Thermal and Hydraulic Response of Turbulent Flow inside Hexagonal Duct Fitted with Various Inserts

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Abstract

The present work shows the results obtained from experimental investigations of the augmentation of turbulent flow heat transfer in a horizontal hexagonal duct fitted with combined wire coil tabulators and a perforated twisted-tape swirl generator. Water is used as a working fluid for Reynolds number range between 2480-9922 under constant wall heat flux thermal boundary condition. In this study, two enhancement heat transfer devices are used. One is the constant/ periodically varying two wire coil pitch ratio that arranged into two different forms; I-coil (Increasing coil pitch ratio arrangement) and ID-coil (Increasing/decreasing coil pitch ratio arrangement). The other type of inserts is the perforated twisted- tape with constant twist ratio (Y = 5.3 and PR= 4.5%) that placed at the core of the coil wire. The experimental data obtained for each enhancement device are compared with those obtained from the plain duct and also from the available literature to ensure the validation of experimental results. The results show that the heat transfer process have been enhanced with by using combined wire coil and twisted-tape inserts or by using each one alone with compared to plain duct. The highest thermal performance factor of around 2.18 is found by using ID-coil in common with the twisted-tap .

Keywords: heat transfer enhancement, wire coil inserts, twisted tape inserts.

التصرف الحراري والهيدروليكي لجريان اضطرابي داخل مجرى سداسي مزود بحشوات مختلفة

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الخلاصة

يبين العمل الحالي النتائج التي تم الحصول عليها من التحريات العملية لتحسين انتقال الحرارة لجريان مضطرب داخل مجرى سداسي افقي مزود بمضطربات سلكية ومولدات دوامة عبارة عن شريط ملتو مثقب .استخدم الماء كمائع الاختبار لرقم رينولدز يتراوح بين 2480-9922 تحت فيض حراري منتظم حدي حراري. في هذه الدراسة تم تحسين عملية انتقال الحرارة باستخدام وسيلتين . الاولى عبارة عن لفائف سلكية ثابتة/ ومتغيرة نسبة خطوة اللفة، والمتغيرة تكون بشكلين الاول المتزايد والاخر المتزايد المتناقص . الوسيلة الاخرى عبارة عن شريط ملتو مثقب مولد للدوامات يوضع في قلب اللفائف السلكية بنسبة التواء ثابتة Y=5.3 و PR = 4.5% . تم مقارنة القيم التجريبية التي تم الحصول عليها لكل جهاز مع تلك التي تم الحصول عليها من المجرى الخالي من هذه الوسائل ومن الادبيات السابقة للتأكد من صحة النتائج العملية . لوحظ ان عملية انتقال الحرارة يتحسن باستخدام اللفائف السلكية والشريط الملتو معا او كل على انفراد مقارنة بحالة المجرى الخالي. ان اعلى عامل أداء حراري حوالي 2.18 وجدت باستخدامم ID-coil مع الشريط الملتوي رينولدز.

الكلمات الرئيسية: تحسين انتقال حرارة، حشر لفائف سلكية، حشر شريط ملتوي.

1. Introduction

Improvement of heat transfer intensity in all types of thermo technical equipment is of great significance for industry. Beside the savings of essential energy, it also leads to a reduction in size and weight. Various heat transfer enhancement techniques have been developed. One of them is using tabulators.

Eiamsa-ard, et al., 2006. Experimentally studied the heat transfer and friction factor characteristics through a circular tube fitted with regularly spaced twisted- tape elements, and showed that the heat transfer coefficient increased with the decrease of twist ratio. **Bhuiya, et al., 2013.** experimentally investigation of Nusselt number, friction factor and thermal performance factor in a turbulent flow through a circular tube equipped with perforated twisted- tape inserts with four different porosities of Rp = 1.6, 4.5, 8.9 and 14.7%. Air as the working fluid and Reynolds number ranging from 7200 to 49,800 under uniform wall heat flux boundary condition. The results revealed that both heat transfer rate and friction factor of the tube fitted with perforated twisted tapes were significantly higher than those of the plain tube. **Syed Jafar, et al., 2014.** experimental investigation was carried out to study the impact of absorber device with nail twisted tape of two different twist ratios of y = 2.0, and 3.0 and using Al_2O_3 / water Nano fluid as the working fluid on the heat transfer and friction factor characteristics of a solar parabolic trough collector. The tests are performed in the laminar range 710-2130 under constant heat flux conditions. It is observed that the nail twisted tape absorber with Nano fluids can significantly improve the heat transfer performance of the solar trough collector. **Yakut,** and **Sahin, 2004.** experimentally studied of using the configuration of coiled wire cross section 4mm & length 1240 mm , by using air as a working fluid with the Reynolds no. varying from 5000 to 35000 and pitches are 10,20, 30 mm. The results show that vortex characteristics of the tabulators should be considered as a selecting criterion with heat transfer and friction characteristics in heat transfer enhancement applications. **Akhavan-behabadi, et al., 2010.** They have performed an experiment with the use of oil as a working fluid and configuration are taken as seven coiled wires having pitches 12 to 69 mm. The experimental analysis that has been carried out at low Reynolds numbers ranging from 10 to 1500 and he found that wire coil inserts with lower wire diameters have better performance, especially at low Reynolds numbers. Also, the increase in the coil pitch made a moderate decrease in performance parameter.

Promvonge, 2008. Experimentally investigated influences of insertion of twisted tapes and wire coils in a circular tube on heat transfer and turbulent flow friction characteristics in by using air as the test fluid. The wire coil used as a turbulator is placed inside the test tube while the twisted tape is inserted in the core of wire coil to create a continuous impinging swirl flow along the tube wall. The effects of insertion of the two turbulator with different coil pitch and twist ratios on heat transfer and friction loss in the tube are examined for Reynolds number ranging from 3000 to 18,000. The experimental results are compared with those obtained from using wire coil alone, apart from the smooth tube.

The results indicate the combined twisted tape and wire coil with smaller twist and coil pitch ratios provides higher heat transfer rate than those with larger twist and coil pitch ratios under the same conditions. **Eiamsa-ard et al., 2010.** Experimentally investigated of heat transfer, friction factor and thermal performance behaviors in a tube equipped with the combined devices between constant/periodically varying wire coil pitch ratio and the twisted tape (TT). The periodically varying three coil pitch ratios were arranged into two different forms: (1) D-coil (decreasing coil pitch ratio arrangement) and (2) DI-coil (decreasing/increasing coil pitch ratio arrangement) while the twisted tapes were prepared with two different twist ratios. The experiments were conducted in a turbulent flow regime with Reynolds numbers ranging from 4600 to 20,000 using air as the test fluid. Compared to each enhancement device, the heat transfer rate is further augmented by the compound devices. Over the range investigated, the highest thermal performance factor of around 1.25 is found by using DI-coil in common with the TT at lower Reynolds number. A comparison of the thermal and hydraulic performances between twisted tape inserts and wire coil inserts was made by **Wang,** and **Sunden, 2002.** For both laminar and turbulent flows. They found that the wire coil performs effectively in enhancing heat transfer in a turbulent flow region whereas the twisted tape yields a poorer thermal performance.

As shown from the literature there is no data on heat transfer and pressure drop inside hexagonal duct with combined wire coil turbulator and a perforated twisted-tape swirl generator at the same time. So, the main purpose of the present work is therefore, to study the thermal and hydraulic performance of turbulent flow through a hexagonal duct fitted with constant perforated twist tape ratio and wire coil with two constant/ varying pitch length with using water as the working fluid .

2. Experimental Work

The experimental set up consists of centrifugal pump , calming section , test section, a fluid reservoir and instrument devices as shown in Fig. 1. The calming section (1000 mm long) is kept long enough to ensure the fully developed flow condition at the entrance of the test section. The end of the clamming section is connected with the test section which is made locally from copper with hexagonal cross sectional dimensions of (L= 1000 mm) long,(a=10 mm) side length ,0.7 mm in thickness and (d_h =17 mm) hydraulic diameter as shown in Fig. 2. The duct was heated by continually winding flexible electrical wires providing a uniform heat flux boundary condition. The electrical output power was controlled by a variac transformer to obtain a constant heat flux along the test section. Over the electrical winding a thick insulation is provided using glass wool to minimize heat loss.

Ten T-type thermocouples, previously calibrated, were inserted in test section and distributed regularly. They are used to measure walls temperatures, inlet and outer water temperatures. The pressure drop across the test section is measured by using U-tube manometer is fitted across the test section .A flow meter of 18 liter/min in capacity was provided to measure the water flow rate. Fig. (3: a, b, c and d) shows the coil wire turbulator and twisted-tape used in the present experiments. The wire coil used is made of steel wire with diameter (d) of 1 mm.

The wire coil is maintained as a hexagonal shape with two constant pitch length (P = 10, 20 mm) and two varying pitch length (I-coil (increasing coil pitch length) and ID-coil (increasing /decreasing coil pitch length).

The perforated twisted-tapes were fabricated from copper at constant porosity, Rp = 4.5 % with pore diameters of 3 mm. **Bhuiya, et al., 2013.** Found that the use of perforated twisted-tape insert with porosity of 4.5% which caused stronger swirl flow or turbulence flow and long residence time in the tube.

The geometric dimensions of tape was; length 1000 mm, width (w) 15 mm and thickness 0.7 mm. The twist ratio of the tape was considered (5.3). The distances between two adjacent holes were 10 mm in axially. The porosity of the tape is defined as the ratio of total pores area to the tape area and the twist ratio is defined here in as the ratio of the pitch or one twist length (y, 180°) to the tape width (w). In the experiment, the twisted tape was put into the coil and both devices were then simultaneously inserted into the duct. All details of the duct with wire coil and twist tape inserts are shown in **Table. 1**.

Initially, water is taken from tank and pumped to the test section through the flow meter. The flow rate of water is varied by using the gate valve for different data and kept constant during the experiments. A minimum of 3L/min is used and it is increased up to 12 L/min .After switching on the electric heater the sufficient time was given to reach to the steady state condition. Experiments were conducted for plain duct, and subsequently by inserting the perforated twisted-tape alone, inserted wire coil with two constant /varying pitch lengths alone and combined wire coil and a twisted-tape at different flow rates. In each run, data were taken for water flow rate, walls temperatures of the test section and inlet and outlet water temperatures.

The pressure drop was measured for each flow rate with the help of a U-tube manometer under isothermal condition of flow without switching on the heater.

3. Data Redaction

Heat transfer rate by heater to the water is calculated by,

$$Q = \dot{m}\, cp\, (T_o - T_i) \qquad (1)$$

The heat transfer coefficient is calculated from,

$$h = \frac{Q}{[As\,(T_s - T_b)]} \qquad (2)$$

Where,

$A_s = (6.\ a.\ L_t)$ is the heat transfer surface area.

The bulk temperature is obtained from the average of water inlet and outlet temperatures

$$T_b = \frac{Ti\ + To}{2} \qquad (3)$$

And

$$Ts = \frac{\sum_{i=1}^{10} T_s}{10} \tag{4}$$

The Nusselt number is calculated as,

$$Nu = \frac{h\, d_h}{k} \tag{5}$$

The Reynolds number is given by,

$$Re = \frac{\rho U_m d_h}{\mu} \tag{6}$$

Where,

d_h: is the hydraulic diameter of the hexagonal duct.

$$d_h = \frac{4Ac}{p} = \frac{4[2.\left(\frac{2.a.\sin 60.a \cos 60}{2}\right)+2.a.\sin 60.a]}{6.a} \tag{7}$$

$$= \frac{4[\left(\frac{\sqrt{3}.a.\frac{a}{2}}{2}\right).2+\sqrt{3}.a.a]}{6.a} = a.\sqrt{3}$$

U_m: Mean water velocity is obtained from,

$$U_m = \frac{\dot{m}}{\rho.Ac} \tag{8}$$

Porosity of the tape was calculated by,

$$R_p = \frac{\frac{\pi}{4} {d_T}^2}{L_t.w} \tag{9}$$

Where d_T is the pore diameter of tape, L_t is the tape length and w is the tape width. Friction factor, f, can be written as:

$$f = \frac{\Delta p d_h}{\frac{\rho\, {U_m}^2 L_t}{2}} \tag{10}$$

Where, ΔP is the pressure drop of the test section.

Thermo-physical properties of water are determined at the overall bulk water temperature from Eq. (3).

The thermal enhancement factor, η, defined as the ratio of the, h of an augmented surface to that of a plain surface, h_a, at an identical pumping power (pp) is suggested by **Webb, 1981.** :

$$\eta = (Nu/Nu_p) / (f/f_p)^{1/3} \quad (11)$$

Where Nu_p and f_p are the Nusselt number and friction factor of a plain duct.

4. Results

In order to prove validity of the experimental facility, the present plain duct results were compared with the results obtained from Gnielinski equation for the Nusselt number and Blasius equation for the friction factor. The Nusselt number for a plain duct is given by the Gnielinski equation **Gnielinski, 1976.** as:

$$Nu_p = 0.0137\ Re^{0.843} pr^{0.33} \quad (12)$$

The friction factor for a plain duct is given by Blasius equation **Incropera,** and **Dewitt**, **1996.** as:

$$f_p = 0.316\ Re^{-0.25} \quad (13)$$

For the Reynolds number range of this work, the experimental data of the present plain duct are formed in good agreement with the results from the previous correlations as shown in **Figs. 4** and **5**, respectively

The effects of perforated twisted-tape alone, wire coil alone and the combination of perforated twisted tape and uniform wire coil (the wire coil with constant coil pitch length P=10 mm, 20 mm) or non-uniform wire coil (the wire coil with varying two coil pitch length, I-coil (a series of increasing two coil pitch length; 10:20: 10:20 mm) and ID-coil (increasing / decreasing of two coil pitch length; 10:20:20:10.mm) on the heat transfer, friction factor and thermal performance factor, are demonstrated in **Figs. 6 –10**.

As seen in **Fig. 6**, the heat transfer for using enhancement devices considerably increases with the increasing Reynolds number. The insert of the twisted tape or wire coil in a duct creates swirling flows that modify the near wall velocity profile due to the various vorticity distributions in the vortex core. The fluid mixing between the duct core and the near wall region is enhanced because of the swirl induced tangential flow velocity component. However, accompanying with the swirl induced heat transfer enhancement, the shear stress and pressure drag in a duct with a coiled wire or the twisted-tape insert are accordingly increased.

At a given Reynolds number, the Nusselt numbers for the duct equipped with compound enhancement devices (ID-coil and twisted- tape) are higher than those with each device alone. This can be explained by the fact that the combined actions of disturbance flow at near wall region by the wire coil and swirl flow by the twist tape, result in a synergy effect on heat transfer enhancement.

Depending on the Reynolds number, the compound devices enhance heat transfer in a range of 3.2 to 4.2 times of the plain tube, 2.5 to 2.85 times of the twisted tape alone and 1.72 to2.14 times of the wire coil alone.

The Nusselt number ratio, Nu/Nu_p, plotted against the Reynolds number is illustrated in Fig.7. From the figure, it is observed that Nusselt number ratio, Nu/Nu_p, is highest for ID-coil with twisted-tape because the devices generate more flow fluctuation and thus better mixing than others.

The highest Nusselt number ratio is about 4.2 for the ID- coil with twisted-tape and the lowest Nusselt number ratio is perforated twisted-tape alone which is 1.47 .
Friction factors for the plain duct and the enhancement devices introducing inside the duct and friction factor ratios (f/f_p), respectively, are displayed in the Figs.8 and 9. It can be observed that the friction factor is slightly decreased with the increasing Reynolds number. At the same Reynolds number friction factor is highest in a combination of the twisted-tape and the wire coil with pitch length 10 mm compared to those induced by the other methods. This can be explained by the following reasons: the presence of both enhancement devices generates flow perturbation and also increases contact area with longer flow path, leading to the increase of pressure loss.
It's clear from Fig.(8) that the friction factor ratio (f/f_p) slightly increases with the increasing Reynolds number and the highest friction factors ratios (f/f_p)found in a combination of the twisted- tape and the wire coil of pitch length 10 mm which has the range 8.97 to 12.3 above the plain duct.
In the present work, the effectiveness of heat transfer enhancement in terms of thermal performance factor (η) is defined using the Nusselt number and friction factor in the duct fitted with the enhancement device as shown in Eq. (11). The thermal performance factor for the duct with various inserts, are compared at the same pumping power in Fig.10. Apparently, the performance factor tends to decrease with the increasing Reynolds number. This suggests that the enhancement devices are superior energy saving devices for the use at lower Reynolds number. In spite of their lower Nusselt number, the compound enhancement devices of the ID-coil and perforated twisted-tape provide higher thermal performance factors than the other devices.

In the studied Reynolds number range, using of the perforated twised-tape (Y=5.3 and Rp= 4.5 %) together with ID-coil, is found to give a maximum thermal enhancement factor of 2.18 at low Reynolds number.

5. **Conclusion**

The heat transfer augmentation, friction factor and overall thermal performance of a hexagonal duct inserted with wire coil inserts alone, perforated twisted-tape inserts alone and the combined devices between the perforated twisted-tape and constant / periodically varying wire coil pitch length are studied. Water is the working fluid for Reynolds number range of 2480-9922 in a turbulent regime. The following conclusions are drawn from the results of this investigation.

1. At a given Reynolds number, the Nusselt numbers for the duct equipped with compound enhancement devices (ID-coil and twisted- tape) are higher than those with each device alone.
2. Depending on the Reynolds number, the compound devices enhance heat transfer in a range of 3.2 to 4.2 times of the plain tube, 2.5 to 2.85 times of the twisted tape alone and 1.72 to2.14 times of the wire coil alone.
3. The highest Nusselt number ratio is about 4.2 for the ID- coil with twisted-tape and the lowest Nusselt number ratio is twisted-tape alone which is1.47.
4. At the same Reynolds number friction factor is highest in a combination of the twisted-tape and the wire coil with pitch length 10 mm compared to those induced by the other methods.
5. The friction factor ratio (f/f_p) slightly increases with the increasing Reynolds number and the highest friction factors ratios (f/f_p) found in a combination of the twisted-tape and the wire coil of pitch length 10 mm which has the range 8.97 to 12.3 above the plain duct.
6. The performance factor tends to decrease with the increasing Reynolds number. This suggests that the enhancement devices are superior energy saving devices for the use at lower Reynolds number.
7. Using of the perforated twised-tape (Y=5.3 and Rp= 4.5 %) together with ID-coil, is found to give a maximum thermal enhancement factor of 2.18 at low Reynolds number.

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Nomenclature

A_s = surface area of test duct, m^2.
A_c = cross sectional area of test duct, m^2.
C_p = specific heat at constant pressure, J/kg.K.
D = coil diameter, m.
d_h = hydraulic diameter of hexagonal duct, m.
f = friction factor.
h = convective heat transfer coefficient, W/m^2. K.
k = thermal conductivity, W/m.K.
L_t = length of duct, m.
$\dot{m}$ = mass flow rate, kg/s.
Nu = Nusselt number.
P = coil pitch, m.
Pr = Prandtl number.
ΔP = pressure drop, Pa.
Q = heat transfer rate, W.
Re = Reynolds number.
Rp = porosity, dimensionless.
T = temperature, °C.
t = thickness of test duct, m.
U = mean velocity in duct, m/s.
w = width of tape, m.
y = tape twist length (180° rotation), m.
Y = twist ratio, y/w.

Greek Symbols

Ρ = density, kg/m^3.
μ = dynamic viscosity, kg/m.s.
η = thermal performance factor.

Subscript

b = bulk
i = inlet
o = outlet
p = plain duct
pp = pumping power
s = duct surface

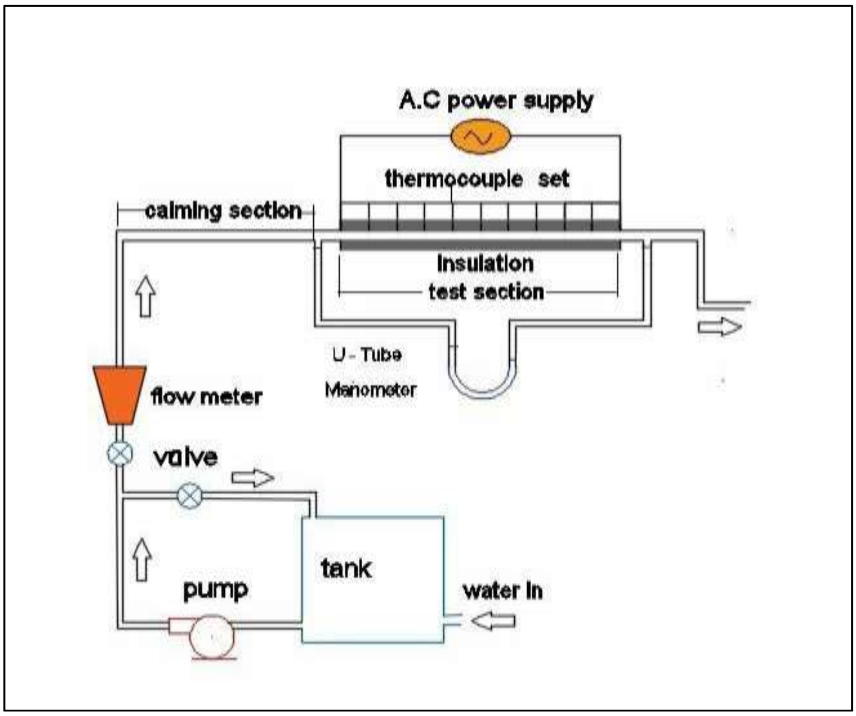
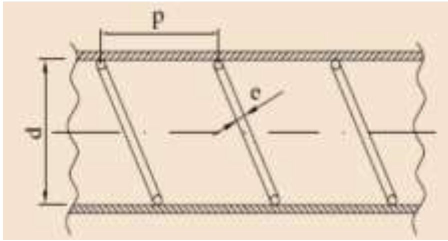
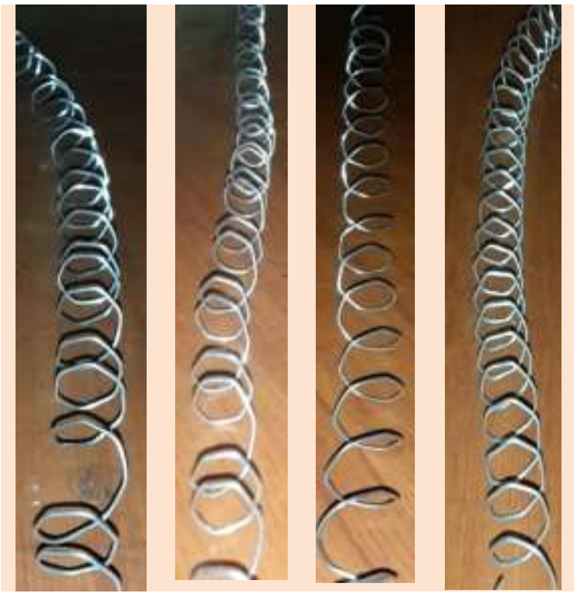


Fig. 1. Schematic diagram of experimental set up.

Fig. 2. (a) Hexagonal duct used in the present study. (b) Sketch of hexagonal cross section.



(a)



I D-coil I-coil P=20mm P=10mm

(b)

(d)

(c)

Fig.3. (a) Sketch of a wire coil fitted inside a plain duct. (b) Types of wire coils insert. (c) Perforated twisted- tape. (d) Wire coil and perforated twisted- tape.

Table 1. Detail of test conditions

Parameter	Range/values
Reynolds number, (Re)	2480 – 9922
Flow rates of water	3, 5, 7, 9, 12 lit. / min
Working fluid	Water
Hexagonal duct	
Test duct Length, L_t	1000 mm
Side length, (a)	10 mm
Duct hydraulic diameter, d_h	17 mm
Test duct thickness ,t	0.7 mm
Material of the duct	Copper
Perforated twisted-tape inserts	
Width,w	15 mm
Thickness,t	0.7 mm
Tape pitch length,y	80 mm
Twist ratio,Y	5.3
Hole diameter,d_T	3mm
Material of the twisted- tape	Copper
Wire coil inserts	
Wire diameter, e	1mm
Wire coil pitch length , P	10 mm, 20 mm
I –coil	10:20:10:20 mm
ID- coil	10:20:20:10 mm
Material of wire coil	Stainless Steel

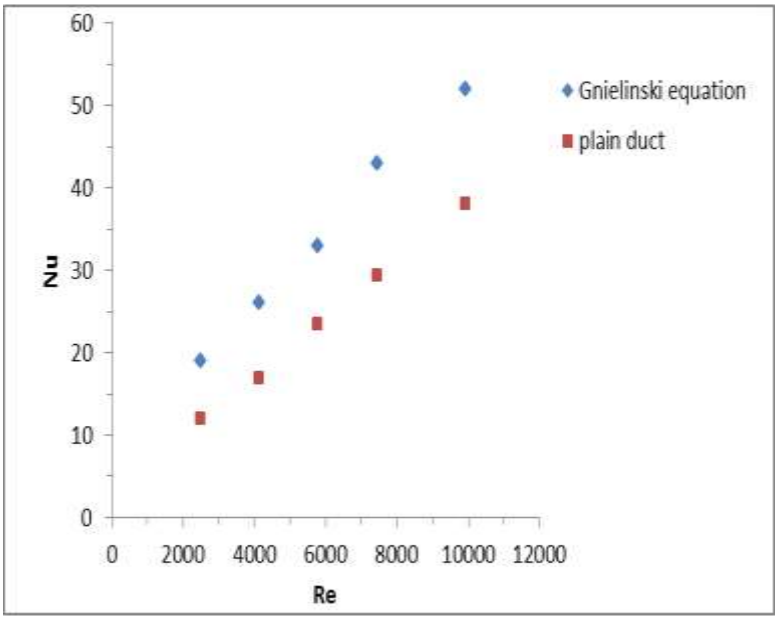


Fig. 4. Verification test of the hexagonal plain duct for Nusselt number.

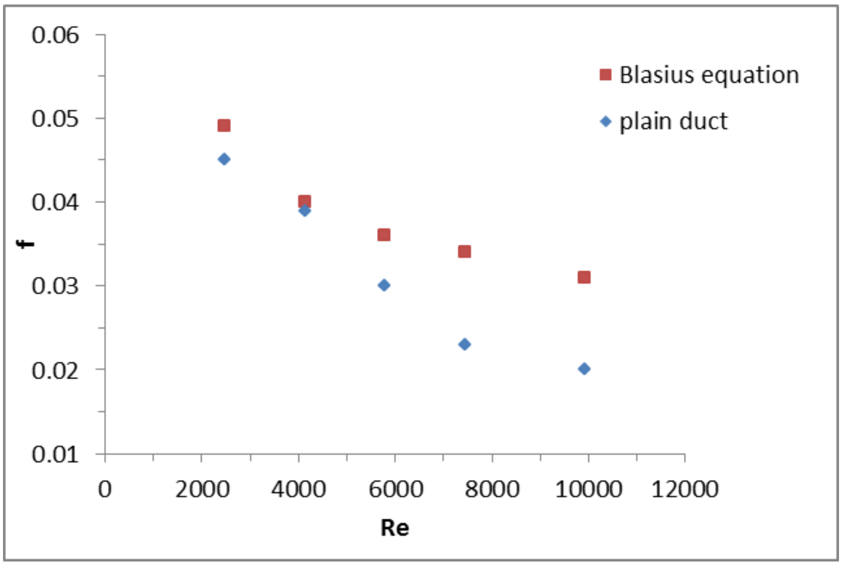


Fig. 5. Verification test of the hexagonal plain duct friction factor.

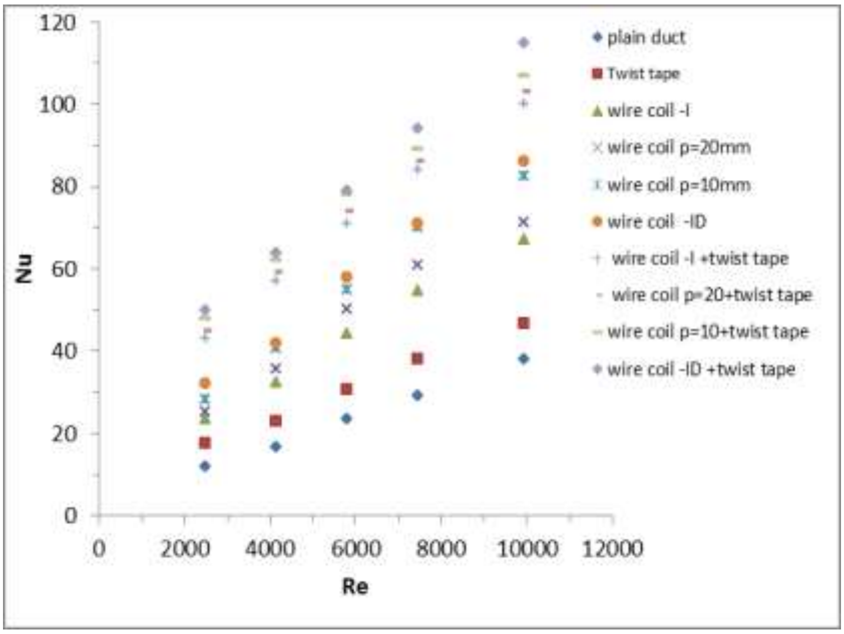


Fig. 6. Variation of Nusselt number with Reynolds number for the duct fitted with wire coil and twisted-tape.

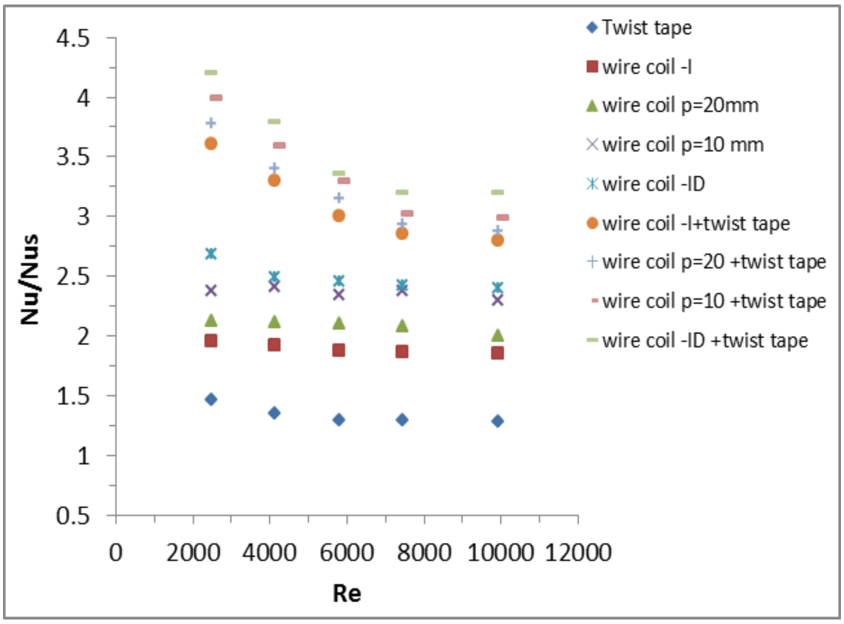


Fig. 7. Variation of Nusselt number ratio with Reynolds number for the duct fitted with wire coil and twisted-tape.

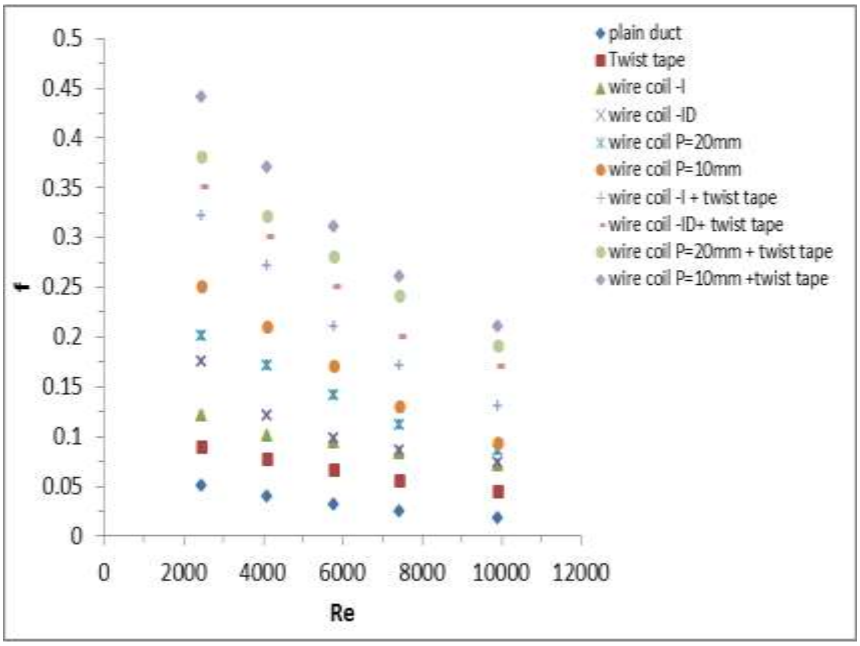


Fig. 8. Variation of friction factor with Reynolds number for the duct fitted with wire coil and twisted-tape

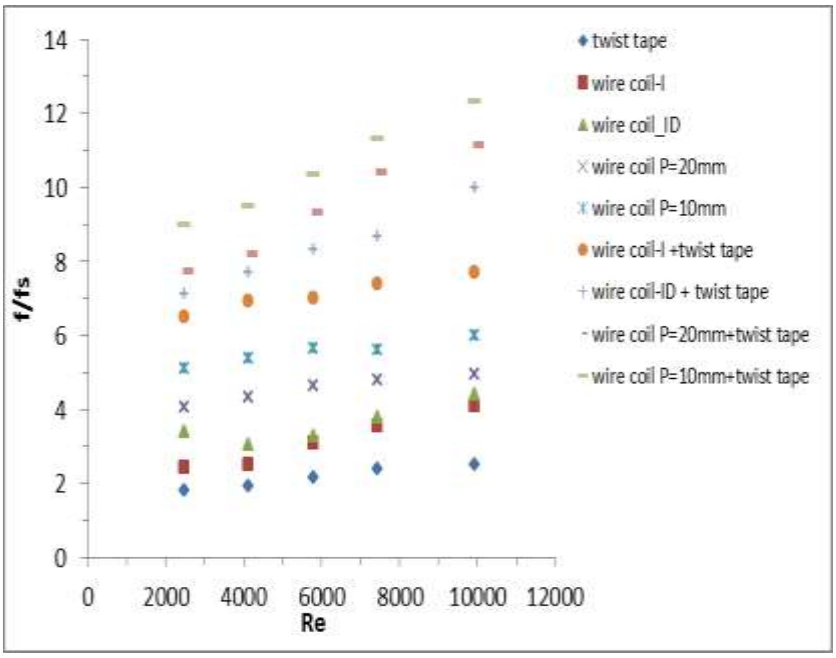


Fig. 9. Variation of friction factor ratio with Reynolds number for the duct fitted with wire coil and twisted-tape.

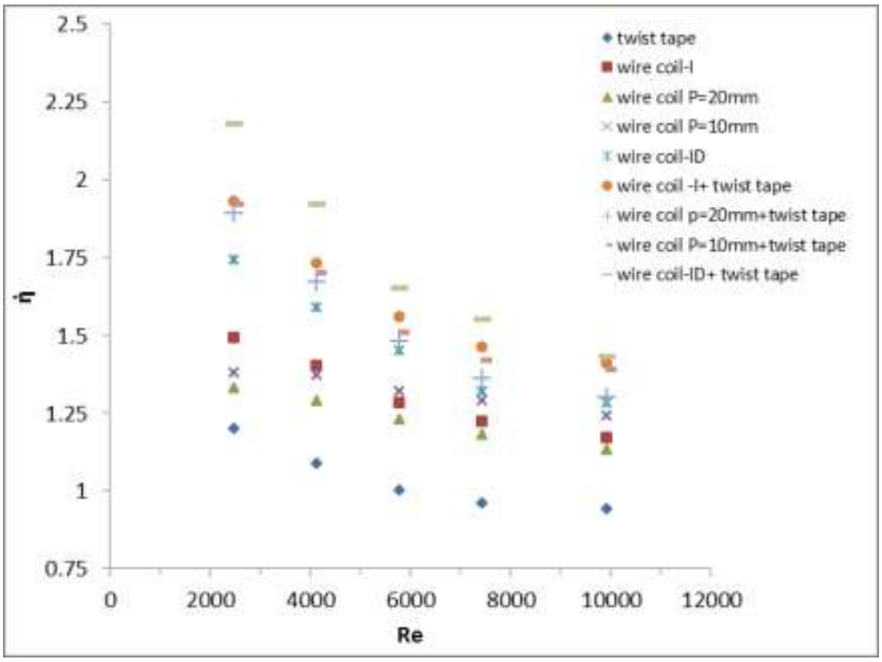


Fig. 10. Variation of thermal performance factor with Reynolds number for the duct fitted with wire coil and twisted-tape.