Transactions of the TSME (2015) Vol. 3, No. 2, 64~74
Journal of Research and Applications in Mechanical Engineering

ISSN 2229-2152 print
DOI: XXXXXXXXXXXXXXXXXX

Research Article

INVESTIGATION OF TURBULENT HEAT TRANSFER IN ROUND TUBES FITTED WITH REGULARLY SPACED OVERLAP DUAL TWISTED TAPE ELEMENTS

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ABSTRACT:
A numerical investigation of turbulent forced convection in three-dimensional tubes with twisted tape inserts is performed in order to gain an understanding of physical behavior of the fluid flow (overlap dual swirling flows), fluid temperature and local Nusselt number in the tubes fitted with RS-O-DTs. Effects of the regularly spaced overlap dual twisted tape elements (RS-O-DTs) in counter arrangement on heat transfer and friction factor in circular tubes are reported. Computations, based on a finite volume method, are performed by utilizing the RNG k-ε turbulence model. Parametric runs are made for Reynolds numbers between 5000 and 15,000 at various free space ratios (s/W = 2.0, 3.0, and 4.0). From the numerical results reveal that the tube with the RS-O-DTs with the smallest free space ratio (s/W = 2.0), yield higher heat transfer rate by about 180% over the plain tube, and by around 3.1% and 4.0%, over the tubes with RS-O-DTs with s/W = 3.0 and 4.0, respectively.

Keywords: *Dual swirl flows, dual twisted tapes, flow-field, heat transfer enhancement*

1. INTRODUCTION

The technology of enhanced heat transfer has received great attention over the decades; heat transfer augmentation techniques find application mainly in the design of more compact heat exchanger in various industries, especially refrigeration, automotive and chemical process industries. Heat transfer enhancement can be classified into two categories: active techniques which require an extra external power sources and passive techniques which require any direct input of external power. The active techniques include mechanical aids, surface vibration, fluid vibration, electrostatic fields, injection or suction of fluid and jet impingement. The passive techniques include the use of treated surfaces, rough surfaces, extended surfaces, displaced enhancement devices, swirl flow devices, coiled tubes and additives for liquids and gases. Twisted tape inserts as the devices in passive techniques are extensively employed in heat exchanger systems for redeveloping the thermal boundary layer, inducing swirl flow and therefore enhancing the heat transfer performance. In recent years, the performances of twisted tape inserts in different designs have been reported [1-3]. Chang et al. [4-5] studied the heat transfer characteristics in round tubes fitted with serrated twisted tapes and broken twisted tapes at different twist ratios. The results of both papers showed similar trends, that the local Nusselt number and Fanning friction factor increased as the twist ratio decreased.

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Again, Chang et al. [6] carried out the heat transfer experiments in an axially rotating tube equipped with twin twisted tapes. Jaisankar et al. [7] investigated the heat transfer and friction factor characteristics of thermosyphon solar water heater system fitted with twisted tapes with full-length twist, fitted with rods and spacers at different lengths and twist ratios. At similar conditions, the twist tape fitted with rod gave higher overall performance than the one fitted with spacer. Hong et al. [8] studied the turbulent heat transfer and flow behaviors in a converging-diverging tube equipped with twin twisted tapes. They reported that friction factors and heat transfer rates of the converging-diverging tubes equipped with twin twisted tapes were higher than those of the converging-diverging tubes without twisted tape by 6.3-35.7 and 1.75-5.3 times, respectively. They also found that the thermal performance factors based on the constant pumping power of the converging-diverging tubes equipped with twin twisted tapes were above unity, reflecting their overall energy saving potential. Eiamsa-ard et al. [9] studied the effects of twin-counter/co-twisted tapes and their twist ratios (*y/w*) on heat transfer and thermal performance characteristics in heat exchanger tubes. They showed that the tubes equipped with twin-counter-twisted tapes yielded higher heat transfer rate than the tube equipped with twin-co-twisted tapes and single twisted tape up to 44.5% and 50%, respectively. The twin-counter-twisted tapes with y/w = 2.5, 3.0, 3.5 and 4.0, gave thermal performance factors up to 1.39, 1.24, 1.12 and 1.03, respectively. Bharadwaj et al. [10] reported the heat transfer and pressure drop in 75-start spirally grooved tube with twisted tape inserts for laminar and turbulent flows. The grooves were clockwise with respect to the direction of flow. Their results revealed that the direction of twist (clockwise and anticlockwise) significantly influenced thermo-hydraulic characteristics. Again, Eiamsa-ard et al. [11] studied the heat transfer enhancement of heat exchanger tubes equipped with regularly-spaced dual twisted tapes. They observed that the heat transfer rate of the tubes equipped with the regularly-spaced dual twisted tapes was decreased with increasing space ratio (*s/D*). The heat transfer rates of the tubes fitted with the regularly-spaced dual twisted tapes (*s/D*) of 0.75, 1.5 and 2.25 were respectively, 40%, 37% and 33% over those of the plain tube. Rahimi et al. [12] examined the flow structure, friction factor, heat transfer and thermal–hydraulic performance characteristics of the round tubes fitted with perforated/notched/jagged twisted tapes. Their results demonstrated that the Nusselt number and thermal performance of the jagged insert were higher than those of the others. Promvonge et al. [13] investigated the heat transfer characteristics in helical-ribbed tubes equipped with twin twisted tapes with different twist ratios between 2.17 and 9.39. It was found that the ribbed tube equipped twin twisted tape yielded higher heat transfer rate than the plain tube and the ribbed tube acting alone. In the present investigation, the heat transfer and friction factor characteristics in a tube fitted with regularly spaced overlap dual twisted tapes elements (RS-DTs) as the swirl generators are studied numerically. The mass, momentum and energy equations were solved using finite volume method by considering the steady state, turbulent and incompressible fluid flow. The RNG k-ε turbulence model are used to prediction the flow structure of tube fitted with regularly spaced overlap dual twisted tape elements (RS-O-DTs) inserts at different free space ratios (s/W = 2.0, 3.0, and 4.0), by using air as the working fluid at the Reynolds numbers from 5000 to 15,000.

2. MATHEMATICAL MODEL AND NUMERICAL METHOD

The available finite difference procedures were employed to solve the governing partial differential equations for swirling flows and boundary layer. Some simplifying assumptions were applied for conventional flow momentum and energy equations to model the heat transfer process in a constant heat flux tube with regularly spaced overlap dual twisted tapes elements (RS-O-DTs) in counter arrangement. The major assumptions are; (1) the flow is steady and incompressible, (2) the flow through the RS-O-DTs is turbulent, (3) natural convection and thermal radiation are neglected and (4) the thermo-physical properties of the fluid are temperature independence. Based on above approximations, the governing differential equations used to describe the fluid flow and heat transfer in a circular tube equipped with RS-O-DTs were established. The continuity, momentum and energy equations for the three dimensional models were employed. For steady flow, the time-averaged incompressible Navier-Stokes equations in the Cartesian tensor notation can be written in the following form:

Continuity equation:

$$\frac{\partial}{\partial x_i}\left(\rho u_i\right) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial\left(\rho u_i u_j\right)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \tag{2}$$

Energy equation:

$$\frac{\partial}{\partial x_i}\left[u_i\left(\rho E + p\right)\right] = \frac{\partial}{\partial x_j}\left(k_{eff}\frac{\partial T}{\partial x_j}\right), \; E = h - \frac{p}{\rho} + \frac{u^2}{2} \tag{3}$$

In the present numerical solution, the time-independent incompressible Navier-Stokes equations and the various turbulence models were discretized using the finite volume technique. QUICK (Quadratic upstream interpolation for convective kinetics differencing scheme) and central differencing flow numerical schemes were applied for convective and diffusive terms, respectively. To evaluate the pressure field, the pressure-velocity coupling algorithm SIMPLE (Semi Implicit Method for Pressure-Linked Equations) was selected. Impermeable boundary condition has been implemented over the tube wall. The turbulence intensity was kept at 10% at the inlet, unless other-wise stated. The solution convergence is met when the difference between normalized residual of the algebraic equation and the prescribed value is less than 10^{-6}.

Two parameters of interest for the present work are friction factor and Nusselt number which used for characterization of friction loss, heat transfer rate, and effectiveness of heat transfer enhancement in the tube with twisted tape insert for a given geometry and flow conditions. Friction factor, f is computed from pressure drop, Δp across the length of the tube, L using the following equation:

$$f = \frac{\Delta p / L}{\frac{1}{2}\rho u^2 D} \tag{4}$$

Nusselt number is defined as:

$$Nu = \frac{hD}{k} \tag{5}$$

Average Nusselt number can be obtained from

$$Nu_{ave} = \int Nu(x)\,\partial x / L \tag{6}$$

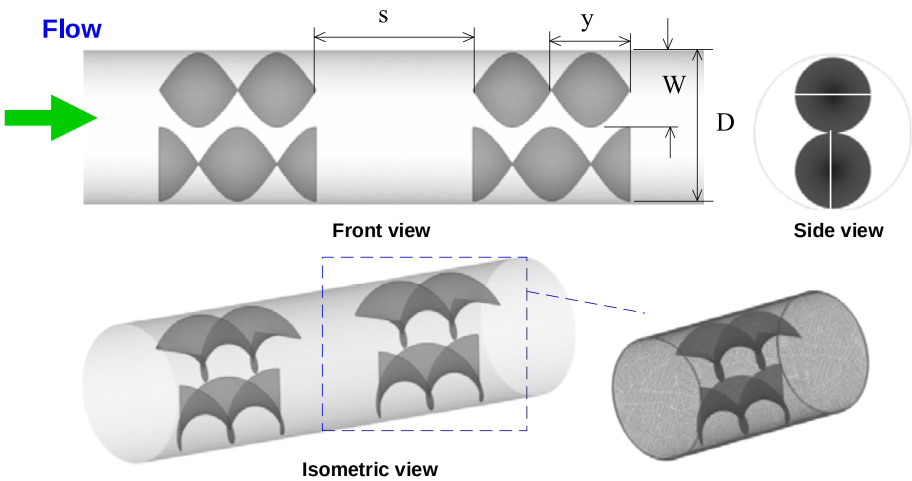


Fig. 1. Computation domain and grid generation of tubes fitted with RS-O-DTs.

3. Flow Configurations

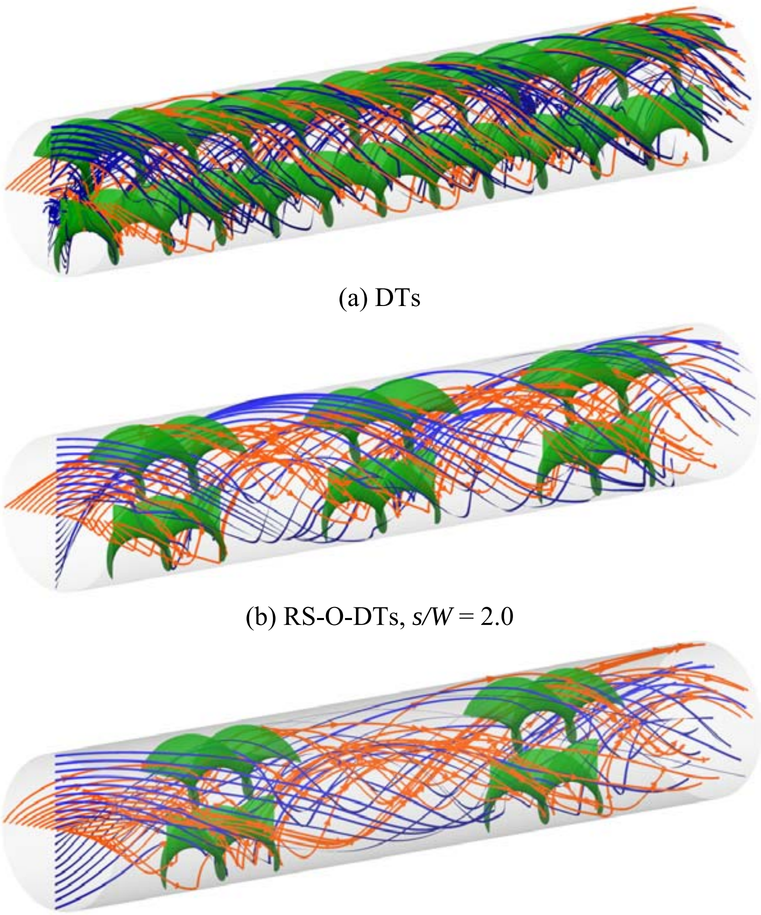
The computational domain for the flow in circular tubes fitted with regularly spaced overlap dual twisted tapes elements (RS-DTs) in counter arrangement was resolved by regular Cartesian elements as seen in Fig. 1. The flow pattern was taken for only 180° twist length (y) due to the periodic flow. The overlap dual counter twisted tapes

(DTs), two tapes were aligned to be twisted in opposite directions to produce counter-swirl flow. The numerical analysis was made for regularly spaced overlap dual twisted tape elements (RS-O-DTs) at three free space ratios, s/W = 2.0, 3.0, and 4.0 at constant twist ratio of y/W = 1.0. Grid independent solution was obtained by comparing the results of the studied cases with different grid levels and then taking the optimum solution among them. The higher numbers of elements employed for the tape with s/W = 4.0, are due to the larger twist length in comparison with the other tapes. The Reynolds numbers used for the computation are referred to the inlet values which are set at 5000, 7500, 10000, 12500 and 15000. The inlet temperature was kept constant at 300 K. The inner tube wall and inlet temperatures were kept constant at 310 K and 300 K, respectively while the outer tube wall was maintained under adiabatic condition.

4. Numerical Results

4.1 Flow and thermal structures

The time-averaged flow structures in the circular tubes fitted with full-length overlap dual twisted tapes (DTs) and regularly spaced overlap dual twisted tapes elements (RS-O-DTs) at free space ratios, s/W = 2.0 and 4.0 can be discerned by considering the stream function plots in Figs. 2(a-c)-3(a-c). It is found that the swirling flows induced by DTs are in continuous swirling form while the ones generated by RS-TTs decay in the spaces between dual tapes, resulting in the decrease of vortex intensity. In addition, the decay of swirling flow is more significant for the RS-TTs with s/W = 4.0, as compared to that of the ones with s/W = 2.0. Therefore, it can be interpreted that the swirling intensity decreases as the space between tapes becomes larger. Contour plots of static pressure in the tubes fitted with DTs and RS-DTs are demonstrated in Fig. 4(a-c). Static pressure is directly related to the swirling intensity since the maximum and minimum static pressures are generated by DTs and RS-O-DTs with s/W = 4.0, respectively.



(a) DTs

(b) RS-O-DTs, s/W = 2.0

(c) RS-O-DTs, s/W = 4.0

Fig. 2. Contour plots of streamline in tube fitted with DTs/RS-O-DTs.

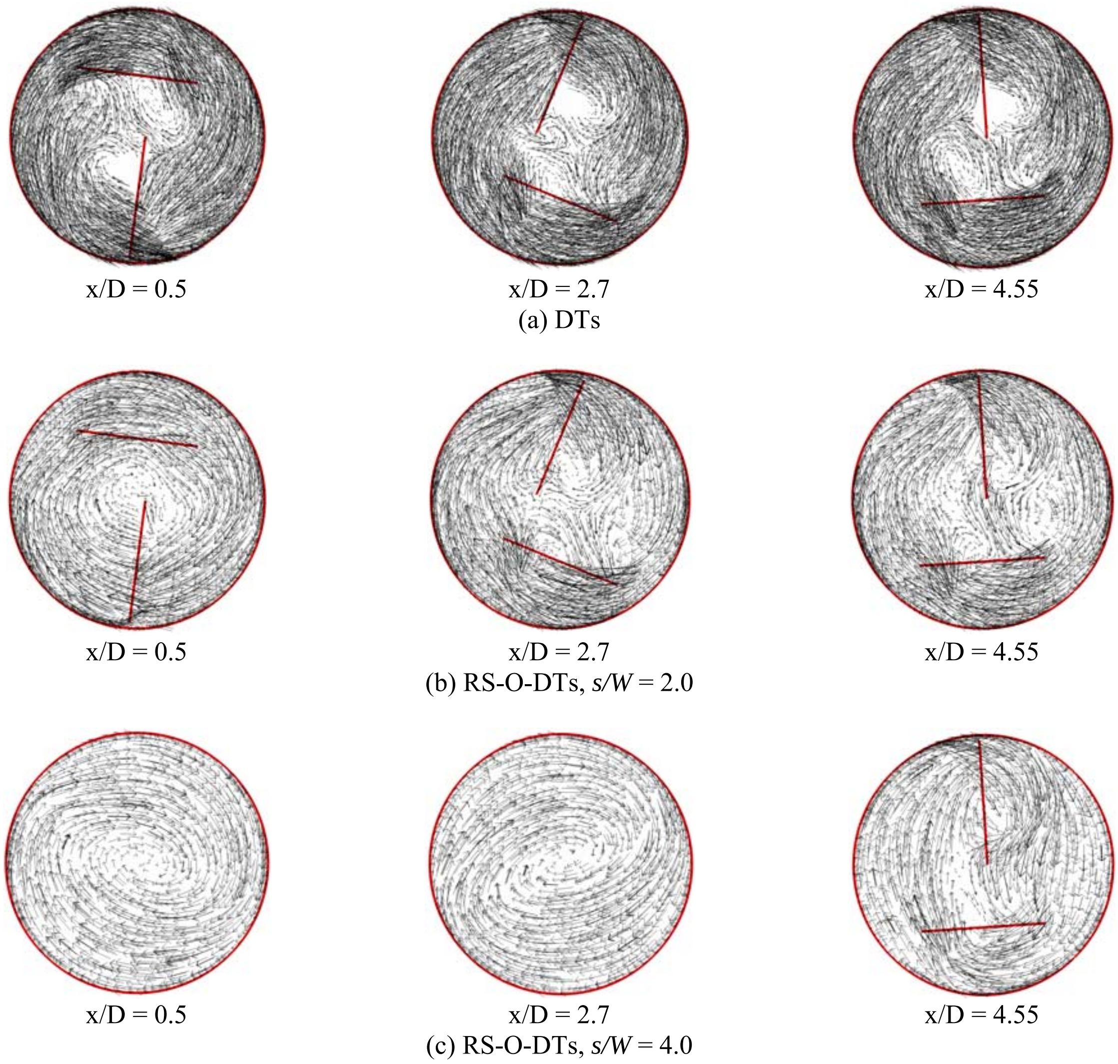
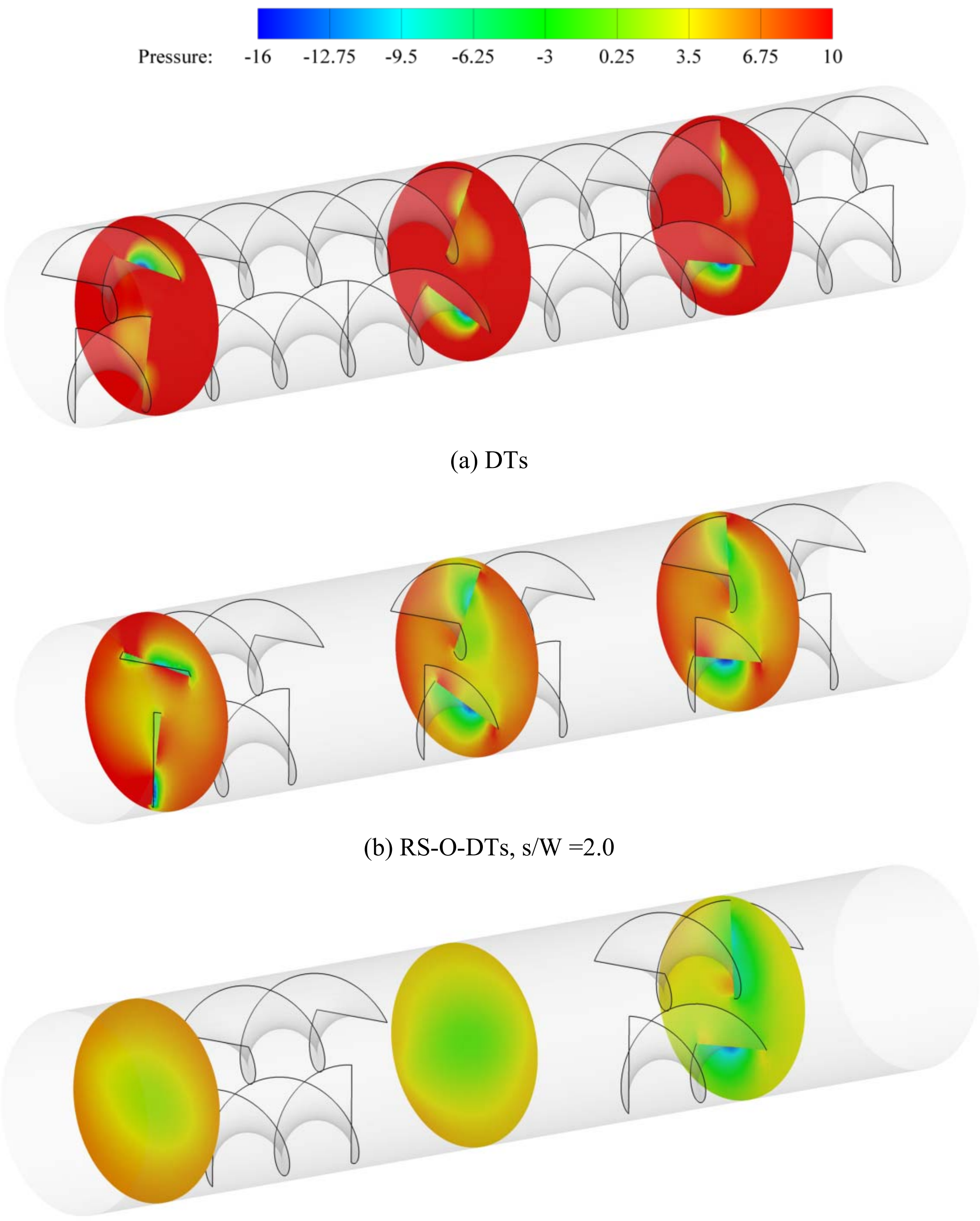


Fig. 3. Vector plots of velocity in tube fitted with DTs/RS-O-DTs.

Figure 5(a-c) shows the temperature distribution and flow mixing in the tubes with full-length overlap dual twisted tapes (DTs) and regularly spaced overlap dual twisted tapes elements (RS-O-DTs) at free space ratios, s/W = 2.0 and 4.0. Among the studied cases, the tube with regularly spaced overlap dual twisted tapes elements (RS-O-DTs) at the largest free space ratio (s/W = 4.0) possesses the highest wall temperature due to the poor fluid mixing. It can also be observed that in the tube with DTs, temperature distributions are uniform and temperature profiles are consistent along the axial direction due to the effect of continuous swirling flow. However, the temperature profiles in the tube with RS-O-DTs are dependent on axial position. Low temperatures (efficient heat transfer) are found at the position where the tapes exist while high temperatures (inefficient heat transfer) are found in the spaces between tapes. The temperature results accord well with the local Nusselt number distributions in Fig. 6. Note that the heat transfer characteristic of the tube with RS-O-DTs at the smallest space ratio (s/W = 2.0) is similar to that of the one with DTs.

4.2 Heat transfer

The relationship between Nusselt number and Reynolds number in a tube equipped with full-length overlap dual twisted tapes (DTs) is shown in Fig. 7. Obviously, the heat transfer rates of the tube fitted with DTs and RS-O-DTs are higher than those of the plain tube. This indicates that the swirl flows enhance boundary layer eruption and convective heat and momentum transfer. In addition, the presence of the inserts also helps to increase the effective Reynolds number, due to the reduced cross-sectional area of flow. On the other hand, the boundary layer eruption improves fluid mixing between the core and the wall regions, thus enhancing the convection process. For the tubes with RS-O-DTs, heat transfer enhancement increases with decreasing space ratio (*s/W*), or increasing swirl intensity. Evidently, the tubes with RS-O-DTs at *s/W* = 2.0, 3.0, and 4.0 yield higher Nusselt numbers than the plain tube up to 197%, 193% and 190%, respectively. In addition, the tube with the full-length overlap dual twisted tapes (DTs) yields higher heat transfer rate than the ones with RS-O-DTs at *s/W* = 2.0, 3.0, and 4.0 by around 4%, 7% and 8.5%, respectively. The superior heat transfer of the tube with DTs is attributed to the stronger swirl intensity of the continuous overlap dual swirling flows. On the other hand, the RS-O-DTs give weaker swirl intensity since swirling flows decay in the spaces between the inserts.

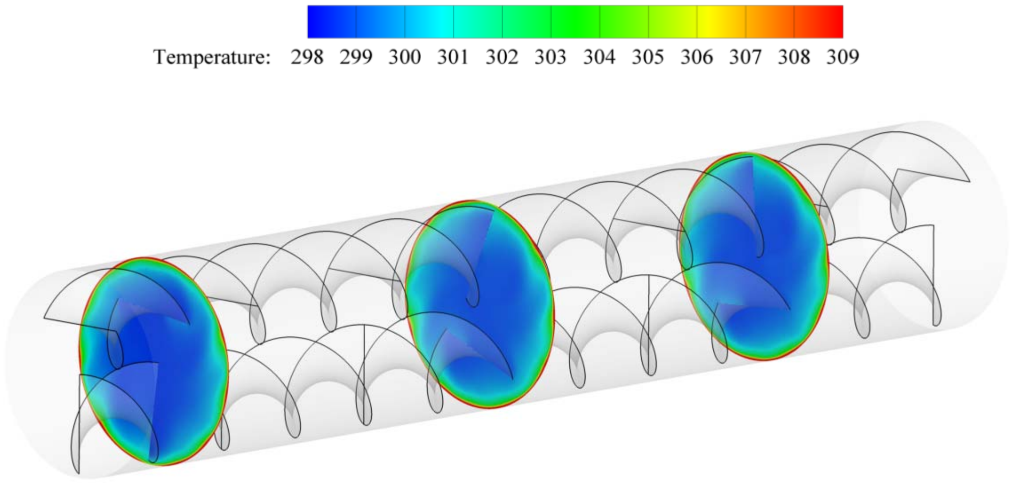


(a) DTs

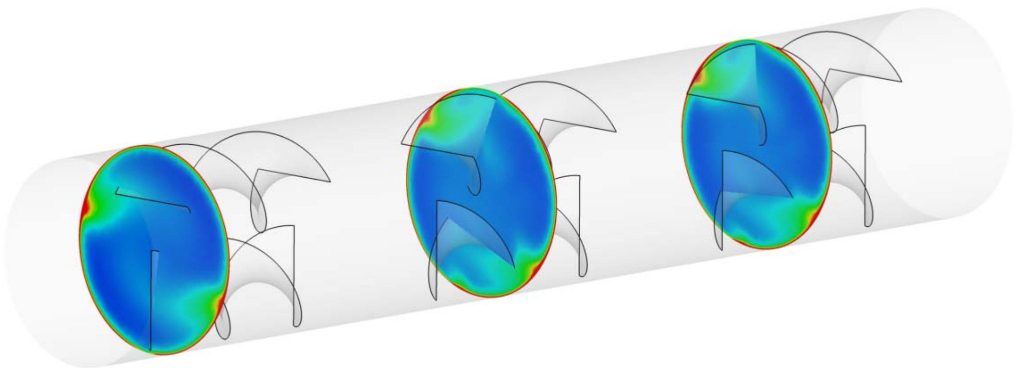
(b) RS-O-DTs, s/W =2.0

(c) RS-O-DTs, s/W =4.0

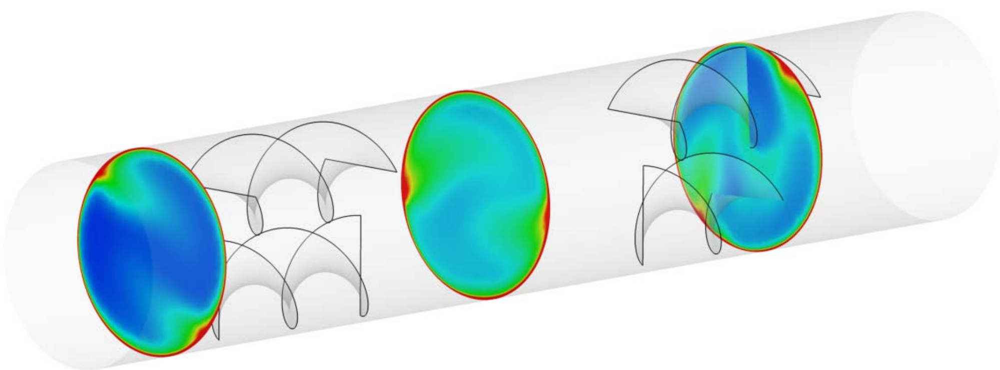
Fig. 4. Contour plots of static pressure in tube fitted with DTs/ RS-O-DTs.



(a) DTs

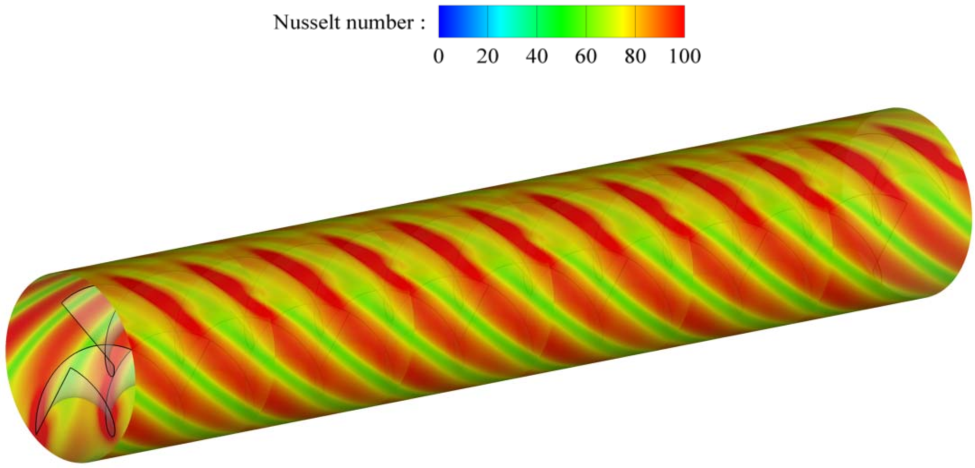


(b) RS-O-DTs, *s/W* =2.0

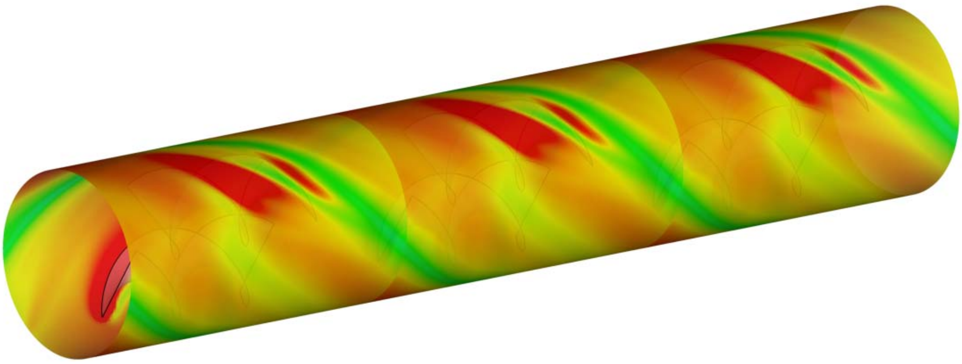


(c) RS-O-DTs, *s/W* =4.0

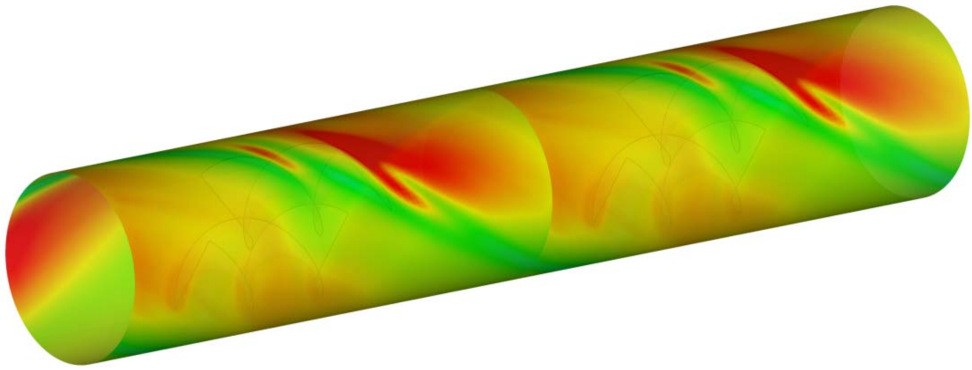
Fig. 5. Contour plots of temperature field in tube fitted with DTs/RS-O-DTs.



(a) DTs



(b) RS-O-DTs, *s/W* =2.0



(c) RS-O-DTs, *s/W* =4.0

Fig. 6. Contour plots of Nusselt number distribution in tube fitted with DTs/RS-O-DTs.

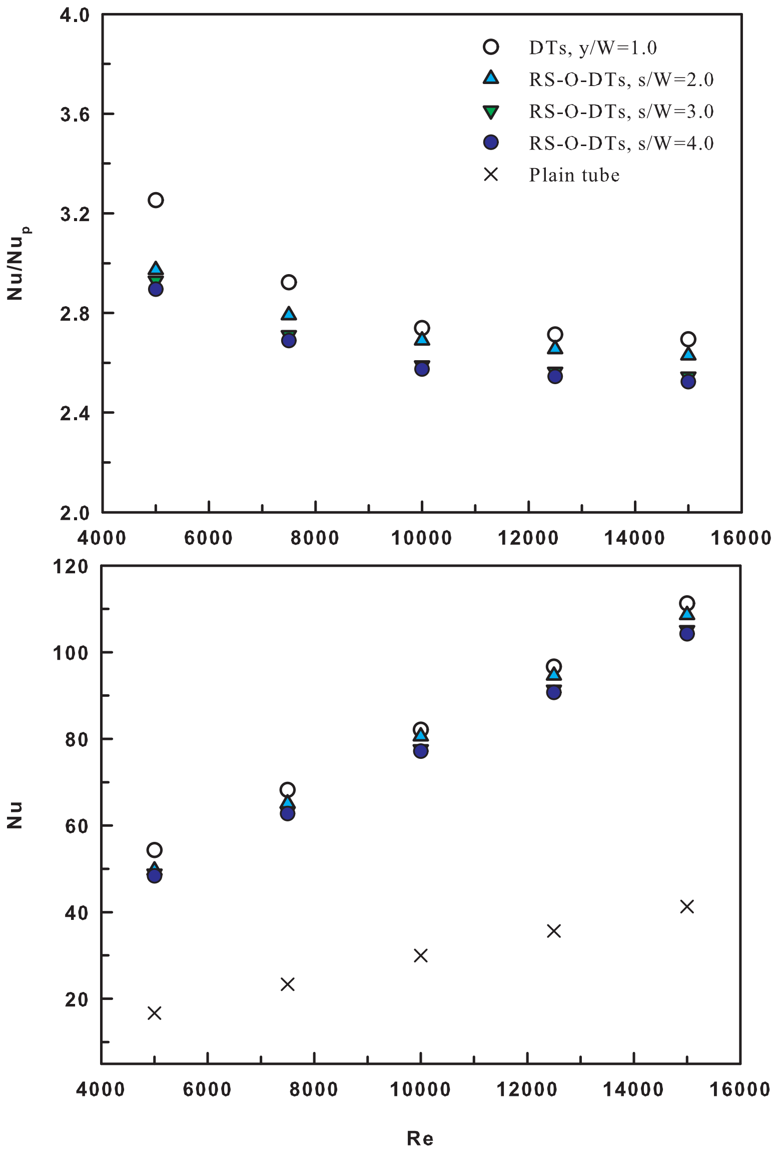


Fig. 7. Influence of the RS-O-DTs at different free space ratios (*s/W* = 2.0, 3.0, and 4.0) on Nusselt number.

4.3 Friction factor

Influence of tube equipped with full-length overlap dual twisted tapes (DTs) and regularly spaced overlap dual twisted tapes elements (RS-O-DTs) at three free space ratios (*s/W* = 2.0, 3.0, and 4.0) on friction factor is depicted in Fig. 8. The friction factors of the plain tube is also presented for comparison. In general, friction factor decreases with increasing Reynolds number. At the same Reynolds number, friction factor in the tube with the DTs is substantially higher than those of the tubes with RS-O-DTs and also the plain tube. This is because of the dissipation of dynamic pressure of the fluid due to high viscosity losses near the tube wall from additional surfaces and the act caused by the re-circulating and turbulence flows. Moreover, the friction has the high possibility to occur by the interaction of the pressure forces with inertial forces in the boundary layer. This is consistent with the form pressure drop occurring at high Reynolds number. The mean friction factors of the tube with tapes DTs are found to be higher than those of the plain tube and the tubes with RS-O-DTs at *s/W* = 2.0, 3.0, and 4.0 by around about 31, 21.1, 17.3 and 12.2 times, respectively.

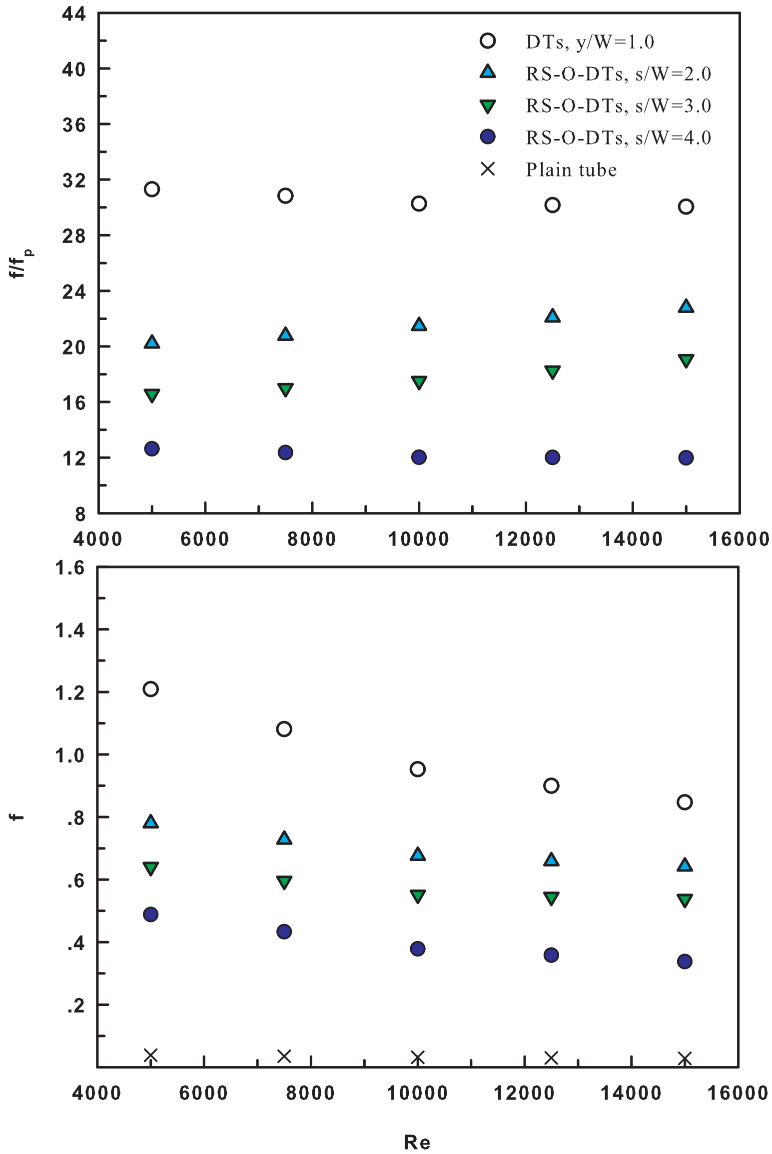


Fig. 8. Influence of the RS-O-DTs at different free space ratios (*s/W* = 2.0, 3.0, and 4.0) on friction factor.

5. CONCLUSION

A numerical investigation using the RNG k-ε turbulence model is conducted to study heat transfer and flow friction behaviors in turbulent tube flows with full-length overlap dual twisted tapes (DTs) and regularly spaced overlap dual twisted tapes elements (RS-O-DTs) at three different free space ratios (*s/W* = 2.0, 3.0, and 4.0). The investigation is conducted for Reynolds numbers from 5,000 to 15,000. Apparently, the DTs which generate continuous swirling flows give more efficient heat transfer and cause higher friction than the RS-O-DTs which induce decaying swirling flows. For RS-O-DTs, heat transfer rate and friction factor increase as free space ratio decreases. The tube with DTs yields higher heat transfer rate than the plain tube and the ones with RS-O-DTs at *s/W* = 2.0, 3.0, and 4.0 by around 190, 4%, 7% and 8.5%, respectively. The mean friction factors of the tube with tapes DTs are found to be higher than those of the plain tube and the tubes with RS-O-DTs at *s/W* = 2.0, 3.0, and 4.0 by around about 31, 21.1, 17.3 and 12.2 times, respectively. The numerical results suggest that the increase in friction factor is much higher than the increase in Nusselt number, at the same Reynolds number.

6. Acknowledgements

The authors would like to acknowledge with appreciation the Energy Policy and Planning Office (EPPO), Ministry of Energy, Thailand for financial support of this work.

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