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NUMERICAL INVESTIGATIONS OF THE THERMO-HYDRAULIC CHARACTERISTICS FOR TURBULENT FLOW CHANNEL WITH QUADRUPLE PLAIN AND MODIFIED TWISTED TAPES INSERTS

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Abstract: A numerical analysis aiming to gain an understanding of the physical behavior for thermal and fluid flow attributes in tubes fitted with quadruple plain and modified twisted tapes inserts (which all occupy an equal volume) for the turbulent Reynolds number range (5,000 to 20,000) is carried out. The tube inserted with quadruple modified twisted tapes showed better thermal enhancement when compared with plain tube and tubes induced with quadruple plain twisted tapes. The simulation included modification on tapes as cuts with; circular, half circle on side, triangular and rhomboidal shapes. The obtained results showed a maximum increase of 31.12% is observed in the Nusselt number by using tube fitted with quadruple circular cuts twisted tapes inserts than that observed with the plain tube. And the higher friction factor obtained of the tube fitted with quadruple circular cuts twisted tapes inserts are up to 32.65% than that of the plain tube.

Keywords: *Multiple Twisted Tapes, Quadruple Inserts, Heat Transfer Enhancement, Core Flow, Multi-Longitudinal Vortices.*

دراسة عددية عن السلوك الخاص بالحرارة و صفات جريان المائع داخل قناة محتوية على أشرطة رباعية مستوية ومعدلة ضمن الجريان المضطرب

الخلاصة: أنجزت الدراسة العددية للحصول على فهم واضح للسلوك الفيزيائي بالنسبة للحرارة وجريان المائع داخل أنبوب محتوي على أشرطة لولبية رباعية مستوية (من دون قطوع) و معدلة (والتي تشغل بمجموعها نفس الحجم من حيز المائع سواء كانت مستوية أو أشرطة تحتوي على تعديلات) على مدى الجريان الاضطرابي المقاس برقم رينولد للمعدل(5000-20000) . اتضح ممن خلال هذه الدراسة إن الأنابيب المحتوية على الأشرطة المعدلة أفضل أداءاً من تلك التي تحوي بداخلها الأشرطة المستوية. إن عملية تمثيل نماذج معدلة تضمنت قطوعات بالأشكال التالية: دائرية و نصف دائرية على جانب الشريط ومثلثة ومعينيه. إن النتائج التي تم الحصول عليها أظهرت زيادة قصوى تصل إلى 31.12% برقم نسلت والذي يمثل التحسين في الانتقال الحراري باستخدام الأنابيب المتضمنة أشرطة رباعية ذات قطوعات دائرية عن تلك الأنابيب التي لا تحتوي أي مدخلات. و أعلى قيمة لمعامل الاحتكاك تم الحصول عليها باستخدام نموذج الأنبوب المتضمن أشرطة رباعية ذات قطوع دائرية حيث وصلت لغاية 32.65% أعلى من قيمة معامل الاحتكاك في الأنابيب غير المحتوية على أشرطة.

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1. Introduction

Many of heat transfer enhancement techniques are widely used in engineering applications such as heat exchangers, chemical reactors, automotive cooling, combustion devices, etc. These techniques have been used to increase heat transfer rate without increment in system size. Generally, one of most important techniques is swirl flow generators. Twisted tapes as swirl flow generators have receiving a huge attention due to its simple configuration, steady performance and low cost.

Twisted tape heat transfer enhancement mechanism depend on produce swirl flow in form of secondary recirculation act on axial flow which increase tangential and radial turbulent velocities lead to mix fluid layers and reduce the thermal and hydrodynamic boundary layer thickness due to increases in turbulent fluctuation and combining occur between core region and near wall region in fluid flow, that cause higher temperature gradient near the wall which lead to increase heat transfer rate.

The using of twisted tapes reduce hydraulic diameter of flow cross sectional area which cause an increase in fluid velocity that need to higher fluid pumping power and causing more friction losses, this point must be taken into account.

A number of investigations have been reported which study the effect of twisted tapes for performance evaluation. Royds [1], reported for single twisted tape insert in circular tube that heat transfer rate increased significantly than tube without inserts and as twist ratio become tighter, the heat transfer rate and pressure drop become greater.

Bergles and Manglik [2], experimented the full length twisted tape insert with three different twist ratios to describe physically the mechanism of enhancement and proposed correlations for Nusselt number and friction factor.

Erdemir *et al* [3], studied numerically the dual twisted tapes inserts with three different widths in turbulent flow regime found that using of dual twisted tapes inserts leads to a considerable increase in Nusselt number and friction factor over the plain tube and the highest heat transfer rate was obtained for the case of smallest tapes width.

Eiamsa-ard *et al* [4], presented an experimental analysis of the turbulent flow in a heat exchanger tube fitted with plain dual twisted tapes and peripherally-cut dual twisted tapes under a constant wall heat-flux condition with water as a working fluid. The experimental results showed that Nusselt number and friction factor of peripherally-cut dual twisted tapes inserts in tube were considerably higher than those of the plain tube and those of the tubes with single plain twisted tape and dual plain twisted tapes. It was found that the smaller cutting pitch ratio model gave higher heat transfer rate, friction factor and thermal performance factors.

Chakole and Sali [5], experimented the multiple (dual, triple and quadruple) twisted tapes inserts in circular tube under turbulent flow conditions. The results shown that Nusselt number and friction factors increased as the number of tapes increased. It must be mentioned that the volumetric efficiency of the tube was not taken in consideration at this or the previous illustrated researches where the dual inserts occupied more from the internal tube volume than single inserts and as the number of inserts increased, the volumetric efficiency for the tube decreased.

Lastly, Liu *et al* [6], simulated multi-longitudinal vortices in a tube induced by triple and quadruple twisted tapes insertion where air flow was considered. The results showed that the number of longitudinal vortices generated equal to the number of twisted tapes inserts in the circular tube where two types of flow exist at the same time, one is a swirl flow which surrounds the core and other is straight flow near the tube wall, they also showed that the main function that governs the type of flow in the center axial line of the tube and the velocity produced is the clearance ratio between the tapes where maximum velocity at center occur at highest clearance ratio. A maximum increase of 171% and 182% is observed in the Nusselt number by using triple and quadruple twisted tapes, respectively. Thus the heat transfer rate in term of Nusselt number of quadruple twisted tapes is better than for the triple twisted tapes. This is due to that a system with more twisted tapes generates more swirl flows by increases velocity due to reduce fluid volume, making the temperature more uniform in the core flow and thus resulting in a thinner thermal or hydrodynamic boundary layer. On the other hand, for the same number of twisted tapes, the Nusselt number decreases as the clearance ratio(distance between tapes) of the twisted tape decreases, with increased the clearance, which results in a better heat transfer enhancement. The friction factors of the tube fitted with triple and quadruple twisted tapes are around 4.06-7.02 times as that of the plain tube.

According to the above review and many other researches[11-14], it has been investigated the single and multiple twisted tapes effect on thermo-hydraulic characteristics by many researchers. Also it has been clarified that as inserts volume increased ,in meaning of twist ratio or number of inserted tapes, the heat transfer performance was apparently improved. The researches on quadruple twisted tapes inserts with different modifications but they all share the same volume are almost nonexistent. Therefore, it presented here quadruple modified twisted tapes inserts which all have the same cuts area and constant volume for all models considered to investigate the effect of cuts configurations on heat transfer and fluid flow without falling into the effects of tube capacity to handle the fluid.

2. Numerical Simulations

2.1 Computational Domains

The geometries, created by *ANSYS Design Modeler*[7], are made up for tubes with different quadruple twisted tapes inserts individually. The tube, as shown in Fig. (1), has dimensions of length (L) equal 1000mm and internal diameter (D) of 50mm.

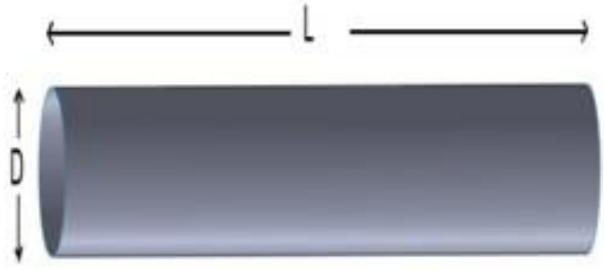


Figure 1. Tube geometry.

Plain tube (PT), tube fitted with quadruple plain twisted tapes(TQPTT), tube fitted with quadruple circular cut twisted tapes (TQCCTT), tube fitted with quadruple side-circle cut twisted tapes (TQSCCTT),tube fitted with quadruple side-triangular cut twisted tapes (TQSTCTT) and tube fitted with quadruple rhomboidal cut twisted tapes (TQRCTT) are designed. The schematic of inlet and outlet cross sectional view of these models and twisted tape dimensions illustrated in Fig.(2) a and b respectively. The geometries of these models are shown in Fig. (3).

The twisted tape inserts runs through the length of the tube have a width (w), thickness (δ) and pitch of 180° twist (y) as explained in Table (1).

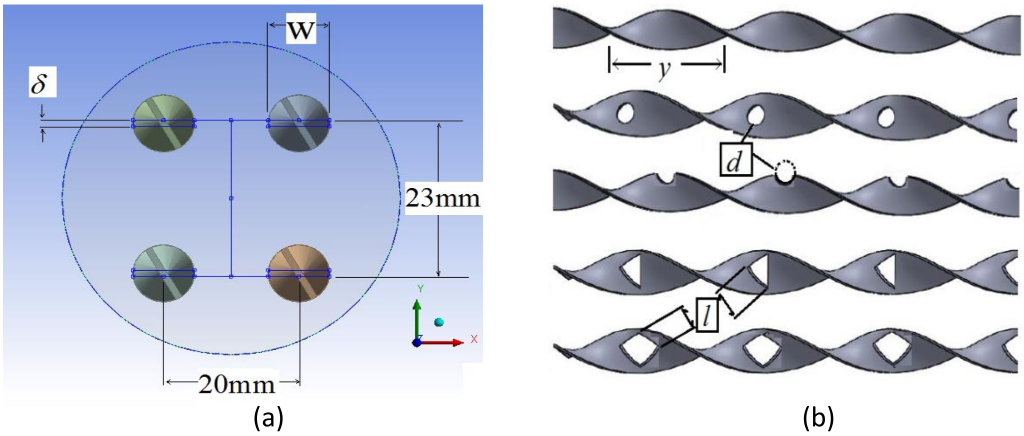


Figure 2. Schematic view on quadruple arrangement for all models; (a) Inlet cross sectional, (b) Cuts dimensions.

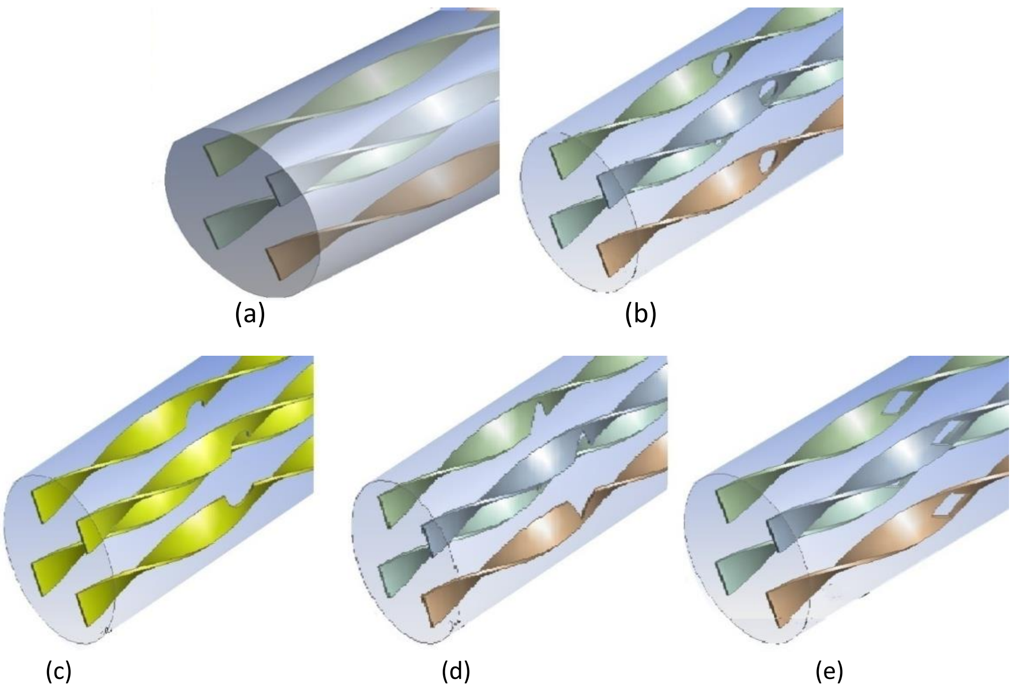


Figure 3. Computational models for the numerical investigations; (a) TQPTT, (b) TQCCTT, (c) TQSCCTT, (d) TQSTCTT, (e) TQRCTT.

Table 1. Dimensions of computational domains.

Model	No. of tapes	Tape width (mm)	Tape pitch (y) (mm)	Cut diameter (d) (mm)	Cut side length (l) (mm)	All tapes volume (mm^3)
TQPTT	4	9.08	60	----	----	41,390
TQCCTT	4	9.67	60	8	----	41,390
TQSCCTT	4	9.67	60	10.425	----	41,390
TQSTCTT	4	9.67	60	----	11.35	41,390
TQRCTT	4	9..67	60	----	8	41,390

All the tapes have thickness of 1mm*

The swirl direction corresponding to tape arrangement was designed as *co-swirl flow*; all tapes were aligned to be twisted in the same direction.

2.2 Numerical method and Boundary Conditions

The analyses are based on the steady and three dimensional continuity, momentum and energy equations.

The numerical analyses were performed by using the computational fluid dynamics (CFD) commercial code, *ANSYS-FLUENT software* [7].

RNG k-ε Model was selected to solve the modeled cases because the effect of swirl on turbulence is included in this model which enhances the accuracy of swirling flows.

The flow is considered as internal flow under forced convection heat transfer process by submitting a uniform heat flux condition with magnitude of (30,000 W/m^2).

No slip condition is also applied to the tube wall.

Results are considered only at fully developed region (L >10D_h), where the (D_h) represent the hydraulic diameter which calculated from the expression [derived from reference no. 8];

$$D_h = \frac{4\,(A_{tube} - A_{twisted\ tape})}{P_{tube} + P_{twisted\ tape}} \quad (1)$$

In Eq. (1); the cross sectional area denoted as (A), and (P) is the wetted perimeter.

At the inlet of the tube, a velocity (V) to give the desired Reynolds number is specified by:

$$Re_{D_h} = \frac{V\,D_h}{\upsilon} \quad (2)$$

Where $Re_{D_h}$is the Reynolds number, υ the kinematic viscosity of the fluid and D_h is the hydraulic diameter. **Water** is considered as the working fluid and calculations for the thermal properties are taken at the inlet temperature of 300k which are; density ρ (= 997.0089 kg/m3), specific heat at constant temperature Cp (= 4179 J/kg.k) , thermal conductivity k (= 0.613 W/m.°c) and the dynamic viscosity μ (= 855×10^{-3} kg/m.s).

For turbulent flow regime, the range of study for Reynolds number is (5,000-20,000).

The inlet region assumed to carry the reference values. At the outlet, a pressure outlet condition is used and the gauge pressure is set to zero. The hydraulic diameter at each inlet and outlet has the same value. And the turbulence intensity obtained from the expression [15];

$$I = 0.16 Re_{D_h}^{-0.125} \quad (3)$$

Other flow quantities are extrapolated from the interior domain by the solver in Fluent software. The SIMPLE (Semi-Implicit Pressure Linked Equations) algorithm were chosen as solver method.

In addition, a convergence criterion of 10^{-6} was used for energy and 10^{-3} for the mass conservation of the calculated parameters.

2.3 Computational Domains Characteristics Calculations

The Nusselt number results obtained in the numerical solution for the plain tube (PT), which extrapolated from *Fluent solver* [7], was validated with the empirical correlation of Gnielinski [8] which is given by;

$$Nu = \frac{\left(\frac{f}{8}\right)\left(Re_{D_h} - 1000\right)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}} - 1\right)} \quad (4)$$

The friction factor (f) was calculated from pressure drop and is defined from Darcy-Weisbach equation [9]:

$$f = \frac{\Delta p}{0.5\, \rho\, V_{in}{}^{2}\left(\frac{L}{D_h}\right)} \quad (5)$$

It was validated with the empirical and theoretical following correlations for the plain tube case;

Petukhov correlation [5]:

$$f = \left(0.79 \ln Re_{D_h} - 1.64\right)^{-2} \quad (6)$$

Blasius correlation[5];

$$f = 0.318 Re_{D_h}{}^{-0.25} \quad (7)$$

2.4 Grid Resolution

The *tetrahedral* cells are used for meshing the domains to avoid blurred curved areas, as shown in Fig. (4). Grid systems with average element volume of ($0.0019 m^3$) which lead to about (1,350,000 ±50,000) elements represent the computational domains and adopted for the calculations.

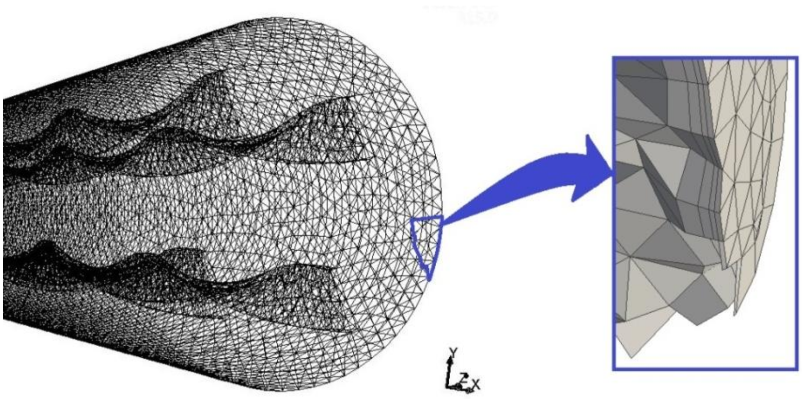


Figure 4. Tetrahedral mesh cells for case of TQPTT with small cutted element to illustrate how cell look like.

3. Results and Discussions

3.1 Flow Structure

3.1.1 Velocity Field

Field of velocity predicted for all models are depicted in Fig. (5), the velocity contours shown are taken for Re=10,000 and at axial location of 0.84m from inlet which guarantees fully developed flow and cut presence.

As seen in the Fig. (5[frame b]), the velocity increase by 39.1678% for TQPTT higher than PT. This increment occurs due to reduction in hydraulic diameter which leads to increase velocity at constant Reynolds number. Mathematically the reduction in hydraulic diameter cause decreasing in cross sectional area of fluid flow which resulted in an increase in mean velocity value to satisfy continuity equation (the rate at which mass enters a system is equal to the rate at which mass leaves the system).

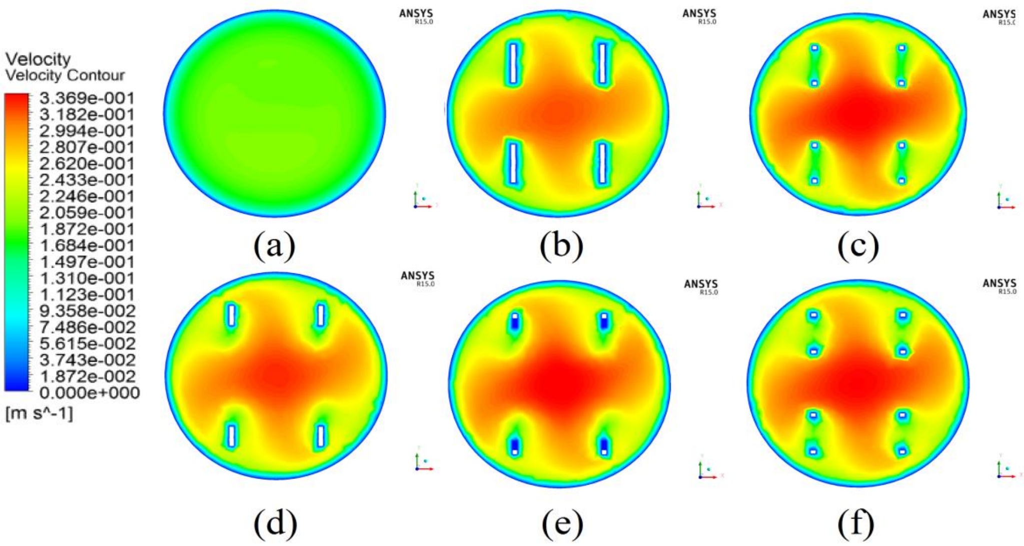
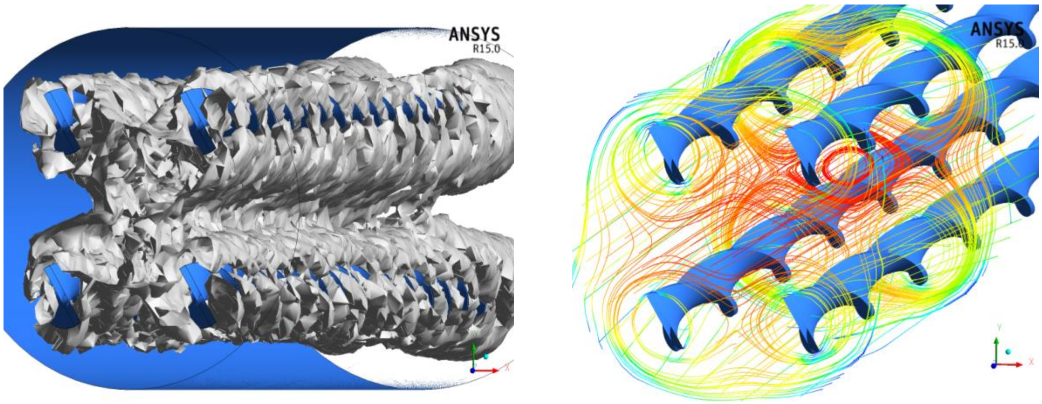


Figure 5. Velocity contours for; (a)PT, (b)TQPTT, (c)TQCCTT, (d)TQSCCTT, (e)TQSTCTT and (f)TQRCTT.

For TQCCTT, TQSCCTT, TQSTCTT and TQRCTT, the velocity increased by 1.3156%, 0.8681%, 0.9701% and 0.9009% higher than that for TQPTT. that due to reduce hydraulic diameters for these cases than case of TQPTT to be all at same volume occupied from fluid flow, and the differentiations return to how much cut area increase or decrease cross section area of fluid at contour location.

Four longitudinal vortices (as in Fig. 6 [a] which shows only swirl motion in the tube space) are generated in around tapes in the core flow area, at the same time, it has been found that a new vortex tends to be generated in the center of the tube as shown in Fig. (6 b).



(a) (b)

Figure 6. Longitudinal vortices for tube fitted with quadruple twisted tapes inserts(TQPTT); (a) 3D view, (b) Streamlines.

By compare the velocities at 0.84m with a region without cut at fully developed condition for the same model, location of 0.8m is chosen for that purpose, for TQCCTT, TQSCCTT, TQSTCTT and TQRCTT the velocity at 0.84m decreased by 0.566%, 0.8563%, 0.7281% and 0.809% than in the upstream at location 0.8m, respectively.

Physically these differentiations occur due to shape of cuts which lead to more (or less) fluid flows through it as a low velocity region (cut region) and this region work as a retarder break the core of forced vortex tube causing decrease of velocity. The velocity decreasing followed by increasing in velocity which leads to pulsing the high velocity over all the fluid body and that is the main reason for enhancement in modified twisted tapes.

3.1.2 Pressure Contour

As a fluid flow through the tube, there will be a pressure drop. In addition to the pressure required to pumping the fluid inside the tube which is in tube with inserts higher than these without. Pressure drop main determinants are fluid velocity and fluid viscosity.

Pressure contours are illustrated in Fig. (7) to all computational domains considered at Reynolds number 10,000 and on longitudinal revolution surface along the axial direction. In the case of TQPTT, Fig.(7 [frame b]), pressure drop is 126.8775% higher Than in PT due to the reduction occurred in hydraulic diameter which lead to reduce fluid cross section area and increase in fluid velocity, also the twisted tape insert increase frictional shear forces within the tube which proportional vary to pressure drop.

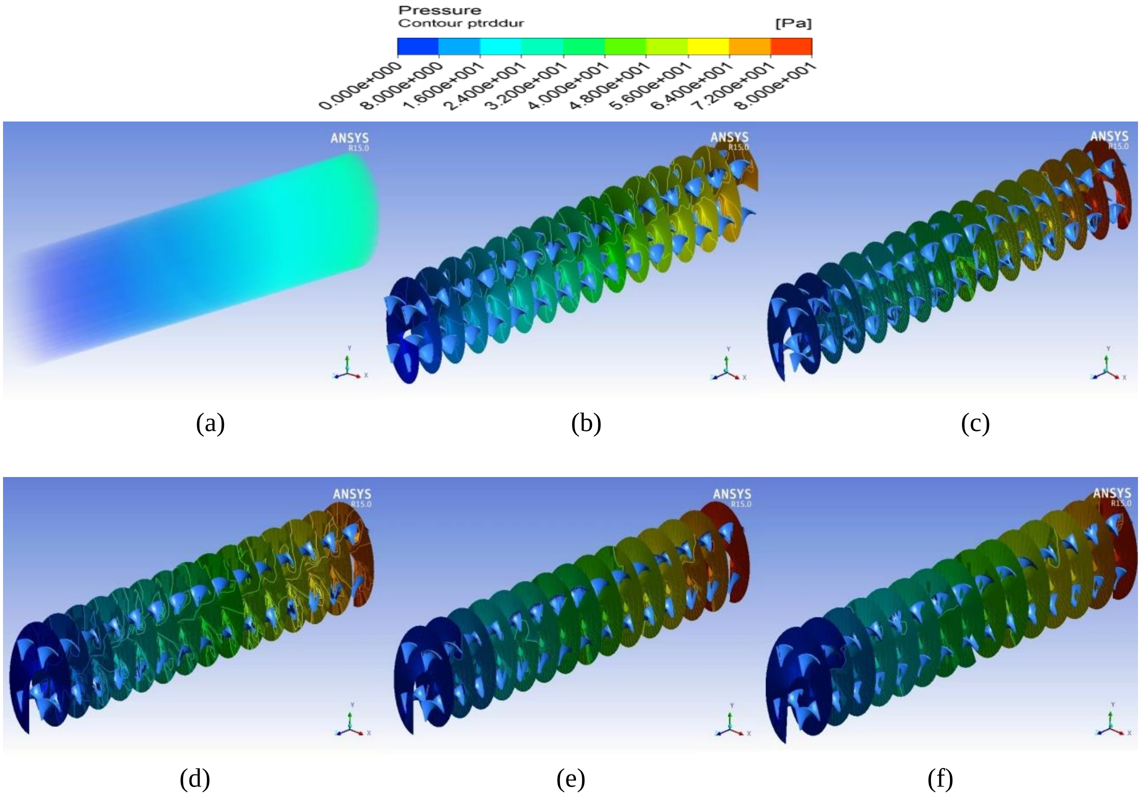


Figure7. Pressure contours for a longitudinal revolution surface along the computational domains; (a)PT, (b)TQPTT, (c)TQCCTT, (d)TQSCCTT, (e) TQSTCTT and (f)TQRCTT.

The pressure drop in TQCCTT, TQSCCTT, TQSTCTT and TQRCTT are 12.9507%, 11.058%, 12.254% and 11.7122% higher than TQPTT, respectively.

That due to swirl motion achieved by each one of them, where the swirl motion effect on velocity proportionally, and velocity gradient effect on pressure drop by effecting on shear forces acting on fluid flow.

Cuts in twisted tapes inserts shown, as above, a noticeable increase in pressure drop. That was return to the increase of fluid area on behalf of wall area at cut cross section. The pressure is reversibly proportion to the area at which it acts. This increase in fluid cross sectional area at cuts regions which distributed on the fluid flow path cause a pressure decreases in these sections which lead to increase pressure drop.

3.1.3 Friction Factor

The friction factor, as in (5) previously, is influenced by velocity variation, pressure drop and other parameters. The models examined numerically in Reynolds number range from 5,000 to 20,000.

The simulated results of PT match the experimental and theoretical results obtained from correlation (6) and (7) with a deviation of range 4.30351- 9.03569%, the results of validation are shown in Fig. (8).

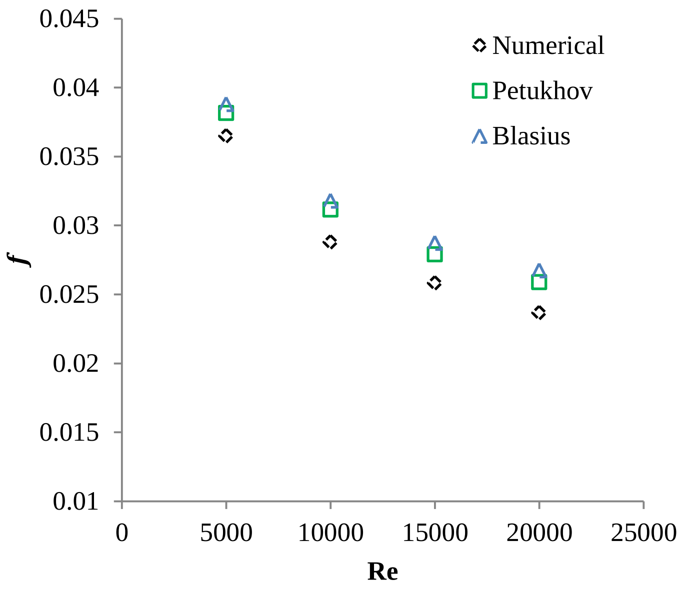


Figure 8. Validation of numerical results for friction factor to the case of plain tube with Blasius and Petukhov correlations.

As the fluid velocity increase, the friction factor decrease. Therefore, friction factor decreases with Reynolds number increasing. This is because Reynolds number increases the momentum overcomes the viscous force of the fluid and consequently lowers the shear between the fluid and the tube wall.

The variation of the friction factor with Reynolds number for the tubes with different designs of quadruple twisted tape inserts are compared in Fig. (9). the tube fitted with quadruple plain twisted tapes inserts (TQPTT) has friction factor of 22.5 to 23.1% higher than plain tube. This is attributed to the flow blockage and swirl flow due to tape insert.

The additional dissipation of pressure of the fluid caused by the fluid disturbance due to the presence of cuts on the tapes results in an increase in pressure drop which cause increasing of friction factor. Consequently, the friction factor of TQCCTT, TQSCCTT, TQSTCTT and TQRCTT is 3.85 to 9.65%, 3.4 to 6.4%, 3.75 to 8% and 3.46 to 6.73% higher than that in TQPTT.

These results by comparing with pressure drop results, illustrated in section (3.1.2), shown the effect of pressure drop which affect on friction factor where the higher pressure drop model has higher friction factor as in the case of tube fitted with quadruple circular cuts twisted tapes (TQCCTT). As from (5), friction factor represent ratio of static pressure difference over dynamic pressure where dynamic pressure in term of inlet velocity have a small change between models due to the differences between hydraulic diameters.

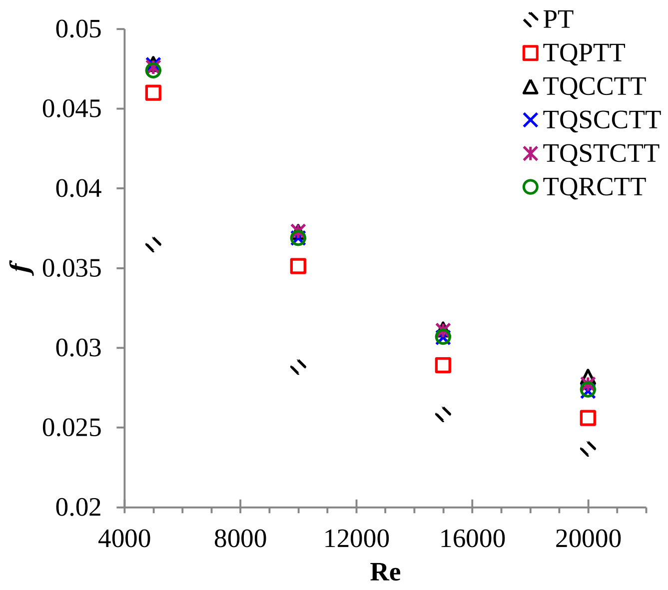


Figure 9. Variation of numerical results for friction factor with Reynolds number plain tube and tube induced with quadruple twisted tapes inserts of different modifications.

3.2 Heat Transfer

The Nusselt number, as shown in (4) previously, is influenced by velocity variation, friction factor, twisted tape dimension and other parameters. The models examined numerically in Reynolds number range from 5,000 to 20,000.

The simulated results of the plain tube (PT) match the experimental results obtained from correlation of Gnielinski (4) with a deviation of 2.6179% - 4.38%; the results of validation are shown in Fig. (10).

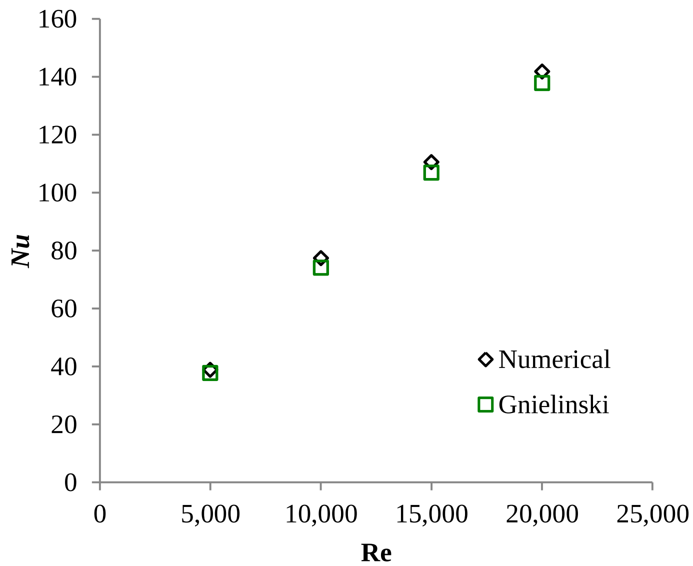


Figure 10. Validation of numerical results for Nusselt number to the plain tube with Gnielinski correlation.

The variation of Nusselt number with Reynolds number for the tubes with different designs of quadruple twisted tape inserts are compared in Fig. (11). The TQPTT has Nusselt number of 9.1 to 16.52% higher than plain tube. It can generally be observed that the Nusselt number increases as the Reynolds number increases. This arises as a result of the momentum that overcomes the viscous force of the fluid as the Reynolds number increases and in effect diminishes the shear between the fluid and the tube wall. It is also evident in Fig. (11) that the Nusselt number in the TQPTT is higher than that in the PT. This is caused by the decrease in the flow cross-sectional area and an increase in the velocity of the induced tube. This resulted in increase of the heat transfer coefficient of the induced tube then increase in Nusselt number. Also because of secondary flow, with greater enhancement being realized at higher Reynolds numbers.

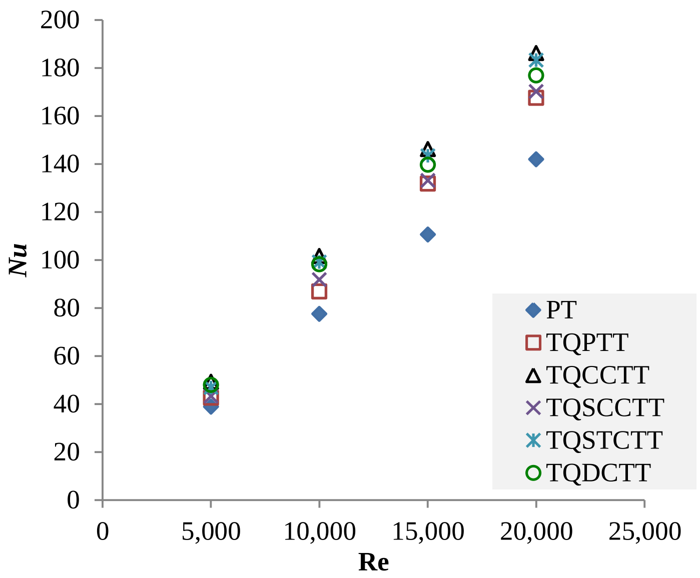


Figure 4.8. Variation of Nusselt number with Reynolds number for plain tube and tubes induced with quadruple twisted tapes of different modifications.

Nusselt number of TQCCTT, TQSCCTT, TQSTCTT and TQRCTT are 10.6 to 14.6%, 4.5 to 5.73%, 9 to 12.5% and 5.4 to 11.9% higher than that in TQPTT. Generally, as Gnielinski (4) introduced the friction factor as a modeling parameter for the Nusselt number, the models of higher friction factor give higher heat transfer enhancement.

4. Conclusions

Heat transfer fluid flow characteristics through tubes induced with quadruple plain and modified twisted tape inserts were numerically investigated. The investigation was carried out for turbulent flow with a Reynolds number range of 5,000-20,000. The findings are presented below;

i- The best thermal performance model in augmenting heat transfer was numerically investigated for turbulent flow of water through induced tubes of different inserts' designs. It was discovered that of all the inserts designs considered, tube fitted with quadruple circular cuts twisted tape (TQCCTT) gave the best heat transfer enhancement. The Nusselt number of TQCCTT was up to 31.12% higher than in plain tube (PT).

ii- Generally, the modified twisted tapes have higher Nusselt number than plain twisted tapes.

iii- The pressure drop in modified twisted tapes inserts is higher than plain twisted tapes and also than plain tube.

iv- The friction factor for plain and modified twisted tapes inserts is higher than plain tube, where the additional pressure dissipation of the fluid caused by the fluid disturbance due to the presence of cuts on the tapes results in an increase in pressure drop which cause an increase in the friction factor, the model (TQCCTT) achieved higher friction factor losses than other tested models.

Abbreviations

D	Tube diameter (mm)
d	Cut diameter (mm)
f	Friction factor
I	Turbulence intensity
L	Tube length (mm)
l	Cut side length(mm)
Nu	Nusselt number
p	Pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
V	Mean velocity (m/s)
w	Tape width (mm)
y	Tape pitch 180° (mm)
δ	Tape thickness (mm)
v	Kinematic viscosity (m^2/s)

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