CFD Simulation of Heat Transfer Augmentation in Constant Heat-Fluxed Tube fitted with Baffled Twisted Tape Inserts

Sami D. Salman, Abdul Amir H. Kadhum, Mohd S. Takriff and Abu Bakar Mohamad

Abstract: This study addresses a numerical simulation of circular tube fitted with twisted tape inserts in laminar flow (200 ≤ Re ≤ 2300) and constant heat flux. A Computational fluid dynamics (CFD) package FLUENT was employed to simulate the heat transfer and friction factor for a Plain and baffled twisted tape (PPT & BTT) inserts with different twist ratio (y = 2.93, 3.91, 4.89) and baffle different angles (β= 0°, -30°, 90°). The results obtained by simulation matched with the literature correlations for plain tube with deviation up to ±8% for Nusselt number and ±7% for friction factor. The results elaborated that the heat transfer in term of the Nusselt number enhanced with Reynolds number, baffle angle increases and the twist ratio decreases. Among the various twist ratios, the baffled twisted tape with twist ratio of y=2.93 and baffle angle β= 30° was offered maximum heat transfer enhancement.

Key words: Heat transfer enhancement, Baffled twisted tape insert (BTT), Fluent, CFD simulation.

INTRODUCTION

Heat transfer enhancement techniques are widely utilized in many applications in the heating processes 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, electric or acoustic fields. Whereas the passive techniques required fluid additives, special surface geometries or swirl/vortex flow devices i.e., Twisted tape inserts. The passive techniques are advantageous compared with 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 inserts is being selected depend on working conditions. Several observational studies on heat transfer augmentation techniques using twisted tape have been reported in the literature (Sarma et al. 2005; Eiamsa-ard & Promvonge 2007; Sundar et. al 2007; Sivashanmugam & Suresh 2007; Eiamsa-ard et. al 2008; Kumar 2009; Rahimi et. al 2009; Jaisankar et. al 2009; Eiamsa-ard 2010; Eiamsa-ard et. al 2010; Guo. et. al. 2011; Pathipakka & Sivashanmugam 2010; Ibrahim 2011; Kapatkar et al. 2011) whereas limited literature is available in the CFD modeling of heat transfer using twist tape inserts. (Jayakumar et al. 2008) conducted a comparison study of CFD simulations to experiment on convective heat transfer in double pipe heat exchanger and developed an empirical correlation for estimation of the inner heat transfer coefficient of a helical coil. (Gang Lei et al. 2009) studied the hydrodynamics and heat transfer characteristics of a heat exchanger with a single-layer baffle and two-layer helical baffles experimentally and numerically using the CFD modeling. They found that the configuration of baffles has an important effect on the heat transfer coefficient and the configuration of a two-layer helical baffle offers better heat performance than that of the single-layer baffle. (Rahul Kharat et al. 2009) developed a new correlation of heat transfer coefficient between concentric helical coils of heat exchanger dependent on experimental work and CFD simulation. Fluent 6.3.26 has been used to improve the heat transfer coefficient correlation for the fuel gas side to optimize the gap between concentric coils. (Nagarajan and Sivashan 2009) proposed a simulation of heat transfer in term of Nusselt number and friction factor characteristics of a circular tube fitted with a right-left helical twist insert with a 100 mm spacer using the CFD method. The results were compared with the experimental data to explain the observed results. In addition, good agreements between the predicted and measured Nu number as well as friction factor values were obtained. (Pathipakka & Sivashanmugam 2010) proposed CFD simulation of the heat transfer characteristics of an Al2O3 nanofluid in a circular tube fitted with helical twist inserts under constant heat flux using Fluent version 6.3.26 in a laminar flow. The Al2O3 nanoparticles in water at different concentrations (0.5%, 1.0%, 1.5%) and helical twist inserts with different twist ratios (y = 2.93, 3.91, 4.89) were used for the simulation. The data obtained by simulation compared with the literature value of water for plain tube helical tape inserts. (Shabanian et. Al2011) reported an experimental and CFD modeling studies on heat transfer, friction factor and thermal performance of an air
cooled heat exchanger equipped with three types of tube insert including butterfly, classic and jagged twisted tape. They found that the predicted results of CFD modeling in terms of turbulence intensity have a good agreement with measured values of Nusselt number and friction factor. (Wang et al 2011) have explicated the optimum configuration of regularly spaced short-length twisted tape in a circular tube by applying computational fluid dynamics (CFD) modelling. Toluene was used as test fluid in the turbulent flow regime with configuration parameters including the free space ratio (s), twist ratio (y) and rotated angle (θ). The results indicated that a larger rotated angle yields a higher heat transfer value and greater flow resistance, whereas the smaller twist ratio resulted in better heat transfer performance except for a larger rotated angle at high Reynolds number. The present work reports a CFD simulation on the heat transfer rate and friction factor characteristics in a circular tube fitted with plain twisted tape and an alternate axis twisted tape inserts of different twist ratios (y=2.93, 3.91, 4.89) and different alternative angles (β=30°, 60°, 90°) based on experimental work mentioned in (Pathipakka & Sivashanmugam 2010). This field can be used as guideline for experimental work.

2. Technical Details of Twisted Tape Inserts:

The geometrical configuration of baffled twisted tape with different angles (β) is shown in Fig. 1. Aluminium twisted tapes of thickness (t) of 0.08 cm and width (W) of 2.545 cm used as an insert with a different twist ratio and 360° twist pitch (H). The twist ratio ‘y= H/W’ defined as the ratio of the length of one full twist (360°) to tape width. Water is selected as the working fluid and the thermophysical properties of fluid are assumed to be temperature independent. The thermo-physical properties of the fluid and materials of tape insert and circular tube are shown in Table 1.

![Fig. 1: (a) Baffled twisted tape insert with baffle angle (β= 0°) (b) Baffled twisted tape insert with baffle angle (β= 30°).](image)

<table>
<thead>
<tr>
<th>Materials</th>
<th>Density (Kg/m³)</th>
<th>Specific heat (J/kg K)</th>
<th>Thermal conductivity (W/m K)</th>
<th>Viscosity (Pa s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>998.2</td>
<td>4182</td>
<td>0.6</td>
<td>0.001003</td>
</tr>
<tr>
<td>Steel</td>
<td>8030</td>
<td>502.48</td>
<td>16.27</td>
<td>-</td>
</tr>
<tr>
<td>Aluminium</td>
<td>2719</td>
<td>871</td>
<td>202.4</td>
<td>-</td>
</tr>
</tbody>
</table>

3. CFD Simulation:

3.1. Geometry and Grid Arrangement:

Geometry and Mesh Building Intelligent Toolkit (GAMBIT) program is used for generation of geometry and grids whereas FLUENT version 6.3.26 is used in the module preprocessing. The geometry and the grid for Baffled twisted tape insert with baffle angle (β= 30°) is shown in Fig. (2). It is created in GAMBIT and imported into FLUENT for simulation. This geometry consists a cylindrical tube of diameter 25.54 mm and length of 1800mm. The geometry of plain twisted tape inserts with different twist ratio is generated winding uniformly strip of 25.54 mm width using the twist option in the sweeping of faces at a twist angle of 360° and a length of 75, 100, and 125mm for various twist ratios namely 2.93, 3.91 and 4.89. Whereas, the geometry of baffled twisted tape inserts with twist ratio (y= 2.93) is generated winding uniformly strip of 25.54 mm width using the twist option in the sweeping of faces at a twist angle of 360° and a length of 75 mm. Small Cuboids at different angles is inserted geometry of twisted tape to produce baffle. The volume required for simulation is created by the subtraction of baffled twisted tape geometry from the plain tube geometry. The edge meshing is applied to each edge by using of the particular interval count, whereas the front circular face is meshed by using tetrahedral and pave type meshing. The meshed face was swept over the entire volume using tetrahedral/hybrid elements and T Grid type. Boundary conditions for the meshed volume; inlet, outlet, wall and type of fluid (water) are defined. Subsequently, the mesh file was exported to FLUENT for simulation.
3.2. Computational Modelling:

A three dimensional steady state laminar flow of constant heat-fluxed tube fitted with twist tape inserts are governed by the following model equations:

3.2.1 Continuity equation for an incompressible fluid.
\[
\frac{\partial p}{\partial t} + \nabla \cdot (\rho \vec{V}) = S_m
\]

3.2.2. Conservation of momentun.
\[
\frac{\partial \vec{V}}{\partial t} + \rho (\vec{u} \nabla) \vec{V} = -\nabla p + \rho \vec{g} + \nabla \cdot \tau + \vec{F}
\]

3.2.2. Conservation of energy.
\[
\rho \frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\vec{V} (\rho E + p)) = \nabla \cdot \left( K_{\text{eff}} \nabla T - \sum h_i (\tau_{\text{eff}} \vec{V}) \right) + S_h
\]

4. Modeling Parameters:

Numerical values of the mass flow rate and heat flux which used in a number of the simulations are given in Table 2.

Table 2: Numerical values of the parameters used for simulation (Pathipakka & Sivashanmugam 2010).

<table>
<thead>
<tr>
<th>Mass flow rate (Kg/s)</th>
<th>Heat flux (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.003</td>
<td>240.03</td>
</tr>
<tr>
<td>0.005</td>
<td>340.77</td>
</tr>
<tr>
<td>0.006</td>
<td>459.15</td>
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<tr>
<td>0.008</td>
<td>563.38</td>
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<tr>
<td>0.01</td>
<td>479.85</td>
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<tr>
<td>0.0116</td>
<td>1001.57</td>
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<tr>
<td>0.0133</td>
<td>1363.26</td>
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<tr>
<td>0.015</td>
<td>1512.68</td>
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<tr>
<td>0.0166</td>
<td>1893.56</td>
</tr>
<tr>
<td>0.02</td>
<td>2130.05</td>
</tr>
<tr>
<td>0.03</td>
<td>2445.25</td>
</tr>
</tbody>
</table>

5. Simulation Procedure:

FLUENT 6.3.26 is used for solver execution and post-processing of the CFD simulation. Solution sequential algorithm (segregated solver algorithm) has been used with settings; implicit formulation, steady (time-independent) calculation, viscous laminar model and energy equation. SIMPLE as the pressure-velocity
coupling method and first-order Upwind scheme for energy and momentum equations as well as default values for under-relaxation factors and convergence criterion.

RESULTS AND DISCUSSION

In this section, the results obtained by CFD simulation are presented and discussed. Fig. 3 and 4 shows the Nusselt number and friction factor obtained by simulation and correlations developed by (Sieder & Tate 1936). The simulated data are compared with these correlations for validation. Its elaborate good agreement with the maximum discrepancy of less than ±8% for Nusselt number and ±7% for friction factor. Figs. 5 and 6 present the variety of Nusselt number and friction factor with a Reynolds number of plain twist tape with different twist ratio. It shows that the Nusselt number and friction factor increases with decreases of twist ratio, the Nusselt number and friction factor for the minimum twist ratio (y = 2.93) is significantly larger than that of twist ratios (y = 3.91, 4.89). This implies that the minimum twist ratio (y = 2.93) generates stronger swirl flow than that of other twist ratios. Figs. 7 and 8 depicts the variation of the Nusselt number and the friction factor with the Reynolds number for tube fitted with plain twisted tape (y = 2.93) and baffled twisted tape with same twisted ratio (y = 2.93, 3.91 and 4.89) and different baffle angles (β= 0°, -30° and 30°). For all simulated data, it is found that the Nusselt number and the friction factor in the tube fitted with a baffled twisted tape of (y = 2.93) and baffle angle (β = 30°) is higher than the other twisted tape. The baffled twisted tape provides an additional turbulence to the fluid in the vicinity of the tube wall and vorticity behind the baffle configuration. Furthermore the simulated values of Nusselt number and friction factor of baffled twisted tapes with twist ratio (y = 2.93) and baffle angle (β = 30°) compared with Right-left helical tape inserts (RLT) with 100 mm spacer (Sivashanmugam et al., 2008) are shown in Figs. 9 and 10. Its found that the BFT offered more heat transfer with less friction factor than those of (RLT).

Fig. 3: Plain tube simulated Nusselt Number vs Literature data.
**Fig. 4:** Plain tube simulated Nusselt Number vs Literature data.

**Fig. 5:** Simulated Nusselt Number for plain twisted tape ($y=2.93$, 3.91 and 4.89) and plain tube.

**Fig. 6:** Simulated Nusselt Number for plain twisted tape ($y=2.93$, 3.91 and 4.89).
Fig. 7: Simulated Nusselt Number for plain vs baffled twisted tapes with different twist ratio and baffle angles.

Fig. 8: Simulated Friction Factor for plain and baffled twisted tapes with different twist ratio and baffle angles.

Fig. 9: Simulated Nusselt Number for Twisted tapes (BTT and RLT).
7. Conclusion:
CFD simulation for the heat transfer augmentation in a circular tube fitted with plain twisted tape inserts \((y=2.93, 3.91 \text{ and } 4.89)\) and baffled twisted tape inserts \((\beta=0^\circ, -30^\circ \text{ and } 30^\circ)\) in laminar flow conditions has been reported using fluent version 6.3.26. The results obtained by simulation for heat transfer and friction factor in concluded as follows:

- The values of Nusselt number and friction factor for the tube with baffled twisted tape are noticeably higher than the values for the plain tube and tube equipped with plain twisted tapes as well.
- Over the range of Reynolds number considered, the tube equipped with the baffled twisted tape \((y=2.93)\) and \((\beta=30^\circ)\) offered supreme heat transfer enhancement than the plain twisted tapes and other baffled twisted tapes used.
- The simulated data for baffled twisted tape with angle \((\beta=30^\circ)\) is compared with theoretical and experimental work for Right-left helical tape inserts (RLT) with 100 mm spacer at same conditions and the same twist ratio \((y=2.93)\). The proposed model of baffled twisted tape offered additional heat transfer enhancement with less friction factor. Consequently, this configuration can be used for heat transfer augmentation.

ACKNOWLEDGMENT

We wish to specially acknowledge the financial assistance (FRGS/1/2013/TK07/UKM/01/1) offered by the University Kebangsaan Malaysia for carrying our this investigation.

Nomenclature:

- \(E\): Energy component in energy equation
- \(F\): Force component in momentum equation, N
- \(F\): Fanning friction factor
- \(g\): Acceleration due to gravity, m/s²
- \(k\): Thermal conductivity in Energy equation, W/m K
- \(m\): mass flow rate of fluid, kg/s
- \(Re\): Reynolds number based on the internal diameter of the tube, dimensionless
- \(Nu\): Nusselt number, dimensionless
- \(p\): Pressure component in momentum equation, N/m²
- \(Sm\): Accumulation of mass, Kg
- \(Sh\): Accumulation of Energy, J
- \(T\): Temperature, °C
- \(v\): Velocity component in momentum equation, m/s
- \(y\): Twist ratio (Length of one twist \((3600)\)/diameter of the twist), dimensionless

Greek symbols

- \(\rho\): Density component in governing equations
- \(\tau\)\(_{\text{eff}}\): Stress component in momentum equation, N.m².
REFERENCES


