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**Original Research Article**

# Availability prediction of a double-pipe exchanger using twisted tape and nanofluid (AL2O3) technology

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## Abstract

*This experimental and theoretical study explores heat transfer enhancement in a horizontal circular tube using a nanofluid composed of Al2O3 nanoparticles suspended in distilled water (H2O), combined with a twisted ribbon insert. The twisted ribbon has a typical twist ratio of 6 (TR=6). The investigation was conducted under fully developed turbulent flow and uniform heat flux conditions, with nanofluid concentrations of 1%, 3%, and 5% by volume. The experimental setup consisted of all the necessary components for analyzing heat transfer within a double-pipe heat exchanger. The tests were conducted over a Reynolds number range of 5000–10500, with heat applied externally as hot water (at 63°C) flowed through the annular space between the tubes, while the nanofluid entered the inner tube at a temperature of 18°C. The twisted ribbon, made from wrought iron, was placed inside the inner tube. In the numerical analysis, the final results were obtained using computational fluid dynamics (CFD) to model the forced convection turbulent flow through the tube. The study found that the maximum thermal performance factor for the nanofluid was 5, achieved at a torsion ratio of 6 and a volume flow rate of 3 liters per minute.*

### HIGHLIGHTS

1. *AL2O3/H2O 0.1% nanofluid in a tube with a typical inserted twisted tape has been investigated experimentally and numerically.*
2. *The key fundamental dimensionless parameters, such as the Reynolds number, Nusselt number, heat exchanger (HX) effectiveness, EXERGY, and friction factor, have been analyzed.*
3. *The results demonstrated a significant enhancement in heat transfer and EXERGY with the inclusion of a standard inserted twisted tape.*

***Keywords:*** *nanofluid; Turbulent flow; CFD; Heat transfer; Typical twisted tape; Thermal performance factor; EXERGY.*

## 1. Introduction

Many researchers have focused on enhancing piping in heat exchanger designs to increase the performance of large heat exchangers composed of multiple smooth pipes, driven by the urgent need to optimize energy usage and improve efficiency. Among the most widely researched and implemented strategies for improving heat exchanger efficiency is the insertion of twisted tape inside the pipe. This approach has been adopted by numerous researchers, including Cong[1] and Wei[2] As well as many other researchers and scientists who have significantly contributed to the advancement of this crucial field.

In response to the ongoing global energy shortage, improving the performance of thermal systems has become a critical concern, as rising energy demand, the depletion of energy resources, and increasing production costs necessitate innovative solutions. Current research aims to optimize the performance of these systems by improving heat transfer, reducing their physical size, and minimizing energy consumption rates. Key parameters influencing the efficiency of thermal systems include the heat transfer coefficient, pressure drop, and exergy availability. Achieving the highest possible heat transfer coefficient requires minimizing thermal stagnation in the boundary layer and enhancing fluid flow turbulence to promote optimal mixing. Given its compact structural design and ability to accelerate the heat transfer process, twisted ribbon tube technology has become an essential technique across various industrial and energy sectors. Furthermore, the introduction of nanofluids—heat transfer fluids containing nanoparticles—has shown to further enhance the thermal properties of base fluids, making this a promising area for ongoing research.

The term "nanofluid" refers to a suspension of metallic and non-metallic nanoparticles dispersed in base fluids such as water, oils, and other liquids.[3] These nanoparticles enhance the thermal conductivity of the base fluid, thereby improving the heat transfer coefficient. Numerous studies have explored the application of nanofluids in thermal systems, including pipelines. Traditionally, heat transfer using conventional fluids like water, oil, and ethylene glycol has been widely used in machine tools across various devices. Factors such as the number of dispersed particles, material type, particle shape, volume ratio, and other variables influence the effectiveness of heat transfer enhancement.

Kumar[4] The researcher carried out an experimental study on iron oxide/water nanofluid with varying mixing ratios, utilizing a heat exchanger equipped with twisted strips at different twist ratios within a turbulent flow regime. The experiments revealed that as both the twist ratio and nanofluid concentration increased, there was a significant enhancement in the heat transfer process, demonstrated by an approximate 39% improvement in the Nusselt number.

Ghazanfari et al[5] .The researchers conducted a numerical analysis using computational fluid dynamics (CFD) to examine a heat exchanger equipped with twisted ribbons at varying pitch lengths of 180 mm, 135 mm, 90 mm, and 45 mm. The study employed nanofluids, consisting of water as the base fluid with the addition of nanoparticles, including Al2O3, Cu, CuO, and TiO2, separately. The objective was to evaluate the effects of these nanoparticles on the non-dimensional properties of the system at flow rates of 0.5 kg/s and 2 kg/s. The results clearly demonstrated the effectiveness of nanofluids in enhancing heat transfer. For instance, using aluminum oxide nanofluids at concentrations of 0.1% and 0.15% by volume led to heat transfer improvements of 1.04 and 1.12 times, respectively, with a slight increase in pressure drop.

Among the selected nanoparticles, aluminum oxide showed the most significant performance, indicating its superiority for industrial and production applications in operational systems.

Maddah et al.[6] The researchers conducted a numerical study on a double-tube heat exchanger, where a nanofluid composed of water as the base fluid and iron oxide particles was circulated at a mixing ratio between 0.08% and 0.1%. A twisted ribbon, with twist ratios ranging from 2.5 to 5.2, defined as the ratio of the twist step length (A) to the ribbon width (B), was introduced into the system. The experiment was carried out under turbulent flow conditions, with Reynolds numbers ranging from 5000 to 28,500. The findings revealed that the combination of the twisted ribbon and nanofluid resulted in a 103.45% increase in the Nusselt number, indicating a significant enhancement in convective heat transfer. These results suggest that integrating twisted ribbons with nanofluids in double-tube heat exchangers is both effective and highly beneficial.

Using nanofluid with twisted tape in a heat exchanger enhances thermal performance by improving heat transfer rates significantly. The nanoparticles in the fluid increase thermal conductivity, allowing for more efficient heat exchange. Twisted tape generates turbulent flow and swirl, which disrupts the thermal boundary layer, facilitating better mixing of hot and cold fluid layers. This combination reduces the required heat exchanger size or improves its efficiency, making it suitable for applications demanding compact, high-performance systems. However, it also increases pressure drop, which should be considered in system design[7], [8], [9], [10].

In conclusion, the integration of twisted tape bending and nanofluids in double-tube heat exchangers offers a promising approach to enhancing heat transfer efficiency. Numerous studies have demonstrated the potential of these techniques to significantly improve thermal performance by increasing turbulence, reducing thermal boundary layer thickness, and improving convective heat transfer rates.[11], [12], [13] The use of nanofluids, with their superior thermal properties, further amplifies these effects. Given the rising demand for more efficient thermal systems in industrial applications, investigating the combined use of twisted tapes and nanofluids provides a viable solution for optimizing heat exchanger designs. This research aims to explore the feasibility of these methods, offering insights into their practical application and potential benefits for energy-intensive industries.

## Methodology

Heat transfer and fluid movement within a heat pipe are inherently complex processes. As such, the effectiveness of thermal CFD simulations depends on a wide range of factors. Key aspects that can influence the success of the simulation include the development of accurate model geometries, their proper integration into a physical domain, the generation of a precise computational grid, and the selection of an appropriate numerical method for computation. To assess performance, experiments on turbulent flow, as well as numerical simulations, were conducted on a smooth tube (i.e., a tube without twisted tape) using a hybrid nanofluid. The results of these studies were then compared to the Dittus-Boelter equation to validate accuracy. The following sections provide a concise overview of the main steps and findings of these studies, highlighting the critical methodologies and observations that shaped the analysis. Additionally, the comparison underscores the importance of selecting the right modeling techniques when dealing with turbulent flow in complex systems.

## Experimental Procedure

### Test Rig

The experimental setup was designed to investigate convective heat transfer within a turbulent flow system. The test section comprised a horizontal copper pipe with a diameter of 25.4 mm (1 inch) and a length of 1 meter. Heating was supplied by circulating hot water at 63°C through the annular space between two pipes, while cold fluid at 20°C passed through the inner pipe. To minimize heat loss, rock wool insulation was applied around the test section. Temperature readings were taken along the hot surface of the pipe using five evenly spaced K-type thermocouples. Additionally, two thermocouples submerged in the fluid measured the inlet and outlet temperatures of the fluid passing through the test section.

All thermocouples were connected to an Arduino system that recorded and displayed temperature data on a computer. A flow meter was used to monitor the flow rate, which ranged between 0 and 20 liters per minute. Pressure loss along the 1-meter length of the test section was measured using an electronic pressure differential manometer. Figure 1 illustrates the experimental setup, while Table 1-1 details the equipment used, including their operating ranges and systematic errors.

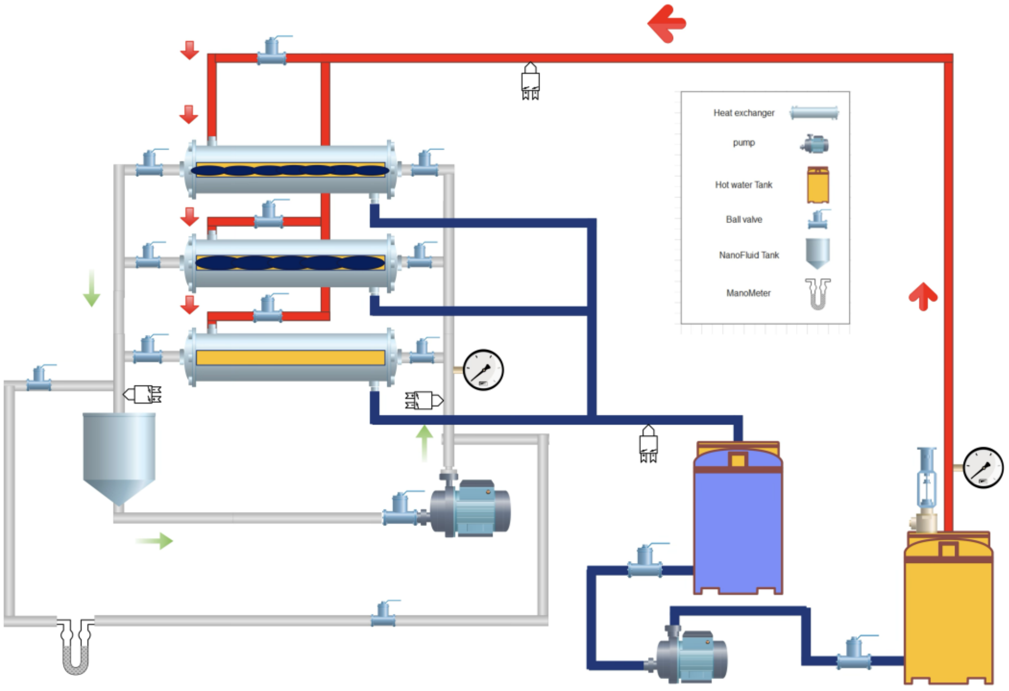


Figure (1) Photo of the test rig

**Table 1: The equipment its operation ranges**

| No. | Equipment | Operation range | Uncertainty |
|---|---|---|---|
| 1 | Flow meter | (0-30) | ±0.1 |
| 2 | Thermocouples | (0-180ºC) | ± 1 |
| 3 | Electronic pressure difference manometer (EPDM) | (0-15.00Kpa) | ± 1 |

## Properties of AL2O3 Nanofluids

Aluminum oxide ($Al_2O_3$) nanofluid, composed of water as the base fluid, has gained significant attention in thermal engineering due to its enhanced heat transfer properties. By incorporating $Al_2O_3$ nanoparticles, which exhibit high thermal conductivity, this nanofluid demonstrates improved thermal performance compared to conventional fluids. The increased surface area of nanoparticles promotes better heat transfer efficiency, making $Al_2O_3$/water nanofluids particularly beneficial in applications such as heat exchangers, cooling systems, and various industrial processes. Furthermore, their ability to operate at lower flow rates while maintaining high thermal conductivity presents opportunities for energy savings and improved system performance. As research continues to explore their properties and applications, $Al_2O_3$/water nanofluids emerge as a promising solution for enhancing thermal management in diverse engineering applications[14], [15], [16] .

**Table 2: Thermal properties of the nanoparticles and base fluid** [14]

| No. | Properties | Water | $Al_2O_3$ |
|---|---|---|---|
| 1 | ρ (Kg/m³) | 997 | 3980 |
| 2 | Cp (J/kg·K) | 4180 | 765 |
| 3 | K (W/m·K) 0 | 0.607 | 40 |

Before preparing the nanofluid, it is essential to determine both the volume of water used in the heat exchanger and the quantity of nanoparticles, which together define the volumetric ratio or particle concentration in the water. The nanoparticles utilized in the experimental evaluation of the heat exchanger's efficiency are aluminum oxide (Al2O3) suspended in water. These materials were combined to create two types of nanofluids. The mass of the solid nanoparticles, to be mixed with water, was calculated for a volume of 13 liters at a volumetric concentration of 0.1% using Equation

$$m_b = \frac{\phi * \rho_p * \left(\frac{m_f}{\rho_f}\right)}{(1-\phi)} \quad ...1$$

Two primary methods were employed for mixing the nanoparticles with water:

1. Mechanical Mixing: The nanoparticles were first mixed with 13 liters of water using an electric mixer, operating for 35-40 minutes until a state of complete homogeneity was achieved as shown figure (2).

**Figure (2) Electric mixer**

2. Ultrasonic Dispersion: The resulting nanofluid was then placed in an ultrasonic device to further disperse the particles and ensure uniform suspension. The ultrasonic device Figure (3) operated for 40 minutes, though this process was conducted in multiple stages due to the device's limited capacity of 1.8 liters.

**Figure (3) Ultrasound device**

Once a homogenous nanofluid was achieved, it was transferred to a designated basin within the apparatus, where an electric mixer operated continuously to maintain a consistent suspension and even distribution of the nanoparticles. To evaluate the time required for nanoparticle settlement, the nanofluid was monitored for the onset of particle separation. For a 0.1% volume concentration, the maximum settling time for the water and aluminum oxide nanofluid was approximately 15 hours.

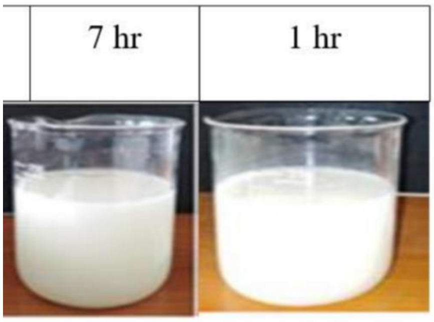


Figure (4-a)

The mixture is continuously monitored, and its condition is carefully observed to ensure the quality and stability of the final result. Detailed observations are recorded throughout the process. Additionally, it is crucial to determine the available time window for conducting the test, as it plays a significant role in maintaining the homogeneity and effectiveness of the nanofluid during the experimental procedures.

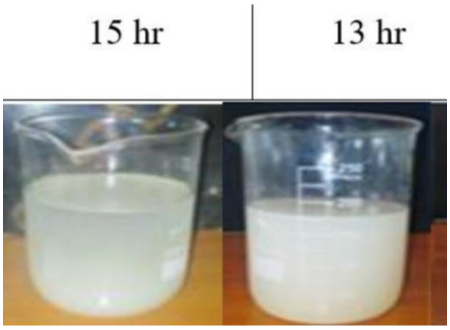


**Figure (4-b)**

## Thermal Conductivity: K

Thermal conductivity (k), a material's capacity to conduct heat, was measured for both water and $Al_2O_3$ nanofluid using a conductivity meter (Type 51TS) with an accuracy of about 1%. The device's cylindrical probe was placed in the center of each sample at specific temperatures and concentrations, with measurements recorded after a set period.

## Density:ρ

Density, or mass per unit volume, was determined by measuring the mass (m) on a sensitive balance and the volume (v) with a graduated flask.

$$\rho = \frac{m}{v}$$

## Twisted Tape:

The twisted strips were fabricated by winding a 1-meter-long metal strip with varying pitches and twist ratios of 4 and 6 turns. The term “twist” refers to the linear distance required to achieve a 360-degree rotation of the strip, while the twist ratio (T.R) is defined as the ratio of the pitch to the width of the strip. The design of the twisted strips was generated using ANSYS software, which facilitated the creation of the typical twisted strip (T.T) that was subsequently sent for manufacturing. The manufacturing process involved the production of the twisted strip from iron, with specific dimensions of 1 meter in length, 25 mm in width, and 2 mm in thickness. As shown in figure (4)

**Figure (4) twisted tape and inner pipe**

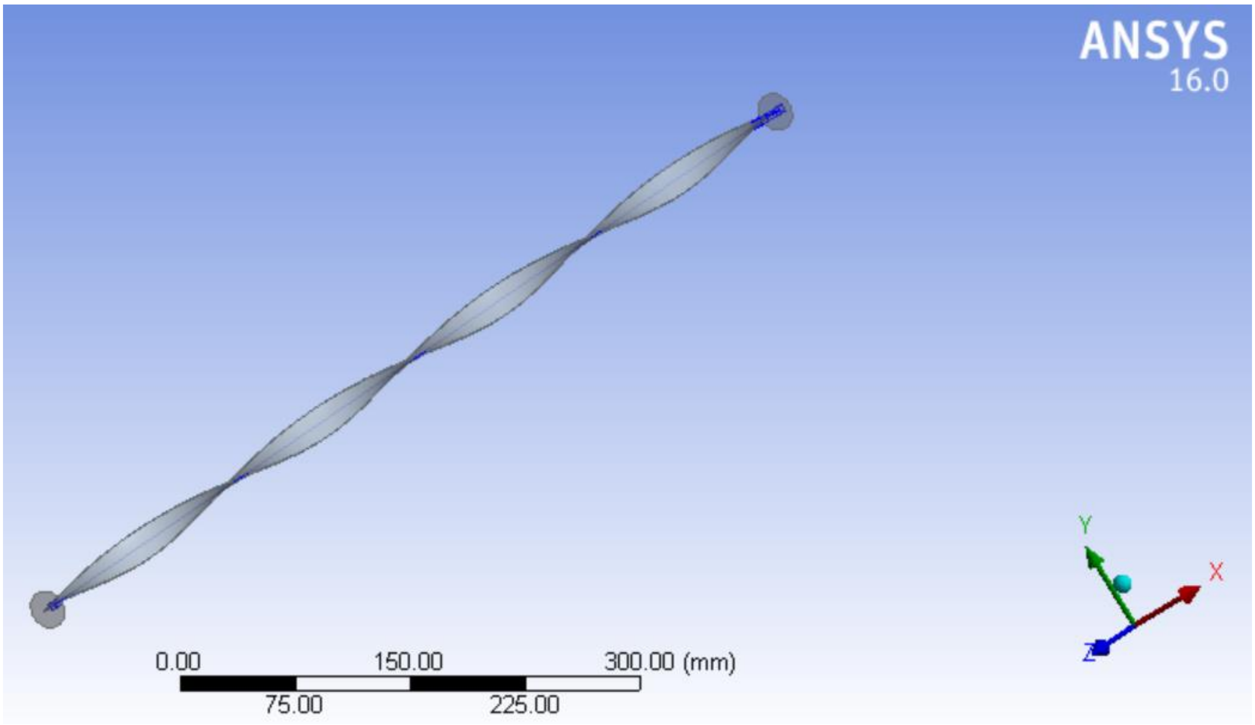


**Figure (5) twisted tape ANSYS software**

## Device operation steps:

This study investigates heat transfer enhancement in a concentric double-tube heat exchanger, providing a full account of the experimental procedures involved. For these experiments, hot water flowed countercurrent to cold water, with initial tests using water alone. The hot water temperature was maintained at 63 ± 1°C using an electric heater, while cold water was kept at 18 ± 1°C. The flow rate of both hot and cold water was initially set at 3 L/min, and readings were recorded once temperatures stabilized. Subsequently, the hot water flow rate remained constant while the cold-water flow rate was adjusted to 3, 4, and 5 L/min to observe temperature changes. Results from these preliminary trials confirmed that counterflow performed better than parallel flow, which supported its use in this study.

The nanofluid was then introduced into its designated basin, following these steps:

1. Water was pumped from storage tanks, and all connections were checked. Pumps circulated the fluid through the exchanger, with flow rate control managed by adjusting the control valve and monitored via flow meters.
2. Cold water entered the inner tube of the exchanger, while hot water, regulated by an electric heater, circulated in the outer shell. The hot water flow rate was set at 3 L/min, and the cold water flow rate was varied between 3, 4, and 5 L/min.
3. To maintain nanoparticle dispersion, an electric mixer in the nanofluid basin operated continuously throughout the experiment.
4. After reaching steady state, thermocouples recorded the inlet and outlet temperatures, and the data was logged for accuracy. The nanofluid was cooled to 18 ± 1°C, and hot water temperature stabilized at 63 ± 1°C. Wall temperatures were also monitored, and an electronic pressure gauge measured the pressure differential (ΔP) across the inlet and outlet points of the test section.

## Error (Uncertainty) Analysis

The quantities used to estimate the Nusselt number are subject to specific uncertainties resulting from measurement errors, which are outlined in this analysis. The approach follows the guidelines proposed by Robert J. Moffat [18], and the accompanying table details the instruments utilized, their measurement ranges, and associated errors.

The result (R) is typically computed from the data set, denoted as XiXi. Therefore, it can be expressed as:

$$R = R(X_1, X_2, X_3, \ldots X_i$$

The uncertainty in RR can be derived as follows:

$$\delta R_{xi} = \frac{\partial R}{\partial X_i} . \delta X_i$$

Subsequently, the total uncertainty δRδR is given by:

$$\delta R = \left[ \sum_{i=1}^{m} \left( \frac{\partial R}{\partial X_i} . \delta X_i \right)^2 \right]^{0.5}$$

The uncertainty interval (S) in the result can be formulated as:

$$S_R = \left[ \left( \frac{\partial R}{\partial \dot{X}_1} S_{X1} \right)^2 + \left( \frac{\partial R}{\partial \dot{X}_2} S_{X2} \right)^2 + \cdots + \left( \frac{\partial R}{\partial \dot{X}_\imath} S_{Xi} \right)^2 \right]^{0.5}$$

In a dimensionless form, this is represented as:

$$\frac{SR}{R} = [(R.S_{X1})^2 + (R.S_{X2})^2 + \cdots + (R.S_{Xi})^2]^2$$

Where:

$$R_{Xi} = \frac{\partial R}{\dot{X}_1}$$

The Nusselt number (Nu) is defined as:

$$Nu = \frac{h_i . d_i}{k} = \frac{Q_{di}}{A_s \Delta T_s k} = \frac{\dot{m} Cp \Delta T_b d_i}{A_s \Delta T_s k}$$

Where:

$\Delta T_{bulk} = T_{out} - T_{in}$ , $\Delta T_s = T_{wall} - T_{bulk}$, $A_s = \pi d_o L$

The uncertainty in the Nusselt number is calculated using the following equation:

$$S_{Nu} = \left[ \left( \frac{\partial Nu}{\partial \dot{m}} S_{in} \right)^2 + \left( \frac{\partial Nu}{\partial \Delta T_b} S_{\Delta T_b} \right)^2 + \left( \frac{\partial Nu}{\partial \Delta T_s} S_{\Delta Ts} \right)^2 \right]^{0.5}$$

The relative error can be expressed as:

$$Relative\ error = \frac{R_{Nu}}{Nu}$$

Sample of the values of Nusselt numbers and uncertainty are given in Tables (3,4)

**Table 3: The calculated Nusselt numbers for water in smooth cases**

| Flow rate L/min | Nusselt number-water Error | Relative error |
|---|---|---|
| 3 | 0.204 | 0.0082 |
| 4 | 0.1609 | 0.00645 |
| 5 | 0.15 | 0.00603 |

**Table 4: The calculated Nusselt numbers for AL2O3 nanofluid for smooth case**

| Flow rate L/min | Nusselt number Al2O3 Error | Relative error |
|---|---|---|
| 3 | 0.2 | 0.00819 |
| 4 | 0.1774 | 0.00819 |
| 5 | 0.146 | 0.00595 |

## Numerical Method

In this study, a three-dimensional model was developed to simulate a horizontal pipe with an inserted twisted tape, using ANSYS Fluent for flow and heat transfer analysis. The design model included a pipe measuring 1000 mm in length, with outer and inner diameters of 25.40 mm and an assumption of turbulent, single-phase, incompressible, and steady-state flow conditions.

To model the turbulent flow in the tube and around the twisted tape, the finite volume CFD technique was employed. To achieve a fully developed flow, an entrance length was added to the test section length, calculated using the equation:

$$\frac{Le}{D} = 4.4\, Re^{\frac{1}{6}} \quad for\ 2300 < Re < 10000$$

$$Re = \frac{\rho d u}{\mu}$$

In these equations, $\rho$ and $\mu$ represent the fluid's density and dynamic viscosity, while (u) is the flow velocity. The minimum and maximum hydraulic entrance lengths were determined to be 0.344 m and 0.396 m, respectively; thus, an entrance length of 0.5 m was chosen to ensure full development.

The simulation incorporated the Navier-Stokes equations, energy equations, and continuity equations to resolve flow distribution. Meshing was concentrated around the pipe wall and twisted insert to accurately predict temperature and velocity distributions. The generated mesh for the test section is illustrated in Figure (). Finally, the results were analyzed, and conclusions and recommendations were formulated.

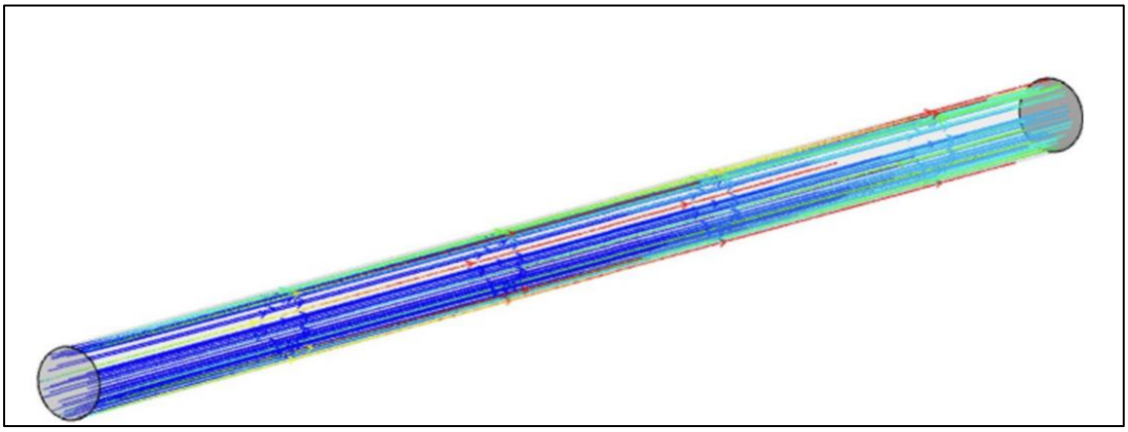


**Figure 6: Geometry shape**

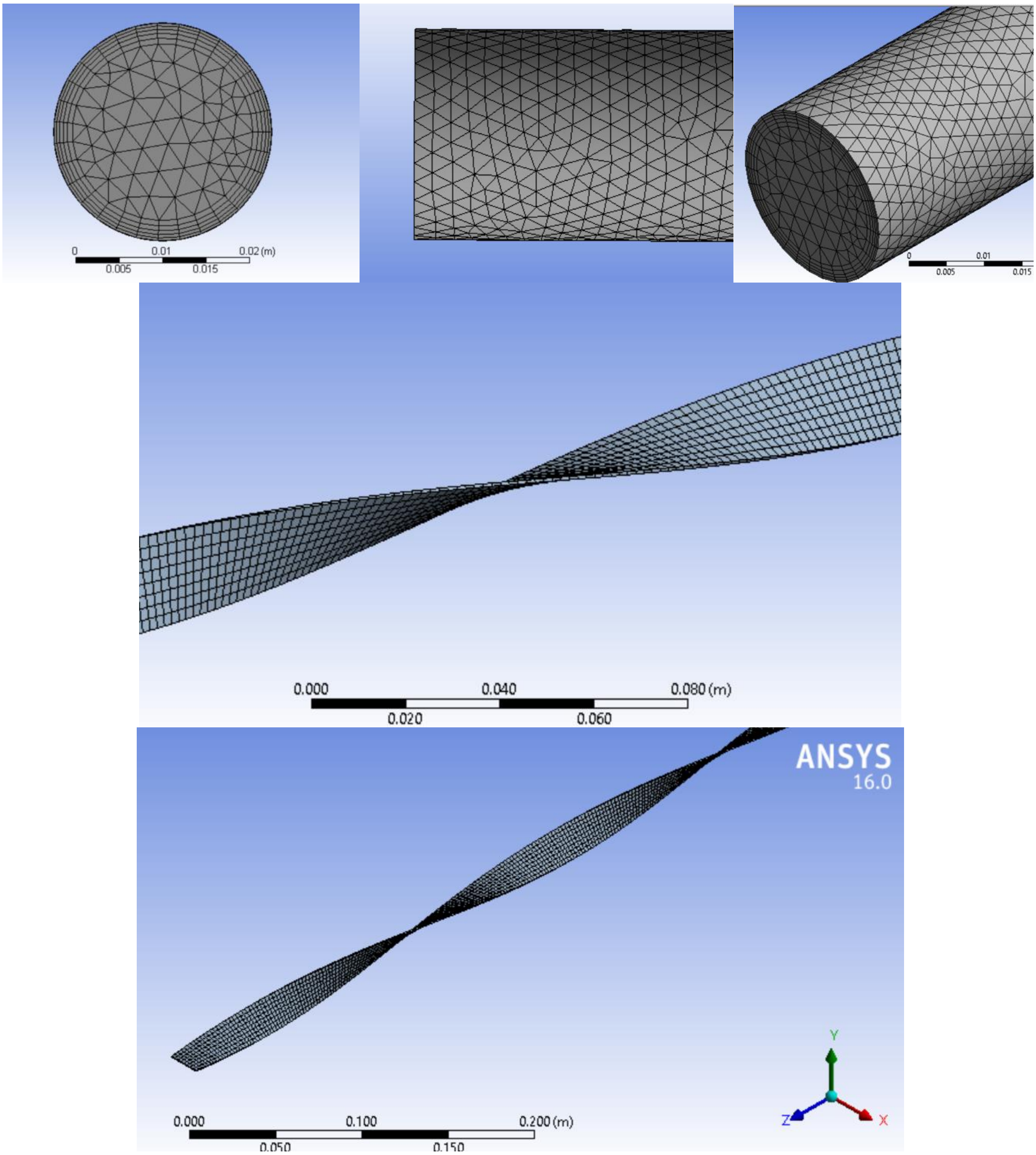


Figure 7: Mesh generation

## Mesh Generation and Grid Independence

Grid independence refers to the improvement of computational results achieved by employing progressively smaller cell sizes in simulations. This concept ensures that calculations yield accurate results as the mesh density is increased, hence the term "grid independence." Typically, computational fluid dynamics (CFD) techniques begin with a coarse mesh, which is gradually refined until the changes in results fall below a predetermined acceptable error threshold.

However, there are challenges associated with this process. First, obtaining reliable results from even a single coarse mesh can be problematic with certain CFD software. Second, refining the mesh by a factor of two or more can significantly increase computational time, which poses a challenge for software intended for engineering applications operating under tight production schedules. These issues contribute to the perception of CFD as a complex, time-consuming, and costly methodology.

In this study, the Nusselt number was recorded and analyzed for grid independence. The simulation employed a total of 97492 nodes and 243478 elements, yielding an error margin of approximately 0.795% in ANSYS Fluent. The resulting data is and illustrated in Figure (8).

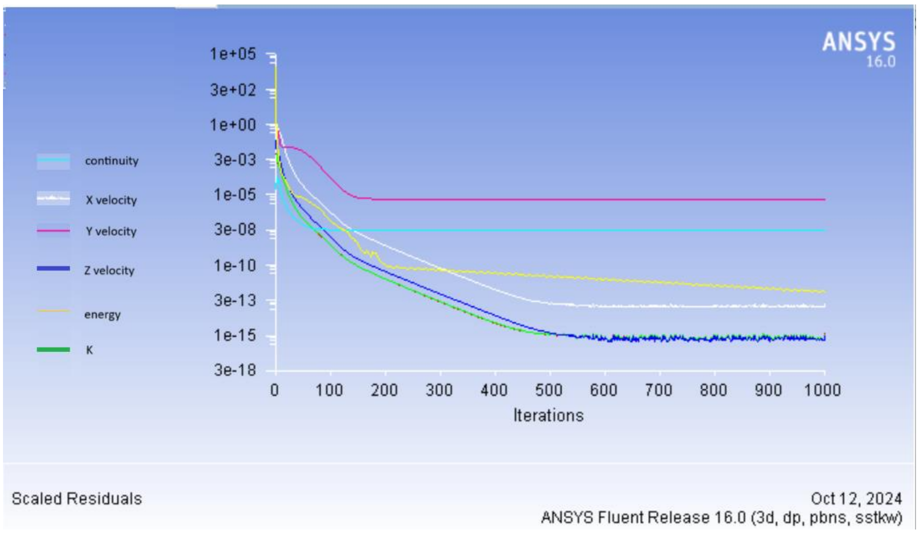


**Figure 8: resulting data ANSYS**

## Results and Discussion:

The measurements obtained for outlet temperature, pressure, and flow rates facilitated the computation of several important thermal performance metrics, including heat transfer rates, friction factors, thermal efficiency, and the local Nusselt number, specifically for turbulent flow conditions. Furthermore, the impact of the twisted tape insert was evaluated across various volumetric flow rates of the hybrid nanofluid, specifically at flow rates of 3, 4, and 5 liters per minute. In this section, we will present and analyze both the numerical simulations and experimental findings, highlighting the interplay between the twisted band's configuration and the thermal performance characteristics of the system.

## Validation:

To ensure the accuracy and reliability of the results, a simple 1-meter-long tube was examined as a test component to verify and validate the heat transfer and pressure loss characteristics. In this investigation, the relationship between the Nusselt number and the Reynolds number for fully developed turbulent flow was analyzed, utilizing pure water as the working fluid. The findings, along with the established Dittus-Bolter equation, are presented in Figure 7-a【20】.

$$Nu = 0.023Re^{0.8}Pr^{0.3}$$

The heat transfer data obtained from the test facility closely align with the previously mentioned equation, exhibiting a maximum deviation of 4.687%. Furthermore, the friction factor shows strong agreement with the published data from the Blasius equation (16), as illustrated in Figure 7-b, where the maximum divergence is noted at 5.152%.

$$Friction = 0.316\, Re^{-0.25}$$

## The Numerical Comparison Between the Straight Pipe and Twisted Tape Insert:

Figure (9) illustrates the variation in the Nusselt number (Nu) for both a straight tube without a twisted ribbon and a tube containing a twisted ribbon, utilizing water as the working fluid across a volume flow rate range of 3 to 5 L/min. For the plain tube, the Nusselt numbers recorded at flow rates of 3 L/min and 5 L/min are 20.578 and 35.928, respectively. In contrast, the tube with the twisted ribbon demonstrates Nusselt numbers of 61.1 at 3 L/min and 82.4 at 5 L/min, achieving a maximum value of 84.414 at higher flow rates. These results indicate a substantial increase of 55.89% in the Nusselt number for the tube with the twisted ribbon compared to the horizontal tube heat exchanger, suggesting that the heat exchanger with the twisted ribbon is more efficient than its standard horizontal counterpart. This enhancement is primarily attributed to the fluid's axial flow behavior in the straight tube; however, the incorporation of the twisted ribbon generates rotational motion that improves recirculation flows between the tube walls and its center. As a result, the fluid travels a longer distance over a specified length inside the tube, and the ensuing secondary flow significantly enhances heat transfer rates. Notably, this increase in the Nusselt number becomes more pronounced at elevated Reynolds numbers.

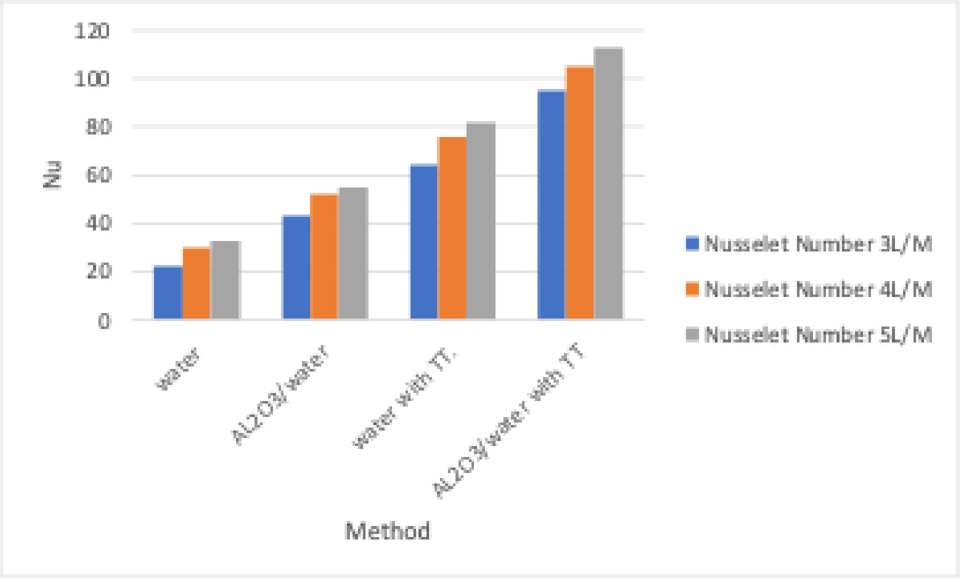


**Figure (9) The Nusselt number is influenced by variations in flow rate, as well as the use of nanofluids and twisted tape inserts.**

## Twisted Tape and AL2O3 0.1% Nanofluid Thermal Effect

As depicted in Figure (10), the simulated data is transformed into heat transfer Effectivness values, which are subsequently converted into Nusselt number (Nu) values along the length of the pipe. The Nusselt number is notably high at a 1.8% volume fraction in the fully developed region, as illustrated in the diagram. This increase in Nu can be attributed to the disruption of fluid flow and the effect of the twisted tape on the thickness of the thermal boundary layer. Figure (11) presents the variation in average Nusselt number with Reynolds number for a pipe equipped with a typical twisted tape. The results indicate that across all ranges of Reynolds numbers, the average Nusselt number increases as the Reynolds number rises. Specifically, at a 1.8% volume fraction, the data reveals a significant 30% enhancement in the Nusselt number.

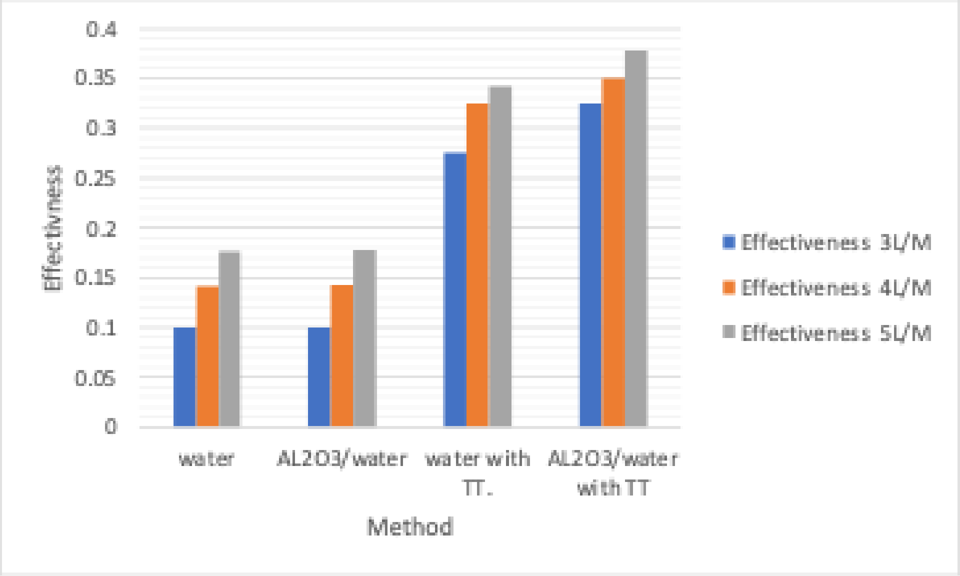


**Figure (10) The Effectivness is influenced by variations in flow rate, as well as the use of nanofluids and twisted tape inserts.**

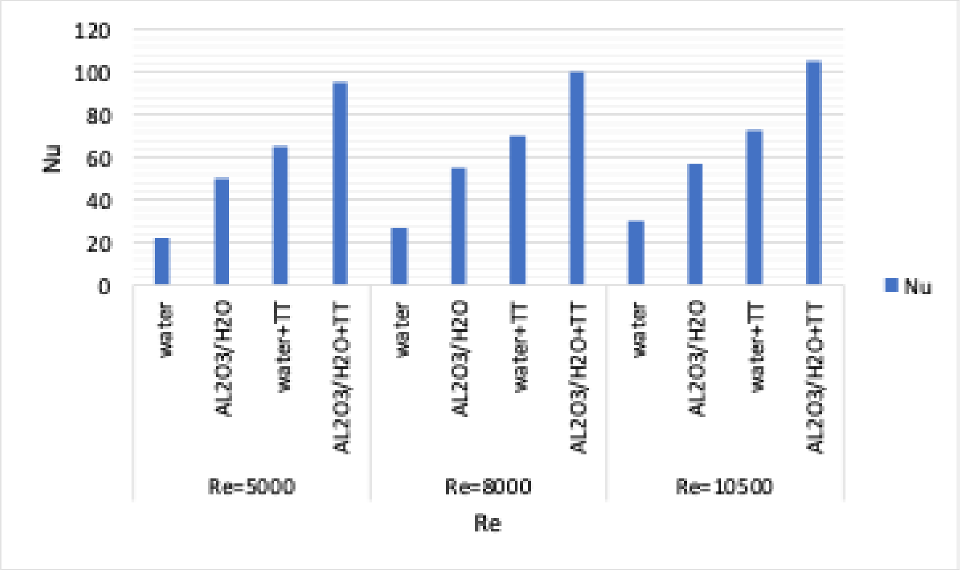
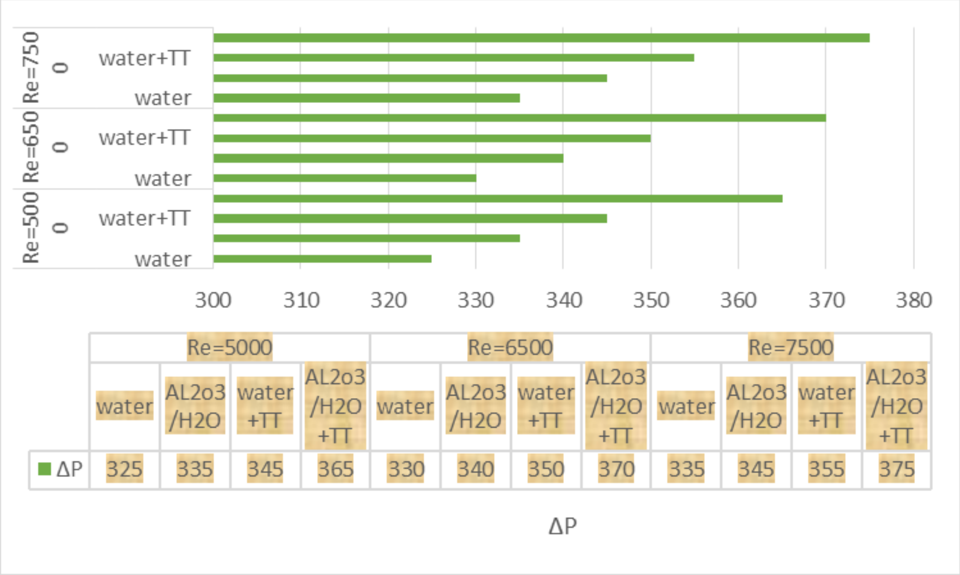


**Figure (11) The relationship between Nusselt number and Reynolds number, as well as the use of nanofluids and twisted tape inserts.**

## Pressure Drop

Figures (12) demonstrate a clear relationship between Reynolds number and pressure drop within the inner tube, This study utilized both plain and twisted ribbon-insert tubes with water and aluminum oxide nanofluids for experimental and theoretical assessments. The findings show that pressure drop increases with Reynolds number, reaching its maximum in the twisted ribbon heat exchanger at a flow rate of 5 L/min, yielding a peak of 715 Pa. In contrast, the plain inner tube exchanger exhibited a maximum pressure drop of 395 Pa. Experimental and theoretical results align closely, with only a 6% deviation attributed to experimental losses from particle deposits on the tube and ribbon surfaces, which the theoretical model assumes are idealized. The pressure drop rise is further attributed to the flow resistance from the twisted ribbon design, magnified by adding aluminum oxide nanofluids at a 0.1% concentration. Additionally, Brownian motion in the nanofluid flowing through the twisted ribbon tube increases viscosity, causing greater pressure drops as aluminum oxide concentration rises to 0.3% and 0.5%. Figure 13 highlights this trend, showing the highest pressure drop at a 0.5% concentration for the exchangers.



| | Re=5000 | | | | Re=6500 | | | | Re=7500 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | water | AL2o3 /H2O | water +TT | AL2o3 /H2O +TT | water | AL2o3 /H2O | water +TT | AL2o3 /H2O +TT | water | AL2o3 /H2O | water +TT | AL2o3 /H2O +TT |
| 🟩 ΔP | 325 | 335 | 345 | 365 | 330 | 340 | 350 | 370 | 335 | 345 | 355 | 375 |

**Figure (12) Relationship between pressure drop and Reynolds number**

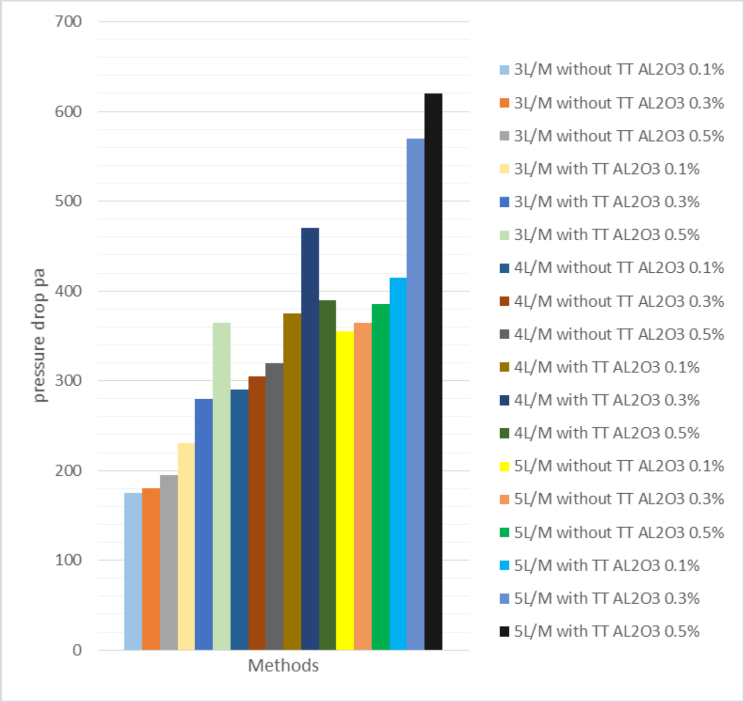


**Figure (13) The relationship between pressure drops and volumetric concentrations of Al2O3 (0.1,0.3,0.6) % with or without the use of twisted tape theoretically (ANSYS DATA)**

## Isothermal Contours

Figure (14) displays the isothermal contour maps illustrating temperature variations within the AL2O3 nanofluids with twisted tape along the tube's length. Additionally, Figure (15) presents the static temperature distribution along the central plane of the tested section for a nanofluid with a volume concentration of $\Phi = 1.8\%$ and Reynolds number Re = 8320

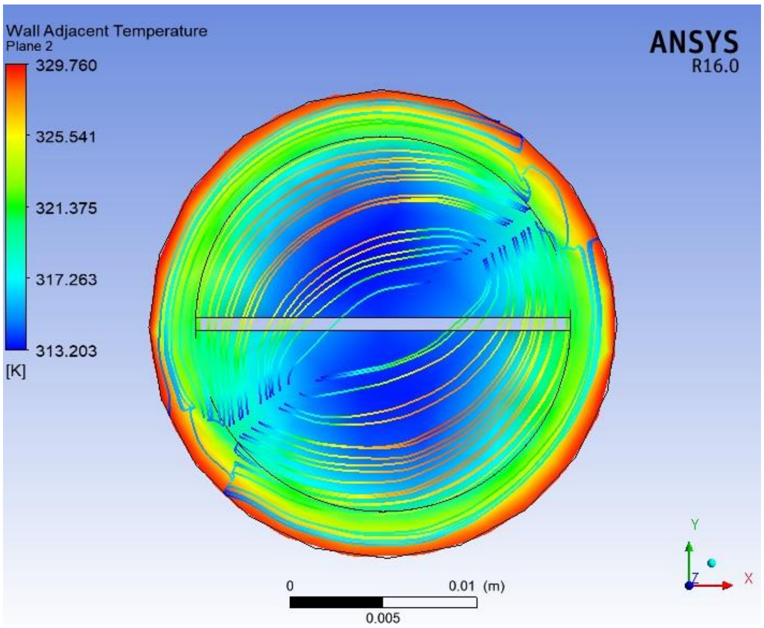


**Figure (14) temperature variations**

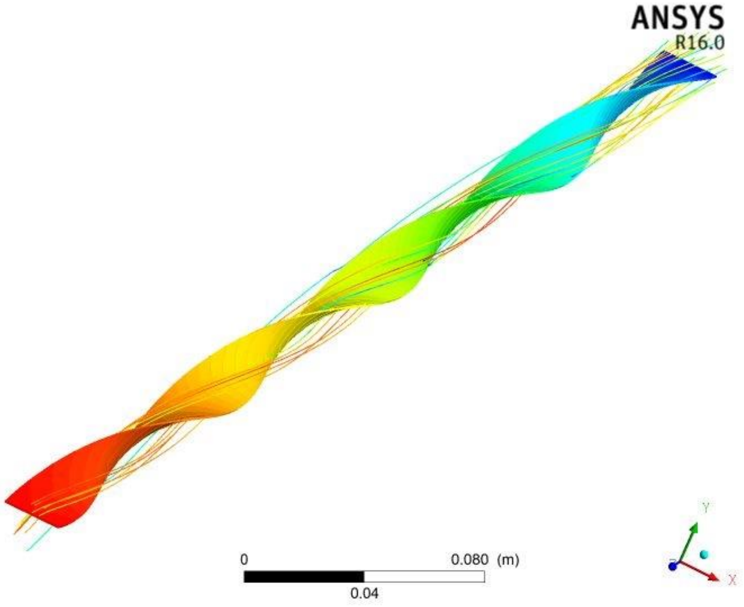


**Figure (15) static temperature distribution**

## Velocity Contours:

Figure (16) illustrates the velocity distribution within the tube section containing the twisted tape, highlighting how velocities vary based on their position relative to the tape transverse distance. This variation in velocity arises from the scattering of fluid particles along their flow path, where increased fluid mixing occurs as the number of twists increases. However, this enhanced mixing also results in a corresponding increase in pressure drop.

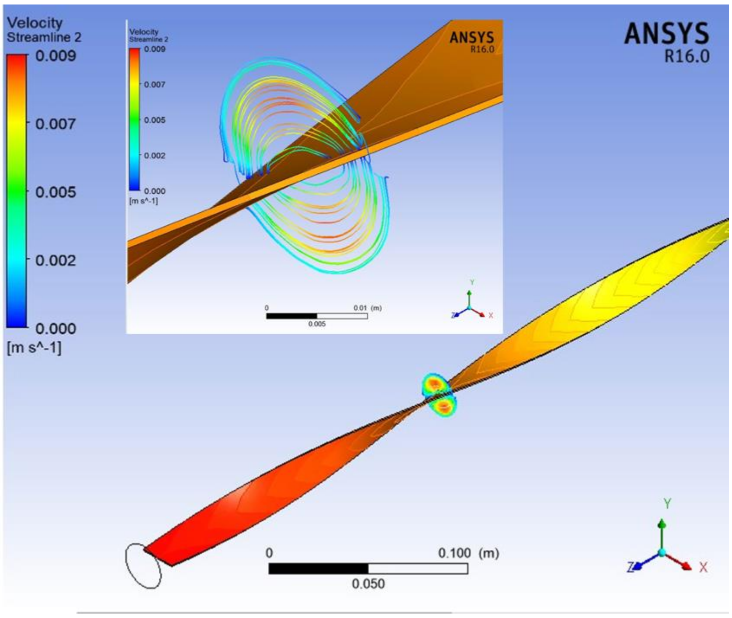


**Figure (16) velocity distribution**

## Entropy generation and exergy:

In a double pipe heat exchanger, exergy and entropy analyses provide critical insights into the system's efficiency and thermodynamic losses. Exergy analysis helps quantify the maximum work potential, allowing assessment of irreversibility's within the exchanger, while entropy generation pinpoints energy losses due to friction, turbulence, and heat transfer inefficiencies. When twisted tape inserts and nanofluids are applied, they enhance heat transfer by creating swirl and increasing thermal conductivity, but they also raise entropy generation due to elevated pressure drops and turbulence. Evaluating exergy and entropy helps in optimizing such enhanced designs, balancing heat transfer gains against potential efficiency losses.

### 1- Entropy:

### Determine Heat Transfer Entropy Generation

$$S_{gen,heat} = \frac{Q}{T_h} - \frac{Q}{T_c}$$

**Where:**

- Q: heat transfer rate across the exchanger
- Th: temperature of the hot fluid (in absolute units, Kelvin)
- Tc: temperature of the cold fluid (in Kelvin)

heat transfer rate across the exchanger calculating by:

$$Q = \dot{m}\,.\,C_p\,.\,\Delta T$$

- m: mass flow rate of the fluid
- cp: specific heat capacity
- ΔT: temperature difference between the inlet and outlet

### Determine Frictional Entropy Generation (due to Fluid Friction)

$$S_{gen,friction} = \frac{\dot{m}.\Delta P}{\rho\,.\,T_{avg}}$$

**Where**:

- m˙˙: mass flow rate
- ρ: fluid density
- Tavg: average temperature of the fluid along the flow path
- ΔP: pressure drop due to the twisted tape in the tube

### Total Entropy Generation

$$S_{gen,total} = S_{gen,heat} + S_{gen,friction}$$

## Result of calculations:

Following a series of mathematical calculations utilizing the experimental data, the results are presented in Table 5.

**Table (5) show the result of expirmantal**

| Flow Rate Cold (L/min) | Q hot (W) | Q cold (W) | S gen total (J/K) |
|---|---|---|---|
| 3 | 1,684,608 | 1684.61 | 24.31 |
| 4 | 1,684,608 | 2246.14 | 32.41 |
| 5 | 1,684,608 | 2807.68 | 40.51 |

### 2- Exergy:

**ambient conditions:**

Reference State $T_{ambient} = 27\ ℃$

Reference pressure=101.3kPa (atmospheric pressure)

**Thermal Exergy Formula:**

$$\dot{E}_{thermal} = \dot{m}.C_p.\left(T_{in} - T_{out} - T_{ref}\, ln\frac{T_{in}}{T_{out}}\right)$$

where TinTin and ToutTout are the inlet and outlet temperatures, TrefTref is the reference temperature, m˙m˙ is the mass flow rate, and CpCp is the specific heat at constant pressure.

### Determine Exergy Loss Due to Friction (Pressure Drop):

$$\dot{E}_{friction} = \dot{m}.\left(\frac{P_{in}}{\rho} - \frac{P_{out}}{\rho} - T_{ref}.\Delta S\right)$$

Here, Pin and Pout are inlet and outlet pressures, ρ is the fluid density, and ΔS is the entropy change across the heat exchanger.

### Total Exergy:

Combine both thermal and friction exergy components:

$$\dot{E}_{total} = \dot{E}_{thermal} + \dot{E}_{friction}$$

## Results and Discussion

The results of this study provide a comprehensive analysis of the thermal performance and entropy generation in a double pipe heat exchanger equipped with twisted tape inserts and utilizing Al2O3/water nanofluid at a concentration of 0.1%. The experimental data indicate a clear enhancement in heat transfer rates due to the introduction of twisted tape, which facilitates improved fluid mixing and promotes turbulent flow.

### 1- Heat Transfer Performance

The Nusselt number (Nu) was significantly higher in the configuration with twisted tape compared to the plain tube setup. For instance, at a flow rate of 3 L/min, the Nusselt number increased from 20.578 (for the plain tube) to 61.1 (for the twisted tape). This corresponds to an impressive enhancement of approximately 195% in heat transfer performance. The turbulent flow regime induced by the twisted tape generates secondary flows that enhance thermal mixing, effectively increasing the contact between the fluid and the heat transfer surfaces.

As the flow rates of both the hot and cold fluids were increased (3, 4, and 5 L/min), a corresponding increase in the Nusselt number was observed. This behavior aligns with the expected performance of heat exchangers, where higher flow rates lead to improved convective heat transfer. The experimental data further confirm that the heat exchanger with twisted tape exhibits superior thermal efficiency compared to conventional designs.

### 2- Pressure Drop and Entropy Generation

The addition of twisted tape inserts also contributed to increased pressure drop across the heat exchanger. The maximum pressure drop recorded for the twisted tape configuration at a flow rate of 5 L/min reached 715 Pa, compared to 395 Pa for the plain tube. While this increase in pressure drop is a concern, it is important to recognize that the enhanced heat transfer performance can justify the higher operational costs associated with pumping power.

Entropy generation analysis revealed that the primary contributions to irreversibilities stem from viscous effects and temperature differences between the hot and cold fluids. The total entropy generation increased with higher flow rates, indicating that while performance improves, there are trade-offs in terms of energy efficiency. The calculations demonstrated that optimizing the flow conditions is crucial for minimizing entropy generation, thus enhancing the overall exergy of the system.

### 3- Exergy Analysis

The exergy analysis indicated that the use of Al2O3/water nanofluid not only improved heat transfer but also highlighted the potential for better energy utilization within the heat exchanger. The calculated exergy values showed that the system's efficiency could be optimized further by adjusting the operational parameters, particularly the flow rates of the fluids and the concentration of the nanofluid.

In summary, the results illustrate that integrating twisted tape inserts and utilizing nanofluids can substantially enhance the thermal performance of double pipe heat exchangers. However, the increases in pressure drop and entropy generation necessitate careful consideration to ensure the overall system efficiency is maximized. Further investigations into various twisted tape configurations and operational parameters could provide additional insights into achieving optimal performance in practical applications.

## Conclusions

This study investigated the thermal performance and entropy generation in a double pipe heat exchanger incorporating twisted tape inserts and utilizing Al2O3/water nanofluid at a concentration of 0.1%. The experimental results indicated that the inclusion of twisted tape significantly enhanced heat transfer rates, as evidenced by the substantial increase in the Nusselt number compared to a plain tube configuration. The analysis revealed that the effective mixing induced by the twisted tape led to improved thermal performance, characterized by higher heat transfer coefficients and reduced thermal resistance.

The entropy generation analysis highlighted the critical role of flow rates and temperature differentials in the overall performance of the heat exchanger. Increased flow rates of both hot and cold fluids correlated with enhanced thermal efficiency, while also resulting in higher pressure drops due to the additional friction introduced by the twisted tape. However, the exergy analysis revealed that the system's efficiency could be further optimized by balancing the operational parameters to minimize irreversibility's.

Overall, this research confirms that employing twisted tape inserts and nanofluids in heat exchangers can lead to significant improvements in thermal performance, but careful consideration of the associated pressure drops and exergy losses is necessary to achieve optimal operational efficiency. Future work may focus on exploring various twisted tape designs and fluid concentrations to further enhance the performance of heat exchangers in practical applications.

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