Heat Transfer Augmentation of Laminar Flow in Horizontal Circular Nano-Composite Tube with Insert

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Abstract. A numerical investigation was carried out to predict the heat transfer behavior and friction factor in heated circular nano-composite tube with two cases: plain tube and inserted tube. Typical twisted tape (TTT) and triangular cut twisted tape (TCTT) were used as insert if twisted tape ratio equal 2 and thickness equal 1 mm. The composite material consist of polyester resin mixed with nano copper with different weight fraction 3%, 7%, 33%, 50% and 75%. The governing equations were solved by using commercial ANSYS Fluent package (2017) with the assistance of Solid Works and Gambit software program. The finite volume approach was used in solving the equations to predict the pressure flow, heat transfer and temperature distribution along the tube. Nano-composite material tube was heated under constant heat flux (1244W/m²). The water flow in the tube was laminar (297 < Re < 1670). The dimensions of circular tube were 800 mm length, 20 mm diameter and 1.5 mm thickness. Numerical results show that the heat transfers was augmented when (TTT or TCTT) was used as a swirl flow devices comparing with plain tube. The water temperature increases significantly at the center line of tube by 25% when TTT is used, while the friction losses increase in an undesirable rate of 155 %. Finally, it can be concluded that the nano-composite tube is efficient in heat transfer applications.

1. Introduction
Enhancement of the heat transferring plays a significant role in maximizing the efficiency of many applications such as heat exchangers, power generation, and microelectronics. Augmentation of the convective heat transfer coefficient will minimize the size and cost of the heat exchanger [1, 2]. For enhancing the heat transfer in heat exchanger, and minimize the surface area with materials cost, different methods is implemented such as passive method, active method and hybrid method. In passive method swirl devices is used in flow passage. The most effective passive techniques on heat transfer improvement are twisted tape and wire coil inserts. The twisted tape is more effective for improving heat transfer compared with wire coil in case of laminar flow inside heat exchanger. There are used for their beneficial such as easy fabrication, process and maintenance low. For increasing the heat transfer coefficient by performing the swirl flow and twisted tape inserts and making heat transfer coefficient higher, many types of research have been implemented on insert devices experimentally and numerically, to examine the behavior of the influence of twisted tape on heat transfer improvement, thermal performance factor, pressure drop, and flow friction specifications in a heat exchanger tube heat transfer enhancement to reach more effective kinds and dimensions of these devices [3]. Kapatkar et al. [4], experimentally examined heat transfer and friction factor in a copper plain tube and when
using a twisted tape as insert. The study was carried out under laminar flow and at constant heat flux. Results show that with increasing Reynolds number, the Nusselt number of full-length twisted tape is raised. This increment in intensity of heat transfer due to swirl flow. For the flow inside smooth tubes, full length twisted tapes produce the enhancement in the mean of the Nusselt number with range of Reynolds number (200 to 2000). At higher Reynolds number beyond laminar flow region, the friction factor is raised due to the growing in the momentum interchange of the molecules. Murugesan et al. [5], evaluated the influence of twisted tape insert with V-cut on heat transfer, friction factor, and characteristics of thermal performance factor. In the test section which involves of two concentric tubes in which hot water flows through the internal tube and the cold water flow through the annulus. Results showed that the twisted tape with V-cut presented a higher heat transfer rate, friction factor, and thermal performance factor compared to the case plain twisted tape. Sivakumar and Rajan [6], carried out an experimental and numerical evaluation of heat transfer coefficient and characteristics of friction factor in a concentric tubes. The test section is consists of an aluminum interior tube of 18 mm interior diameter and 20 mm exterior diameter of 2.2 m length. The twisted tape material was copper. Results show that the heat transfer improvement took place with increment of Reynolds number. Saud [7], studied numerically the improvement of heat transfer and fluid flow properties inside circular tube with twisted tape insert. A different type of insert has been tested such as triple, dual and quadruple twisted tapes. The results of turbulent flow under constant heat flux forced convection proofed that tube close-fitting with dual linked twisted tapes (TDCTT) is the best thermal performance. Farhad et al. [8], investigated friction factor and heat transfer enhancement in case of dual twisted tapes or normal in converge-diverge tubes. The range of Reynolds number is10000 to 20000 for twisted tapes with different holes in, at constant heat flux using working fluid (water). The results show that, the Nusselt number will be improves by 9% when a dual twisted tape was used. Mahdi et al. [9], investigated the heat transfer improvement for a single tube with and without insert. The heat exchanger performance was studied if the tube in oblique and horizontal directions. The circular tube of heat exchanger is made of copper material with dimensions: length - (1000 mm) and inner and outer diameters of (23 and 25) mm, respectively. Distilled water under laminar flow condition (Re =1056 – 2002) flows through an insulated tube. The insert tape was made of copper strip with 0.8 mm thickness. The employed of the inserted tape yields a considerable increase in the coefficient of heat transfer about (16-27%) more than plain tube. Shuai et al. [10], studied experimentally and numerically the thermal-hydraulic features in circular tubes with twisted tape and wire coil inserts. Experimental results show that friction factor and Nusselt number in tubes with twisted tape inserts were 38%- 57% and 148%- 202%, respectively, which are greater than plain tubes. When wire coil was inserted in plain tubes, friction factor and Nusselt number raised by 685%-792% and 75%- 94%, respectively. Nusselt number and friction factor in tubes with twisted tape and wire coil inserts were (113% - 139%) and (836% - 874%), respectively, greater than plain tubes. The aim of the present work is to predict the heat transfer behavior and friction factor in heated circular nano-composite tube with two cases: plain tube and inserted tube. Typical twisted tape (TTT) and triangular cut twisted tape (TCTT) were used as insert.

2. Numerical Analysis and Solution
In the present work a numerical study of heat transfer and the flow field through a test nano-composite tube is carried out. Test tube is subject to constant heat flux. Study is consisting of two category; plain tube and inserted tube [11,12]. Typical twisted tape (TTT) and triangular cut twisted tape (TCTT) were used as insert twisted tape ratio. The analysis depends on a modeling of fluid flow through a test tube including heat transfer, pressure drop that related to the physical phenomena. Finite volume method is used to solve the conservation equations (continuity, momentum, and energy equations) with the given boundary conditions. In the numerical solution, an ANSYS FLUENT package 17.0 commercial copy with SOLID WORK and GAMBIT software was employed.
2.1 Physical Domain Simulation
SOLID WORK programs used to make solid models of plain tube and tube with twisted tape insert [13]. Figure 1 illustrates the tube with typical twisted taped TTT and triangular cut twisted tape TCTT insert.

![Image](image_url)

Figure 1. The wire frame of inserted tube with TCTT & Triangular cut of twisted tape.

2.2 Governing Equations
In the present work, the working fluid is water and the flow characteristics are assumed to be steady state, Newtonian fluid, incompressible, three dimensional, forced convection and internal laminar flow.

The conservation equation for continuity, momentum, and energy equations can be written as follows Versteeg and Malalasekera [14].

**Continuity Equation**

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}
\]

Where u, v, and w are the velocity in x, y, and z directions.

**Momentum Equation**

The equations in (x, y, and z) direction are;

\[
\rho \left( \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \tag{2}
\]

\[
\rho \left( \frac{\partial v}{\partial x} + u \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \tag{3}
\]

\[
\rho \left( \frac{\partial w}{\partial x} + u \frac{\partial w}{\partial y} + v \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \tag{4}
\]

where \( \rho, p, \) and \( \mu \) are the density, pressure and viscosity of fluid.

**Energy Equation**

\[
\rho c \left( \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \tag{5}
\]

where \( c, k, \) and \( T \) are the specific heat, thermal conductivity and temperature.
2.3 Mesh Generation

An unstructured grid was used in present work. It is vital to have enough number of cells for a good resolution [15, 16]. For the present cases, an average of (1612012) million cells is used. Figure 2 illustrates the mesh building of straight circular tube inserted with TTT & TCTT.

![Mesh buildings](image)

**Figure 2.** Mesh buildings of a) Smooth tube, b) TCTT, c) Inserted tube with TTT.

The maximum number of iterations has been done in the present cases is 600 iterations as shown in figure 3.

![Residuals](image)

**Figure 3.** Residuals for running of numerical calculation.

2.4 Implementation of Boundary Conditions

The material of the tube is nano-composite (polyester + nano copper). The properties are: (k=295 W/m. K, \(c_p=563.2 \text{ kJ/kg. K}, \rho=398 \text{ kg/m}^3\)). The test tube has a length of 800 mm, 20 mm ID and 1.5 mm thickness. Boundary conditions for each zone of the computational domain are; the wall of the tube was heated under constant heat flux equal to 1244 W/m², the water flow in the tube was laminar (297 < Re < 1670), the temperature of water at the inlet tube is constant 20°C, and the pressure is assumed to be atmospheric pressure at the exit of tube. No slip boundary condition is specified for the wall of tube [17, 18].
3. Model Validation

Figure 4 shows the behavior of the inside wall surface temperature of the tube with axial distance. It can be seen from figure there is an error from 9% to 17% between the numerical and experimental results.

![Figure 4. Comparison between present numerical results and experimental results [12] at q=1244W/m².](image)

4. Results and Discussion

4.1 Temperature Contours

Figures 5 and 6 clarify the contouring outcomes for temperature distribution at different axial sections along the tube length. For the domain of plain tube with DI-water represented in figure 5, the contours present the evolution of thermal boundary layer starting from the inner wall tube (at which the heat flux supplied) to the tube center. Thus, the thermal boundary layer thickness ($\delta th$) is increased where axial location is increased from $z=0$ to 800 mm reaching to nearly the same at which the flow becomes thermally fully devolved. As it can be seen, the maximum inner wall temperature ($T_{miw}$) and thicker $\delta th$ are existed at the lower inlet velocity $u_i=0.013$ m/s. These values start to calm down where inlet velocity is increased which are reasonable outcomes because the fluid gather much longer time inside the tube at lower velocities that source heat gain inside the flowing fluid and thicker $\delta th$ therefore, heat transfer rate is less than for higher velocities.

![Figure 5. Temperature contours for water at different Reynolds number and various axial distances for plain heated tube with 1244 W/m² heat flux.](image)
From figure 6, it can be realized from tube different sections the advantage of putting in the twisted tape (TTT) for twisted ratio \( Y=2 \) and thickness = \( 1\text{mm} \) inside the sleek tube which generates a swirling flow path that supply a better mixing between the viscous fluid layers allowing for more heat to transfer from inner wall tube that enhances heat transfer rate.

![Figure 6. Temperature contours for tube inserted with TTT with twisted ratio = 2 and thickness = 1mm at different Reynolds number and 1244 W/m² heat flux at different axial distance.](image)

From figure 7, it can be realized from the half tube different sections the benefits of inserting the twisted tape (TTT) and (TCTT) inside the smooth tube which generates a swirling flow path that provides a better mixing between the viscous fluid layers allowing for more heat to transfer from inner wall tube that enhances heat transfer rate. Figure 7(a) shows the behavior of water flow through a nano-composite tube under the influence of constant heat flux (1244 W/m²) and Reynolds number (Re=297). It is evident that the water in contact with the surface of the inner tube is heated with the length of the tube while the water away from the surface remains at the same temperature. Figure 7(b) shows the effect of adding a TTT type inside tube to improve heat transfer from the tube to the water. The increase in heat transfer from the surface of the tube to the water can be explained to generate a vortex flow that breaks down the boundary layer adjacent the tube and increases the tangential velocity near the tube surface. Figure 7(c) shows the effect of adding a TCTT type. The figure also shows an increase in the improvement of heat transfer, but in a smaller percentage compared to the addition of (TTT).

Figure 8 shows the pressure contours of water through the nano-composite tube in three cases (plain tube, tube with TTT, tube with TCTT) as insert when the flow is laminar (297 < Re <1670). Figure 8 indicates the presence of pressure losses in the flow of water through the pipeline. The pressure drop in the plain tube reaches 99%, while in the two cases of adding an insert (TTT, TCTT), it becomes (135% and 155%), respectively. The reason for the increased losses is the addition of TTT and TCTT to the tube. Increased losses through the tube lead to increased pumping capacity, and this is an undesirable case in engineering applications.
Figure 7. Temperature contours for water flowing inside: (a) plain tube, (b) tube inserted with TTT, (c) tube inserted with TCTT at Re=297 and 1244W/m² heat flux at different longitudinal sections.
Figure 8. Pressure contours for water at different Re with 1244 W/m² heat flux along the, (a) plain tube, (b) tube inserted with TTT, (c) tube inserted with TCTT.
5. Conclusions
From the numerical results, it is concluded that heat transfer improvement and pressure loss occurs by means of utilizing the twisted tapes that be subject to on the twist ratio, thickness, and the twisted tapes cutting form. The results showed that when the tube was exposed to a constant heat flux (1244 W/m²) heat transfer increased when using TTT and TCTT, compared to the plain tube. Typical twisted tape showed well performance in heat transfer enhancement but with higher friction losses comparing to plain tube. The water temperature increases significantly at the center line of tube by 25% when TTT is used, while the friction losses increase in an undesirable rate of 155%. Finally, it can be concluded that the nano-composite tube is efficient in heat transfer applications.

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