefficient of air, W/m^2K
k: Thermal conductivity, W/m K
L: The tube length before making the helical coil, m
P: Pitch of helical coiled tube, m
Nu: Average Nusselt number of air
Q: Heat transfer rate, W
q: Heat flux, W/m^2
Re: Reynolds number
T:Temperature, K
V: Velocity of air, m/s

SUBSCRIPTS

s: Surface temperature
sm: Average surface temperature
∞: Free stream air temperature or velocity

GREEK LETTERS

μ: Dynamic viscosity of air, kg/m s
ν: Kinematics viscosity of air, μ/ρ, m^2/s
ρ: Density of air, kg/m^3

INTRODUCTION

Heat transfer in curved and helical circular tubes has been the subject of several studies and it has been widely reported in literature that heat transfer rates in helical coils are higher as compared to a straight tube. They are widely used in industrial applications such as power generation, nuclear industry, process plants, heat recovery systems, refrigeration, food industry, etc. Patankar et al.[1] discussed the effect of the Dean number on friction factor and heat transfer in the developing and fully developed regions of helically coiled pipes. Good agreements were obtained from comparisons between the developing and fully developed velocity profiles, the wall temperature for the case of axially uniform heat flux with an isothermal periphery obtained from calculation and those obtained from experiments. In the model mentioned above, the effects of the torsion and the Prandtl number were not taken into account. Yang et al.[2] presented a numerical model to study the fully developed laminar convective heat transfer in a helicoidally pipe having a finite pitch. The effects of the Dean number, torsion, and the Prandtl number on the laminar convective heat transfer were discussed.

Rennie and Raghavan[3] simulated the heat transfer characteristics in a two-turn tube in- tube helical coil heat exchanger. Various tube-to-tube ratios and Dean Numbers for laminar flow in both annulus and in-tube were examined. The temperature profiles were predicted using a computational fluid dynamics package. The results showed that the flow in the inner tube at the high tube-to-tube ratios was the limiting factor for the overall heat transfer coefficient. This dependency was reduced at the smaller tube to- tube ratio, where the influence of the annulus flow was increased. Inagaki et al.[4] carried out experiments to investigate the flow-induced vibration, heat transfer and pressure drop of helically coiled tubes of an intermediate heat exchanger for a high-temperature engineering test reactor. They used Air as a working fluid. The heat exchanger model consisted of 54 helically coiled tubes separated into three layers. The results showed that the forced convective heat transfer of the tube from outside was a function of $Re^{0.51} Pr^{0.3}$. The heat transfer rates between a helically coiled heat exchanger and a straight tube heat exchanger were compared by Prabhanjan et al.[5].

Rogrers and Mayhew[6] concentrated their attention on heat transfer and pressure loss in helically coiled tubes with turbulent flow. Three different coils having mean diameters of 10.2, 12.5 and 190 mm, made of 9.45 mm ID copper tubes were heated by steam at slightly above atmospheric pressure. The heat transfer data resulted in the empirical equation for the Reynolds number of 104–105 through which the flow was assumed turbulent. Manlapaz and Churchill[7] studied the laminar convection heat transfer in helical coils and proposed correlations of friction factor and Nusselt number for the case of coils with constant wall heat flux and constant wall temperature. Moawed[8] reported an experimental investigation of steady state natural convection heat transfer from uniformly heated helicoidally pipes oriented vertically and horizontally. He used four helicoidally pipes having different ratios of coil diameter to pipe diameter (D/do) and pitch to pipe diameter (p/d_o) with a range of Rayleigh numbers from 1.5×10^3 to 1.1×10^5. The results showed that the overall Nusselt number increases with the increase of (D/d_o), and (p/d_o) for the vertical helicoidally pipes.

Prabhanjan et al.[9] performed an experimental investigation of natural convection heat transfer from helical coiled tubes in water. They correlated outside Nusselt number to the Rayleigh number using different characteristic lengths and finally considered the coil height as the best representation for a vertical coil. Their prediction procedure shows a promise as a method of predicting the outlet temperature from a coil given the inlet temperature, both temperature and coil dimensions. Conte et al.[10] performed numerical investigations to understand forced laminar fluid flow over coiled pipes with circular cross-section. They focused on exploring the convective heat transfer from conical and helical coils with comparative studies. The same numerical investigation method was applied to the two differentially coiled pipes (helical and conical) and for different Reynolds numbers corresponding to five cases of exterior flow arrangement. The results show better heat transfer performance for cases of conical coils where much flow turbulence was observed due to an effective flow arrangement.

Parabhanjan et al[11] studied the comparison of heat transfer rates between a straight tube heat exchanger and a helically coiled heat exchanger. The study focused on constant wall temperature and constant heat flux with fluid-to-fluid heat exchanger. The results showed that the heat transfer coefficient was affected by the geometry of the heat exchanger. Ko and Ting[12] produced analyzes to the optimal Reynolds number for the steady, laminar, fully developed forced convection in a helical coiled tube with constant wall heat flux based on minimal entropy generation principle. It is found that the entropy generation distributions are relatively insensitive to coil pitch. An experimental investigation regarding the laminar to turbulent flow transition in helically coiled pipes was studied by Andrea and Lorenzo[13].

Timothy et al.[14] have studied the double-pipe helical heat exchanger. Two heat exchanger sizes were used and both parallel and counter flow configuration were tested. The result showed that, the heat transfer rates were much higher in the counter flow configuration due to the larger average temperature difference between the two fluids. Comini et al[15] studied the Forced convection heat transfer from banks of helical coiled resistance wires. Average convection heat transfer coefficients were determined for each branch. Neither significant interaction was detected between adjacent coils or between upstream and downstream coils. The results were compared with the origin correlation of forced convection from single tube in cross flow. No modification of the original correlation was needed to account for the boundary conditions of uniform heat flux, possibly because of the small diameter and high thermal conductivity of the resistance wires.

Sibel et al[16] studied the heat transfer and pressure drop for a helical coiled wire inserted tube in turbulent flow regime. The coiled wire has equilateral triangular cross section and was inserted separately from the tube wall. The experiments were performed with coiled wire with two different ratio of equilateral triangle length side to tube diameter (a/D=0.0714, a/D=0.0892). The results show that the Nusselt number increases with the increase of Reynolds number, as expected while the wire with a/D=0.0892 provides higher heat transfer than the one with a/D=0.0714 for overall Reynolds. The effect of geometric parameters on water flow and heat transfer characteristics in micro channel heat sink with triangular reentrant cavities is numerically investigated by Guodong et al[17]. The heat transfer enhancement mechanism of the micro channel with triangular reentrant cavities can be attributed to not only the vortices formed inside by the reentrant cavity leading to chaotic advection and convective fluid mixing but also the interrupted and redeveloped periodically thermal boundary layer along the constant cross-section surface.

Mohsenzedhet al.[18] investigated numerically the effect of tandem heated triangular cylinders in a plane channel for Reynolds number of 100, 250 and 300. Their results showed that wall proximity has different effect on first and second triangle in fluid characteristics especially in lower gap spaced and the same behavior was seen for heat transfer. The effect of wall proximity on forced convection in a plane channel with a built-in triangular cylinder has recently been investigated numerically for Reynolds number 100~450 by Farhadi et al.[19]. Their results showed that the vortex formation at the downstream of the obstacle has a main effect on the flow separation over the surface of the lower channel wall.

Mohamed et al[20] produced experiments on forced convection heat transfer from the outer surface of horizontal triangular surface cylinders in cross flow of air. Four equilateral triangular cylinders have been used with cross section side length of 0.03, 0.05, 0.08 and 0.12 m, corresponding to blockage ratios 0.066, 0.110, 0.175 and 0.263 respectively. The cylinders are heated using internal constant heat flux heating elements. The overall averaged Nusselt numbers are correlated with the Reynolds numbers for the two positions of the cylinders in cross flow using the side length of the triangular cylinders. The effects of twisted tapes with alternate axes and wings in three different shapes including triangle on heat transfer, flow friction and thermal performance factor characteristics are investigated by Khwanchit and Smith[21]. The results showed that the twisted tapes with combined alternate axes and wings, the tape with trapezoidal wings provides the highest Nusselt number, friction factor as well as thermal performance factor, followed by the one with rectangular wings and then the one with triangular wings . Moawed[22] studied the forced convection from outside surfaces of helical coiled tubes with a constant wall heat flux. The experimental results indicated that these parameters (D/d_o and P/d_o) have important effects on the average heat transfer coefficient. The average Nusselt number (Nu_m) increases with the increase of D/d_o at constant Re and P/d_o. Also, Nu_m increases with the increase of P/d_o at constant Re and D/d_o.

From all cited papers above, it is clear that there is a lack of studies on forced convection from a constant heat flux of equilateral triangular helically coiled-tubes. So, this investigation presents an experimental study of equilateral triangular helically coiled-tubes in cross flow of air. The experiments were carried out for nine helical coiled-tubes of different parameters. The range of diameter ratio (D/a) from 6.77 to 15.43 and pitch ratio (P/a) from 1.127 to 3.062 are employed for equilateral triangle helically coiled tubes in the present study. General correlations are obtained for Nusselt number as a function of Reynolds numbers, D/a and P/a for each equilateral triangle helically coiled tubes.

1. EXPERIMENTAL APPARATUS

The experiments were performed in an open-circuit airflow wind tunnel system operated in suction mode. Along its path of flow, air from the laboratory space passed through the test section, flow control regulating valve by means of which the air velocity through the tunnel is regulated and blower from which it is discharged. Figure 1 shows the schematic diagram of the wind tunnel with the arrangement of tested coiled tube. The test sections of 300 mm by 300 mm cross section and 320 mm length are specially designed and fabricated. The lower and upper walls of the test section are fabricated from sheets of compressed wood covered with formic. The sidewalls are made from glass, so that the internal surface and tubes arrays are visible. To guard against leakage, strips of rubber material are laid in longitudinal grooves milled into the top and the bottom edges of the sidewalls. The assembled test section is held together with the wind tunnel by positioning screws. This construction allows easy removal and insertion of equilateral triangular cross-sectioned helical coiled tubes within the duct. The equilateral triangular helically coiled are made from copper tubes using wood mandrel to convert the circular copper tubes (d_o=12.7 mm) into equilateral triangular tubes (a=13.3 mm) then heaters are inserted inside the straight tubes and fine sand filled the gap between the heaters and the inside walls of the tubes. Then, each of the straight tubes is wounded on the wood pattern (Figure 2) of a desired diameter to form helical coil. The dimensions and parameters of the coils used in this investigation are shown in Table 1. The surface temperatures of the tube wall are measured by K-type of copper–constantan thermocouples of 0.2 mm diameters, which are placed on the local wall of the tube and calibrated within ±0.2 °C deviation by thermostat before being used. All thermocouples are connected via switching box to a digital thermometer with uncertainty of 0.1%. The distribution of the thermocouples on the outer surface and cross-sectioned of the helical tube is shown in Figure 3. Each coil has a number of thermocouples depend on the number of turns, where two of the thermocouples are located on each turn in the opposite direction. Also, the free stream temperature of the air is measured by another calibrated copper-constantan thermocouple located upstream the tested equilateral triangular helically coiled. The tested equilateral triangular cross-sectioned helical are heated by electrical heaters inserted inside the tubes to give a certain constant heat flux for each run. The electrical output power was controlled by a variac transformer to provide constant heat flux along the entire length of the test section. Each heater is made by wounding a nickel–chrome wire of 0.4 mm diameter on the fine electric insulation wire and it is covered by electrical insulation tape. The input electric current and volt are measured by digital Ammeter and digital Voltmeter with a resolution of 0.01 A and 0.01 V respectively. The air velocities across the tunnel are measured using a Pitotstatic tube connected to a micro manometer. The uncertainty in velocity measurements is estimated to be in order of 2.5 %. The experiments are carried out with two of equilateral triangle length side at five different pitches and coil diameter of helical coil in the range of Reynolds number from 5.2×10^2 to 2.2×10^3. It is important to mention that all measurements are performed at the steady-state condition. During the experiments, the input electric power to the heater is controlled and changed by a voltage regulator and the velocity of the air through the wind tunnel is changed and controlled by a regulating valve mounted at the inlet of the air. When the steady-state condition is established, the readings of all thermocouples, the stream air velocity and the input power are recorded.

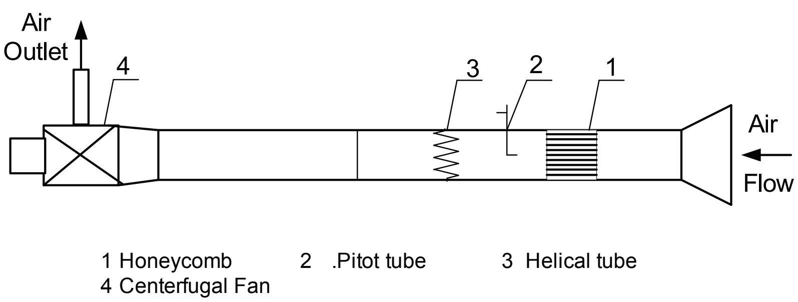

Figure 1
Experimental Set up

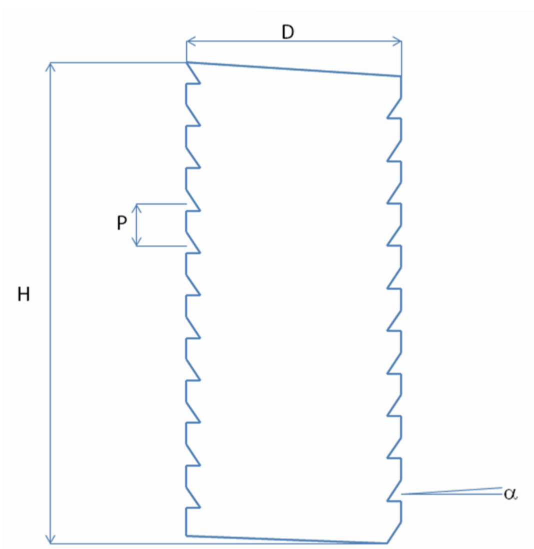

Figure 2
Wood Pattern Used to Fabricate the HelicalTriangular Coils

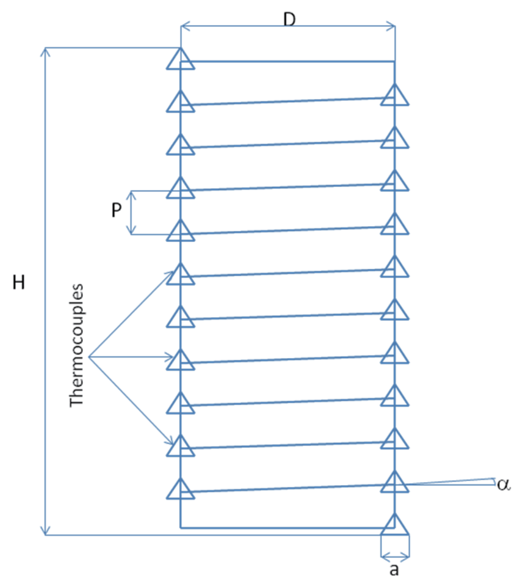

Figure 3
Physical Parameters of Helical Coiled Tubes

Table 1
Tested Coil Dimensions

Coil no.	D (m)	P (m)	a (m)	D/a	P/a	H (m)	N
1	0.09	0.015	0.0133	6.77	1.127	0.1765	11
2	0.12	0.015	0.0133	9.03	1.127	0.1315	8
3	0.145	0.015	0.0133	10.91	1.127	0.1165	7
4	0.17	0.015	0.0133	12.79	1.127	0.1015	6
5	0.205	0.015	0.0133	15.43	1.127	0.0865	5
6	0.205	0.0197	0.0133	15.43	1.481	0.1100	5
7	0.205	0.0277	0.0133	15.43	2.082	0.1500	5
8	0.205	0.0347	0.0133	15.43	2.609	0.1850	5
9	0.205	0.0407	0.0133	15.43	3.060	0.2150	5

2. UNCERTAINTY ANALYSIS

The various characteristics of the flow, the Nusselt number, and the Reynolds numbers were based on the average of tube wall temperature and outlet air temperature. The local wall temperature, inlet and outlet air temperature and airflow velocity was measured for heat transfer of the heated tube. The average Nusselt numbers were calculated and discussed where all fluid properties were determined at the overall bulk mean temperature. In order to quantify the uncertainties, the reduced data obtained experimentally were determined. The uncertainty in the data calculation was based on Ref. [23]. The maximum uncertainties of non-dimensional parameters are ±3% for Reynolds number and ±10% for Nusselt number. The uncertainty in the axial velocity measurement was estimated to be less than ±4%, whereas the uncertainty in temperature measurement at the tube wall was about ±0.5%. The experimental results were reproducible within these uncertainty ranges. Generally, the accuracy of the experimental results depends upon the accuracy of the individual measuring instruments and the measuring techniques.

3. DATA REDUCTION

The data reduction of the measured results is summarized in the following procedures:

The mean heat transfer coefficient for helical tube is calculated as:

$$h_m = q/(T_{sm} - T_\infty) \tag{1}$$

Where q is the convective heat transfer rate from the surface of the helical tube, T_{sm} is the average of the surface temperature and T_∞ is the free stream air temperature.

Energy dissipated from the electric heating wire (q_t) is transported by convection to the flow and radiation to the surroundings which can be calculated from:

$$q_t = VI\ /(3aL) \tag{2}$$

Where I and V are the electric current and the voltage input from the DC power supply to the helical tube, where a, L is the length of the equilateral triangle and straight tube before making helical coil respectively.

Thus the convective heat transfer rate from the surface of the helical tube was calculated from the energy balance for the heated cylinder as:

$$q = q_t - q_r \tag{3}$$

Where q_r is the heat transfer by radiation from the helical tube to the surroundings. The radiation heat losses was calculated from the following equation assuming that the helical tube surface is gray and the surrounding is a black body at the ambient temperature and is completely surrounding the helical tube:

$$q_r = 3aL\sigma\,\varepsilon\left[(T_{sm}+273)^4 - (T_\infty + 273)^4\right] \tag{4}$$

Where ε is tube surface emissive (polished copper), σ is Stefan-Boltzmann constant. The radiation heat transfer from the helical tube was within 2% of the input heat during all the experiments. Heat average transfer coefficient is computed in non-dimensional form by means of Nusselt number.

$$Nu = h_m a / k \tag{5}$$

The Reynolds number defined in the conventional way as:

$$\mathrm{Re} = V_\infty a/\nu \tag{6}$$

Where V_∞ is the free stream velocity and ν is kinematics viscosity of free stream of air.

4. RESULTS AND DISCUSSIONS

The effect of heat flux on the average Nusselt number is illustrated in Figs. 4–8 for a range of $5.2\times10^2 \le \mathrm{Re} \le 2.2\times10^3$ at a different values of D/a and a constant value of P/a = 1.127. It is seen from these figures that there is minor effect of heat flux (q) on the Nusselt number. The change in heat flux from 472 W/m^2 to 629 W/m^2 results in a variation of about 1.5% to 3% in Nusslet number.

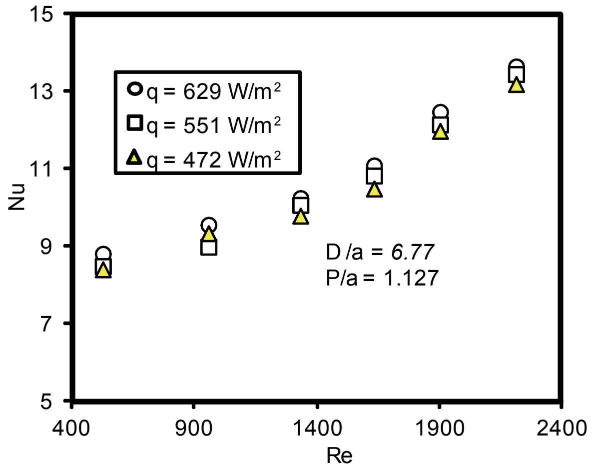

Figure 4
Variation of Nu with Re, at Different Heat Flux at the Ratio of D/a Equal 6.77

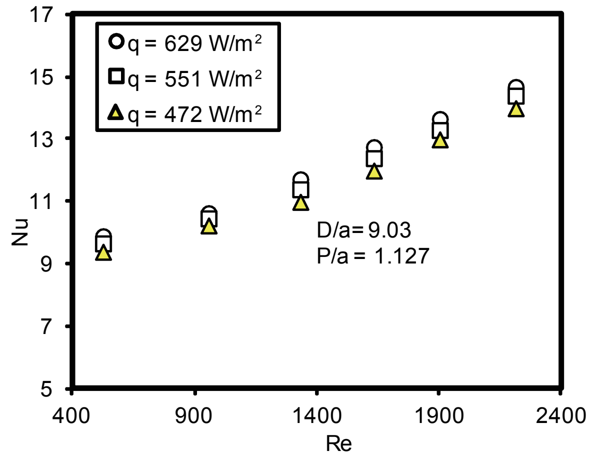

Figure 5
Variation of Nu with Re, at Different Heat Flux at the Ratio of D/a Equal 9.03

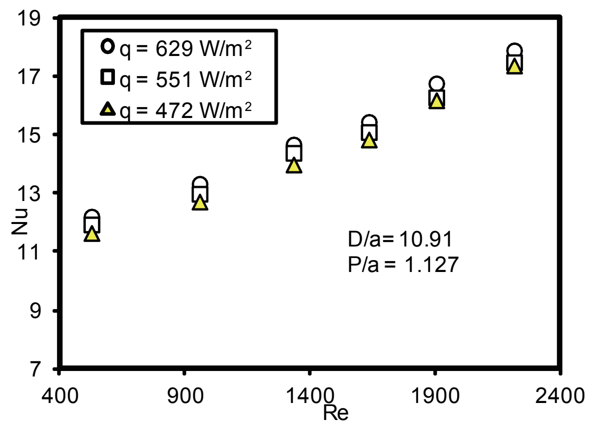

Figure 6
Variation of Nu with Re, at Different Heat Flux at the Ratio of D/a Equal 10.91

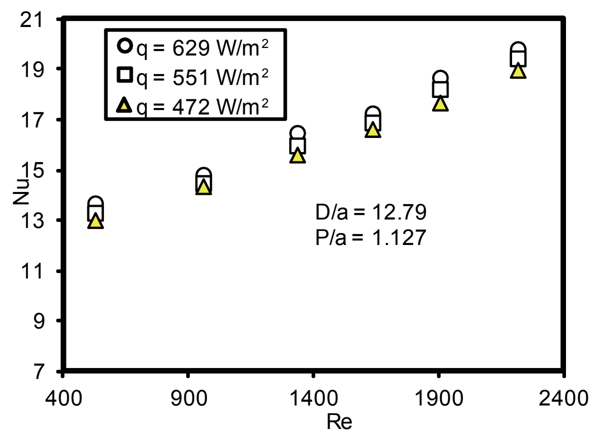

Figure 7
Variation of Nu with Re, at Different Heat Flux at the Ratio of D/a Equal 12.79

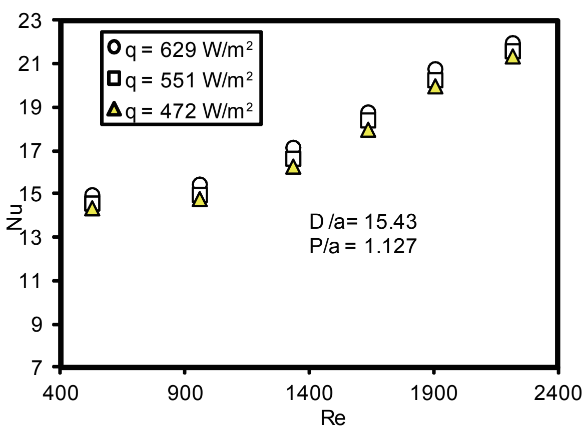

Figure 8
Variation of Nu with Re, at Different Heat Flux at the Ratio of D/a Equal 15.43

The Variation of (T_{sm}/T_{∞}) with Re at different D/a and at constant P/a = 1.127 was shown for the five different equilateral triangular helical coils in Figure 9. It can be seen from these figures that the ratio of (T_{sm}/T_{∞}) decreases with the increase of Re for all cases. For the same values of Re, the ratio of (T_{sm}/T_{∞}) decreases with the increase of D/a. This can be attributed to the increase of the lateral surface of the helical coil exposed to the free stream of the air and the large volume of movement of air inside the coil core due to increase of coil diameter.

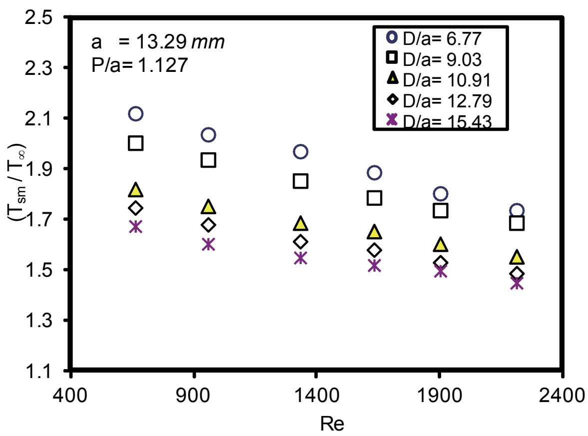

Figure 9
Variation of (T_{sm}/T_∞) with Re at Different D/a

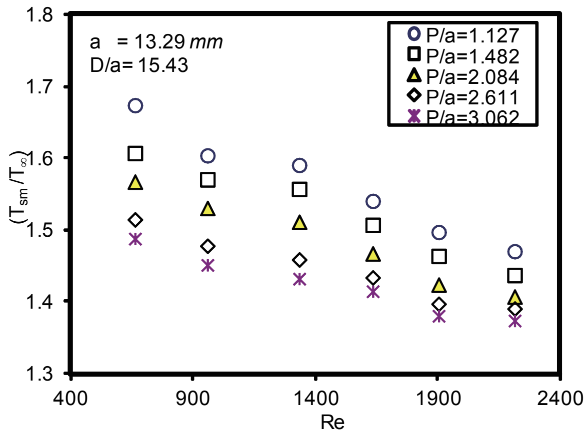

Figure 10
Variation of (T_{sm}/T_∞) with Re at Different P/a

Figure 10 presents the variation of (T_{sm}/T_∞) with Reynolds number at varies P/a and at constant D/a of 15.43. The variation of (T_{sm}/T_∞) decreases with the increase in the pitch of equilateral triangular helical coils. This can be attributed to the increase of flow of air between the turns of the coil and the core coil as pitch of the equilateral triangular helical coils increases, which gives more cooling to the coil surface.

The present experimental study is focused on the investigation of the heat characteristics of an equilateral triangular cross-sectioned helical tube under uniform heat flux boundary condition. The experiments were performed with helical coils with equilateral triangles and the effect of D/a on heat transfer for a constant pitch ratio of P/a = 1.127 is presented in Figure 11. It is clear from this figure that the Nusselt number increases with the increase of Reynolds number and D/a. The higher Nu is observed at D/a = 15.43 and the lower values at D/a = 6.77, this can be explained from the behavior of air stream inside the coil-core and outside the coil-face. At large coil diameter, there are high core-area and high curvature of the coil turns which permit more air flowing inside the core and outside the surface of the coil which lead to increase of heat transfer coefficient compared to the coil of small coil diameter. This can be also referred to the interface of the boundary layer at coil-core and between turns of the lower values of coil diameter compared with the higher values of coil diameter.

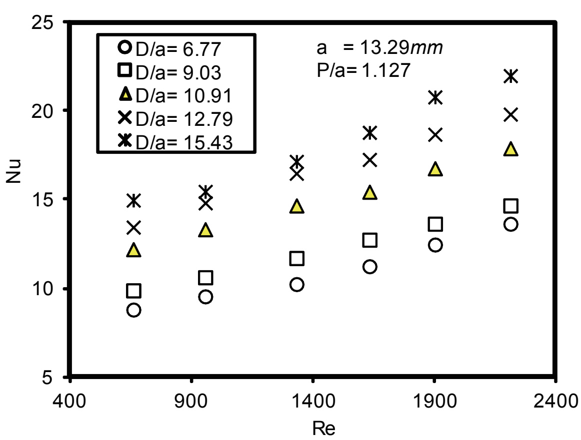

Figure 11
Variation of Nu with Re at Different D/a

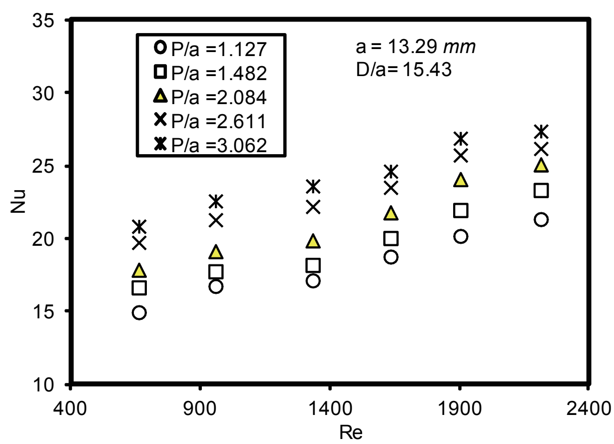

Figure 12
Variation of Nu with Re at Different P/a

The effect of (P/a) on the average Nusselt number for equilateral triangles helical coils at constant pitch ratio of D/a = 15.43 is shown in Figure 12. This figure shows that the Nusselt number increase with the increase of Re and P/a. This can be attributed to the increase of P/a which results in enlarging the distances between coil turns that let the air flow increases between the coil turns and inside the core coil which leads to an increase in the heat transfer coefficient.

5. CORRELATION OF THE RESULTS

The general correlation of the Nu as a function of Re, D/a and P/a of the experimental results is expressed as the following:

$$Nu = b\,\mathrm{Re}^{c}(D/a)^{d}(P/a)^{e} \quad (7)$$

The experimental data at the length of equilateral triangular helically coiled-tubes (a) equal to 13.29 mm is fitted to get the constants and the following correlation can be obtained:

$$Nu_{m} = 0.0943\,\mathrm{Re}^{0.48}(D/a)^{0.6481}(P/a)^{0.277} \quad (8)$$

$5.2\times10^{2} \le \mathrm{Re} \le 2.2\times10^{3}$, $6.77 \le D/a \le 15.43$ and $1.127 \le P/a \le 3.062$

The calculated average Nusselt number (Nu_{mcal}) from Eq. (8) is plotted versus experimental average Nusselt number (Nu_{mexp}) in Figure 13. As shown from this figure the maximum deviation between the experimental data and the correlation is ± 14 %.

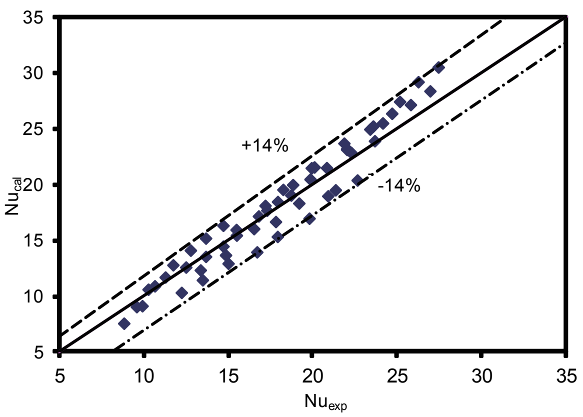

Figure 13
Nu_{cal} Against Nu_{exp} for Equilateral Triangle Helical Coiled

6. COMPARISON WITH THE PREVIOUS WORK

Comparison between the present data with the previous work of Moawed[22] of the same experimental ranges is shown in Figs. 14 and 15. Moawed[22] used circular cross-sectioned helical tubes having the same testing conditions. The average enhancement of Nusslet number are about 1.16 ~ 1.25 times that of Moawed[22] for all coil diameters used at the same pitch and Reynolds number as shown in Figure 14 and the average enhancement of Nusslet number are about 1.12 ~ 1.16 times that of Moawed[22] for all Reynolds numbers used at the same pitch and coil diameter as shown in Figure 15. This means that the average enhancement of Nusslet number for triangular cross-sectioned helical is better than for circular cross-sectioned helical at all testing conditions.

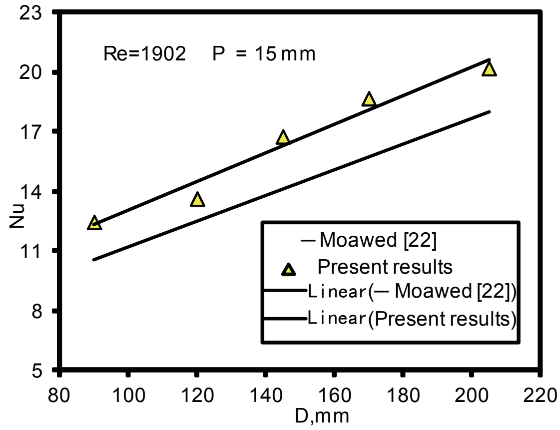

Figure 14
Comparison Between the Present Results of Nu Versus D at Constant P & Re with that of Reference [22]

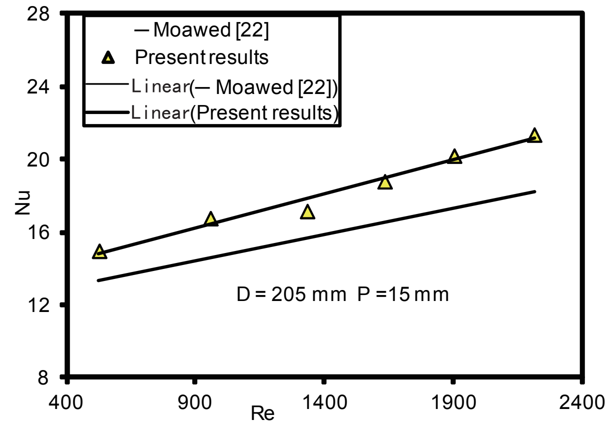

Figure 15
Comparison Between the Present Results of Nu Versus Re at Constant P & D with that of Reference [22]

CONCLUSION

The present experimental study was focused on the investigation of the heat characteristics of an equilateral triangular cross-sectioned helical tube under uniform heat flux boundary condition. The experiments were performed using groups of equilateral triangles helical tubes. Nine helical coiled-tubes of equilateral triangular cross-sectioned with various pitches and coil diameters are used. The experiments covered a range of Reynolds number of $5.2\times10^{2} \le \mathrm{Re} \le 2.2\times10^{3}$. The experimental results indicated that the key design parameters length, diameter and pitch of equilateral triangular cross-sectioned helical tube have important effects on the average heat transfer coefficient. The results revealed that the highest value of Nusselt number can be obtained with higher values of D/a at the same P/a ratio, while the Nusslet number increases with the increase of Re and P/a ratio at the same D/a ratio. A comparison between the present experimental data with a previous work [22] done with circular cross-sectioned helical tubes having the same testing conditions was achieved. From this comparison, it is clear that the average enhancement of Nusselt number for equilateral triangular cross-sectioned helical is about 1.12 ~ 1.25 times the circular cross-sectioned helical for all tested conditions. A general correlation of the average Nusselt number as a function in Re, D/a and P/a ratios is obtained to describe the forced convection from the equilateral triangle cross sectioned coiled tube.

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