Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879

Computational Analysis of Heat Transfer Enhancement in a Circular Tube Fitted with Different Inserts

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ARTICLE INFO

Article history:
Received 11 December 2017
Received in revised form 25 December 2017
Accepted 28 December 2017
Available online 30 December 2017

Keywords:
Coiled wire and twisted tape insert, heat transfer, pressure drop, overall enhancement efficiency, turbulent flow regime

ABSTRACT

Heat transfer enhancement of air flow using wire coiled of an isosceles triangular cross-section and twisted tape inserted in a tube have been investigated under turbulent flow regime. A simulation technique is employed to simulate the swirling flow with three different pitch ratios (P/D = 1,2, and 3). The isosceles triangle side length to tube diameter is (a/D = 0.2 and 0.4) and (a/D=0.93) of the twisted tape at a distance (s) of 2 mm from the tube wall for the both in the range of Reynolds number from 4000 to 20,000. The heat transfer enhancement represented by a Nusselt number (Nu) and friction factor (f) in turbulent flow regime is numerically investigated using CFD package (Ansys FLUENT) to investigate the physical behavior of the thermal and fluid flows under uniform heat-flux. The results show that the use of twisted tape and isosceles coiled wire lead to a considerable increase in heat transfer and pressure drop in comparison with the plane tube. The Nusselt number increases with the increase of triangle side length and twist width and with the decrease of pitch ratio. The highest overall enhancement efficiency of 126% and 150% are achieved for the isosceles triangle wire coil with a/D = 0.4 and twisted tape, respectively at P/D = 1 and Reynolds number of 20000.

1. Introduction

Enhancing heat transfer surface are used in many engineering applications such as heat exchanger, air conditioning, chemical reactor and refrigeration systems, hence many techniques have been investigated on the enhancement of heat transfer rate and decrease the size and cost of the involving equipment especially in heat exchangers [1-7].

Heat exchangers particularly useful in the thermal processing of biochemical, food, plastic, and pharmaceutical media, to avoid thermal degradation of the end product. On the other hand, heat exchange systems in spacecraft, electronic devices, and medical applications, for example, may rely primarily on enhanced thermal performance for their successful operation [8-15]. Several heat

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transfer enhancement techniques are utilized in literature in order to improve the heat transfer or thermal performance of heat exchangers.

The wire coil is one of the popular ways for this purpose. The heat transfer and the thermal stress using wire coil inserted in tube sheet have been studied numerically [16]. The results showed that the smooth tube has lower thermal stresses in comparison with the wire coil inserted tube and the maximum thermal stresses ratio occurred in the p = 2d case for 3 m/s mean water inlet velocity. A numerical study has been achieved to investigate the turbulent heat transfer and pressure drop in circular cross-sectioned rings inserted tube [17]. They concluded that the overall enhancement ratio increases with increasing ring spacing and the best overall enhancement of 18% were achieved at Re=15.6 and spacing between rings is 3d.

Moreover, another numerical investigation has been performed to study the effect of the clearance ratio on heat transfer enhancement, friction factor and thermal performance factor of twisted tapes with two different twist ratios (y/w=2.5 and 5.0) under constant wall temperature conditions with turbulent flow regime [18]. The results indicated that, in comparison with those of the plain tube. The tube with loose-fit twisted tape inserts with CR=0.1, 0.2 and 0.3 provide heat transfer enhancement around 15.6%, 33.3% and 31.6% lower than those with CR=0.0 (the tight-fit twisted tape). Nevertheless, a comparative numerical study has been performed between a center-cleared twisted tape and short-width twisted tape in laminar tubular flows [19]. The results showed that the flow resistance can be reduced by both methods; however, the heat transfer and thermohydraulic performance using a tube with short-width twisted tapes is weakened by cutting off the tape edge. While the heat transfer can be enhanced in the tube with center-cleared twisted tapes with a suitable central clearance ratio. The thermal performance factor of the tube with center-cleared twisted tape can be enhanced by 7-20% as compared with the tube with conventional twisted tape.

Furthermore, a computational fluid dynamics modeling study has been carried out on heat transfer, friction factor and thermal performance of water in concentric tube heat exchanger using twisted tapes (Plain, V-cut, double V-cut, Jagged V-cut) with different twist ratios (y=2.0, 4.0). The maximum thermal performance factor was obtained by the Jagged V-cut twisted tape insert compare to other twisted tapes [20]. Additionally, an experimental study of heat transfer augmentation of laminar flow through a circular duct fitted with helical screw-tape with oblique teeth inserts and wire coil insert. The results concluded that the helical screw-tape with oblique teeth inserts in combination with wire coil inserts performs significantly better than the individual enhancement technique acting alone up to a certain value of the fin parameter [21] . However, an experimental study has been conducted for investigating heat transfer characteristics of air in the turbulent region using varying width twisted tape inserts under constant wall heat flux. The twisted tape has been used with three different twist ratios (3, 4 and 5) each with five different widths (26-full width, 22, 18, 14 and 10 mm) respectively. The result indicated that the enhancement of heat transfer with twisted tape inserts as compared with plain tube varied from 36 to 48% for full width and 33 to 39% for reduced width (22 mm) inserts. Reduction in tape width causes a reduction in Nusselt numbers as well as friction factor the friction factor rise to about 18% for 26mm and 17.3% for reduced width inserts compared to plain tube [22].

To the best of the author's knowledge, no studies have been performed previously to investigate the heat transfer enhancement of air flow using wire coiled of an isosceles triangular cross-section and twisted tape inserted in a circular tube under turbulent flow regime. Therefore, a simulation technique is employed to simulate the swirling flow with three different pitch ratios (P/D = 1,2, and 3). The isosceles triangle side length to tube diameter ratios are (a/D = 0.2 and 0.4) while for the twisted tape is (a/D=0.93) with Reynolds number from 4000 to 20,000.

2. Numerical Modeling

In the present study, the governing differential equations energy and K-ε were solved numerically by incorporating FLUENT, ANSYS package using finite volume method based on SIMPLE technique. Also, the second-order upwind scheme was used to solve the momentum and energy equations. Moreover, the geometries of the computational domains and the generated mesh were made with Ansys Fluent. A grid independence of the solution was done for all the case studies to ensure that the obtained results were not dependent on the adopted grid density. The optimums triangular mesh had chosen for TWC1A are 10000 and 20000 elements. In addition, the finer mesh is used by non-uniform mesh due to the importance of velocity and temperature gradient near the wall. Also, the order of convergence criteria for continuity and k-ε 10-3, meanwhile, the convergence criteria for energy equation was 10-6. The pressure-velocity coupling was solved by a SIMPLE algorithm. Momentum and energy equations were solved by second-order upwind. The numerical analysis has been achieved based on the steady state condition and three- dimensional continuity, momentum and energy equations [23] using CFD program as follows:

Conservation of mass (continuity) equation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0 \tag{1}$$

Conservation of momentum equation :

$$\frac{\partial \rho}{\partial t}(\rho \overline{V}) + \nabla.(\rho \vec{V}\vec{V}) = -\nabla P + \nabla(\overline{\overline{\tau}}) + \rho \vec{g} + \vec{F} \tag{2}$$

Energy equation:

$$\frac{\partial \rho}{\partial t}(\rho E) + \nabla(\vec{V}(\rho E + p)) = \nabla(k_{eff} \nabla T - \sum{}_{j} h_j \vec{J}_i + (\overline{\overline{\tau}}_{eff} . \vec{V})) + S_h \tag{3}$$

The pipe geometry is drawn by design modeler in Ansys fluent and the details of the geometries are explained in Table 1. The CFD model was made of 3D- model since the domain is a pipe. Suitable development lengths were given to nullify the effects of the boundary conditions. The mesh is of good quality meshes with boundary layers at the wall region to predict the wall effects exactly. Mesh was refined in two steps and the results were checked. The results showed no change to the previous mesh step. So, a grid independence test was conducted and the final mesh results were presented in the report. The details for the CFD model and mesh are given below, first mesh 4844945, second mesh 4035744 for T.T3A, a good quality mesh is used in the model the good results.

Table 1
The geometry details for all study

Insertion type	symbol	a	p	D	a/D	p/D	L
Isosceles triangle wire coil	TWC1A	11.2	56	56mm	0.2	1	3100mm
	TWC1B	11.2	112	56mm	0.2	2	3100mm
	TWC1C	11.2	168	56mm	0.2	3	3100mm
	TWC2A	22.4	56	56mm	0.4	1	3100mm
	TWC2B	22.4	112	56mm	0.4	2	3100mm
	TWC2C	22.4	168	56mm	0.4	3	3100mm
Twisted tape	T.T3A	52	56	56mm	0.93	1	3100mm
	T.T3B	52	112	56mm	0.93	2	3100mm
	T.T3C	52	168	56mm	0.93	3	3100mm

Table 2 explains mesh independence for all geometry. When the numbers of mesh element are decreased, the solution time is also decreased, however, Fig. 1 illustrated the description of wire coil geometry, while, Fig. 2 shows the model geometry and its mesh.

Table 2
Mesh independency of all geometry

Mesh elements	Reynolds numbers	Nusselt number	Fraction
	Isosceles triangular wire coil TWC1A		
13530502	4000	38.1104	0.43992
3756541	4000	37.0595	0.43774
	Isosceles triangular wire coil TWC1B		
6221666	4000	27.7505	0.21081
4243518	4000	27.2922	0.21176
	Isosceles triangular wire coil TWC1C		
6253061	4000	26.14409	0.155049
4954348	4000	26.07032	0.155572
	Isosceles triangular wire coil TWC2A		
10716775	4000	45.0035	0.45271
9676508	4000	44.6241	0.44976
	Isosceles triangular wire coil TWC2B		
5457087	4000	29.6863	0.242253
4155947	4000	29.1110	0.242042
	Isosceles triangular wire coil TWC2C		
6102743	4000	31.03113	0.17971613
5514607	4000	30.57566	0.17965503
	Twisted tapeT.T3A		
4844945	4000	61.954	0.617525
4035744	4000	60.944	0.610281
	Twisted tapeT.T3B		
5799638	4000	56.5956	0.43358
4799351	4000	55.7992	0.43018
	Twisted tapeT.T3C		
8554365	4000	50.24104	0.3329
4448216	4000	49.68529	0.3454

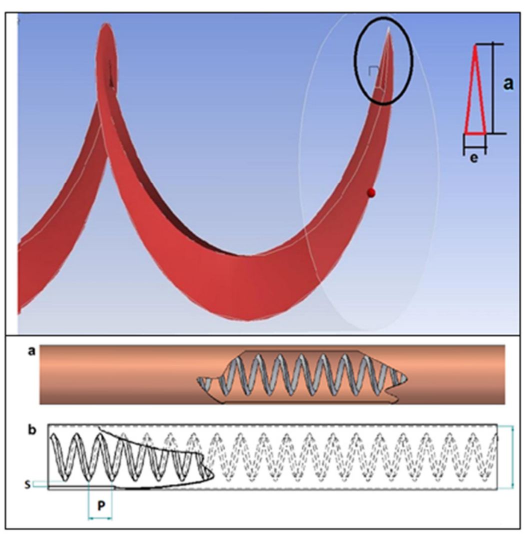
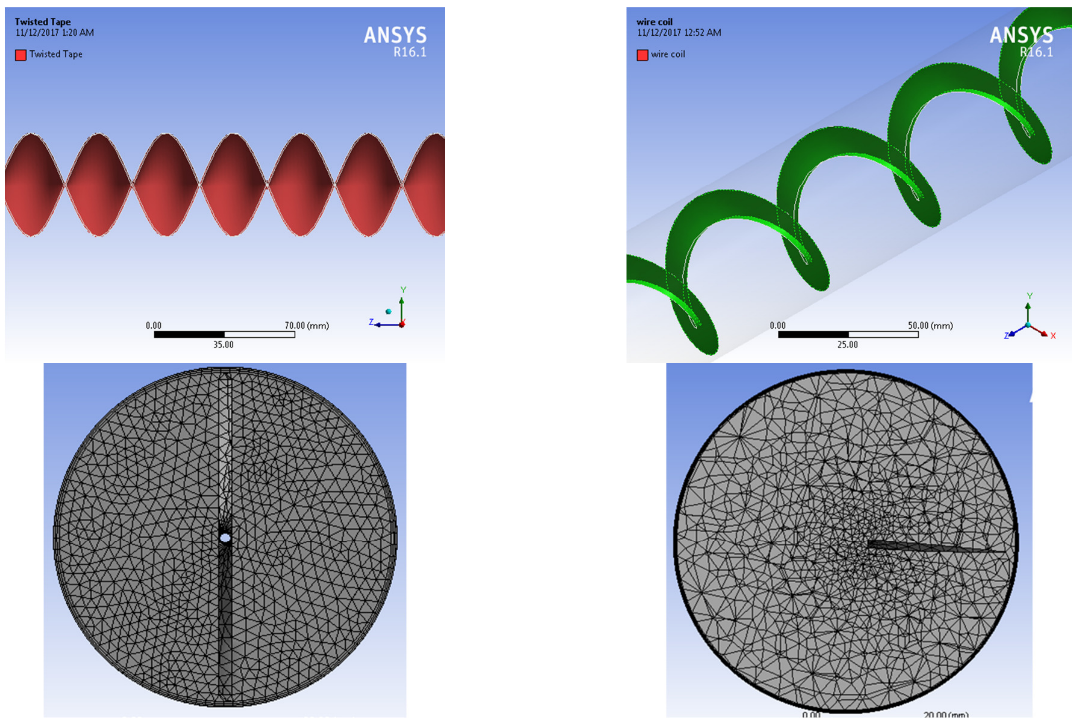


Fig. 1. Description of wire coil geometry

The Boundary condition of this investigation is fully developed turbulent flow and the constant temperature was considered at the inlet of the pipe. The axisymmetric conditions for velocity and temperature were assumed at the pipe. On the pipe wall, no-slip conditions were enjoined for the momentum equation. Also, constant heat flux condition was specified for the energy equation. As shown in Table 3 below.

Table 3
Boundary condition for all geometry

Boundary conditions	
Reynolds numbers range	4000-20000
working fluid	Air
Temperature inlet	300k
Heat flux	$500 \mathrm{w/m^2}$



(a) Twisted tape (b) Isosceles triangle wire coil

Fig. 2. Geometry model and mesh

3. Data deduction

In this investigation, the air used as the working fluid flow through an insulated tube under uniform heat flux. The local convection equation of heat transfer coefficient through the heated test pipe in an axial *x*-direction is defined as

$$h(x) = \frac{q}{(T_i w(x) - Tb(x))} \tag{4}$$

where, $T_i w(x)$ and $Tb(x)$ symbolized the local internal wall pipe temperature of the heated test pipe and local bulk temperature of the fluid, respectively. The determination of these temperatures is given in detail in Reference [16]. All of the thermophysical properties of air were determined at the overall bulk to mean temperature. Therefore, the Nusselt Number can be calculated based on the following equation

$$Nu(x) = \frac{h(x)\, D}{k} \tag{5}$$

where *k* is the conductive heat transfer coefficient of fluid of air

The Reynolds number is defined by

$$Re = \frac{\rho U D}{\mu} \tag{6}$$

The friction factor, *f* is calculated as follows

$$F = \frac{2\Delta P D}{\rho {U^2}_{mean}\ L} \tag{7}$$

where *U* indicates the mean fluid velocity in the pipe.

According to constant pumping evaluation criteria [24],

$$\left(\dot{V}\Delta P\right)_s = \left(\dot{V}\Delta P\right)_c \tag{8}$$

and the relationship between the friction factor and Reynolds number can be given as

$$(fRe^3)_{s=} (fRe^3)_c \tag{9}$$

$$Res\ = Rec\ (fc/fs)^{1/3} \tag{10}$$

The overall enhancement efficiency (η) in heat exchanger is expressed as the ratio of the, hc of an enhanced pipe with coiled wire insert to that of a plane tube, hs at a constant pumping power in this system

$$\eta = \left.\frac{h_c}{h_s}\right|_{pp} = \left.\frac{Nu_c}{Nu_s}\right|_{pp} = \left(\frac{Nu_c}{Nu_s}\right)\left(\frac{f_s}{f_c}\right)^{1/3} \tag{11}$$

Colburn Equation [25].

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{12}$$

Petukhov Equation [26].

$$f = (0.790\ln \mathrm{Re} - 1.64)^{-2} \tag{13}$$

4. Results and Discussion

In this study, the results of nine numerical for the wire coil insert and twisted tape of different configurations are presented. Numerical simulation was performed to predict the thermal hydraulic performance of plane tube. Validation of numerical results was carried out based on the comparison with empirical correlations as shown in Figs. 3 and 4 for the Nusselt number and friction factor respectively.

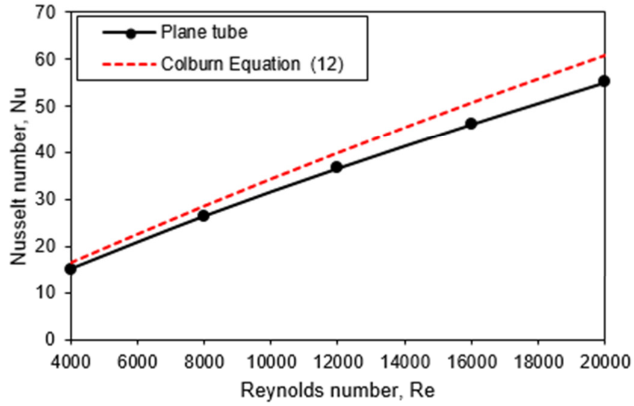


Fig. 3. Verification of Nusselt number

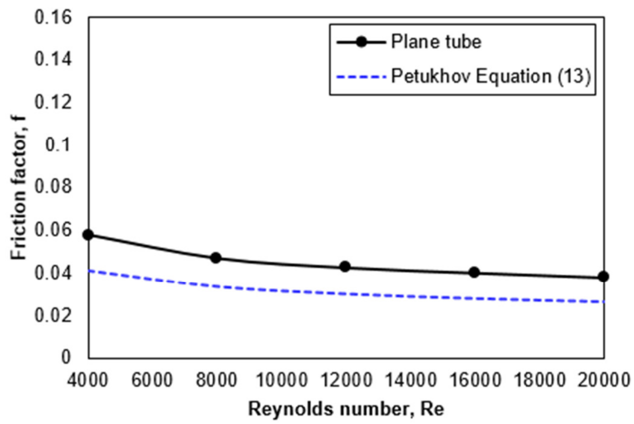


Fig. 4. Verification of Friction factor

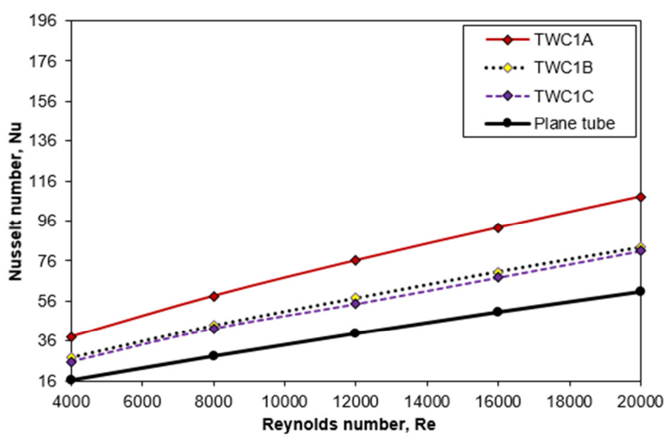


Fig. 5. Variation of Nusselt number with Reynolds number for wire coil (TWC1)

Additionally, the effects of geometrical parameters, such as TWC1A, TWC2A, T.T3A diameter and pitch on heat transfer and pressure drop of enhanced pipe were tested to optimize thermal-hydraulic in order to obtain the optimum of heat transfer enhancement. Furthermore, Figs. 5 and 6 illustrate the variation of Nusselt number and friction factor with Reynolds number respectively for wire coil (TWC1) at (a/D=0.2), with three different twist ratios of (1, 2, and 3) as described in the form of (TWC1A, TWC1B and TWC1C) respectively. The result shows that with the decrease of twisted ratio the Nusselt number and friction factor increases, meanwhile, the usage of the wire coil provide the higher Nusselt number and friction factor compared with the plane tube.

Simultaneously, Figs. 7 and 8 show the effect of increase Reynolds number on the Nusselt number and friction factor respectively, using (TWC2) at (a/D=0.4) with three twist ratios of (1, 2, and 3) as labeled in the arrangement of (TWC2A, TWC2B, and TWC2C) respectively. It can be observed that both Nusselt number and friction factor increases with decrease the twisted ratio, however, the utilizing of wire coil with (a/D=4) provide higher enhancement for both Nusselt and friction factor comparing with (a/D=0.2).

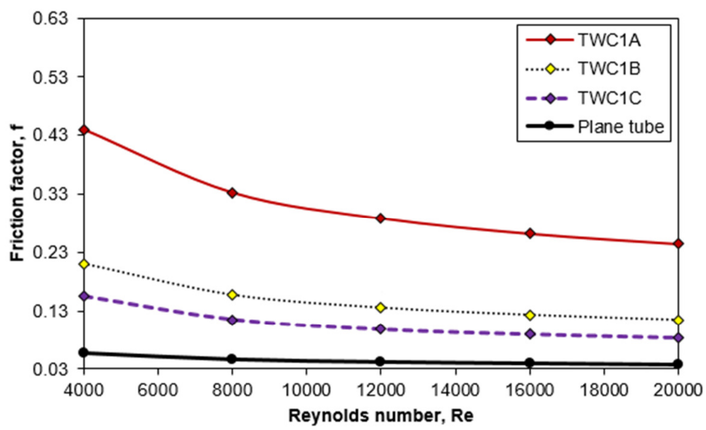


Fig. 6. Variation of friction factor with Reynolds number for wire coil (TWC1)

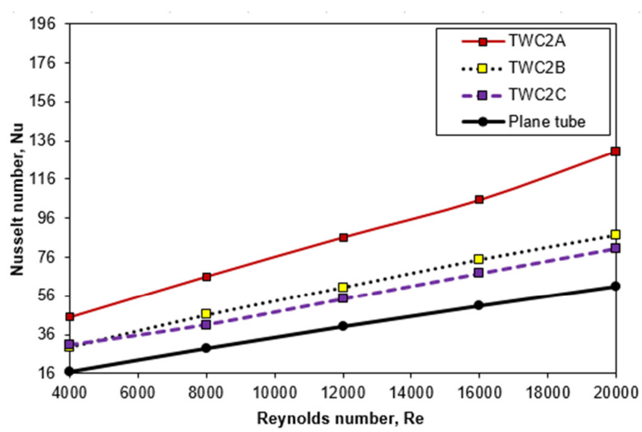


Fig. 7. Variation of Nusselt number with Reynolds number for wire coil (TWC2)

Nevertheless, Figure 9 and 10 present the results of using twisted tape at (a/D=0.93) with twisted ratios of (1, 2, and 3) represented as (T.T3A, T.T3B, and T.T3C) respectively. The results indicated that the usage of twisted tape enhance the Nusselt number and friction factor and provide higher enhancement compared to the wire coil results of (a/D=0.2 and a/D=0.4).

In order to evaluate the optimum enhancement among the studied cases, the overall enhancement efficiency has been adopted, where the results that presented in figure 11, indicate that the twisted tape comparing to the plane tube has provided higher enhancement with average heat transfer enhancement of 149%, 150% and 140% for (T.T3.A, T.T3.B, and T.T3.C) respectively.

Moreover, the wire coil with (a/D=0.4) enhances the heat transfer efficiency with (126%, 103%, and 113%) for (TWC2A, TWC2B, and TWC2C). Meanwhile, the wire coil with (a/D=0.2) enhances the heat transfer efficiency with (106%, 102%, and 107%) for (TWC1A, TWC1B, and TWC1C) respectively. It can be concluded from this result that the twisted tape has the ability to enhance the heat transfer with higher efficiency comparing to the wire coils isosceles triangle cross-section.

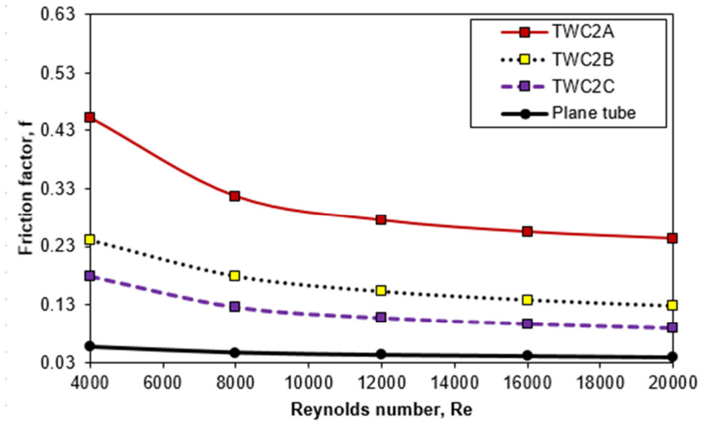


Fig. 8. Variation of friction factor with Reynolds number for wire coil (TWC2)

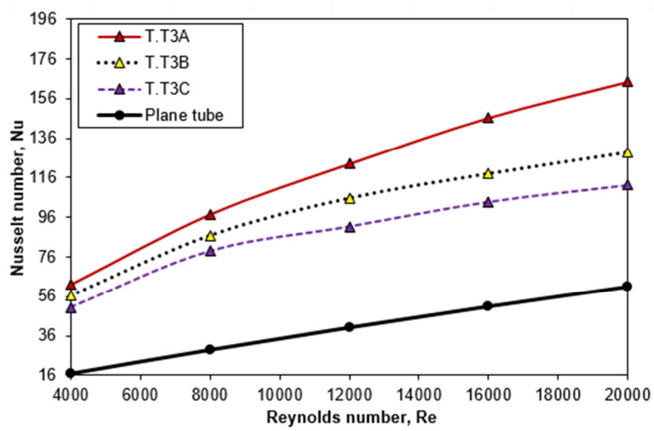


Fig. 9. Variation of Nusselt number with Reynolds number for twisted tape

In order to evaluate the optimum enhancement among the studied cases, the overall enhancement efficiency has been adopted, where the results that presented in figure 11, indicate that the twisted tape comparing to the plane tube has provided higher enhancement with average heat transfer enhancement of 149%, 150% and 140% for (T.T3.A, T.T3.B, and T.T3.C) respectively. Moreover, the wire coil with (a/D=0.4) enhances the heat transfer efficiency with (126%, 103%, and 113%) for (TWC2A, TWC2B, and TWC2C). Meanwhile, the wire coil with (a/D=0.2) enhances the heat transfer efficiency with (106%, 102%, and 107%) for (TWC1A, TWC1B, and TWC1C) respectively. It can be concluded from this result that the twisted tape has the ability to enhance the heat transfer with higher efficiency comparing to the wire coils isosceles triangle cross-section.

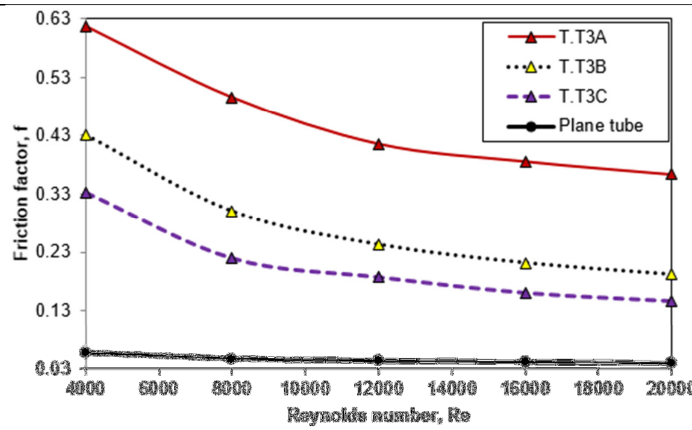


Fig. 10. Variation of friction factor with Reynolds number for twisted tape

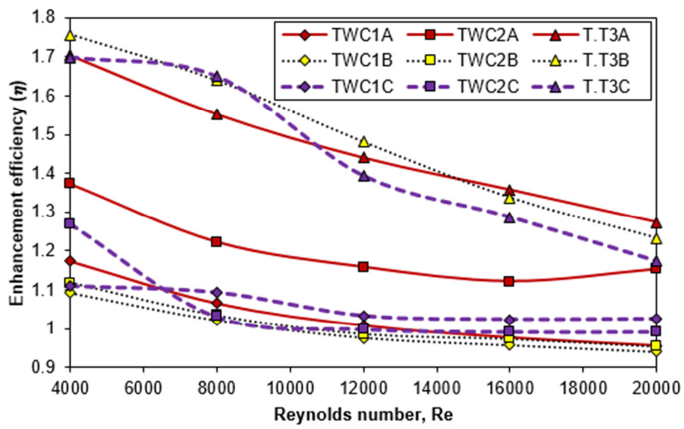


Fig. 11. Enhancement efficiency for all cases

5. Conclusion

A numerical study has been performed to examine the airflow friction and heat transfer properties in a circular tube fitted with Isosceles triangular wire coil tabulators and twisted tape under the turbulent regime. The use of twisted tape provides a high-pressure drop, which depends mainly on twisted tape pitches and also provides significant heat transfer improvement. However, The Nusselt number increases with the increase the Reynolds number, triangle side length, twist width and with the decrease of twisted ratio. Meanwhile, the friction factor decreases with increasing the Reynolds number, decrease the triangle side length, decrease the twist width and with an increase of twisted ratio. However, based on the thermal evaluation of the overall heat transfer enhancement efficiency, it can be concluded that the twisted tape has the ability to enhance the heat transfer with higher efficiency comparing to the wire coils isosceles triangle cross section and plane tube under the present conditions.

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