Thermohydraulic performance evaluation of heat exchangers equipped with centrally perforated twisted tape:
Laminar and turbulent flows

Krit RUENGPAYUNGSAK*, Anucha SAYROSROY**, Khwanchit WONGCHAREE*** and
Smith EIAMSA-ARD*

*Department of Mechanical Engineering, Faculty of Engineering
Mahanakorn University of Technology, Bangkok, Thailand
**Faculty of Engineering and Industrial Technology
Phetchaburi Rajabhat University, Phetchaburi, Thailand
***Department of Chemical Engineering, Faculty of Engineering
Mahanakorn University of Technology, Bangkok, Thailand
E-mail: smith@mut.ac.th

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Abstract
Convective heat transfer enhancement in a round tube mounted with a centrally perforated twisted tape (CP-TT) was numerically investigated. Influences of space of cut ratio ($s/w=0.5, 0.7$ and 0.9) and twist ratio ($y/w=2.0, 3.0$ and 4.0) under laminar and turbulent flow regimes on heat transfer characteristics were determined. Numerical encompassed Reynolds numbers ($Re$) from 400 to 2000 for laminar flow and 5000 to 15,000 for turbulent flow. At a given Reynolds number, the tubes with centrally perforated twisted tape (CP-TT) inserts offer higher heat transfer rate than those the plain tube alone. Heat transfer enhancement in a round tube equipped with centrally perforated twisted tape (CP-TT) is strongly dependent on twist ratio ($y/w$) and space of cut ratio ($s/w$). The results also found that the heat transfer rate ($Nu$) and friction factor ($f$) increase as twist ratio ($y/w$) and space of cut ratio ($s/w$) decreases. The thermal enhancement factor ($TEF$) increases as space of cut ratio ($s/w$) and twist ratio ($y/w$) decreases in laminar flow regime while the opposite trend is observed in the turbulent flow regime. Over the studied range, the tube equipped with centrally perforated twisted tape (CP-TT) with $s/w=0.5$ and $y/w=2.0$ gives the maximum thermal enhancement factor ($TEF$) of 8.92 for laminar flow at $Re=2000$. In turbulent flow at $Re=5000$, the centrally perforated twisted tape (CP-TT) with $s/w=0.9$ and $y/w=3.0$ yields the maximum thermal enhancement factor ($TEF$) of 1.33. In addition, the flow structure, temperature field and local Nusselt number of heat exchanger tubes equipped with centrally perforated twisted tape (CP-TT) are also reported for the clarification of heat transfer and flow topology mechanisms.

Keywords : Heat transfer augmentation, Heat transfer mechanism, Centrally perforated twisted tape, Swirl, Turbulent flow

1. Introduction
One of the widely applied techniques for enhancing thermohydraulic performance in a heat exchanger tube is inserting a twisted tape swirl generator into a duct/tube core. In general, a twisted tape produces a swirl flow that interrupts hydrodynamic and thermal boundary layers of the fluid inside the tube. The effect directly improves the heat transfer coefficient in a tube. Because its versatilities in several applications for example compact heat exchangers, solar air collectors, refrigeration, solar water collectors, food industries and electronic packages, etc., this enhancement technique has been extensively reported. The influences of modified tape geometries on the heat transfer augmentation, pressure loss and thermohydraulic enhancement factor have been reported such as typical twisted tape (Wang et al., 2016), counter twisted tape (Bhuiya et al., 2014), twisted tape at different entrance angle (Bhattacharyya and Chattopadhyay, 2017), square/V-cut twisted tape (Saravanan et al., 2016), multiple twisted tape (Eiamsa-ard and Kiatkittipong, 2014), multiple twisted tape (Eiamsa-ard, 2010), multiple square perforated twisted tape (Singh Suri et al., 2018), perforated/V/ U-cut
twisted tape (Hasanpour et al., 2017), helically twisted tape (Eiamsa-ard et al., 2012), twin twisted tape (Abdolbaqi et al., 2016), regularly spaced twisted-tape elements (Jiao and Deng, 2012), regularly spaced overlap dual twisted tape elements (Changcharoen et al., 2015), triple-channel twisted tape (Eiamsa-ard et al., 2016), perforated/notched/jagged twisted tape (Rahimi et al., 2009), helical twisted tape (Jaisankar et al., 2009), non-uniform twisted-tape (Eiamsa-ard et al., 2013), perforated twisted-tapes with/without parallel wings (Thianpong et al., 2012a-b), and overlapped large/small twin twisted tape (Hong et al., 2017a). Guo et al. (2011) studied the thermohydraulic performance in a tube inserted with center-cleared twisted tape (CC-TT). Their results showed that the CC-TT inserts are a promising insertion device for heat transfer augmentation in laminar flow regime. They reported that the CC-TT inserts enhanced thermal enhancement factor (TEF) up to 20% over those of tube inserted with typical twisted tape. Naik et al. (2014) examined the influence of twisted tape combined with wire coil on the heat transfer augmentation behavior by using nanofluid as the testing fluid at different CuO/water volume concentrations, twist ratios and pitch ratios. In general, heat transfer increased with increasing nanofluid concentration. By using the nanofluid with concentration of 0.3%, the tube mounted with twisted tape and the one with wire coil improved thermal enhancement factors (TEF) up to 1.24 and 1.36 times as compared to those obtained by using water as the working fluid. Li et al. (2015) studied the thermohydraulic performance in a tube fitted with CP-TT at different hollow-widths and hollow-clearances under laminar flow regime. The thermohydraulic performance of CP-TT insert was increased by 28% over that of the tube with the typical tape insert. They reported that the heat transfer performance was improved as hollow-clearances decreased. Safikhani and Abbasi (2015) carried out the thermohydraulic performance in a flat tube equipped with twisted tape inserts using nanofluid as the testing fluid. Three different twisted tape types were employed: typical twisted tape and co/couter-dual twisted tapes. Among the twisted tapes, the counter-dual ones yielded the highest heat transfer and also caused the maximum pressure loss. Hasanpour et al. (2016) reported the thermohydraulic performance in a corrugated tube mounted with different perforated/V-cut/U-cut twisted tape in turbulent regime. Tapes were tested at various twist/hole-diameter/width/depth ratios of the cuts. They observed that the pressure drop and heat transfer rate of corrugated tube inserted with all type of modified twisted tapes were higher than that of the corrugated tube alone. Singh et al. (2016) reported the influence of solid ring tubular combined with twisted tape swirl generator on the thermohydraulic performance behaviors in turbulent regimes. The combined devices offered the thermohydraulic performance up to 1.61 times over than those the plain tube alone under the same pumping power criteria. Bhuinya et al. (2016) conducted the influence of heat exchanger tube inserted with perforated double counter twisted tapes at various porosity ratios on thermohydraulic performance characteristics. Their reports indicated that the thermohydraulic performance were decreased with increasing porosity except porosity ratio of 1.2%. Saysroy and Eiamsa-ard (2017) investigated the thermohydraulic performance mechanisms in the heat exchanger tube inserted with multi-channel twisted tapes at various channel numbers. Their numerical results found that the maximum thermohydraulic performance up to 7.28. Hong et al. (2017b) performed experiment to investigate the thermohydraulic characteristics of tubes with overlapped multiple twisted tape inserts in counter large/small combinations. They found that the heat transfer rate decreased with decreasing tape number and increasing overlapped twisted ratio. The maximum thermohydraulic performance given by the tube mounted with overlapped multiple tapes was 1.08 times of those the plain tube alone. Man et al. (2017) carried out the thermohydraulic performance of tube mounted with alternation of clockwise and counterclockwise twisted tape (ACCT) in turbulent flow regime. The ACCT provided higher thermohydraulic performance than the typical tapes. The maximum performance evaluation criteria of 1.42 was achieved by using the ACCT inserts. The above literature review shows that the heat transfer augmentation in tube inserted with modified twisted tape is strongly dependent on the tape geometry and arrangement.

The previous works of the authors (Eiamsa-ard et al., 2012, 2013 and 2014) focused on the designing twisted tapes for enhancing the high heat transfer rate. However, those twisted tapes caused very high pressure loss in the system. The present work focuses on reducing the pressure loss and maintaining heat transfer rate to be in reasonable tradeoff with the increased pressure loss in order to improve thermal performance as compared to those reported in other works. In the present work, the centrally perforated twisted tape was modified from a typical helical screw tape. The modifications include (1) creating double helical screw tape in each test section and (2) introducing the small tape width to reduce pressure loss while swirling flow was maintained near tube wall region. The aim of the present work is to simulation the heat transfer mechanism, pressure loss, flow field, turbulent kinetic energy, fluid temperature, Nusselt number distribution and thermal enhancement factor behaviors of water flow in the heat exchanger tubes inserted with CP-TT in laminar and turbulent regions with Reynolds number ranging from 400-2000 and 5000-15,000. The influences of space of cut ratio ($s/w = 0.5, 0.7, 0.9$) and twist ratios ($v/w = 2.0, 3.0$ and $4.0$) on thermohydraulic performance were also described.
2. Physical model of centrally perforated twisted tape

In the present study, the detail of computational domain of periodic flow of tube inserted with centrally perforated twisted tape (CP-TT) is displayed in Fig. 1. The parameters shown in the figure are twisted length \( y \), tape width \( w \), and a space of cut \( s \). To investigate the effects of the interaction between tapes, the space of cut ratio, \( s/w \) was varied from 0.5 to 0.9 while twist ratio \( y/w \) was varied between 2.0 and 4.0. The details of the tube inserted with centrally perforated twisted tape (CP-TT) configurations are shown Fig. 1. The computations were performed with the following conditions: (1) the inlet and outlet of the computational flow domain are under the periodic condition; (2) the temperature of the tube wall is constant at 310 K; (3) water which is assumed to be incompressible enters the tube under a constant mass flow rate at the fluid temperature \( T_{in} \) of 300 K \((Pr = 5.86)\) and; (4) the centrally perforated twisted tape is subjected to an adiabatic wall condition.

Fig. 1. Geometry of tube inserted with centrally perforated twisted tape and computational domain of periodic flow.

3. Details of mathematical foundation and boundary conditions

The phenomenon under consideration is governed by the steady three-dimensional form of the continuity and the time-averaged incompressible Navier-Stokes equations. In the Cartesian tensor system these equations can be written as below:

**Continuity equation:**

\[
\frac{\partial}{\partial x_i} (\rho u_i) = 0
\]

**Momentum equation:**

\[
\frac{\partial}{\partial x_j} \left( \rho u_i u_j \right) = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right) \right]
\]

**Energy equation:**

\[
\frac{\partial}{\partial x_j} \left( \rho u_i T \right) = \frac{\partial}{\partial x_j} \left( \left( R' + R'' \right) \frac{\partial T}{\partial x_j} \right)
\]

Where \( R' = \frac{\mu}{Pr} \) and \( R'' = \frac{\mu_u}{Pr_u} \)

For Reynolds averaged Navier-Stokes equation, the Reynolds stresses, \( -\rho u'_i u'_j \) in Eq. (2) needs to be modeled. The Boussinesq hypothesis relates the Reynolds stresses to the mean velocity gradients as shown in the following equation:
\[
-k \nabla T = \nabla \cdot (k \nabla T)
\]

The RNG \( k-\varepsilon \) model is one of the two-equation models that employ the Boussinesq hypothesis. The steady state transport equations can be written as:

\[
\frac{\partial}{\partial x_i} \left( \rho u_i \varepsilon \frac{\partial k}{\partial x_j} \right) + G_k - \rho \varepsilon = 0
\]

\[
\frac{\partial}{\partial x_i} \left( \rho u_i \varepsilon \frac{\partial \varepsilon}{\partial x_j} \right) + C_k \varepsilon \frac{\varepsilon}{k} \left( G_k - C_{\varepsilon} - \frac{\varepsilon^2}{k} - R_e \right)
\]

where

\[
G_k = -\rho \varepsilon \frac{\partial u_i}{\partial x_i}
\]

The numerical prediction for the tube fitted with multi-channel twisted tapes was performed using finite volume method (Patankar, 1980; ANSYS, 2017). The governing equations are solved by using a finite volume approach and the SIMPLE algorithm. The physical properties of the fluid are solved at average bulk temperature. Impermeable boundary and no-slip wall conditions are implemented over the tube wall. The temperature of the tube wall is kept constant at 310 K. The centrally perforated twisted tape (CP-TT) surface is assumed as adiabatic wall. Flows are classified into two flow regimes: (1) laminar flow regime \((400 \leq Re \leq 2000)\), and (2) turbulent flow regime \((5000 \leq Re \leq 15,000)\).

For the grid independence test in case of the centrally perforated twisted tape (CP-TT) with twist ratio of \(y/w = 3.0\) and space of cut ratio of \(s/w = 0.5\), different cell numbers including 101952, 235171, 423460, 602103 and 1032080 are applied. The tetrahedral grid is used for meshing and \(y^+\) values were below 3.5. The results show that the further increasing cell number beyond 423460 cells, both of heat transfer \((Nu)\) and pressure loss \((f)\) vary less than 2.5%. Thus, grid number of 423460 is taken as criterion for grid independence.

| Table 1: Summary of the grid independence for tube fitted with CP-TT |
|----------------------|---------------|---------------|---------------|
|                      | \(y/w = 2.0\) | \(y/w = 3.0\) | \(y/w = 4.0\) |
| Typical twisted tape (TT) | 296,846       | 472,330       | 560,514       |
| CP-TT, \(s/w = 0.5\)     | 284,169       | 423,460       | 562,655       |
| CP-TT, \(s/w = 0.7\)     | 322,158       | 477,503       | 636,095       |
| CP-TT, \(s/w = 0.9\)     | 358,575       | 488,415       | 658,975       |

4. Parameters

Four parameters of interest for this investigation are expressed as follows.

\(Nu\) number:

\[
Nu = \frac{hD}{\kappa}
\]

Average Nusselt number \((Nu_{avg})\) is calculated by using the equation below.

\[
Nu_{avg} = \frac{1}{A} \int Nu dA
\]

Friction factor \((f)\) is determined from the measured pressure loss, \(\Delta P\), across the pressure taps between the inlet and outlet of the tube fitted with CP-TT.

\[
f = \frac{\Delta P}{\rho u_m^2 (L/2D)}
\]

where \(u_m\) is mean fluid velocity and \(L\) is the test section length.

Reynolds number, \(Re\), at each experiment is calculated from the measured velocity water flow rate \((u_m)\) of the fluid/water flowed through the tube, the measured inner diameter of the test tube \((D)\), the density of the water flow \((\rho)\) and the viscosity of the water flow \((\mu)\) that determined based on the average water temperature \((T_{bulk})\).
\[ \text{Re} = \rho \nu \frac{D}{\mu} \quad (12) \]

Thermal enhancement factor (TEF) of the tube inserted with CP-TT is determined under the constant pumping power criterion which it is useful for heat exchanger tube design (Webb and Kim 2015; Yakut et al., 2014; Yerra et al., 2007) as
\[
\text{TEF} = (\frac{N_u}{N_{up}}) / (\frac{f}{f_p}) \quad (13)
\]
where \(N_u\) and \(f\) are the Nusselt number and friction factor of tube inserted with centrally perforated twisted tape (CP-TT) while \(N_{up}\) and \(f_p\) are Nusselt number and friction factor of the plain tube alone.

Fig. 2. Validation test of plain tube for laminar flow region: (a) Nusselt number and (b) friction factor

Fig. 3. Validation test of plain tube for turbulent flow region: (a) Nusselt number and (b) friction factor.

Fig. 4. Geometry of the tube equipped with typical twisted tape.

Fig. 5. Validation test of plain tube inserted with typical twisted tape for turbulent flow region: (a) Nusselt number and (b) friction factor.
Fig. 6. Contour plots of velocity ($x/D = 3.0$) of the tubes inserted with centrally perforated twisted tapes at various space ratios ($s/w$) and twist ratios ($y/w$) for $Re = 5000$.

Fig. 7. Contour plots of turbulent kinetic energy ($x/D = 3.0$) of the tubes inserted with centrally perforated twisted tapes at various space ratios ($s/w$) and twist ratios ($y/w$) for $Re = 5000$.

5. Numerical results and discussion

5.1 Data validation

Data verification was carried out to ensure the reliability of the prediction. The cases verified are the plain tube with and without classical/typical twisted tape inserts. The prediction results are shown in terms of average Nusselt number ($Nu$) and friction factor ($f$). Nusselt number ($Nu$) and friction factor ($f$) of the plain tube alone are verified by comparing the present works with those in the standard correlations under the same operating condition. The reference data are selected from the open literature (Incropera and Dewitt, 1996), in which the exact solutions of the Nusselt number and...
friction factor for laminar and turbulent flows. Figures 2 and 3 demonstrate the comparisons for Nusselt number and friction factor. The present numerical data are in excellent agreement with the mentioned exact solution values within ±0.5% and ±0.0% maximum deviation for Nusselt number and friction factor for laminar flow regime. For turbulent flow regime, Nusselt numbers deviate from Dittus and Boelter correlation within ±6.5% while friction factors deviate from those obtained from Petukhov correlation within ±9%. This performs a strong confidence in further study of the plain tube inserted with CP-TT. The present results of the round tube with classical/typical twisted tape are validated with those obtained from correlation of Manglik and Bergles (Manglik and Bergles, 1993a, b). Details of the classical/typical twisted tape are presented in Fig. 4. The typical twisted tape width is smaller than that of the inner diameter of the tube. The twist/pitch is a distance required for the tape to rotated 180°, the twist ratio is 3.0 that used to compare with those the previous correlations. The deviations of the present Nusselt number and friction factor from those obtained from Manglik and Bergles (1993a, b) are within ±12% and ±6.5% for laminar flow and within ±11.5% and ±9% for turbulent flow as displayed in Fig. 5. The comparisons indicate that the simulation results in the present study are sufficiently accurate.

5.2 Thermohydraulic behaviors

The numerical results of the flow structure of the swirling flow, velocity field, turbulent kinetic energy (TKE), and temperature field of a plain tube alone and the tubes inserted with classical/typical twisted tape (TT) and centrally perforated twisted tape (CP-TT) inserts at Reynolds number of 5000 are demonstrated in Figs. 6-11. The results of classical/typical twisted tapes (TT) are compared with those of the centrally perforated twisted tapes (CP-TT) under the same twist ratio and boundary conditions. For the plain tube, high-speed flow appears in a core region while low speed flow appears near the tube wall, this results in a thick thermal boundary layer.

Fig. 8. Contour plots of temperature stream lines and temperature fields of the tubes inserted with centrally perforated twisted tapes at various space ratios (s/w) and twist ratios (y/w) for Re = 5000.
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Fig. 8. Contour plots of temperature stream lines and temperature fields of the tubes inserted with centrally perforated twisted tapes at various space ratios ($s/w$) and twist ratios ($y/w$) for $Re = 5000$. (continued)

Fig. 9. Contour plots of temperature fields ($x/D = 3.0$) of the tubes inserted with centrally perforated twisted tapes at various space ratios ($s/w$) and twist ratios ($y/w$) for $Re = 5000$.

The presence of centrally perforated twisted tape (CP-TT) helps in promoting thermal boundary layer disruption. In general, as compared to typical twisted tapes, centrally hollow narrow twisted tapes (CP-TT) generate stronger swirl flows. This results in higher efficient flow disturbance and thermal boundary disruption and thus higher heat transfer (Fig. 8).

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11). In the tubes with centrally perforated twisted tape (CP-TT) inserts, swirl flow covers larger area and turbulent kinetic energy (TKE) is higher at lower space of cut \((s/w)\) and twist ratio \((y/w)\). In other words, as the space of cut ratio \((s/w)\) of centrally perforated twisted tape increases, velocity distribution streamline, turbulent kinetic energy (TKE) and iso-surface temperature become similar to that of the plain tube resulting in thicker thermal boundary layer (Figs. 6-11) because more fluid is directed in common axial flow. The velocity distributions (Fig. 8) in the tube with CP-TT at the low space of cut ratios \((s/w = 0.5)\) is similar to that typical twisted tape inserts. It is also found that the temperature change in tube with the twisted tape at the largest space of cut ratio space of cut ratio \((s/w = 0.9)\) is insignificant. This indicates the poor fluid mixing which results in inefficient heat transfer (Fig. 11).

![Fig. 10. Contour plots of iso-surface temperature (27°C) of the tubes inserted with centrally perforated twisted tapes at various space ratios \((s/w)\) and twist ratios \((y/w)\) for \(Re = 5000\).](image-url)
Fig. 10. Contour plots of iso-surface temperature (27°C) of the tubes inserted with centrally perforated twisted tapes at various space ratios \(s/w\) and twist ratios \(y/w\) for \(Re = 5000\). (continued)

Fig. 11. Contour plots of Nusselt number of the tubes inserted with centrally perforated twisted tapes at various space ratios \(s/w\) and twist ratios \(y/w\) for \(Re = 5000\).
5.3 Heat transfer

The variations of heat transfer rate in terms of Nusselt number (Nu) and heat transfer enhancement ratio (Nu/NuP) with Reynolds number (Re) of the tubes inserted with centrally perforated twisted tapes (CP-TT) at various space of cut ratios (s/w = 0.5, 0.7, and 0.9) and twist ratios (y/w = 2.0, 3.0, and 4.0) in both of laminar and turbulent flow regions are demonstrated in Figs. 12, 13(a-b) and 14(a-b). Generally, the heat transfer rate (Nu) increases with increasing Re. Heat transfer enhancement ratio (Nu/NuP) increases with increasing Re in laminar flow region. However, the contrary trend is found in turbulent flow region. This can be explained that the thermal boundary layer in laminar regime is thick, thus the change of the thermal boundary layer thickness in the tube with a centrally perforated twisted tape (affected by swirl flow) as compared to that in the plain tube is significant with increasing Reynolds number. On the other hand, the thermal boundary layer in turbulent regime is thin, thus the change of thermal boundary thickness by the effect of swirl flow becomes less significant as Reynolds number increases. The numerical results show that the heat transfer ratio (Nu/NuP)
in the tube with centrally perforated twisted tape (CP-TT) is enhanced up to 18.9 times in laminar flow regime at Reynolds number, $Re = 2000$ whereas the enhancement is only 1.8 times in turbulent flow regime at $Re = 15,000$. For both of laminar and turbulent flow regions, the heat transfer ($Nu$) increases with decreasing twist ratio ($y/w$) and space of cut ratio ($s/w$) because of the stronger flow disturbance as described in subsection 5.2. The heat transfer rate ($Nu$) of tube with CP-TT inserts with lowest twist ratio ($y/w$) of 2.0 is higher than those with $y/w = 3.0$ and 4.0 by around 8% and 15% for laminar flow regime and 4% and 9% for turbulent flow regime. The numerical results also reveal that the heat transfer rate ($Nu$) offered by CP-TT with the lowest space of cut ratio of $s/w = 0.5$ is higher than those with $s/w = 0.7$ and 0.9 by around 26% and 45% for laminar flow regime and 7% and 15% for turbulent flow regime. At a given Reynolds number, CP-TTs give higher heat transfer rate than the typical tapes due to the higher turbulent flow near the both sides of cutting edge (see in Fig.7). In addition, the heat transfer rate of the tubes fitted with CP-TT at the smallest space of cut ratio, $s/w = 0.5$ and twist ratio, $y/w = 2.0$ is higher than those of the plain tube alone by 1100% in laminar regime and by 92% in turbulent regime.

![Graph](image-url)

Fig. 13. Effect of centrally perforated twisted tape inserts at various space ratios ($s/w$) and twist ratios ($y/w$) on heat transfer rate in laminar flow region.

### 5.4 Friction factor

Effects of tube with centrally perforated twisted tape (CP-TT) inserts at various twist ratios ($y/w$) and space of cut ratios ($s/w$) on pressure loss ($f$ or $f/f_P$) characteristics are displayed in Figs. 15, 16(a-b) and 17(a-b). Friction factor ratio ($f/f_P$) increases with increasing $Re$. However, the change of $f/f_P$ with $Re$ in laminar regime is more substantial than that in turbulent regime. The results accord with those reported by Chang et al. (2007, 2015). Most friction factors of the tubes inserted with CP-TT are lower than those with the typical tapes due to the smaller tape surface area. Among the centrally hollow narrow twisted tapes (CP-TT), the ones with smaller twist ratios ($y/w$) and space of cut ratios ($s/w$) cause higher pressure loss and thus friction factor due to the larger interface between CP-TT surface and fluid, and stronger swirl flow. The twisted tape with the lowest twist ratio ($y/w = 2.0$), respectively causes the rise of friction factor up to 18%, and 30% over those caused by ones with the twist ratio ($y/w$) of 3.0 and 4.0 in laminar region.
Fig. 14. Effect of centrally perforated twisted tape inserts at various space ratios ($s/w$) and twist ratios ($y/w$) on heat transfer rate in turbulent flow region.

Fig. 15. Relationship between Reynolds number ($Re$) and friction factor ($f$) in laminar and turbulent flow regions.
Fig. 16. Effect of centrally perforated twisted tape inserts at various space ratios (s/w) and twist ratios (y/w) on friction factor in laminar flow region.

Fig. 17. Effect of centrally perforated twisted tape inserts at various space ratios (s/w) and twist ratios (y/w) on friction factor in turbulent flow region.
5.5 Thermal performance

Figure 18 displays the thermal enhancement factors (TEF) of tubes inserted with centrally hollow narrow twisted tapes (CP-TT) with various space of cut ratios (s/w) and twist ratios (y/w). The TEF was evaluated under the constant pumping power criterion shown in Eq. (13) which was widely applied in several researches works (Webb and Kim, 2015; Yakut et al., 2014). The TEF is derived based on the constant pumping criteria that means the pumping power used in the tube with enhancement device is same as that used in the plain tube. This assumption is used for evaluating the practical use of the enhancement device in the view point of energy saving potential (thermal enhancement factor above unity means overall energy gain). In general, higher value of TEF indicates the superior energy saving. As found, TEF tends to increase with increasing Reynolds number (Re) in laminar flow region. In contrast, TEF tends to decrease with increasing Re in turbulent region. With the use of tubes inserted with CP-TT, thermal enhancement factors (TEF) fall within the range of 2.8 to 8.92 in laminar flow region and 1.15 to 1.33 in turbulent flow region. The results indicate that the use of centrally perforated twisted tape (CP-TT) in laminar flow region is more promising than that in turbulent region in view point of energy saving.

Fig. 18. Effect of centrally perforated twisted tape inserts at various space ratios (s/w) and twist ratios (y/w) on thermal enhancement factor (TEF).
In laminar regime, \( TEF \) increases with decreasing twist ratio \((y/w)\) and space of cut ratio \((s/w)\). The centrally perforated twisted tape (CP-TT) with \( y/w = 2.0 \) offers higher \( TEF \) than the ones with \( y/w = 3.0 \) and 4.0 by about 5% and 10%, respectively. The use of CP-TT with cut ratio of \( s/w = 0.5 \) results in higher \( TEF \) than those with \( s/w = 0.7 \) and 0.9 by about 10% and 23%, respectively. The increased \( TEF \) is the consequence of the greater influence of promoted heat transfer higher than that of the increased pressure loss. On the other hand, \( TEF \) decreases with decreasing space of cut ratio \((s/w)\) in the turbulent region. This is attributed to the high-pressure loss in the tube with large blockage at high \( Re \). The tapes with cut ratio of \( s/w = 0.5 \) provide lower \( TEF \) than those with \( s/w = 0.7 \) and 0.9 by about 1.5% and 4.8%, respectively, while the tapes with the lowest twist ratio \((y/w)\) of 2.0 provide lower \( TEF \) than the ones with \( y/w = 3.0 \) and 4.0 by around 4.2% and 4.4%, respectively. In laminar flow regime, the \( TEF \) of the tubes fitted with CP-TT are 4.5% to 22.5% over than those of the tube with typical tape insert, and 280% to 890% higher than those of the plain tube. In turbulent flow regime, the \( TEF \) of the tubes fitted with CP-TT are higher than those of the plain tube alone and the tube equipped with typical tape inserts by 13% to 32% and 20% and 30%, respectively.

6. Conclusions

The heat transfer enhancement characteristics in tubes inserted with centrally hollow narrow twisted tapes (CP-TT) have been studied numerically in laminar flow (400 \( \leq Re \leq 2000 \)) and turbulent flow (5000 \( \leq Re \leq 15,000 \)). The influences of space of cut ratio \((s/w = 0.5, 0.7, \text{ and } 0.9)\) and twist ratio \((y/w = 2.0, 3.0 \text{ and } 4.0)\) on flow and heat transfer mechanism are also described. The main findings in the present investigation can be concluded as follows:

- The tapes with large cut ratios \((s/w = 0.7 \text{ and } 0.9)\) cause considerably lower pressure loss than the classical/typical twisted tape while the one with small cut ratio \((s/w = 0.5)\) causes comparable pressure drop with the typical tape. The tape with small \( y/w \), gives high heat transfer which is accompanied with the high pressure loss penalty. In laminar flow region, both of space of cut ratios \((s/w)\) and twist ratio \((y/w)\) show significant effect on \( TEF \) especially at the smallest cut ratio \((s/w = 0.5)\) and twist ratio \((y/w = 2.0)\). However, both parameters show insignificant effect on \( TEF \) in the turbulent flow region.

- The heat transfer rate of the tubes fitted with CP-TT at the smallest space of cut ratio, \( s/w = 0.5 \) and twist ratio, \( y/w = 2.0 \) is higher than those of the plain tube alone by 1100% in laminar regime and by 92% in turbulent regime.

- In both laminar and turbulent flow regimes, heat transfer rate and pressure loss of the tubes inserted with the centrally perforated twisted tape (CP-TT) increase with decreasing \( y/w \) and \( s/w \). Thermal enhancement factor \((TEF)\) increases with \( y/w \) and \( s/w \) in laminar flow while contradictory trend is observed in turbulent flow.

- In laminar flow regime, the \( TEF \) of the tubes fitted with CP-TT are 4.5% to 22.5% over than those of the tube with typical tape insert, and 280% to 890% higher than those of the plain tube. In turbulent flow regime, the \( TEF \) of the tubes fitted with CP-TT are higher than those of the plain tube alone and the tube equipped with typical tape inserts by 13% to 32% and 20% and 30%, respectively.

- In laminar flow, the maximum \( TEF \) of 8.92 is achieved at \( y/w = 2.0 \) and \( s/w = 0.5 \) and \( Re = 2000 \). In turbulent flow, the maximum \( TEF \) of 1.33 is obtained by the use the twisted tape with twist ratio of \( y/w = 3.0 \) and space of cut ratio of \( s/w = 0.9 \) at \( Re = 5000 \).

References
Abdolbaki, M.K., Azmi, W.H., Mamat, R., Mohamed, N.M.Z.N., Najafi, G., Experimental investigation of turbulent heat transfer by counter and co-swirling flow in a flat tube fitted with twin twisted tapes, Int. Commun. Heat Mass Trans., Vol. 75 (2016), pp. 295-302.
ANSYS, Inc., ANSYS Fluent Theory Guide, 18th version, U.S.A., (2017).
Bhattacharyya, S., Chattopadhyay, H., Haldar, A., Design of twisted tape turbulator at different entrance angle for heat transfer enhancement in a solar heater, Beni-Suef University J. Basic and Applied Sciences, Vol. 7 (2018), pp. 118-126.
Bhuiya, M.M.K., Azad, A.K., Chowdhury, M.S.U., Saha, M., Heat transfer augmentation in a circular tube with perforated double counter twisted tape inserts, Int. Commun. Heat Mass Trans., Vol. 74 (2016), pp. 25-33.
Chang, S.W., Yang, T.L., Liou, J.S., Heat transfer and pressure drop in tube with broken twisted tape insert, Exp. Therm. Fluid Sci., Vol. 32 (2007), pp. 489-501.

Chang, S.W., Yu, K.W., Lu, M.H., Heat transfers in tubes fitted with single, twin and triple twisted tapes, Exp. Heat Trans., Vol. 18 (2005), pp. 279-294.

Changcharoen, W., Somravysin, P., Promthaisong, P., Eiamsa-ard, P., Nanan, K., Eiamsa-ard, S., Investigation of turbulent heat transfer in round tubes fitted with regularly spaced overlap dual twisted element, J. Res. Appl. Mech. Eng., Vol. 3 (2015), pp. 64-74.

Dewan, A., Mahanta, P., Raju, K.S., Kumar, P.S., Review of passive heat transfer augmentation techniques, J. Power Energy, Vol. 218 (2004), pp. 509-525.

Eiamsa-ard, S., Kiatkittipong, K., Heat transfer enhancement by multiple twisted tape inserts and TiO$_2$/water nanofluid, Appl. Therm. Eng., Vol. 70 (2014), pp. 896-924.

Eiamsa-ard, S., Promthaisong, P., Thianpong, C., Pimsarn, M., Chuwattanakul, V., Influence of three-start spirally twisted tube combined with triple-channel twisted tape insert on heat transfer enhancement, Chemical Engineering and Processing: Process Intensification, Vol. 102 (2016), pp. 117-129.

Eiamsa-ard, S., Somkleang, P., Nuntadusit, C., Thianpong, C., Heat transfer enhancement in tube by inserting uniform/non-uniform twisted-tapes with alternate axes: Effect of rotated-axis length, Appl. Therm. Eng., Vol. 54 (2013), pp. 289-309.

Eiamsa-ard, S., Study on thermal and fluid flow characteristics in turbulent channel flows with multiple twisted tape vortex generators, Int. Commun. Heat Mass Trans., Vol. 37 (2010), pp. 644-651.

Eiamsa-ard, S., Yongsiri, K., Nanan, K., Thianpong, C., Heat transfer augmentation by helically twisted tapes as swirl and turbulence promoters, Chemical Engineering and Processing: Process Intensification, Vol. 60 (2012), pp. 42-48.

Guo, J., Fan, A., Zhang, X. and Liu, W., A numerical study on heat transfer and friction factor characteristics of laminar flow in a circular tube fitted with center-cleared twisted tape, Int. J. Thermal Sci., Vol. 50 (2011), pp. 1263-1270.

Hasanpour, A., Farhadi, M., Sedighi, K. Experimental heat transfer and pressure drop study on typical, perforated, V-cut and U-cut twisted tapes in a helically corrugated heat exchanger, Int. Commun. Heat Mass Trans., Vol. 71 (2016), pp. 126-136.

Hasanpour, A., Farhadi, M., Sedighi, K., Intensification of heat exchangers performance by modified and optimized twisted tapes, Chemical Engineering and Processing: Process Intensification, Vol. 120 (2017), pp. 276-285.

Hong, Y., Du, J., Wang, S., Experimental heat transfer and flow characteristics in a spiral grooved tube with overlapped large/small twin twisted tapes, Int. J. Heat Mass Trans., Vol. 106 (2017a), pp. 1178-1190.

Hong, Y., Du, J., Wang, S., Turbulent thermal, fluid flow and thermodynamic characteristics in a plain tube fitted with overlapped multiple twisted tapes, Int. J. Heat Mass Trans., Vol. 115 (2017b), pp. 551-565.

Incropera, F., Dewitt, P.D., Introduction to Heat Transfer. 3rd edition, John Wiley & Sons Inc., (1996).

Jaisankar, S., Radhakrishnan, T.K., Sheeba, K.N., Studies on heat transfer and friction factor characteristics of thermosyphon solar water heating system with helical twisted tapes, Energy, Vol. 34 (2009), pp. 1054-1064.

Jiao, F., Deng, X.H., Heat transfer enhancement in the shell side of the self-support in rectangular converging-diverging tube bundle heat exchangers with different inserts, Heat Trans. Research, Vol. 43 (2012), pp. 615-631.

Li, P., Liu, Z., Liu, W., Chen, S.G., Numerical study on heat transfer enhancement characteristics of tube inserted with centrally narrow short twisted tapes, Int. J. Heat Mass Trans., Vol. 88 (2015), pp. 481-491.

Man, C., Lv, X., Hu, J., Sun, P., Tang, Y., Experimental study on effect of heat transfer enhancement for single-phase forced convective flow with twisted-tape inserts, Int. J. Heat Mass Trans., Vol. 106 (2017), pp. 877-883.

Manglik R.M., Bergles, A.E., Heat transfer and pressure drop correlations for twisted-tape inserts in isothermal tubes: Part I-Laminar flows, Transaction of ASME, J. Heat Trans., Vol. 115 (1993a), pp. 881-889.

Manglik R.M., Bergles, A.E., Heat transfer and pressure drop correlations for twisted-tape inserts in isothermal tubes: Part II-Transition and Turbulent flows, Transaction of ASME, J. Heat Trans., Vol. 115 (1993b), pp. 890-896.

Naik, M.T., Fahad, S.S., Sundar, L.S., Singh, M.K., Comparative study on thermal performance of twisted tape and wire coil inserts in turbulent flow using CuO/water nanofluid, Exp. Therm. Fluid Sci., Vol. 57 (2014), pp. 65-76.

Rahimi, M., Shabanian, S.R., Alsairafi, A.A., Experimental and CFD studies on heat transfer and friction factor characteristics of a tube equipped with modified twisted tape inserts, Chemical Engineering and Processing, Vol. 48 (2009), pp. 762-770.

Patankar, S.V., Numerical Heat Transfer and Fluid Flow, McGraw-Hill, New York, (1980).

Saffikhani, H., Abbasi, F., Numerical study of nanofluid flow in flat tubes fitted with multiple twisted tapes, Advanced Powder Technology, Vol. 26 (2015), pp. 1609-1617.

Saravananan, A., Senthilkumar, J.S., Jaisankar, S., Performance assessment in V-trough solar water heater fitted with square and V-cut twisted tape inserts, Appl. Therm. Eng., Vol. 102 (2016), pp. 476-486.

Sayyad, A., Eiamsa-ard, S., Enhancing convective heat transfer in laminar and turbulent flow regions using multi-channel twisted tape inserts, Int. J. Thermal Sci., Vol. 121 (2017), pp. 55-74.

Singh Suri, A.R., Kumar, A., Maithani, R., Effect of square wings in multiple square perforated twisted tubes on fluid flow and heat transfer of heat exchanger tube, Case Studies in Thermal Engineering, Vol. 10 (2017), pp. 28-43.
Singh, V., Chamoli, S., Kumar, M., Kumar, A., Heat transfer and fluid flow characteristics of heat exchanger tube with multiple twisted tapes and solid rings inserts, Chemical Engineering and Processing: Process Intensification, Vol. 102 (2016), pp. 156-168.

Thianpong, C., Eiamsa-ard, P., Promvonge, P., Eiamsa-ard, S., Effect of perforated twisted-tapes with parallel wings on heat transfer enhancement in a heat exchanger tube, Energy Procedia, Vol. 14 (2012a), pp. 1117-1123.

Thianpong, C., Eiamsa-ard, P., Eiamsa-ard, S., Heat transfer and thermal performance characteristics of heat exchanger tube fitted with perforated twisted-tapes, Heat and Mass Transfer/Waerme- und Stoffuebertragung, Vol. 48 (2012b), pp. 881-892.

Wang, L., Liu, Q., Fukuda, K., Experimental and numerical study of transient heat transfer for forced convection flow of helium gas over a twisted plate, Bulletin of the JSME: Journal of Thermal Science and Technology, Vol. 11 (2016), pp. 1-15, Paper No.15-00388.

Webb, R.L., N.H. Kim, Principles of Enhanced Heat Transfer, 2nd edition, New York: Taylor & Francis, (2005).

Yakut, K., Sahin, B., Canbazoglu, S., Performance and flow-induced vibration characteristics for conical-ring turbulators, Applied Energy, Vol. 79 (2004), pp. 65-76.

Yerra, K.K., Manglik, R.M., Jog, M.A., Optimization of heat transfer enhancement in single-phase tubeside flows with twisted-tape inserts, International Journal of Heat Exchangers, Vol. 7 (2007), pp. 1-22.