Research Article

CFD Simulation of Heat Transfer and Friction Factor Augmentation in a Circular Tube Fitted with Elliptic-Cut Twisted Tape Inserts

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This paper presents the application of a mathematical model for simulation of the swirling flow in a tube induced by elliptic-cut and classical twist tape inserts. Effects of the twist ratio ($\gamma = 2.93, 3.91, \text{ and } 4.89$) and cut depth ($w = 0.4, 0.8, \text{ and } 1.4 \text{ cm}$) on heat transfer enhancement (Nu) and friction factor (f) in laminar flow are numerically investigated. The simulation is carried out using commercial CFD package (FLUENT-6.3.26) to grasp the physical behaviour of the thermal and fluid flows of a constant heat-fluxed tube fitted with elliptic-cut twist tape in the laminar flow regime for the Reynolds number ranging from 200 to 2100. The simulated results matched the literature correlations of plain tube for validation with 8% variation for Nusselt number and 10% for friction factor. The results show that the heat transfer rate and friction factor in the tube equipped with elliptic-cut twist tape (ECT) are significantly higher than those fitted with classical twist tape (CTT). Moreover the results also reveal that the Nusselt number and the friction factor in the tube with elliptic-cut twisted tape (ECT) increase with decreasing twist ratios (γ) and cut depths (w).

1. Introduction

The heat transfer augmentation techniques are widely utilized in many applications in the heating process to enable reduction in weight and size or increase the performance of heat exchangers. These techniques are classified as active and passive techniques. The active technique required external power such as surface vibration and electric or acoustic fields, whereas the passive techniques required fluid additives, special surface geometries, or swirl/vortex flow devices, that is, twisted tape inserts. The passive techniques are advantageous compared with the active techniques because the swirl inserts manufacturing process is simple and can be easily employed in an existing heat exchanger. Moreover the passive techniques can play an important role in the heat transfer augmentation if a proper configuration of the insert is being selected depending on working conditions that have been reported in the literature [1–9]. Due to advances in computer software, the Computational Fluid Dynamics (CFD)

modelling technique was developed as a powerful and effective tool for more understanding the hydrodynamics of heat transfer when using twist tape inserts.

Zhang et al. [10] investigated the heat transfer characteristics of a helically baffled heat exchanger combined with a finned tube using CFD modeling. Sivashanmugam et al. [11] reported the modeling of heat transfer augmentation in circular tube fitted with helical twist insert in a laminar and turbulent flows using CFD.

Eiamsa-ard et al. [12] have conducted a numerical study on a tube equipped with loose-fit twisted tapes using four turbulence models. The results showed that the prediction obtained by SST k - ω turbulence model has a better agreement with measurement results compared with other models.

Nagraj and Sivashanmugam [13] conducted CFD simulations of heat transfer characteristics of Al_2O_3 nanofluid in a circular tube fitted with helical twist inserts under constant heat flux using Fluent version 6.3.26. Different concentrations of Al_2O_3 nanoparticles (0.5%, 1.0%, and 1.5%) and twist tape

TABLE 1: Thermophysical properties of materials at 298 K.

Materials	Density (Kg/m ³)	Specific heat (J/kg K)	Thermal conductivity (W/m K)	Viscosity (Pa s)
Water	998.2	4182	0.6	0.001003
Steel	8030	502.48	16.27	—
Aluminium	2719	871	202.4	—

FIGURE 1: Elliptic-cut twisted insert.

inserts with different twist ratios ($\gamma = 2.93, 3.91$, and 4.89) have been used for the simulation. The results showed that the Nusselt number and the friction factor are increased with increasing the nanofluid concentration and decreasing the twist ratios (γ).

Pathipakka and Sivashanmugam [14] proposed CFD simulation of heat transfer and friction factor behavior for the circular tube fitted with right-left helical twist insert with 100 mm spacer. The simulated Nusselt number and friction factor were compared with the experimental data and observed to have good agreement.

Shabanian et al. [15] have carried out an experimental and CFD modeling on heat transfer and friction factor characteristics in air cooled heat exchanger using butterfly twist tape insert. They found that the insert configuration has a main effect on the Nusselt number, friction factor, and thermal performance factor and the maximum thermal performance factor was obtained by the configuration of butterfly insert with an inclined angle of 90° . The results verified that there was a good agreement between the predicted and measured values of Nusselt number and friction factor values.

In the present study, a new configuration of twist tape inserts is presented using CFD simulation to predict the Nusselt number and friction factor in laminar flow regimes based on experimental data listed in [14]. This study can be used as guideline for experimental works.

2. Physical Model

The geometry of the elliptic-cut twisted tape (ECT) insert is illustrated in Figure 1. Twist tape with thickness (t) of 0.08 cm and width (W) of 2.45 cm and relative twisted ratios ($\gamma = 2.93, 3.91$, and 4.89) fits in a tube with a diameter (D) of 2.54 cm and length (L) of 180 cm. Different cut depth ($w = 0.4, 0.8$, and 1.4 cm) is used for twisted tape with twist ratio $\gamma = 2.93$. Steel and aluminium were selected as the material of construction of the tube and twisted tape. Water was selected as the working fluid, and the thermophysical properties were assumed to be temperature independent. The thermophysical properties of water and materials used for simulation are listed in Table 1.

The Reynolds number (Re), the Nusselt number (Nu), and the friction factor (f) are defined by the following equations:

$$\begin{aligned} Re &= \frac{\rho u D}{\mu}, \\ Nu &= \frac{h D}{k}, \\ f &= \frac{16}{Re}, \end{aligned} \quad (1)$$

where ρ is the density, u is velocity, μ is dynamic viscosity, and k is the thermal conductivity of the fluid. h is the heat transfer coefficient, and D is the inner diameter of the tube.

3. Numerical Simulations

Three-dimensional numerical simulation of the conjugate heat transfer was conducted using the CFD code FLUENT 6.3.26. The modeling was carried out in order to predict and explain the effect of elliptic-cut configuration on the Nusselt number and friction factor at steady-state laminar flow for constant heat-fluxed tube. The CFD modeling involves numerical solutions of the conservation equations for mass, momentum, and energy. These equations for incompressible flows can be written as follows.

3.1. *Continuity Equation for an Incompressible Fluid.* It is given as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m. \quad (2)$$

3.2. *Conservation of Momentum.* It is given as follows:

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho (\vec{v} \cdot \nabla) \vec{v} = -\nabla p + \rho \vec{g} + \nabla \cdot \tau_{ij} + \vec{F}. \quad (3)$$

3.3. *Conservation of Energy.* It is given as follows:

$$\begin{aligned} &\frac{\partial}{\partial t} (\rho E) + \nabla \cdot \{ \vec{v} (\rho E + p) \} \\ &= \nabla \cdot \left\{ K_{\text{eff}} \nabla T - \sum_j h_j (\vec{\tau}_{\text{eff}} \cdot \vec{v}) \right\} + S_h. \end{aligned} \quad (4)$$

4. Geometry and Grid Arrangement

The geometry and the grid of plain tube and elliptic-cut twisted tape were generated in GAMBIT and the CFD code

FIGURE 2: Grid for the plain tube.

FIGURE 3: Grid for the plain tube with elliptic-cut twisted tape (ECT) insert.

FLUENT was used for simulation. The geometry consists of a cylindrical tube of diameter 25.54 cm and length of 180 cm. Figure 2 shows the grid for the plain tube configuration using a quadrilateral face mesh over the volume of the cylinder. Different types of meshing twisted tapes are available to mesh the volume but tetrahedral/hybrid and T grid type elements were the best mesh for irregular shapes. The grid generated in the tube fitted with ECT inserts is shown in Figure 3. The boundary conditions for the geometry were defined for inlet, outlet, wall of twist tape and cylinder wall, the continuum volume of fluid was defined as water. The mesh file is exported to FLUENT successfully.

5. Modeling Parameters

Numerical values of experimental data mentioned in [14] were used in a number of simulations that are given in Table 2.

6. Numerical Method

The commercial CFD package of Fluent 6.3.26 software was chosen as the CFD tool to solve the Navier-Stokes equation in common with energy equation accompanied with boundary conditions. Solution sequential algorithm (segregated solver algorithm) has been used with the following settings; implicit formulation, steady (time-independent) calculation, viscous laminar model, and energy equation.

FIGURE 4: Plain tube simulated Nusselt number versus literature data.

FIGURE 5: Plain tube simulated friction factor versus literature data.

7. Results and Discussion

7.1. Validation of Plain Tube Simulation Results. The simulated results of Nusselt number and friction factor for plain tube were compared with the correlations developed by Sieder and Tate [16] for validation. The predicted values of Nusselt number and friction factor are demonstrated in Figures 4 and 5; apparently, the present results reasonably

TABLE 2: Numerical values of the parameters used for simulations [14].

Flow rate (kg/sec)	0.003	0.005	0.006	0.008	0.01	0.116	0.0133	0.015	0.0166	0.02	0.03
Heat flux (w/m ²)	240.03	340.77	459.15	563.38	749.85	1001.57	1363.26	1512.68	1893.56	2130.05	2445.25

FIGURE 6: Simulated Nusselt number for plain tube and twisted tape with different twist ratios (γ). FIGURE 8: Simulated Nusselt number for elliptic-cut twisted tape with $\gamma = 2.93$ and different cut depth (w). FIGURE 7: Simulated friction factor for plain tube twisted tape with different twist ratios (γ). FIGURE 9: Simulated friction factor for elliptic-cut twisted tape with $\gamma = 2.93$ and different cut depth (w).

FIGURE 10: Simulated Nusselt number for elliptic-cut twisted tape (ECT) and classical twist tape (CTT).

agree well with the available correlations with 8% variation for Nusselt number and 20% for friction factor.

7.2. Effect of Twist Ratio on Heat Transfer and Friction Factor.

The simulated data of the Nusselt number and friction factor and their variation with a Reynolds number of cut twisted tape inserts with twist ratios ($\gamma = 2.93, 3.91$, and 4.89) are shown in Figures 6 and 7. Figure 6 indicates that the Nusselt number increases with Reynolds number increasing and the heat transfer rate is higher for the twist tape set than for the plain tube because of strong swirl flow in the presence of the twist tape. It is found that the heat transfer rate with the twist ratio ($\gamma = 2.93$) is higher than those with other ratios ($\gamma = 3.91$ and 4.89); this means that the turbulent intensity obtained from the lower twist ratio is higher than those from higher ratios (γ). Figure 7 shows the variation of friction factor with a Reynolds number for different twist ratios ($\gamma = 2.93, 3.91$, and 4.89). The friction factor obtained from the tube with twisted tape insert is significantly higher than the plain tube. Moreover, the use of smaller twist ratio leads to higher tangential contact between the swirling flow and the tube surface. Therefore, the twisted tape with twist ratio ($\gamma = 2.93$) has a maximum friction factor.

7.3. Effect of Cut Depth on Heat Transfer and Friction Factor.

The Nusselt number and friction factor and their variation with a Reynolds number of ECT inserts with twist ratio $\gamma = 2.93$ and cut depth ($w = 0.4, 0.8$, and 1.4 cm) are shown in Figures 8, 9, 10, and 11. For a given Reynolds number, Nusselt number and friction factor are increased with decreasing the cut depth; this is mainly due to the combined effect of common swirling flow by the twisted tape and turbulence

FIGURE 11: Simulated friction factor for elliptic-cut twisted tape (ECT) and classical twist tape (CTT).

FIGURE 12: The velocity field of classical twist tape in an axial slice inside the tube.

generated by the alternative cuts along the edge of the twisted tape. Subsequently this leads to the destruction of the thermal boundary layer and creating better flow mixing between the fluids at the core and heating wall surface.

7.4. Velocity Field.

Figures 12 and 13 show the velocity field of classical and Elliptic-cut twisted tape inserts with a twisted ratio ($\gamma = 2.93$) and cut depth ($w = 0.4$) for $Re = 2300$. The figures illustrate that the predicted velocity in tube fitted with elliptic-cut twisted tape insert is higher than the classical twist tape insert and the vortices generated by the alternative cuts along the edge of the twisted tape are higher than those of classical twist tape. This can be the reason for more heat

FIGURE 13: The velocity field of elliptic-cut twist tape in an axial slice inside the tube.

transfer rate obtained by the Elliptic-cut twisted tape as compared to classical twist tape insert.

8. Conclusion

In the present study, a circular tube inserted by Elliptic-cut twisted tape and classical twist tape insert with twisted ratios ($\gamma = 2.93, 3.91$, and 4.89) and cut depths ($w = 0.4, 0.8$, and 1.4 cm) in laminar flow conditions has been simulated using fluent version 6.23.26. The data obtained by simulation match the literature value for plain tube with a maximum discrepancy of 8% for Nusselt number and 10% for friction factor. The simulated results show that the elliptic-cut twisted tape with twist ratio ($\gamma = 2.93$) and cut depth ($w = 0.4$ cm) offered higher heat transfer rate and friction factor compared to the plain tube and other twisted tape. Furthermore, the influence of the cut depth ($w = 0.4$ cm) was more dominant than that of the cut depths ($w = 0.8$ and 1.4 cm) for all the Reynolds number.

Nomenclature

- E : Energy component in energy equation
 F : Force component in momentum equation, N
 f : Fanning friction factor
 g : Acceleration due to gravity, m/s^2
 k_{eff} : Thermal conductivity in energy equation, W/m K
 m : Mass flow rate of fluid, kg/s
 Re : Reynolds number based on internal diameter of the tube, dimensionless
 Nu : Nusselt number, dimensionless
 p : Pressure component in momentum equation, N/m^2
 S_m : Accumulation of mass, Kg
 S_h : Accumulation of energy, J
 T : Temperature, $^{\circ}\text{C}$
 v : Velocity component in momentum equation, m/s
 γ : Twist ratio (length of one twist (360°)/diameter of the twist), dimensionless.

Greek Symbols

- ρ : Density component in governing equations
 $\vec{\tau}_{\text{eff}}$: Stress component in momentum equation, N/m^2 .

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