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Experimental investigation of heat transfer and pressure drop inside elliptic tube with inserted helical coils

دراسة عملية لانتقال الحرارة وانخفاض الضغط داخل أنبوبه بيضاوية الشكل بداخلها ملفات حلزونية

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KEYWORDS:
Heat transfer; turbulent flow, helical coil; elliptic tub

الملخص العربي:-تناول البحث دراسة تجريبية لتأثير وضع ملفات حلزونية من النحاس دائرية المقطع ذات اقطار سلك مختلفة 2 و 6مم (بخطوات مختلفة من 20 و 45 و 135 و 225 مم) على انتقال الحرارة وهبوط الضغط داخل ماسورة بيضاوية الشكل والتى تم تسخينها من الخارج بسخان كهربى. السلك النحاسى المكون للملف الحلزوني ملاصق للماسورة من الداخل .رقم رينولد للسريان يتغير من 11000 الى 37500. النتائج التجريبية تبين أن استخدام سلك حلزوني داخل أنبوبة بيضاوية الشكل يؤدي إلى معدل انتقال حرارة أعلى من الانبوبة الملساء. وقد اظهرت النتائج ان تغير القطر وتغيير الخطوات بين الحلقات الحلزونية لهم تأثير على انتقال الحرارة وهبوط الضغط داخل الماسورة تحسين الكفاءة لقطر الملفات الحلزونية 6مم يزيد من الملفات الحلزونية بقطر 2مم في الخطوة بين اللفائف الحلزونية 20ملم بمقدار 2.3٪ في عدد رينولدز منخفض Re=11000. وترتبط النتائج أيضا في شكل علاقة بين كل من عدد نوسلت ومعامل الاحتكاك وكفائة التحسين كدالة فى رقم رينولدز، الخطوات وقطر الأسلاك الحلزونية

Abstract— **The paper deals with an experimental study of the influence of varying helical coil cross section diameter and pitches of helical coil on heat transfer and friction characteristics in an elliptical tube. The present work studies the effects of copper helical coils of circular cross section formed with different diameters of 2 and 6 mm at varying pitches (20, 45, 135 and 225 mm) inside elliptic tube. In the experiments, cold air at ambient condition is passed through the uniform heat flux circular tube for Reynolds numbers in a range of 11000 to 37500. The experimental results demonstrate that the use of helical coil inserts in elliptic tube leads to a higher heat transfer rate than that of the plain surface tube. Also, increasing helical coil cross section diameter and decreasing pitches of the helical yield a better heat transfer than the plain tube. The enhancement efficiencies of the helical coil cross section 6 mm over wire cross section 2 mm diameter at a pitch of 20 mm is 2.3% at Re=11000. The results are also correlated in the form of Nusselt number, friction factor and enhance efficiency as a function of Reynolds number, pitches and diameter of helical coil.**

I. INTRODUCTION

A heat exchanger is a device that facilitates the convective heat transfer of fluid inside the tubes and utilized widely in many applications, such as energy conservation, solar collectors, chemical processing plants, air conditioning equipment and refrigerators. To date, endeavors have been made to decrease the size and cost of heat exchangers.

Turbulators are inserted in the flow to supply redevelopment of the boundary layer, increase the heat transfer surface area, increasing the fluid mixing or by turbulence. In this way, a more economical heat exchanger with lower operation cost can be obtained.

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For last years, many helical coils used for augmentation of turbulent flow heat transfer have been reported and discussed.

NOMENCLATURE

A	Area	m^2
a	Major axis of the elliptic tube	m
b	Minor axis of the elliptic tube	m
C	Constant.	-
C_p	Specific heat of air at constant pressure.	j/kg.K
D_{eq}	Equivalent diameter of elliptic tube	m
d_h	Diameter of helical coil.	m
f_o	Average friction factor.	-
f_s	Friction factor for smooth tube.	-
g	Acceleration of gravity	(m/s^2)
h_c	Heat transfer coefficient of tube with inserted coil.	$(W/m^2\ K)$
h_m	Average heat transfer coefficient	$(W/m^2\ K)$
I	Current supply to heater	Amp
k	Thermal conductivity of air.	(W/m K)
L	Tube length	m
m°	Mass flow rate of air	Kg/m^3
Nu_c	Nusselt number of tubes with inserted coil.	-
Nu_m	Mean Nusselt number, h_m D/K.	-
Nu_s	Nusselt number of smooth tubes.	-
Pr	Prandlt number, $c_p\mu/k$	-
P_{static}	Static pressure	Pa
P	Pitch of coil	m
q	Heat flux density	W/m^2
Q	Total heat flow.	W
Re	Reynolds number	
R_e	Electrical resistance of heater	Ω/m
t	Thickness of tube	m
T_a	Air temperature	ºK
T_{mf}	Mean fluid temperature.	ºK
T_{ms}	Mean surface temperature.	ºK
T_f	Fluid temperature.	ºK
T_i	Inlet air temperature.	ºK
T_o	Outlet air temperature.	ºK
T_s	Local surface temperature.	ºK
V	Flow velocity	m/s
V_{avg}	Average velocity	m/s
V_c	Voltage supplied to the heater	Volt
X	Local distance.	m
ΔP	Pressure drop across test tube.	N/m^2
ΔT_s	Difference of surface temperature.	ºK
ΔT_{ms}	Mean surface temperature difference.	ºK
	Greek letters:	
μ	Dynamic viscosity of air	kg/m.s
ν	kinematic viscosity of air,	m^2/s
ρ	Density of air	kg/m^3

Few researchers have found for helical coils with circular cross section inserts in elliptic tube. This has been noticed in the work of Ibrahim [1] who studied the heat transfer Enhancement inside Elliptic tube by means of ring inserts. The results indicated that Nusselt number and friction factor increased with decreasing ring spacing. Qasim et al. [2] presented experimental and numerical investigation to enhance the performance of helical coiled tube heat exchanger by using turbulators, the helical coils used for increasing the heat transfer have been reported and discussed. The use of coiled wire causes an increase in pressure drop. Bhuiya et al. [3] talked about the performance of heat transfer for turbulent flow through a tube using double helical tape inserts. The results showed that the Nusselt number obtained for the tube with inserting double helical tape was 305% higher in comparison to the results of the plain tube values. Sharafeldeen et al. [4] carried out the experimental investigation of heat transfer and pressure drop of turbulent flow inside tube with inserted helical coils. It has been inferred from the experimental results the higher values of Nusselt number and friction factor are obtained at higher values of the wire diameter ratio and small values of the coil pitch ratio. A comparison of the heat transfer and the pressure drop performances between wire coil inserts and ring inserts was introduced by Vahidifar and Kahrom [5]. Several investigations were conducted to determine the effect of the coiled wire on the heat transfer and friction factor for a long time [6-9]. Some investigations were compared between coiled circular and square wire in circular tube [10-11], the results indicated that use of coiled square wire causes a high pressure drop increase and provides considerable heat transfer. Desale et al. [12] studied the heat transfer enhancement in tube in tube heat exchanger using Passive techniques. The results of the experiment indicate that the compound devices of the twisted tape and DI-coil, shows the highest thermal performance over the wire coil alone. Several investigations were conducted to determine the effect of the wire coil on the heat transfer [13-16], it was found that the heat transfer was enhance with wire coil inserts as compared to smooth tube. Biswas and Salam [17] studied the transfer enhancement of the inserted wire coil. Reynolds numbers were varied from 8317 to 17821 in the experiment. The experimental results show the heat transfer coefficient for tube with wire coil insert increased from 1.5 to 2.3 times compared to that of plain tubes.

The literature survey on investigations of different type of tube inserts indicates that these inserts are generally attached to the tube walls in order to enhance the heat transfer. This work different from those in the literature by attaching the helical coil inserts the elliptic tube wall in order to enhance the heat transfer.

This paper aims to study the heat transfer and friction factor in a horizontal elliptic tube with a circular helical coil inside it. Four different pitches are considered as (20, 45, 135 and 225 mm). Constant heat flux is applied through the outer surface of the elliptic tube and the air passing inside the tube.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

The present study is carried out to investigate experimentally convective heat transfer and pressure drop on the elliptic tube with inserted helical coils of wire diameters 2 and 6mm, and different pitches of 20, 45, 135 and 225mm for Reynolds number range from 11000 to 37500.

An experimental apparatus is constructed to study the phenomena of forced convection inside tube with an inserted helical coil under constant heat flux. Figure (1.a) and (1.b) shows the setup schematic of an open-loop air flow circuit and comprises the following major component**.**

1- Test section with entrance length
2- Air blower
3- Instrumentations
4- Power supply with associated controls

The assembly is well supported by iron frames and precautions were taken to reduce the vibrations of the setup components, hence a stable uniform flow with low turbulence level is maintained.

The test section consists of elliptic copper tube, helical coils inserts, the heating element, thermal insulation layer, thermocouples and exit section.

The entrance section is elliptic tube made of copper having a 58 mm major axis and 43 mm minor axis (hydraulic diameter= 51 mm), 800mm long (L) and 1.5 mm thick (t).

Figure (2) shows the test rig in detailed and shows the distribution of thermocouples a long test tube. The test-section is elliptic tube and made of copper having a 58 mm major axis and 43 mm minor axis (hydraulic diameter = 51 mm), 1250 mm long (L) and 1.5 mm thick (t). The outlet and inlet air temperature are measured by using thermocouples.

Thirty-two thermocouples of 0.5mm diameter in test section are used to record the temperature along the tube surface. These thermocouples are cemented on the drilled holes at sixteen axial locations such that a pair of thermocouples is installed at every station.

The test tube with helical coil wire insert and its details are given in Fig.3. From this figure, it is clear that this test section lets good connections between the elliptic tube and helical coils.

The tube is heated using electrical resistance wire made of nickel chrome of 0.6 mm diameter, 5.14Ω/m and 2035 cm long. Firstly, the test section is covered by an electrical insulating tape which is wounded around the tube to avoid short circuit which may result between the heating wire and the tube. The heating wire is wound around the test section with constant pitch to uniformly distribute the heat generated from the electric heater.

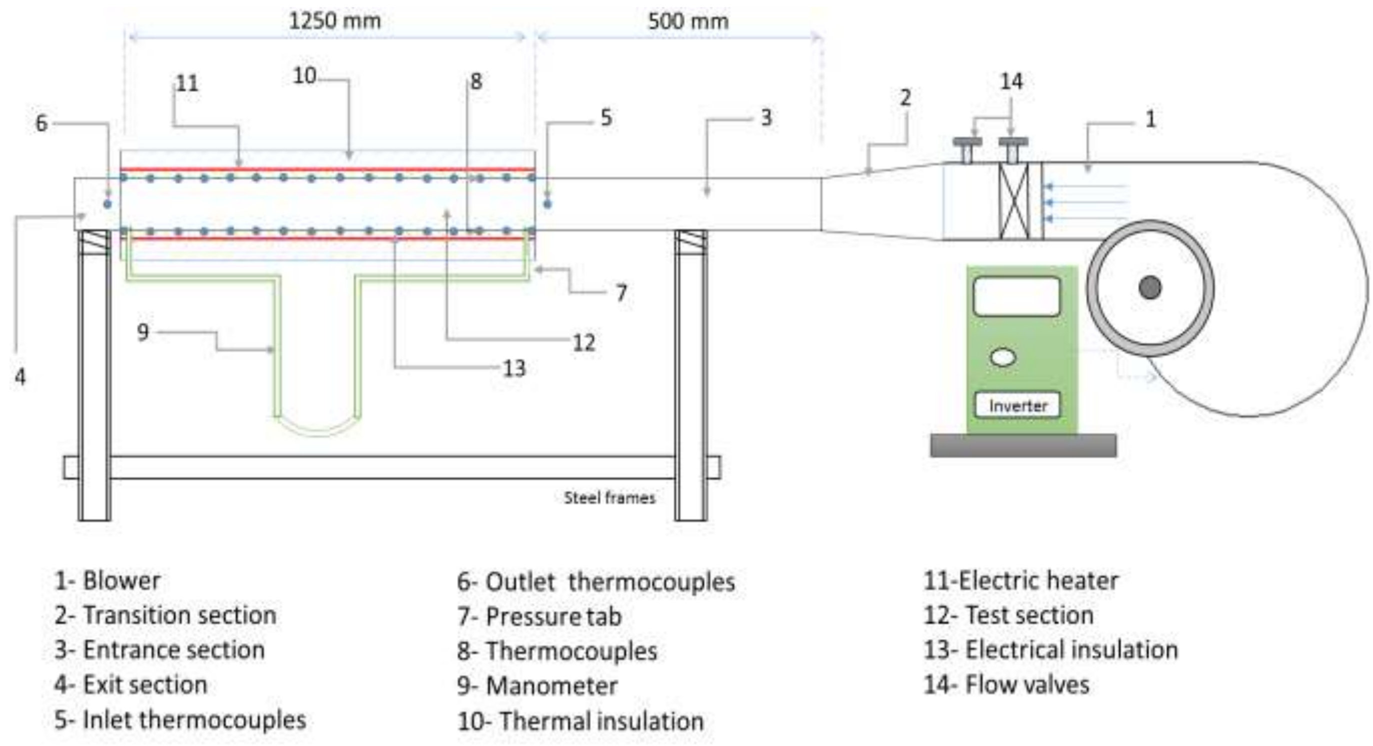

Figure (1.a) Schematic drawing of experimental set up

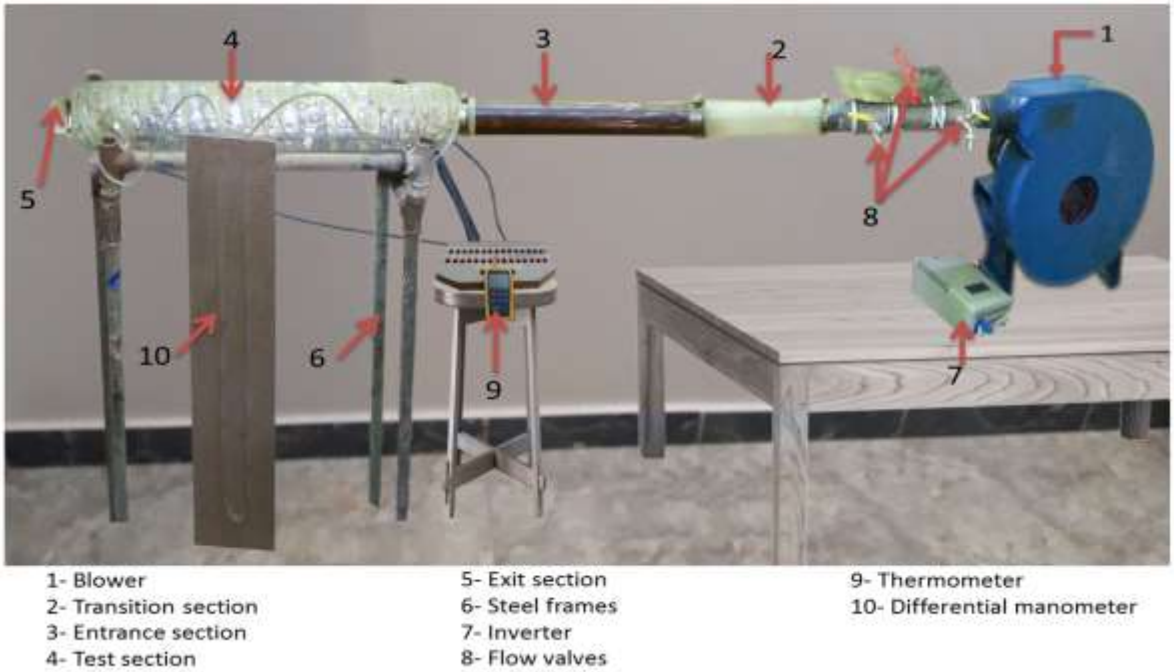

Figure (1.b) Photograph for the setup

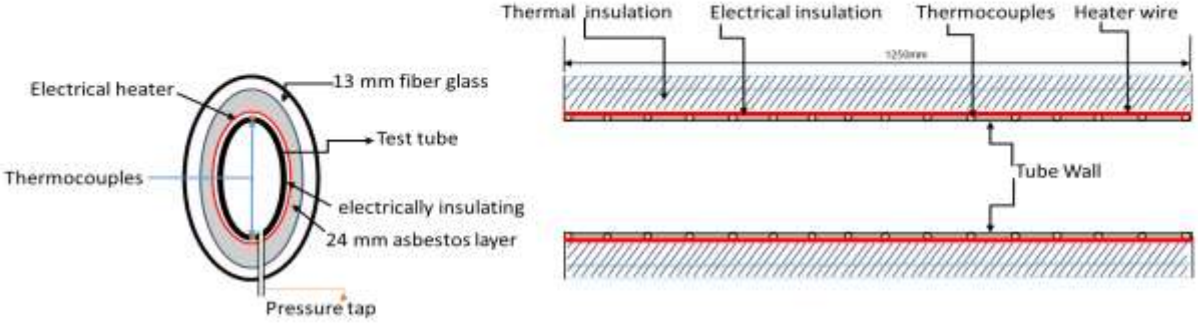

Figure (2) shows the details of test section

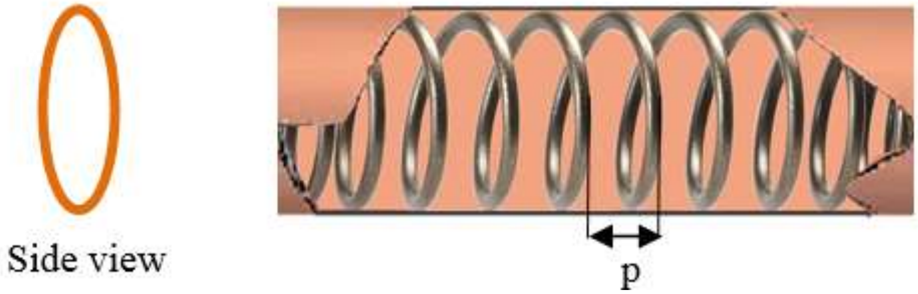

Fig.3 test section of elliptic tube fitted with helical coil

The test section is covered by two insulation layers the first is 24mm thickness asbestos layer with thermal conductivity of 0.2 W/m.K and the second layer is 13mm black fiber Glass with thermal conductivity 0.038 W/m.K. The electrical output power is controlled by a voltage regulator to obtain a predetermined constant heat flux along the entire length of the test section.

III. UNCERTAINTY ANALYSIS

The uncertainty in the axial velocity measurement was estimated to be about ±2.9 %, while the uncertainty was about ±6% in the measurement of the temperature of the tube wall.

The uncertainty in the calculation of the data was based on Reference [18]. The maximum uncertainties of non-dimensional parameters are ±4. 9% for Reynolds number and ±11. 8% for Nusselt number.

IV. DATA REDUCTION

In the present work, the air is used as the tested fluid and flowed through a uniform heat flux tube. The steady state of the heat transfer rate assumed to be equal to the heat transferred from the test tube to the flowing air, which can express as:

$$Q_a = Q_c \tag{1}$$

i.e:

$$Q_a = m \cdot C_{pa} (t_o - t_i) = VI \tag{2}$$

The heat transfer coefficient of the air is calculated as:

$$h_c = Q_a / A\,(t_{ms} - t_a) \tag{3}$$

Where:

$$t_a = (t_o + t_i) / 2 \tag{4}$$

$$t_{ms} = \sum t_s / 32 \tag{5}$$

In which t_s is the local surface temperature at the outer wall of the test tube. The mean surface temperature t_{ms} calculated from 32 points. The mean Nusselt number, Nu is calculated as follows:

$$Nu = h_c\, d_i / k \tag{6}$$

The Reynolds number of the air flow inside the tube is given

$$Re = \frac{\rho \;\; V_{avg} \;\; D_{eq}}{\mu} \tag{7}$$

The friction factor, can be written as

$$f = \frac{2 \times \Delta p \times \dfrac{d}{L}}{\rho \times V^2} \tag{8}$$

The efficiency index (η) can be written as follows [1]:

$$\eta = (Nu_c / Nu_s) / (f_c / f_s)^{1/3} \tag{9}$$

V. RESULTS AND DISCUSSION

The heat transfer and friction factor of the plain elliptic tube were compared with Incropera [19] for the circular tube as illustrated in Figures 4 and 5 respectively. The circular tube data were found to be in good agreement with the earlier correlations of [19] for both the Nusselt number and the friction factor within ± 6% and 9 % respectively.

Nusselt number correlation is: [19]

$$Nu = 0.023\, Re^{0.8}\, Pr^{0.4} \tag{10}$$

$$\text{For } Re \geq 10000$$

The friction factor equation is: [19]

$$f = (0.790 \,\text{Ln}\, Re - 1.64)^{-2} \tag{11}$$

$$\text{For } 3000 \leq Re \leq 5 \times 10^6$$

The effect of using varies helical wire pitches (20, 45, 135, 225 mm) with circular cross section wire of 2 mm and 6 mm diameter at heat transfer coefficient are presented in Fig. 6 and 7 respectively. From these figures, it is apparent that the use of helical wire leads to significantly raise heat transfer rates than the plain tube for all that pitches of helical wire. Nusslet number increases using the elliptic tube with circular cross section wire of 2mm diameter inserts for about 95% to 128%, 80% to 117%, 60% to 83%, and 51% to 75%, than that of the smooth tube at pitches of 20, 45, 135, 225mm respectively for Re varying from 11000 to 37500. While this increases by using circular cross section wire 6 mm diameter are about 119% to 151%, 101% to 130%, 78% to 106%, and 70% to 96%, than that of the smooth tube at the same pitches and Re range as shown in Fig 6 and 7 respectively. This increase can be attributed to the boundary layer disturbance effects a better chaotic mixing between the core and the wall areas. This shows that the effects of reverse flow and boundary layer disruption can help to enhance the convection heat transfer and momentum processes. In addition, the use of the low pitch of helical leads to increases of the heat transfer than that of the high pitch. This is because the turbulence intensity and the flow path obtained from the lowest pitch are greater than that from the higher.

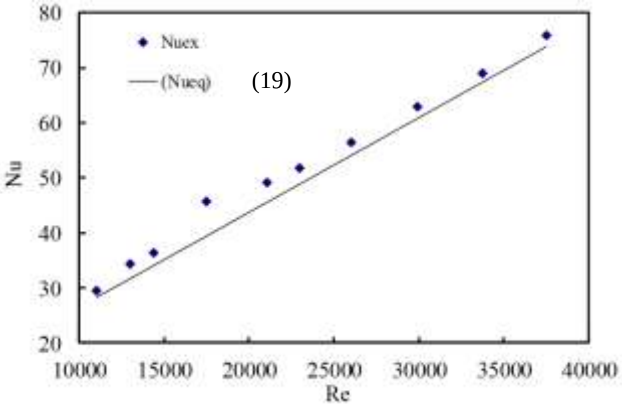

Fig.4 Nusslet number versus Reynolds number for smooth tube

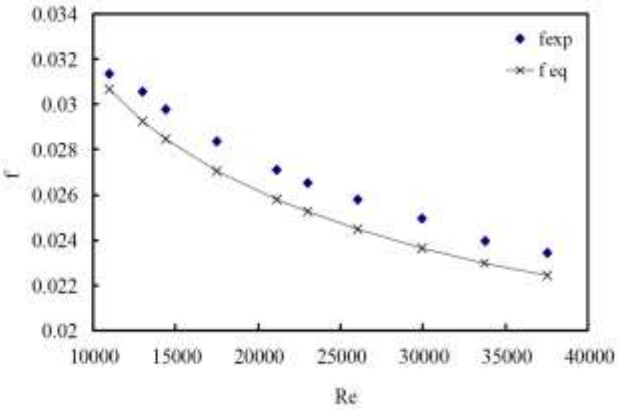

Fig. 5 Friction factor versus Reynolds number for smooth tube

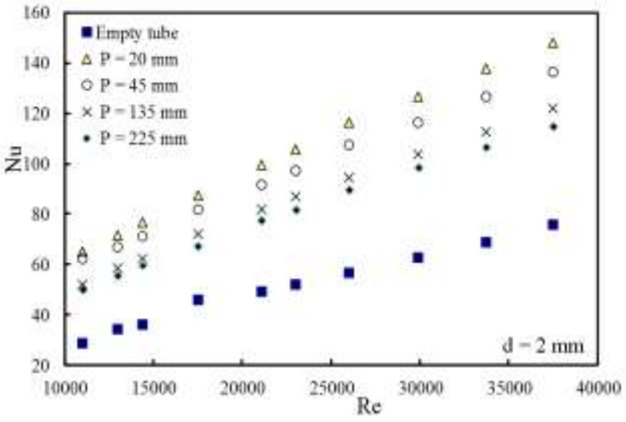

Fig.6 Variation of Nusselt number with Reynolds number for different pitches at 2mm wire diameter.

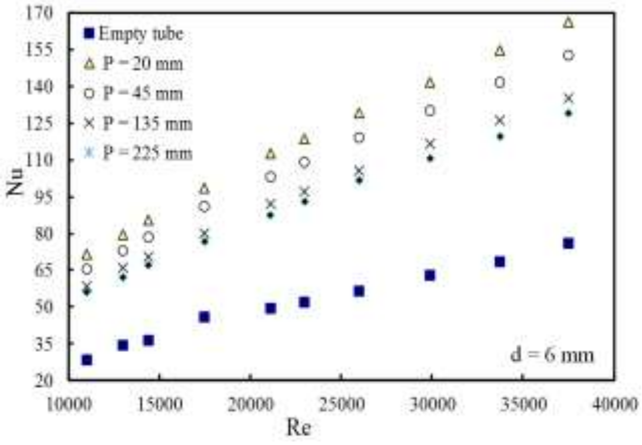

Fig.7 Variation of Nusselt number with Reynolds number for different pitches at 6mm wire diameter.

The results of Nusselt number in a tube with wire coil inserts of varying wire diameter at different pitches, are explained in Fig. 8 and 9.

From these figures, it is clear that the increases in Nusslet number by using the elliptic tube with wire diameter of 6 mm inserts than that of the using wire diameter of 2 mm at all pitches of helical wire.

This is because the wire of 6 mm diameter provides better fluid mixing in the flow field, which leads to an increase in turbulence intensity and consequently yields higher heat transfer rate.

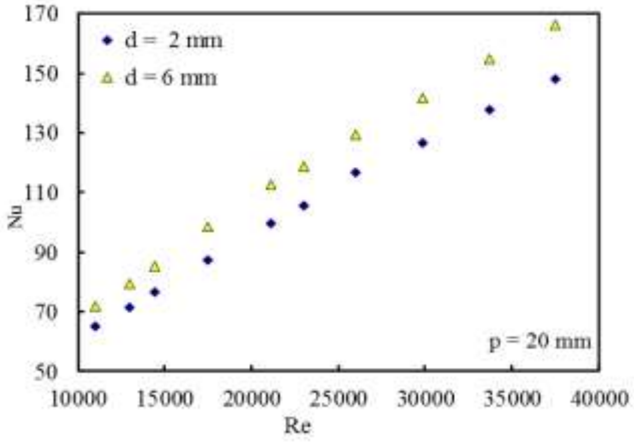

Fig.8 Variation of Nusselt number with Reynolds number for different wire cross sections at the same pitches.

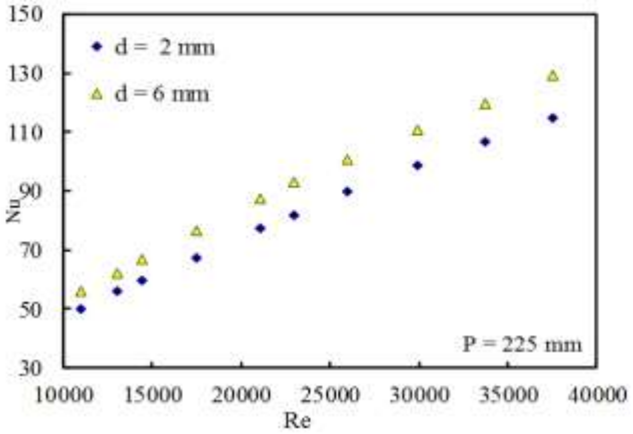

Fig.9 Variation of Nusselt number with Reynolds number for different wire cross sections at the same pitches.

Heat transfer improvement was found at the expense of an increased pressure drop caused by tube insertions. For this reason, a performance analysis is important for the evaluation of the net energy gain to determine if the method employed to increase the heat transfer is effective from an energy point of view. Fig. 10 and 11 present the relation between the overall enhancement ratio and Reynolds number of varying wire cross section inserts in elliptic tube respectively. From these figures, it is interesting to note that the enhancement, efficiency illustrations a rapid decrease with the rise of Reynolds number. The enhancement, efficiency peak was at the lowest pitches of 20 mm helical wires for cross section circular inserts in elliptic tube respectively.

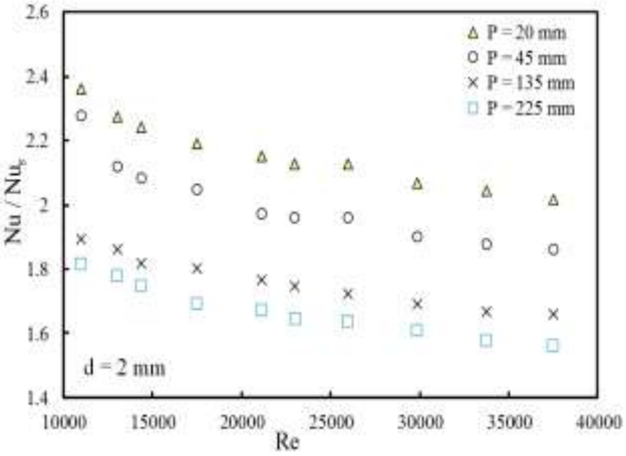

Fig.10 Variation of overall enhancement ratio with Reynolds number for different pitches at same diameter.

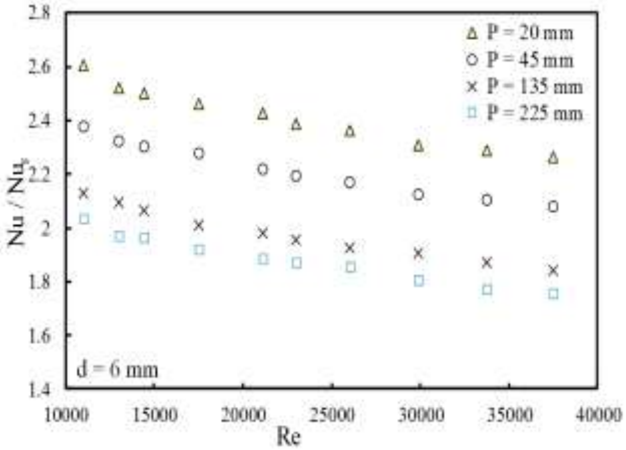

Fig.11 Variation of overall enhancement ratio with Reynolds number for different pitches at same diameter.

Fig. 12 and 13 illustrates the variation of friction factor with different pitches of helical wire for various Reynolds numbers of different wire cross sections fitted with elliptic tube. It is evident that the friction factor increases with helical wire pitch decrease. The maximum friction factor was obtained at 20 mm pitch of helical wire for all Reynolds numbers range and all wire inserts in elliptic tube. This is expected because of the high turbulence and well contact surface area between fluid and heating wall surface. The friction factor increases for 20 mm pitch of helical wire was 157% to 206 % and 222% to 285% for both 2mm and 6 mm wire diameter inserts in elliptic tube respectively more than the smooth elliptic tube respectively.

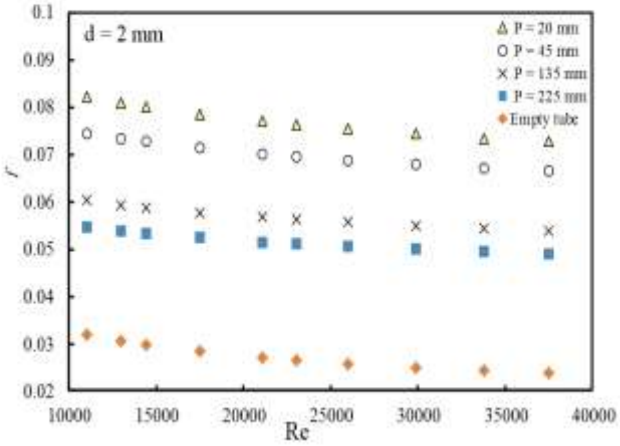

Fig.12 Variation of friction factor with Reynolds number for different pitches at same diameter.

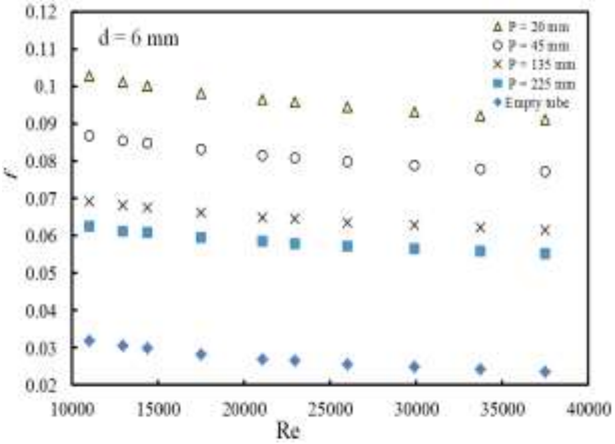

Fig.13 Variation of friction factor with Reynolds number for different pitches at same diameter

The variation between the enhancement efficiency and Reynolds numbers at varying wire cross section diameter inserts in the elliptic tube at different pitches of helical wire coils are shown in Fig. 14 and 15. It is show that the improved efficiencies (η) generally are above unity at all pitches. Also, these figures show that the enhancement efficiency increases with decreasing pitches.

Figs. 16 and 17 show the plote of efficiency index (η) versus Reynolds number (Re) at different helical wire diameter and different helical coil pitch. The improved efficiency tends to increase at cross sectional wire diameter inserts in the elliptic tube at all pitches of helical wire. The enhancement, efficiency increases with decreased pitch of helical coil, especially at a lower Reynolds number.

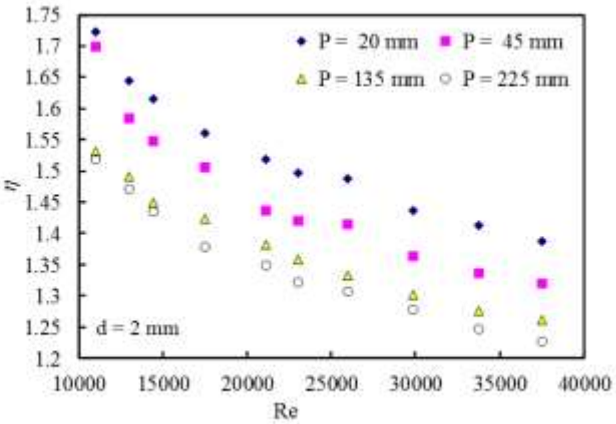

Fig.14 Variation of efficiency with Reynolds number for various pitches at same diameter.

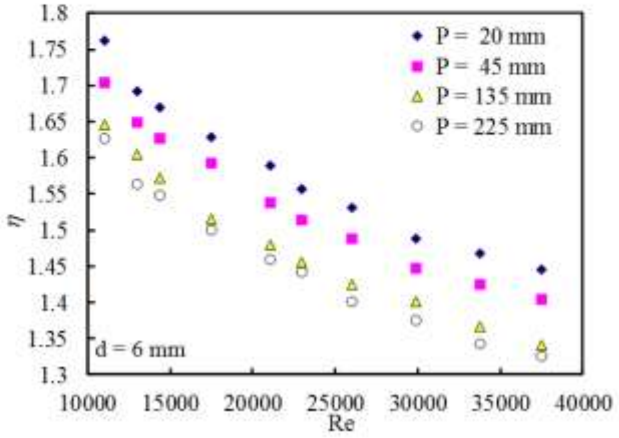

Fig.15 Variation of efficiency with Reynolds number for different pitches at same diameter.

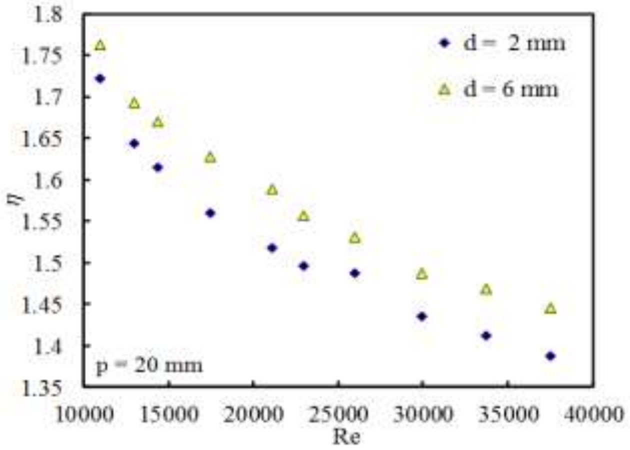

Fig.16 Variation of efficiency with a Reynolds number of different wire cross sections of the same pitches.

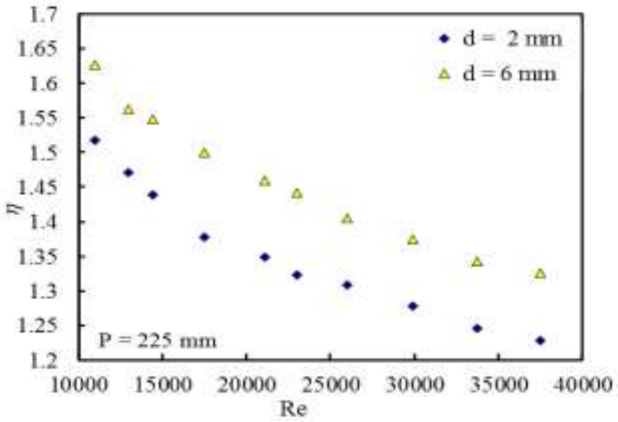

Fig.17 Variation of efficiency with Reynolds number for different wire cross sections at the same pitches.

COMPARISON WITH PREVIOUS WORK

Figure 18 and 19 shows comparison between the present work and reference [4]. In these figures, the friction factor and Nusslet number of elliptic tubes fitted with circular helical coils are higher than the circular tube fitted with circular helical coils.

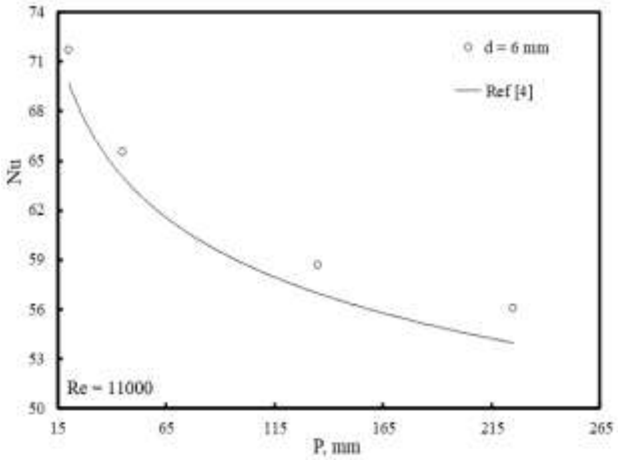

Fig.18 Variation between present work and ref [4]. at Re=11000.

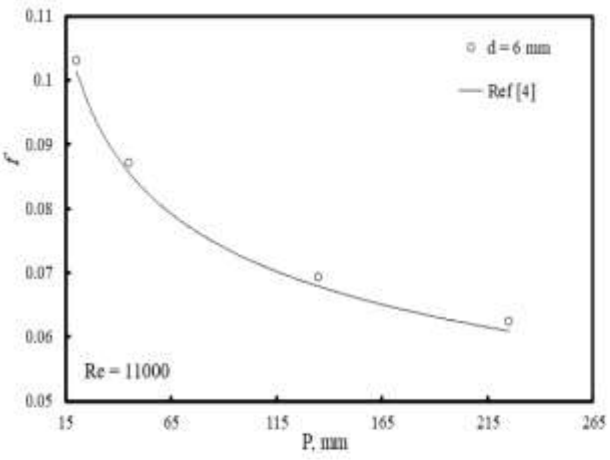

Fig.19 Variation between present work and ref [4]. at Re=11000

CORRELATION OF THE RESULTS

The experimental results are fitted, using power regression, to determine the following empirical correlations for helical wire inserts in elliptic tube:

$$Nu = 0.106\ Re^{0.6820}\ (p / d_i)^{-0.105} \quad (12)$$

$$f = 0.186\ Re^{-0.096}\ (p / d_i)^{-0.188} \quad (13)$$

$$\eta = 7.785\ Re^{-0.167}\ (p / d_i)^{-0.042} \quad (14)$$

$0.392 \le P/d \le 4.411$, $11\times10^3 \le Re \le 3.375\times10^4$,

Figs. 20 to 22 show the relation between the experimental value of Nu_{exp}, f_{exp}, η_{exp} and the values of Nu_{calu}, f_{calu}, η_{calu} calculated from equation 12 to 14 respectively . From these figures, it is clear that the results of the present work agree with the fitted correlations.

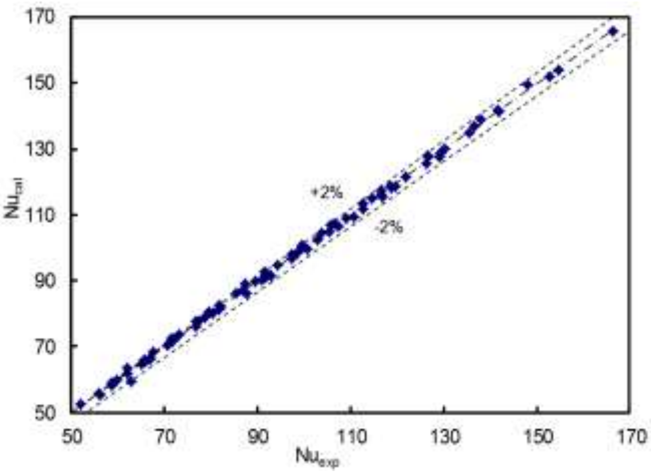

Fig.20 relation between Nu_{exp} and Nu_{cal}.

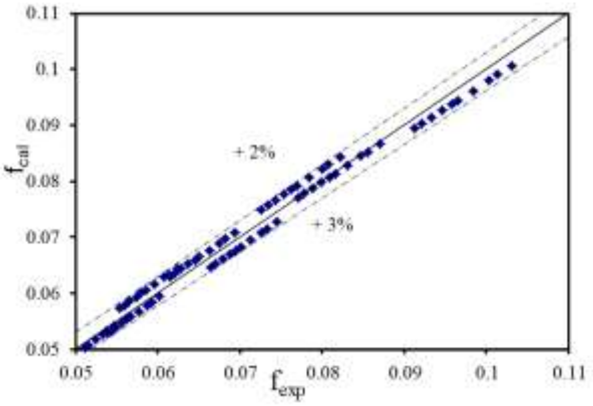

Fig.21 relation between f_{exp} and f_{cal}.

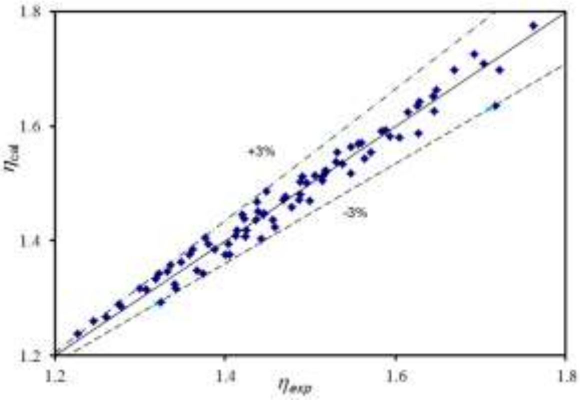

Fig.22 relation between η_{exp} and $\eta_{cal.}$.

VI. CONCLUSION

Heat transfer and friction factor for different wires of circular cross section inserts in elliptic tube are experimentally investigated for $11000 \le Re \le 37500$. The tube was heated by a continuous winding electrical wire to provide a uniform heat flux. Several pitches of helical wire were changed from 20 mm to 225 mm. The comparisons between the present experimental work and previous research results are presented. from the previous discussion the following are concluded:

1) The use of helical wire coil fitted with elliptic tube causes higher heat transfer rates and friction factor than the plain tube for all pitches of helical coil.
2) Decreasing pitches of helical coil and increasing diameters of the helical wire lead to increasing Nusselt number and friction factor.
3) Nusslet number increase from 95% to 128%, using the 2mm helical wire diameter, while Nusslet number increases from 119% to 151%, using 6 mm helical wire diameter, than that of the smooth tube at pitches of 20mm.
4) The highest values of the friction factor are found with the pitch of helical coil equal to 20 mm for helical wire inserts in elliptic tube.
5) The enhancement efficiency increases with decrease pitch of helical coils.
6) Correlations of Nusslet number, friction factor and efficiency as a function of Reynolds number, (p / d_i) at a certain value of (d_h / d_i) are presented.

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