Heat transfer augmentation of Al₂O₃-Cu/water hybrid nanofluid in circular duct with inserts

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Abstract: Nanotechnology has opened up new avenues for industrial efficiency and performance. The Al₂O₃-Cu/water hybrid nanofluid with and without insert is analyzed numerically and validated to show heat transfer enhancement. A circular duct with inserts, a tube length of 3 m, a hydraulic diameter of 0.01 m, tube wall with a constant heat flux of 20 kW/m², and a twist ratio of 125 were used to examine Al₂O₃-Cu/water hybrid nanofluid in turbulent regime. At Re = 20,000, due to insertion of twisted tape, there is an additional mixing of fluid that takes place, leading towards increase in temperature of around 1–1.75% when compared with that of without inserts. The Nusselt number is improved for plain twisted tape tube by 1.5–2.0% higher than plain tube as revealed in the result. Moreover, there is a 1.01 times improvement in performance evaluation criteria when twisted tape is inserted instead of plain tube.

Subjects: Mechanical Engineering; Thermodynamics; Heat Transfer; Thermodynamics; Fluid Mechanics

Keywords: nanofluids; active method; Passive method; Nusselt number; performance evaluation criteria

1. Introduction

The world’s temperature is steadily rising above pre-industrial levels due to an increase in energy demand, and the release of radiation and toxic gases has resulted in extreme weather conditions (Harish Kumar et al., 2022). As a result, the use and development of several heat transfer enhancement techniques was prompted by the engineering understanding of the need to improve the thermal performance of heat exchanger in order to effect energy, cost, material, as well as a consequential mitigation of environmental degradation (Emad et al., 2017). Due to their superior qualities, research on various nanofluids for improving performance in thermal applications has attracted a lot of attention in recent years (Ahmed et al., 2012; Pehlivan et al., 2013). One of the most difficult issues that thermal engineers face is improving heat transfer in heat exchangers. As technology advances, the demand for faster and more efficient heat transfer from smaller regions or across smaller temperature differences grows. Because water, oil, and ethylene glycol mixtures lack sufficient heat transfer qualities to fulfill the increasing demand for improved heat transmission (Hamdi et al., 2019; Jiat Kendrick Wong, 2021; Moghaddami et al., 2012).

Nanotechnology has opened up new avenues for industrial efficiency and performance. The use of nanofluids to improve heat transfer performance is one of the suggested petitions. To increase the effectiveness of temperature exchangers, nanofluids are frequently employed. The thermal conductivity of nanoparticles, size, diameter, and volume...
concentration were all factors in determining the rate of heat transfer (Kumar & Dr, 2017; Mehrjou et al., 2015). Cars, energy storage, electronic component cooling, solar absorbers, and nuclear reactors (Nasrin et al., 2021) are among the most common uses of nanofluids. In flowing fluid, mechanical and heat transfer qualities are of particular interest due to their numerous industrial uses in chemicals, energy, machinery, and other industries. To boost heat transfer efficiency, nanoparticles are included in the base fluid in this example (Arjun, K. S., Rakesh, K., 2020). The advent of nanotechnology has forced numerous fields of basic science and engineering to confront new problems (Lin et al., 2022). In engineering thermal systems, convective heat transfer must be increased in order to reduce heat exchanger size, weight, and cost. It is being tried multiple times to improve heat transfer by using roughened surfaces. A variety of rib-groove channel layouts and temperature gradients have been researched during the past few decades by researchers (Abdulwahab, 2014). M. E. Nakachi and J. A. Esfahani (Navaei et al., 2015) examined the heat transfer and friction factor of CuO nanoparticles dispersed in water/proplylene blend in a plain tube (PT) with and without twisted tape inserts. As the volume concentration of nanoparticles in the base fluid rises, the Nusselt number of CuO nanofluids increases significantly over that of the base fluids. Nanofluids have a negligible effect of friction on the base fluid in a planar tube. It is possible to improve heat transfer in CuO nanofluids by using tape inserts with several twists, which reduce friction while improving heat transfer. S. Aljabair et al. (Nakchi & Esfahani, 2020) numerically examined H$_2$O-Al$_2$O$_3$ nanofluid heat transfer by natural convection inside symmetrical and asymmetrical corrugated annuli at various nanoparticle volume fractions and Rayleigh numbers. The stream function intensity and heat transfer rate increase with increasing nanoparticle volume fraction and Rayleigh number. In contrast to symmetrical annuli, unsymmetrical annuli have a higher rate of heat transfer.

H. Shiravi et al. (Aljabair et al., 2020) carried out an experimental investigation using carbon nanofluid in turbulent regime to assess the variation of CHTC, Nusselt number, and pressure drop in concentrations of 0 to 0.4 mass% of nanofluid. The result shows that the value of CHTC enhanced with increasing nanofluid concentration up to 0.21% and then reduced. Moreover, increasing Reynolds leads to improvement in both Nusselt number and the CHTC, but friction factor is decreased.

A.A. Rabienataj Darzi et al. (Hossein Shiravi et al., 2020) conducted experiments to analyze the effect of nanofluid on turbulent heat transfer and pressure drop inside concentric tubes using base fluid (H$_2$O) and nanoparticle (SiO$_2$) with mean diameter of 30 nm, respectively. Study was performed for both PT and five roughened tubes with different heights and pitches of corrugations. Thus, the results show that adding the nanoparticles in tube with high height and small pitch of corrugations enhances the heat transfer with a minimum pressure drop penalty.

For nanofluid flow, S. Kumar et al. (Rabienataj Darzi et al., 2012) and A. S. Navaei et al. (Kumar et al., 2017) evaluated the turbulent heat transfer in square channels with protruding rib morphologies varying from 4000 to 18,000 Reynolds numbers. In addition, nanoparticles (Al$_2$O$_3$, CuO, and ZnO) of various concentrations ($\phi$) and sizes (dnp) are disseminated in water (base fluid). The results demonstrate that Al$_2$O$_3$ nanofluid has the highest average Nusselt number value in comparison to other nanofluids. As concentration increases, the average Nusselt number rises, while the average particle diameter decreases. Increases in volume fraction, roughness height, and Reynolds number all contributed to a rise in the Nusselt number. However, when the nanoparticles diameter increased, it dropped. After glycerin and ethylene glycol, water-SiO$_2$ was found to have the lowest Nusselt number, followed by water and glycerin. Ashkan Vatani and H.A. Mohammed (Navaei et al., 2015) and Sh.M. Vanaki et al. (Ashkan & Mohammed, 2013) also come to similar conclusions.
Nanofluid flow through a thermally growing, hydraulically developing pipe was studied numerically by Masoud Ziaei-Rad and Maryam Beigi (Sh et al., 2014). According to experimental results, with increasing nanoparticle volume fraction, the thermal entrance length is reduced and heat transfer rises as a result. Increasing the volume fraction of nanoparticles by 10% increases the average Nusselt number by a whopping 15%.

According to the experiments of A. Moghadassi et al. (Ziaei-Rad & Beigi, 2016) and S. Suresh et al. (Moghadassi et al., 2015), the Nusselt number was increased by 13.56% at a Reynolds number of 1730 compared to the water Nusselt number. According to the experimental results, Al₂O₃-Cu/water nanofluids have a slightly greater friction factor than Al₂O₃/water nanofluids. There is a good match between experimental data and the empirical correlations for the friction factor and Nusselt number.

Ing Jiat Kendrick Wong and Ngien Tze Angnes Tiong (Hamdi et al., 2019) show that the heat transfer performance of circular pipes is superior and the pressure drop is greater than that of noncircular ducts. As a result of lack of sharp edges in circular pipe, the heat transfer rate was increased. A hybrid nanofluid of Al₂O₃-Cu and water has a higher pressure drop than

| Authors | Parameters | Main findings |
|---------|------------|---------------|
| Sakanova et al., 2014 | Al₂O₃/water nanofluid φ = 0.01, 0.05 | Al₂O₃ water-based nanofluid is used as a coolant to improve heat transfer performance, with volume concentrations of 1% and 5%. According to the results, the nanofluids produce superior cooling performance at larger concentrations; consequently, concentrations of 5% and 1% improve cooling performance by 17.3% and 10.6%, respectively. |
| Raei et al., 2016 | Al₂O₃/water nanofluid φ = 0.05%, 0.15% | The findings indicated that pure water has a lower Nusselt number than nanofluids. Additionally, when the flow rate, temperature, and particle volume percentage of the nanofluid increased, so did the Nusselt number. The biggest improvements in this study's heat transfer coefficient and friction factor, which were 23 and 25%, respectively, were at a nanoparticle concentration of 0.15%. |
| Abdollahi et al., 2017 | SiO₂, Al₂O₃, ZnO, CuO, base fluid water φ = 0.01, 0.015, 0.02dₕ = 30, 40, 60nm | The findings showed that among the investigated nanofluids and pure water, SiO₂ nanofluid exhibits the highest Nusselt number value. The average Nusselt number improved as the volume fraction of nanoparticles increased. |
| Peyghambarzadeh et al., | CuO, Al₂O₃, base fluidwater φ = 0.01, 0.02, 0.03, 0.04 | CuO nanofluids at 0.2% and 1% volume concentrations increased the heat transfer coefficient to 27.0% and 49%, respectively, but had a higher pressure drop when compared to pure water. |
| Xia et al., 2016 | Al₂O₃, TiO₂, base fluidwater φ = 0.001, 0.005, 0.01 | Al₂O₃ and TiO₂ nanofluids exhibit increased thermal conductivity and dynamic viscosity with increasing volume concentration. Utilizing Al₂O₃ nanofluids, the performance of heat transfer in a fan-shaped microchannel heat sink is improved as compared to a rectangular microchannel heat sink. |
water. The hybrid nanofluid pressure drop in a circular duct can be 4.79 times greater than water. The increased viscosity of the hybrid nanofluid is responsible for the increased pressure drop.

Recep Ekiciler et al. (Suresh et al., 2012) analyzed the flow of Al₂O₃/water nanofluid and Al₂O₃-Cu/water nanofluid 1% volume concentration nanoparticle in a duct with ellipse, square, and triangular rib under turbulent flow condition. The result reveals that adding Al₂O₃/water nanoparticle and Al₂O₃-Cu/water nanoparticle into the base fluid enhances the rate of heat transfer in all cases. Moreover, some of the related literatures are listed in Table 1.

The above studies show that nanofluids are a promising method for heat transfer enhancement by increasing thermal conductivity even for small volume fraction of suspended nanoparticles. Thus, this research work studied numerically for further enhancement of heat transfer by adding twisted tape insert. Thermal power plants, process industries, and evaporator heating and cooling can all benefit from mixed method of heat transfer augmentation that is both active and passive method. There will be an added advantage of enhancement of heat transfer due to two methods adopted; however, pressure drop must be considered during flow. An efficient heat exchanger can be designed with the above method of adoption. An existing heat exchanger can benefit from these strategies. Thus, the current research aims to increase heat transfer by adding twisted tape insert in PT using working fluid hybrid nanofluid (Al₂O₃-Cu) with base fluid of water.

2. Materials and methods

2.1. Physical modeling

The geometries examined in this study were circular tube and plain twisted tape (PTT) tube. To guarantee that the flow was hydrodynamically and thermally fully developed, the length of the tube was adjusted to 3 m, and the hydraulic diameter was 0.01 m, as shown in Figure 1 based
Table 2. Thermophysical properties of water and hybrid nanofluid Al$_2$O$_3$–Cu/water (Hamdi et al., 2019)

| Material                  | Density, $\rho$ (kg/m$^3$) | Heat capacity, $C_p$ (J/kg · K) | Thermal conductivity, $k$ (W/m · K) | Dynamic viscosity, $\mu$ (kg/m · s) $\times 10^{-3}$ |
|---------------------------|-----------------------------|---------------------------------|------------------------------------|-----------------------------------|
| Water                     | 995.7                       | 4178.00                         | 0.615                              | 0.800                             |
| 0.1% Hybrid Nanofluid     | 998.91                      | 4163.53                         | 0.619                              | 0.900                             |
| 0.5% Hybrid Nanofluid     | 1011.74                     | 4106.58                         | 0.633                              | 1.200                             |
| 1% Hybrid Nanofluid       | 1027.78                     | 4037.40                         | 0.652                              | 1.602                             |
| 2% Hybrid Nanofluid       | 1059.86                     | 3905.30                         | 0.685                              | 1.935                             |

on the work of Ing Jiat Kendrick Wong and Ngieng Tze Angnes Tiong (Hamdi et al., 2019). Further, to intensify heat transfer, we have adopted passive method along with active method; for this, it has been provided with twisted strip for a full-length tube. Further, the tube of 3 m length has been extruded 5 mm on either side of the tube in order to avoid back flow during analysis and a twist ratio of $\eta = 125$ has been provided for a twist tape.

2.2. Thermophysical properties of water and hybrid nanofluids

Copper and alumina hybrid nanofluids were used in this investigation. Studies have demonstrated that as particle loading rises, Al$_2$O$_3$–Cu/water accelerates heat transfer (Hamdi et al., 2019). Table 2 displays the characteristics of water and hybrid nanofluids at various volume concentrations. For our analysis, thermophysical properties of hybrid nanofluid Al$_2$O$_3$–Cu/water with volumetric concentration of 1% have been chosen and it has been validated with Ing Jiat Kendrick Wong and Ngieng Tze Angnes Tiong (Hamdi et al., 2019); further, to intensify heat transfer, passive method has been adopted by inserting twisted tape into PT.

3. Mathematical model and Numerical method

3.1. Governing equations and boundary conditions

In this article, alumina–copper–water (Al$_2$O$_3$–Cu/H$_2$O) hybrid nanofluid is viewed as an incompressible boundary layer and steady-state flow. The equations of conservation of mass, momentum, and energy for boundary layer approximations can be stated as follows, given specific physical hypotheses:

Conservation of mass

$$\nabla \cdot \rho \mathbf{V} = 0 \quad (1)$$

Momentum equation

$$\frac{\partial}{\partial x_j} (\rho u_j v_j) = - \frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] + \frac{\partial}{\partial x_j} \left( \rho |u_i| u_j \right) \quad (2)$$

Energy equation

$$\nabla \left[ \rho \left( h - \frac{P}{\rho} \right) + \frac{v^2}{2} \right] = \nabla \cdot (k \nabla T) \quad (3)$$
where \((k + k_t)\) is the effective thermal conductivity, \((k_t)\) is the turbulent thermal conductivity, \(T\) is the temperature, \(v\) and \(u\) are the velocity components, \(P\) is the static pressure, \(\mu\) is the viscosity, \(\delta\) is the Kronecker delta, \(h\) is the sensible enthalpy, and \(\rho\) is the fluid density. To resolve the turbulent kinetic energy, \(k\), and dissipation rate, \(\varepsilon\), the standard–turbulence model with enhanced wall treatment was chosen.

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_i} \left( \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right) + G_k - \rho \varepsilon
\]  
(4)

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_i} \left( \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right) + C_{\mu} \frac{\varepsilon}{k} G_k - C_2 \rho \varepsilon^2
\]  
(5)

\[
\mu_t = \rho C_p \frac{k^2}{\varepsilon}
\]  
(6)

\[
I = 0.16 \text{Re}_{0}^{\frac{1}{2}}
\]  
(7)

where \(t\) is the time, \(u_i\) is the velocity component, \(\mu\) is the viscosity, \(\sigma_k\) and \(\sigma_\varepsilon\) are the turbulent Prandtl numbers for the kinetic energy and dissipation rate of the turbulent flow, respectively, \(G_k\) is the turbulent kinetic energy generated by the mean velocity gradient, \(\mu_t\) is fluid’s Eddy viscosity, and \(I\) is turbulence intensity. For the transport equations, the constants \(C\) are 1.44 for \(C_{1s}\), 1.92 for \(C_{2s}\), and 0.09 for \(C_p\).

The range of 0.1–2% was given for the volume fraction of hybrid nanoparticles. At a weight percentage ratio of 9:1, \(\text{Al}_2\text{O}_3\)-Cu hybrid nanoparticles were used in the simulations. The density \((\rho)\) and heat capacity \((C_p)\) of hybrid nanofluid were calculated using Eqs. 8–12. The subscripts \(bf\), \(hnf\), and \(nf\), respectively, stand for the base fluid (water), hybrid nanofluid, and single-particle nanofluid. The hybrid nanofluid volume fraction is denoted by \(\phi\) in Eq. (12).

\[
\rho_{nf} = (1 - \phi)\rho_{bf} + \phi\rho_{np}
\]  
(8)

\[
\rho_{hnf} = (1 - \phi)\rho_{bf} + \phi C_{\rho C} C_{\rho C} + \phi_{\text{Al}_2\text{O}_3} \rho_{\text{Al}_2\text{O}_3}
\]  
(9)

\[
(\rho C_p)_{nf} = (1 - \phi)(\rho C_p)_{bf} + \phi (\rho C_p)_{np}
\]  
(10)

\[
(\rho C_p)_{hnf} = (1 - \phi)(\rho C_p)_{bf} + \phi (\rho C_p)_{np} + \phi_{\text{Al}_2\text{O}_3} (\rho C_p)_{\text{Al}_2\text{O}_3}
\]  
(11)

\[
\phi = \phi_{\text{Cu}} + \phi_{\text{Al}_2\text{O}_3}
\]  
(12)

Boundary conditions
The governing equations were solved in accordance with the provided boundary conditions. The fluid entered the domain with a uniform velocity profile because its flow was parallel to the border. The axial velocity of nanofluid was determined using the Reynolds number. It was required that the inlet temperature be 300 K. The outflow boundary condition was applied to the outlet border. There was no slip boundary condition imposed on the tube walls. Following a study by Ing Jiat Kendrick Wong and Ngien Tze Angnes Tion (Hamdi et al., 2019), the above boundary condition and tube wall of constant heat flux of 20 kW/m² were chosen.

3.2. Numerical method
A tool for commercial computational fluid dynamics software ANSYS-Fluent is utilized. Fluent employs the finite volume technique to solve the governing equations and boundary conditions given above. The thermo-hydraulic properties of a tetrahedral mesh element with a small significant center and an inflating layer are used to produce thin elements that record velocity and temperature gradients near no-slip barriers. The Navier–Stokes and energy equations are discretized in the model using standard pressure and second-order upwind discretization. The simple method is used to handle the pressure–velocity relationship. There are also convergence conditions of $10^{-6}$ and $10^{-8}$ for the continuity and velocity components, respectively. Figure 2a–c shows the grid resolution test, and the temperature value in cells 2602844 (model 1) and 3364281 (model 3) differs by 1−1.5% from that in cell 3114836 up to section 55. As a result, the grid with the number of cells of 3114836 (Model 2, Figure c) was chosen for the PTT tube for $Re = 20,000$.

3.3. Data reduction
The average convective heat transfer coefficient ($h_{av}$), Nusselt number ($Nu$), and the Reynolds number ($Re$) of the fluid were determined using Eq. (5).

$$h_{av} = \frac{q''}{(T_W - T_f)}$$  \hspace{1cm} (13)
\[ T_f = \frac{T_{out} - T_in}{2} \]  
(14)

\[ Nu = \frac{h_D h}{k} \]  
(15)

\[ Re = \frac{\rho v D_h}{\mu} \]  
(16)

\[ D_h = \frac{4A}{P} \]  
(17)

where \( A \) is the cross-sectional area, \( P \) is the perimeter, \( T_w \) is the wall temperature, \( T_f \) is the film temperature, \( T_{in} \) is the intake temperature, \( T_{out} \) is the outlet temperature, and \( q'' \) is the heat flux. To compute the friction factor (\( f \)) and pressure drop (\( P \)) for the flow behavior of hybrid nanofluid, the formulas listed below are used. Additionally, thermal performance factors of hybrid nanofluid were assessed using performance evaluation criteria (PEC) according to Eq. (20).

\[ f = \frac{2 \Delta P D}{\rho v^2 L} \]  
(18)

\[ \Delta P = P_{in} - P_{out} \]  
(19)

\[ PEC = \frac{Nu_{enhanced}/Nu_{bf}}{(f_{enhanced}/f_{bf})^{1/3}} \]  
(20)

Nusselt number of water was calculated for validation reasons using the Dittus–Boelter correlation, and water’s friction factor was determined using Eq. (23). The Dittus–Boelter correlation has validity ranges of 0.6 \( \leq Pr \leq 160 \), \( Re \geq 10,000 \), and \( \frac{L}{D_h} > 10 \), whereas Eq. (23) has validity ranges of \( 3000 \leq Re \leq 5 \times 10^6 \) (Ekiciler & Samet Ali Çetinkaya, 2021).

\[ Nu = 0.023 Re^{0.8} Pr^{0.4} \]  
(21)

\[ Pr = \frac{C_p \mu}{k} \]  
(22)

\[ f = (0.790 \ln Re - 1.64)^{-2} \]  
(23)

4. Result and discussions

4.1. Flow field investigation

Figure 8 shows velocity contour plot for circular tube/PT for Al\(_2\)O\(_3\) Cu/water, \( Re = 20,000 \), at different axial locations. Because plain tube is not induced by twisted tape naturally, where
there is no obstacle, velocity will be maximal at that place, as shown in Figure 8, and there is a 1% to 1.25% variation between present work and previous work of Ing Jiat Kendrick Wong and Ngieng Tze Angnes Tiong (Hamdi et al., 2019).

Figure 10 shows velocity contour plot for PTT tube for $\text{Al}_2\text{O}_3$.Cu/water, $Re = 20,000$, at different axial locations. Thus, it has been observed that there is a decrease in velocity during the flow near towards tape wall due to swirling action but, there is an increase in velocity which can be observed as shown in Figure 10. However, there is a decrease in velocity along the path flow, and results of velocity contours have been shown in sections S1 to S5 (inlet, 1 m, 1.5 m, 2 m, 2.5 m, and 3 m).

4.2. Temperature contours for circular tube and PTT tube
Figure 6 shows temperature contour plot for PT for water, $Re = 20,000$, at different axial locations, and it can be observed that there is an increase in temperature along the flow.
Due to boundary layer formation at the wall, there is an increase in pressure which leads to temperature raise which can be seen in Figure 6.

Figure 7 shows temperature contour plot for PT for Al₂O₃-Cu/water, Re = 20,000, at different axial locations. Due to active method adoption of hybrid nanofluid, there is an increase in temperature from 1% to 1.5% when compared with that of water which can be seen along the path from section S1 to S5.

Figure 9 shows temperature contour plot for PTT for Al₂O₃-Cu/water, Re = 20,000, at different axial locations. There is an intensification of temperature of around 1% to 1.75% when compared with that of without inserts. This is due to a mixed method of active and passive employed in this analysis. Due to insertion of twisted tape, an additional mixing of

| DOMAIN   | TEMPERATURE (K)       |
|----------|-----------------------|
|          | [1]                   |
|          | 3.030e+002            |
|          | 3.029e+002            |
|          | 3.028e+002            |
|          | 3.027e+002            |
|          | 3.026e+002            |
|          | 3.025e+002            |
|          | 3.024e+002            |
|          | 3.023e+002            |
|          | 3.022e+002            |
|          | 3.021e+002            |
|          | 3.020e+002            |
|          | 3.019e+002            |
|          | 3.018e+002            |
|          | 3.017e+002            |
|          | 3.016e+002            |
|          | 3.015e+002            |
|          | 3.014e+002            |
|          | 3.013e+002            |
|          | 3.012e+002            |
|          | 3.011e+002            |
|          | 3.010e+002            |
|          | 3.009e+002            |
|          | 3.008e+002            |
|          | 3.007e+002            |
|          | 3.006e+002            |
|          | 3.005e+002            |
|          | 3.004e+002            |
|          | 3.003e+002            |
|          | 3.002e+002            |
|          | 3.001e+002            |
|          | 3.000e+002            |
|          |                       |
| INLET    | 1.0m                  |
| S1       | 1.5m                  |
| S2       | 2.0m                  |
| S3       | 2.5m                  |
| S4       | 3.0m                  |
| S5       | 3.5m                  |
| Temperature Contour                        |
| [3]     |                       |
| 3.030e+002|                     |
| 3.029e+002|                     |
| 3.028e+002|                     |
| 3.027e+002|                     |
| 3.026e+002|                     |
| 3.025e+002|                     |
| 3.024e+002|                     |
| 3.023e+002|                     |
| 3.022e+002|                     |
| 3.021e+002|                     |
| 3.020e+002|                     |
| 3.019e+002|                     |
| 3.018e+002|                     |
| 3.017e+002|                     |
| 3.016e+002|                     |
| 3.015e+002|                     |
| 3.014e+002|                     |
| 3.013e+002|                     |
| 3.012e+002|                     |
| 3.011e+002|                     |
| 3.010e+002|                     |
| 3.009e+002|                     |
| 3.008e+002|                     |
| 3.007e+002|                     |
| 3.006e+002|                     |
| 3.005e+002|                     |
| 3.004e+002|                     |
| 3.003e+002|                     |
| 3.002e+002|                     |
| 3.001e+002|                     |
| 3.000e+002|                     |

Figure 5. PEC of 1% Al₂O₃-Cu /water hybrid nanofluid in PT and PTT tube.

Figure 6. Temperature contour plot for PT for water, Re = 20,000, at different axial locations.
fluid takes place, leading towards increase in temperature near towards wall of both pipe domain and twisted tape domain. These results can be observed along the path which has been shown between sections S1 and S5.

Figure 7. Temperature contour plot for PT for Al₂O₃-Cu/water, Re = 20,000, at different axial locations.

| DOMAIN | TEMPERATURE (K) |
|--------|----------------|
| INLET  | S1, 1.0m       |
| S2, 1.5m |
| S3, 2.0m |
| S4, 2.5m |
| S5, 3.0m |

Figure 8. Velocity contour plot for PT for Al₂O₃-Cu/water, Re = 20,000, at different axial locations.

| DOMAIN | VELOCITY m/s |
|--------|--------------|
| INLET  | S1, 1.0m     |
| S2, 1.5m |
| S3, 2.0m |
| S4, 2.5m |
| S5, 3.0m |

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4.3. Heat transfer and friction factor

Using the numerical data gathered by Ing Jiat Kendrick Wong and Ngieng Tze Angnes Tiong (Hamdi et al., 2019), the current numerical analysis for PT validated the results of the Al$_2$O$_3$-Cu/water hybrid nanofluid at 1% as illustrated in Figure 3. Therefore, there is a good agreement between the current findings and those of Ing Jiat Kendrick Wong and Ngieng Tze Angnes Tiong (Hamdi et al., 2019).

Figure 9. Temperature contour plot for PTT for Al$_2$O$_3$-Cu/water, Re = 20,000, at different axial locations.

Figure 10. Velocity contour plot for PTT for Al$_2$O$_3$-Cu/water, Re = 20,000, at different axial locations.
The validated hybrid 1% Al₂O₃-Cu/water nanofluid in PT has a good agreement when compared to Nusselt number of Ing Jiat Kendrick Wong and Ngieng Tze Angnes Tiong (Hamdi et al., 2019), as shown in Figure 3. The slope of Nusselt number for the water is more linear than that of the Al₂O₃-Cu/water hybrid nanofluid as it is revealed in Figure 3. By adding a small amount, copper nanoparticles can dramatically improve the thermal properties of an Al₂O₃ nanofluid. A hybrid Al₂O₃-Cu/water nanofluid has a superior thermal conductivity than water because of the higher conductivity of metallic copper nanoparticles. When compared to base fluid and mono nanofluid, hybrid nanofluid can dramatically raise the Nusselt number, especially at higher Reynolds numbers. This result is highly agreed with Behrouz Takabi and Hossein Shokouhmand (Takabi & Shokouhmand, 2015) too as shown in Figure 3.

Further to enhance the heat transfer, a passive method is adopted for hybrid fluid flow in PT by inserting twisted tape. An increase of 1.5% to 2% heat transfer can be observed as shown in Figure 3. It clearly shows that due to flow disruption and formation of swirl, there is an increase in Nusselt number which leads to the augmentation of heat transfer.

Figure 4 compares the Darcy friction factor (f) of the current investigation to those of Ing Jiat Kendrick Wong and Ngieng Tze Angnes Tiong (Hamdi et al., 2019) to establish the validity of hydrodynamic results for 1% hybrid nanofluid in the range of Reynolds number. A good agreement was found between the computed friction factor and those obtained from these correlations. Moreover, the same report is also reported by Behrouz Takabi and Hossein Shokouhmand (Takabi & Shokouhmand, 2015) as shown in Figure 4.

Further due to increase in pressure drop in PTT tube, there is a rise in friction factor when compared with that of without inserts. Clearly from Figure 4, it can be seen that there is a drop of friction factor with rise in Reynolds number.

4.4. Thermal performance factor
Hybrid nanofluids with PEC ratios higher than 1 demonstrate that the overall heat transfer capability of fluid predominates over flow resistance because water has a PEC ratio of 1 at all Reynolds numbers.

The merits of nanofluids for heat transfer enhancement depend on the compromise between thermal conductivity increase and viscosity increase. In this objective, Figure 5 shows the evolution of this energetic criterion with the Reynolds number in the case of nanofluids for PT and PTT tube. We can notice that all measurements lead to PEC values under those corresponding to the case of water in the study by Ing Jiat Kendrick Wong and Ngieng Tze Angnes Tiong (Hamdi et al., 2019). Clearly due to insertion of twisted tape, there is a rise in PEC of 1.01 times than in the work of Ing Jiat Kendrick Wong and Ngieng Tze Angnes Tiong (Hamdi et al., 2019) PT.

5. Conclusions
In the present study, turbulent thermal performance factor of Al₂O₃-Cu/water hybrid nanofluid in circular tube/PT ducts was numerically investigated. The following conclusions can be drawn based on the current study:

- Due to insertion of twisted tape, an additional mixing of fluid takes place, leading towards increase in temperature of around 1% to 1.75% when compared with that of without inserts at Re = 20,000.
- Heat transfer is further enhanced by adopting passing method for hybrid fluid flow in PT by inserting twisted tape. An increase of 1.5% to 2% heat transfer can be observed due to flow disruption and formation of swirl.
- Twisted tape inserts have a higher heat transfer rate due to enhanced fluid mixing along the tube wall.
Due to insertion of twisted tape, there is a rise in PEC of 1.01 times than in the work of Ing Jiat Kendrick Wong and Ngieng Tze Angnes Tiong (Hamdi et al., 2019) PT.

Nomenclatures

| Symbol   | Description                                      |
|----------|--------------------------------------------------|
| Cu       | copper                                           |
| d        | diameter, m                                      |
| CuO      | copper oxide                                     |
| L        | length, m                                        |
| CHTC     | convective heat transfer coefficient             |
| w        | width, m                                         |
| h        | convective heat transfer coefficient, kW/m²K     |
| Nu       | Nusselt number                                   |
| h_av     | average convective heat transfer coefficient     |
| q''      | heat flux, kW/m³                                 |
| SiO₂      | silicon oxide                                    |
| Pr       | Prandtl number                                   |
| Al₂O₃     | aluminum oxide                                   |
| Re       | Reynold number                                   |
| φ         | volume number                                    |
| f        | friction factor                                  |
| PEC      | performance evaluation criteria                  |
| PPT      | plain twisted tape                               |
| y/₁𝑤     | twist ratio                                      |
| PT       | plain tube/circular tube                         |
| Al₂O₃–Cu/H₂O | alumina–copper–water             |
| ZnO      | zinc oxide                                       |
| A        | cross-sectional area, m²                         |
| T_w      | wall temperature, K                             |
| T_f      | film temperature, K                             |
| T_in     | intake temperature, K                           |
| T_out    | outlet temperature, K                           |
| ZnO      | zinc oxide                                       |

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Data availability

The data used to support this study are included within the article.

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