FLOW-FIELD AND THERMAL BEHAVIORS OF TURBULENT FLOW THROUGH A ROUND TUBE EQUIPPED WITH DUAL TWISTED TAPES

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Abstract. The article presents the application of a mathematical model for numerical simulation of the dual swirling flows in a tube induced by regularly spaced dual twisted tapes elements (RS-DTs) insertion. The numerical simulation was carried out in order to gain an understanding of physical behavior of the fluid flow (dual swirling flows), fluid temperature and local Nusselt number in a tube fitted with RS-DTs in the turbulent flow regime for the flow Reynolds number in range between 5000 and 15,000. The Navier-Stokes equation in common with the energy equation was solved using the SIMPLE technique with the RNG k-ε turbulence model. Influences of RS-DTs with different various free space ratios (s/W = 2.0, 3.0, and 4.0) on the thermal performance characteristics were described. The numerical results shown that, on the heat transfer rate, the RS-DTs with the largest free space ratios (s/W = 4.0) offered highest thermal performance as they induced low pressure loss than those other RS-DTs.

Keywords: Flow-field, Flow visualization, Swirl flow, Dual twisted tapes, Heat transfer enhancement

Introduction. In the recent year, attention of heat transfer enhancement in a heat exchanger has been investigated by many researchers [1-4]. Heat transfer enhancement have been developed and widely applied to heat exchanger applications for example, automotive, process industry, solar air/water heater, refrigeration, etc. Twisted tape inserts extensively appear in heat exchanger systems for redeveloping the thermal boundary layer, inducing swirl flow and therefore enhancing the heat transfer performance. Hong et al. [5] studied the turbulent heat transfer and flow behaviors in a converging-diverging tube equipped with twin twisted tapes. Their reported that the increases in the heat transfer rate and friction factor of a converging-diverging tube equipped with twin twisted tapes were, respectively, up to 6.3-35.7 and 1.75-5.3 times of converging-diverging tubes. They also found that a converging-diverging tube equipped with twin twisted tapes performed a good thermal performance factor higher than unity that consideration at the constant pumping power condition. Eiamsa-ard et al. [6] studied the effects of tube equipped with twin-counter/co-twisted tapes on thermal performance characteristics in a heat exchanger. They showed that the tube equipped with twin-counter-twisted tapes provided higher heat transfer rate than those the tube equipped with twin-co-twisted tapes and single twisted tape up to 44.5% and 50%. Effect of the twist ratios were also examined and found that the highest thermal performance obtained at the constant pumping power by the twin-counter/co-twisted tapes with y/w = 2.5, 3.0, 3.5 and 4.0, were 1.39, 1.24, 1.12 and 1.03, respectively. Chang et al. [7] also carried out the heat transfer in an axially rotating tube equipped with twin twisted tapes. Promvonge et al. [8] investigated the heat transfer characteristics in a helical-ribbed tube equipped with twin twisted tapes with different twist ratios between 2.17 and 9.39. Their reported that the ribbed tube equipped twin twisted tape performed heat transfer rate higher than those the plain tube and the ribbed tube acting alone. Again, Eiamsa-ard et al. [9] conducted the heat transfer enhancement of heat exchanger tube equipped with regularly-spaced dual twisted tapes. They observed that the heat transfer rate of tube equipped with
the regularly-spaced dual twisted tapes was decreased with increasing space ratio (s/D). The heat transfer rate of 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 the plain tube.

The aim of this article was to investigation the heat transfer, friction factor and thermal performance behaviors in a tube equipped with regularly spaced dual twisted tapes elements (RS-DTs). The mass, momentum and energy equations were solved using finite volume method by considering the steady state, turbulent and incompressible fluid flow. The physical behavior of the thermal/fluid flow (fluid temperature and local Nusselt number) were investigated in the presence of the vortex generators at various free space ratios (s/W). In this paper, the regularly-spaced dual twisted tapes were equipped in a tube with three different free space ratios (s/W = 2.0, 3.0, and 4.0), defined as a ratio of space length to tape width that examined in tube by using air as the working fluid at the Reynolds number, based on the tube diameter (Re), in a range of 5000 to 15,000.

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 dual twisted tapes elements (RS-DTs). The major assumptions are; (1) the flow is steady and incompressible, (2) the flow through the RS-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-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:**

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

(1)

**Momentum equation:**

\[
\frac{\partial (\rho u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \right) \right] + \frac{\partial}{\partial x_j} (-\rho u_i u'_j)
\]

(2)

**Energy equation:**

\[
\frac{\partial}{\partial x_j} \left[ u_j (\rho E + p) \right] = \frac{\partial}{\partial x_j} \left( k_{eff} \frac{\partial T}{\partial x_j} \right), \quad E = h - \frac{p}{\rho} + \frac{u^2}{2}
\]

(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 differing 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 otherwise 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.

Three parameters of interest for the present work are: (1) friction factor, (2) Nusselt number and (3) thermal performance factor which respectively 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. The friction factor, \( f \) is computed from pressure drop, \( \Delta p \) across the length of the tube, \( L \) using following equation:
\[ f = \frac{\Delta p/L}{\frac{1}{2} \rho u^2 D} \quad (4) \]

The Nusselt number is defined as:

\[ Nu = \frac{hD}{k} \quad (5) \]

The average Nusselt number can be obtained by

\[ Nu_{ave} = \int Nu(x) \, dx/L \quad (6) \]

The thermal performance factor is given by

\[ \eta = \left( \frac{Nu / Nu_0}{f / f_0} \right)^{1/3} \quad (7) \]

where \( Nu_0, Nu, f_0 \) and \( f \) are the Nusselt numbers and friction factors for the plain tube with/without RS-DTs.

**Flow configurations.** The computational domain for the flow in tube fitted with RS-DTs was resolved by regular Cartesian elements as seen in Fig. 1. The pattern was applicable for only 180° twist length \( (y) \) due to the periodic flow. The numerical analysis was made for RS-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 solution for different grid levels. 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 and set at 5000, 7500, 10000, 12500 and 15000. The inlet temperature was kept constant at 300 K and the tube wall condition was maintained under constant wall heat flux of 600 W/m². 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.

**Flow and thermal structures.** The contour plots of streamline and vector plot of tube with full-length dual twisted tapes (DTs) and regularly spaced dual twisted tapes elements (RS-DTs) at free space ratios, \( s/W = 2.0 \) and \( 4.0 \) is demonstrated in Figs. 2 and 3. It is clearly observed that continues swirling flows were introduced along with axial flow in the tubes with DTs while RS-TTs produces high dual swirls in the tape regions and swirls apparently decayed in the spaces between
dual tapes, resulting in the decrease of vortex intensity. It is also seen that the low decaying swirl flow or tangential velocity as shorter vector length or lower velocity field of both RS-DTs between the spaces of dual tapes compared to those DTs.

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

Fig. 3. Vector plots of velocity in tube fitted with DTs/RS-DTs.
In addition, the lower static pressure fields and lower mixing between the spaces of dual tapes is found from the temperature fields of the fluid of both s/W = 2.0 and 4.0 (Figs. 4 and 5) due to higher decaying dual swirl flows and poorer mixing in the spaces between dual tapes and thus, noticeably thicker thermal boundary layers in the radial direction. On the other hand, the DTs performed the strongest dual swirling flows, resulted in better mixing and the most uniform temperature distribution. It is also observed that the local Nusselt number distributions are high at the location of the contact zone between the tapes and tube wall seen in Fig. 6. The highest local Nusselt number is achieved in the tube with DTs with similar trend as the RS-DTs at the smallest space ratio (s/W = 2.0).
Fig. 6. Contour plots of Nusselt number distribution in tube fitted with DTs/RS-DTs.

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

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

Heat transfer. Effect of the tube equipped with regularly spaced dual twisted tapes elements (RS-DTs) at different free space ratios (s/W = 2.0, 3.0, and 4.0) on heat transfer rate is showed in Fig. 7. It is interesting that the tube with RS-DTs yields higher heat transfer rate than that the plain tube which can be attributed to better mixing due to increasing of radial dual swirling flows from the RS-DTs that provides the thinner of thermal boundary layer along the tube wall. In addition, dual swirls caused the flow to be turbulent, which led to even better convection heat transfer
between the cold fluid and hot wall. It is also found that the effect of RS-DTs inserts decreased for high space ratios (s/W = 4.0), this phenomenon is related to the speed of dual swirling flows and low flow velocity results of the destruction of the velocity/thermal boundary layer level. Thus, the increase in heat transfer rate is low value at larger space ratios (s/W) and higher heat transfer values for the smaller space ratios (s/W). Although as the similar trend is found for using all of RS-DTs inserts, this improvement is around 175%, 167% and 165% for s/W = 2.0, 3.0, and 4.0, higher than those found from the plain tube alone. In addition, it is provided that the full-length dual twisted tapes (DTs) yielded the higher heat transfer values than those the RS-DTs with s/W = 2.0, 3.0, and 4.0 around 4.1%, 7.3% and 8.2%, due to stronger of the continuous dual swirling flow while the RS-DTs performed the decaying dual swirl between each elements.

Friction factor. Variation of friction factor with Reynolds number for the tube fitted with regularly spaced dual twisted tapes elements (RS-DTs) for three free space ratios (s/W = 2.0, 3.0, and 4.0) is demonstrated in Fig. 8. The friction factor of the plain tube is also presented for comparison. It is found that the friction factors obtained from using all of free space ratios are in a similar trend and decrease with the rise of Reynolds number. A similar trend is found for using regularly spaced dual twisted tapes elements (RS-DTs), the increasing for s/W = 2.0, 3.0, and 4.0 is found to be 20.4, 16.7 and 11.9 times of those plain tube, respectively, due to the dissipation of dynamic pressure of the fluid due to higher surface area and the act caused by the dual swirl flows. For comparison with those the typical or full-length dual twisted tapes (DTs), the reduction of friction factors of RS-DTs with s/W = 2.0, 3.0, and 4.0 are found to be 42.5%, 73% and 150%, respectively.

Thermal performance factors. Effect of the tube equipped with regularly spaced dual twisted tapes elements (RS-DTs) at different free space ratios (s/W) on the thermal performance factors that consideration under the same pumping power is showed in Fig. 9. It is found that the thermal performance tends to decrease with increasing Reynolds number for all RS-DTs studied. It is interesting that RS-DTs with the largest free space ratios (s/W = 4.0) performs the highest thermal performance than those the smaller space ratios, s/W = 2.0 and 3.0 at around 16.2% and 12.3%, respectively, while it is also performs better thermal performance factor than those the typical or full-length dual twisted tapes (DTs) around 25.6% due to the very low pressure loss than those other tape inserts.In addition, the RS-DTs with s/W = 2.0, 3.0, and 4.0 and DTs give the best thermal performance factors above higher unity at around 1.09, 1.15, 1.24 and 1.03, respectively, at the lowest Reynolds number of 5000.

![Fig. 9. Effect of the RS-DTs at different free space ratios (s/W = 2.0, 3.0, and 4.0) on thermal performance factor.](image)
Conclusion. Enhancement of heat transfer in tubes equipped with regularly spaced dual twisted tapes elements (RS-DTs) was numerically studied. The investigation encompassed RS-DTs with various free space ratios (s/W). In the presents, the RS-DTs were fitted inside a circular tube at three free space ratios of s/W = 2.0, 3.0, and 4.0, respectively. All of the numerical were conducted at similar inlet conditions with the Reynolds number, based on the tube diameter, in a range of 5000 to 15,000. The numerical results performed that RS-DTs induced dual swirling-flows which played an important role in improving fluid mixing and heat transfer enhancement. It is also found that the RS-DTs were responsible for pressure loss behaviors. The heat transfers coefficient and pressure loss decreased with increasing free space ratios (s/W) while the highest thermal performance occurred in case of largest free space ratios (s/W = 4.0).

REFERENCES