

# Influence of Hybrid Nanofluid on the Enhancement of Heat Transfer in a Heat Exchanger with Tape Inserts

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**Abstract:** The thermohydraulic performance of a shell-and-tube heat exchanger (STHX) is explored utilizing a combined heat transfer enhancement strategy that includes twisted tape inserts, helical baffles, and hybrid nanofluids. Graphene oxide (GO), GO-SiO<sub>2</sub>, and GO-TiO<sub>2</sub> hybrid nanofluids are chosen for their better thermophysical characteristics. A numerical research is carried out for a STHX fitted with helical baffles inclined at an optimal angle of 40° to analyze heat transfer enhancement and flow characteristics. In parallel, experiments are carried out on the tube side using twisted tape inserts with pitches of 50, 100, 150, and 200 mm to isolate the effect of swirl-induced turbulence. The experimental findings show that the Nusselt number increases by up to 31.21% when compared to the standard arrangement, with optimal thermo-hydraulic performance reached at a twisted tape pitch of 150 mm, according to performance evaluation criterion (PEC) analysis. The combination of hybrid nanofluids, twisted tape inserts, and helical baffles has been shown to be a viable technique for improving heat transfer performance while minimizing hydraulic penalties. The findings of this study give valuable design insights for increasing the efficiency of shell-and-tube heat exchangers in real-world thermal engineering applications.

**Keywords:** Hybrid Nanofluids; Nusselt Number, Friction Factor, PEC etc.

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## I. INTRODUCTION

In this century, providing effective cooling and maintaining the required temperature using a typical heat exchanger is the most challenging task. Nanofluid is an alternate working medium in traditional heat exchangers that achieves good cooling and temperature control. The thermal conductivity of the working fluid is improved by suspending

meat particles in a working medium with a higher thermal conductivity than the fluids. There are several criteria for providing optimal functioning and desired temperature in a variety of applications, including thermal power plants, food processing, chemical, and pharmaceutical industries, as well as refrigeration and air conditioning units.

➤ *Nomenclature:*

Symbol	Description	Unit
(A)	Heat transfer area	m <sup>2</sup>
(Cp)	Specific heat capacity	J·kg <sup>-1</sup> ·K <sup>-1</sup>
(D)	Inner diameter of tube	m
(f)	Friction factor	–
(h)	Convective heat transfer coefficient	W·m <sup>-2</sup> ·K <sup>-1</sup>
(k)	Thermal conductivity of fluid	W·m <sup>-1</sup> ·K <sup>-1</sup>
( $\dot{m}$ )	Mass flow rate	kg·s <sup>-1</sup>
(Nu)	Nusselt number	–
PEC	Performance evaluation criterion	–
(Q)	Heat transfer rate	W
(Re)	Reynolds number	–
(T <sub>in</sub> )	Inlet temperature	K
(T <sub>out</sub> )	Outlet temperature	K
( $\Delta T_{lm}$ )	Log mean temperature difference	K

Despite this, the effect of nanofluids is examined in relation to past publications by many writers. Mezaache et al. [2025][1] investigated nanofluid flow in wavy channels partially embedded with porous materials. The study evaluated packed granular media and metal foam materials, examining the impact of porous layer thickness ( $\delta$ ) and Reynolds number (Re). The study found that packed granular media performed better thermally, especially at higher  $\delta$  and Re. This highlights the need of customized porous integration for optimal entropy formation and heat dissipation. The thermal behaviour and stability of  $\text{MnCoFeO}_4/\text{H}_2\text{O}$  nanofluid in a twin pipe heat exchanger were investigated experimentally by Mousazadeh et al. [2025][2]. The study found that higher nanoparticle concentration and flow rates greatly enhanced heat transfer—up to a 40% improvement—with only slight increases in pressure drop and friction factor, demonstrating the system's feasibility for real-world thermal systems. Zeta potential and visual inspection were used for stability validation. Using Cu-W and  $\text{Al}_2\text{O}_3$ -W nanofluids, Balakrishnan et al. [2025][3] investigated the function of nanoparticle concentration in shell and tube heat exchangers. A 0.12 weight percent addition of nanoparticles increased the thermal conductivity of Cu and  $\text{Al}_2\text{O}_3$  nanofluids by 29% and 39%, respectively, without using any surface treatment. Notably,  $\text{Al}_2\text{O}_3$  showed a better pressure drop profile, showing its benefit in low-resistance uses.

Saravanan and Sureshkumar [2025][4] performed a numerical study on green nanofluids generated from *Azadirachta indica* and *Melia composita* for usage in helically coiled tube heat exchangers. The results showed that *Melia*-based nanofluids had improved thermal performance. ANSYS simulations confirmed experimental findings, highlighting the environmental and thermal advantages of green-synthesized nanoparticles. Anjaneya et al. [2024][5] used computational fluid dynamics (CFD) to compare  $\text{Fe}_3\text{O}_4$ -water and MWCNT-water nanofluids in microchannel heat exchangers for electronic cooling. Simulations in five- and eight-channel topologies revealed that 0.2% MWCNT nanofluid dramatically lowered the system's peak temperature, indicating greater thermal regulation capabilities in nanoscale cooling systems. Jasim et al. [2024][6] conducted numerical simulations of hybrid nanofluid flow in a shell-and-double coil heat exchanger using  $\text{TiO}_2$ - $\text{MgO}$ /water and AG-HEG/water.  $\text{TiO}_2$ - $\text{MgO}$  nanofluid beat AG-HEG in thermal performance, owing to improved turbulence and convective flow. Increasing the concentration increased the rate of heat transfer.

Mohadjer et al. [2024][7]. This work analyzed thermohydraulic behaviour in tubular heat exchangers using twisted tape turbulators and water- $\text{TiO}_2$  nanofluids. Although the Nusselt number improved by up to 65.1%, pressure decreases increased dramatically. In other circumstances, total system efficiency was lowered by up to 11.8%, underscoring the need of turbulator tuning. Al-Obaidi et al. [2024]. [8] A systematic analysis of hybrid nanofluids in heat exchangers found CuO-Cu/water to be highly efficient. However, concerns such as particle agglomeration and higher viscosity were raised. To get the best results, the study suggested mixing hybrid nanofluids with turbulence-

enhancing geometries. Babar et al. [2024][9]. This bibliometric and scientific review looked at improved nanofluids and heat exchanger upgrades such as fins, grooves, and magnetic field applications. These changes considerably improved heat transmission, but typically came at the price of increased pressure drop. The study laid out future research areas in small thermal management, particularly for electric cars and high-performance electronics.

Using ANSYS Fluent, Ali et al. [2023][10] investigated the effect of ZnO-water nanofluids on the thermal efficiency of a shell and tube heat exchanger. Nanoparticle volume fractions of 0.2% and 0.35% improved the Nusselt number by 10% and 19%, respectively. Friction factor increases were marginal, confirming enhanced thermal performance across Reynolds numbers from 200 to 1400. Tavousi et al. [2023][11] used  $\text{Al}_2\text{O}_3$ -water nanofluid. Using ANSYS Fluent, this simulation research investigated how ZnO-water nanofluids affect the thermal efficiency of a shell and tube heat exchanger. The Nusselt number increased by 10% and 19% when the nanoparticle volume fraction was 0.2% and 0.35%, respectively. Friction factor increases were minor, showing improved thermal performance spanning Reynolds numbers 200 to 1400. Zafar et al. (2023) [12] This thorough analysis focused on nanofluid performance in cavity-based thermal systems, including natural convection, inclined enclosures, and magnetohydrodynamic effects. The study highlighted the importance of nanoparticle type, volume percentage, and cavity design, indicating circular cavities as the most thermally efficient. Nanofluids significantly improved heat transmission in all of the applications tested.

In a study conducted by Karikalan et al. [2022][13], CNT-based nanofluids in shell and tube heat exchangers were evaluated experimentally and numerically. Varying volume fractions and temperatures revealed significant enhancements in thermal conductivity and specific heat capacity. CNT nanofluids also showed promise for reducing  $\text{CO}_2$ ,  $\text{NO}_2$ , and  $\text{SO}_2$  emissions in industrial systems, supporting environmental sustainability. Shahsavari et al. [2021][14] An experimental and numerical research was conducted to evaluate CNT-based nanofluids in shell and tube heat exchangers. Thermal conductivity and specific heat capacity increased significantly when volume fractions and temperatures varied. CNT nanofluids have shown potential in lowering  $\text{CO}_2$ ,  $\text{NO}_2$ , and  $\text{SO}_2$  emissions in industrial systems, promoting environmental sustainability. Wen et al. [2021][15] investigated microchannel heat sinks with serrated fins using ZnO-ethylene glycol/water nanofluids at concentrations of 0.75% and 1.5%. Thermal conductivity increased by 4.2%, while Nusselt numbers grew by 10.6% and 13.2%, respectively. Predictive ANN models accurately estimated thermal performance measures, even with increasing viscosity and friction factors (MARD < 0.4%).

Vinton and Sachuthananthan [2021][16] tested microchannel heat sinks with pentagonal and triangular profiles. They used hybrid nanofluids including  $\text{Al}_2\text{O}_3$  and CuO distributed in DI water. Experiments under 50  $\text{kW/m}^2$  heat flow showed that the pentagonal design was 21.12% more efficient than the triangular equivalent. The hybrid

nanofluid had greater heat transmission and a lower pressure drop, however nanoparticle sedimentation was seen after 36 hours. Heidarshenas et al. [2021][17] conducted an experiment using ionic liquid-coated  $\text{Al}_2\text{O}_3$  nanoparticles in cylindrical microchannel heat sinks. At 0.1% concentration and Reynolds numbers ranging from 400 to 1200, the 50 nm particle size produced the greatest results, with up to 26% improvement in Nusselt number compared to water. Stability was verified using zeta potential and sedimentation analysis. Alnaqi et al. [2021][18] simulated a zigzag microchannel heat sink using MWCNT-SiO<sub>2</sub> hybrid nanofluids in an EG-water basis. Increased flow velocity and channel length improved heat dissipation. Although thermal performance was enhanced, greater nanoparticle concentrations increased viscosity and pumping power requirements, showing a trade-off between performance and energy consumption.

In a study by Gugulothu and Sanke [2022][19], helical baffles at angles of 20°, 30°, and 40° were used alongside nanofluids ( $\text{Al}_2\text{O}_3$ , CuO, SiO<sub>2</sub>). The 5%  $\text{Al}_2\text{O}_3$  nanofluid with 40° baffles had the highest performance, with up to 10.33% increase in heat transfer compared to water. The helical baffle configuration consistently outperformed segmental baffles across all volume concentrations. Anil Kumar et al. [2021][20] combined numerical and the 5%  $\text{Al}_2\text{O}_3$  nanofluid with 40° baffles outperformed water by up to 10.33% in terms of heat transmission. The helical baffle design consistently beat segmental baffles at all volume concentrations. Saleh and Sundar [2021][21] studied the thermohydraulic and exergy performance of a corrugated plate heat exchanger using Ni/water nanofluids. At 0.6% volume concentration and  $\text{Re} = 707$ , the Nusselt number increased by 42.68%, and exergy efficiency increased by 42.27%. However, increased friction and viscosity reduced the performance index ratio due to increased pumping power requirements. At 0.6% volume concentration and  $\text{Re} = 707$ , the Nusselt number improved by 42.68%, while exergy efficiency increased by 42.27 percent. However, higher friction and viscosity lowered the performance index ratio due to increased pumping power needs.

In a study by Satish Kumar et al. [2020][22], the heat transfer performance of magnetohydrodynamic (MHD) hybrid nanofluids over a stretching surface under thermal radiation effects was numerically investigated. The base fluid was water, and nanoparticles included Cu- $\text{Al}_2\text{O}_3$  mixed with Single Wall Carbon Nanotubes (SWCNTs). Cu-based nanofluids demonstrated superior heat transfer (higher Nusselt number) and lower flow resistance compared to  $\text{Al}_2\text{O}_3$ -based fluids. Ahmed F. et al. [2021][23] The base fluid was water, and the nanoparticles were Cu- $\text{Al}_2\text{O}_3$  combined with SWCNTs. Cu-based nanofluids have better heat transfer (higher Nusselt number) and lower flow resistance than  $\text{Al}_2\text{O}_3$ -based fluids. Ahmed F. et al. [2021][24] studied the thermo-hydraulic behavior of  $\text{Al}_2\text{O}_3$ , TiO<sub>2</sub>, and Graphene Oxide nanofluids in water at different concentrations (1%, 2%, and 4%) using triangular sub-channels. The  $\text{Al}_2\text{O}_3$ -water nanofluid at 4% volume concentration demonstrated optimum heat transfer and hydraulic efficiency. Hussein et al. [2021][25] investigated shell-and-helically coiled tube heat exchangers using  $\text{Al}_2\text{O}_3$  and SiO<sub>2</sub> nanofluids. Various

inclination degrees (0°, 30°, 60°, and 90°) were examined. At 0.1% volume concentration, the coil-side Nusselt number increased by 11% for water, 8.3% for  $\text{Al}_2\text{O}_3$ , and 7.5% for SiO<sub>2</sub> nanofluids, suggesting improved heat transport with nanoparticle inclusion.

Mohammad Fares et al. [2020][26] employed 0.2 wt.% graphene-water nanofluids in vertical shell-and-tube heat exchangers, resulting in a 29% increase in heat transfer and 13.7% increase in total thermal efficiency. Mohammad Hojjat et al. [2020][27] investigated the heat transfer behaviour of TiO<sub>2</sub> and  $\text{Al}_2\text{O}_3$  nanofluids in STHX systems using both computational and experimental approaches. Using artificial neural network (ANN) modelling, they discovered that the Nusselt number increased by 30% while the pressure drop fell by 10% when compared to base fluids. Amol F. Niwalkar et al. [2019][27] investigated SiO<sub>2</sub>-water nanofluids in a helically coiled heat exchanger. The HTC increased by 28.71%, while the friction factor increased with greater mass flow rate and volume concentration.

The current study is to assess the thermo-hydraulic performance of a shell-and-tube heat exchanger using a combined improvement technique. Numerical studies are conducted for hybrid nanofluids (GO, GO-SiO<sub>2</sub>, and GO-TiO<sub>2</sub>) in a STHX with helical baffles inclined at an optimal angle of 40°. Furthermore, experimental investigations are carried out utilizing twisted tape inserts with varied pitches on the tube side under identical operating circumstances, but without nanofluids, to isolate the influence of swirl-induced turbulence. The study focuses on heat transfer enhancement, pressure drop characteristics, and overall performance assessment using the performance evaluation criteria (PEC). The current study is unique in that it evaluates hybrid nanofluids, twisted tape inserts, and helical baffles all in the same shell-and-tube heat exchanger arrangement.

## II. NUMERICAL METHODOLOGY

The numerical study is carried out on STHXs at different mass flow rates of working fluid. Helical baffles are placed at a 40-degree angle on the shell side, while twist tapes are put on the tube side. The numerical analysis is carried out using ANSYS R24/25, with appropriate boundary conditions.

### ➤ Heat Exchanger Configuration

The STHXs have a single shell-pass and a single tube-pass at the shell and tube of the heat exchanger, respectively. A cylindrical shell has four bundles of circular tubes. Twisted tape inserts are put within the tubes to improve tube-side heat transmission, while helical baffles angled at 40° are attached on the shell side to encourage crossflow and equal fluid distribution. The exterior diameters of the tube and shell are 25.40 mm and 109.94 mm, respectively. The inner diameters of HX tubes and shells are 20.32mm and 101.10mm, respectively. The pitch is specified as 31.75 mm. The hydraulic diameter is measured at 25.13mm as shown in the figure 1.

➤ *Twisted Tape Inserts*

Twisted tape inserts with pitches of 50, 100, 150, and 200 mm developed and inserted into the tubes. The variation in pitch allows for controlled modification of swirl intensity and turbulence generation within the tube-side flow as shown in the figure 1 and 2.

➤ *Nanofluids*

High thermal conductivity materials are added to the base fluid to improve the working fluid properties. In the

current study, hybrid nano particles are used as a medium at the tube side to transport heat from the shell side fluid. Graphine oxide (GO), graphine oxide and silicon dioxide (GO-SiO<sub>2</sub>), and graphine oxide and titanium dioxide (GO-TiO<sub>2</sub>) are utilized as hybrbird nanofluids. All thermal and physical properties of the hybrid nanofluid are estimated using expresssriion.

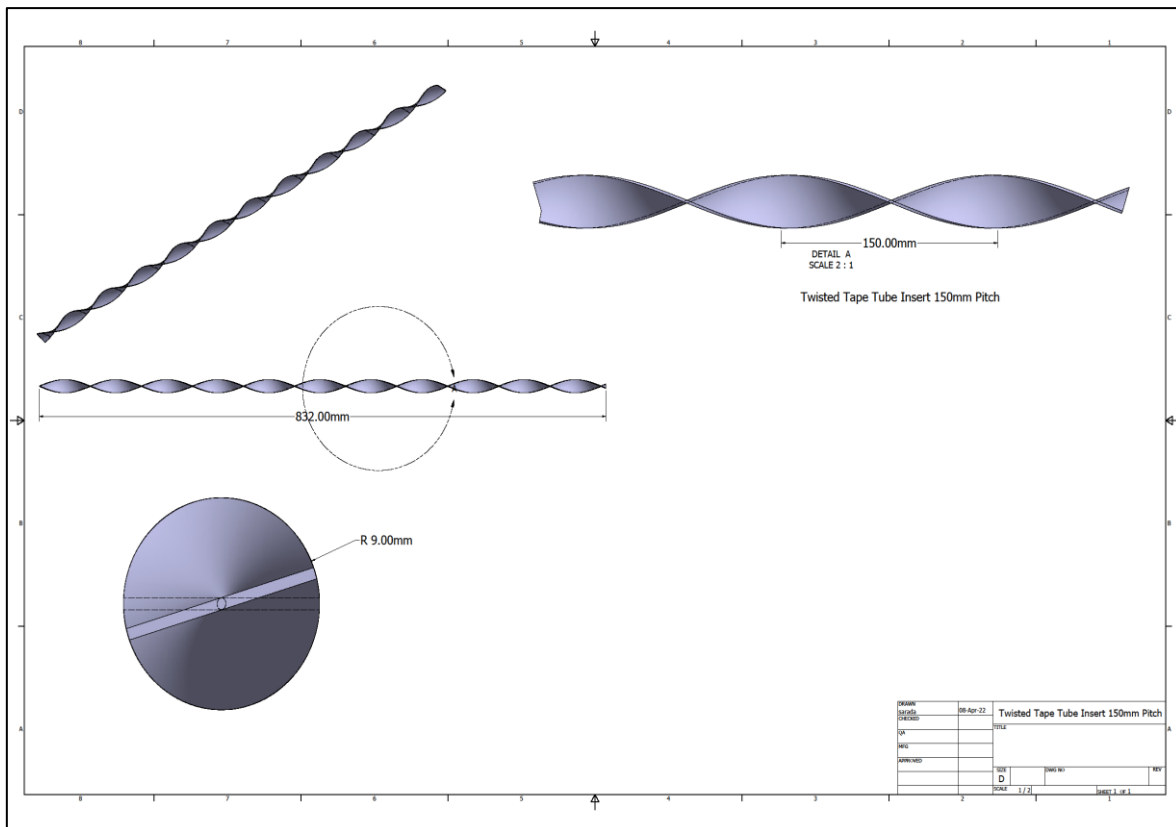


Fig 1 Twist Tape Inserts with Various Pitches

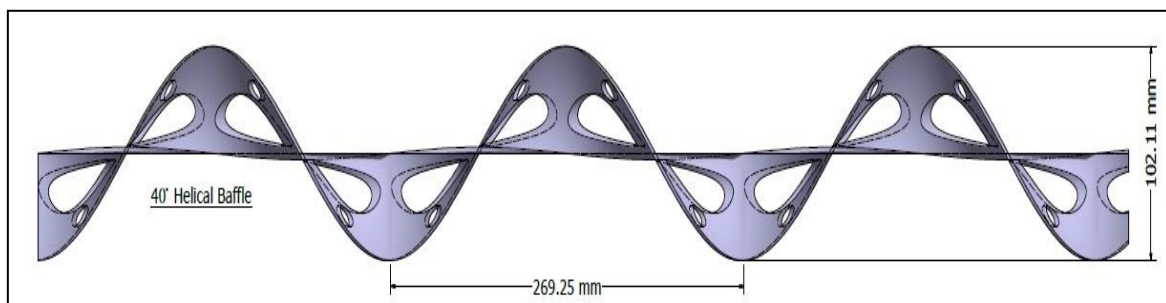


Fig 2 Helical Baffles with an Angle of 40°

➤ *Generation of Mesh and Grid Independence Test*

The mesh is built with various element sizes to predict an accurate solution in mesh modular. The element size varies from m to m (with nodes ranging from 0.5 million to 3.28 million). At 3.28 million nodes, the cold and hot outlet temperatures have stabilized. As a consequence of analyzing

the grids and taking the findings into account, 3.28 million nodes with element sizes of 0.001 m are considered optimal grids, and subsequent simulations are run using that grid system. Figure 4 depicts the average orthogonal quality of 0.83, skewness of 0.22, and aspect ratio of 2.62 shown in figure3.

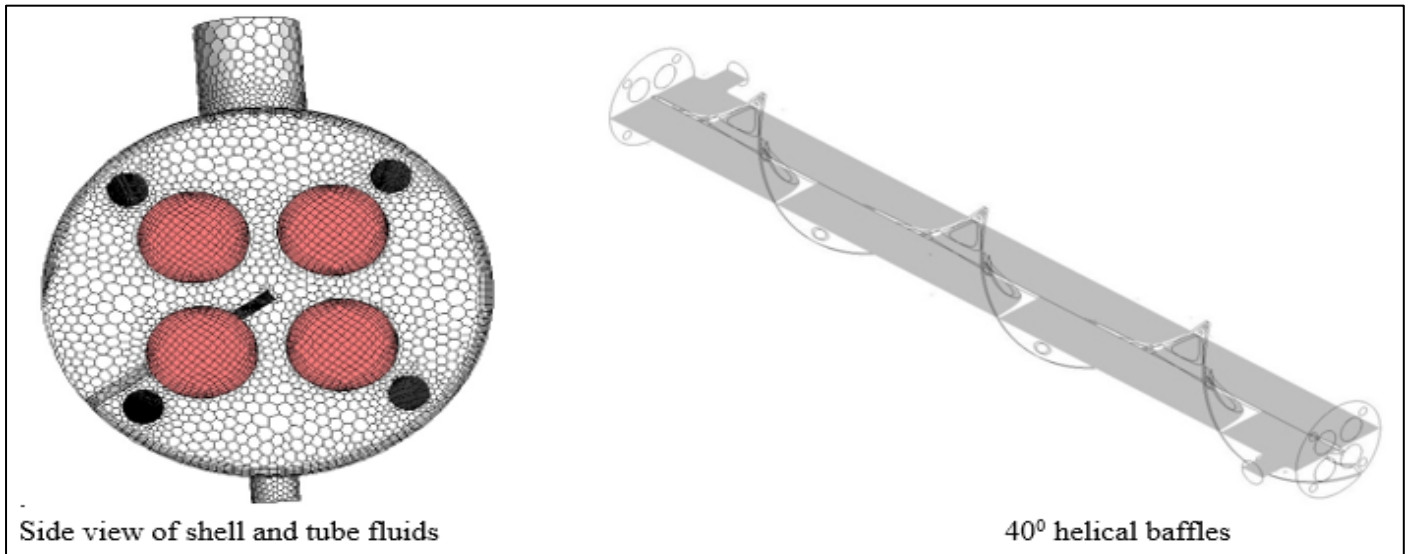


Fig 3 Mesh Generated for STHXs

➤ *Governing Equations*

The simulation model utilizes k-ε turbulence models to provide accurate and optimal results. It enhances wall flow, vortex production, fluid rotation, and so forth. This analysis

takes into account both steady-state heat transfer and turbulent in-compressible fluid flows. The governing equations are as follows, solved with boundary conditions [28, 29, 30]:

$$\text{Law of Conservation of Mass: } \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\text{Navier-Stokes equations: } \frac{\partial(\rho u_i u_k)}{\partial x_i} + \frac{\partial p}{\partial x_k} = \frac{\partial\left(\mu \frac{\partial u_k}{\partial x_i}\right)}{\partial x_k} \tag{2}$$

$$\text{Steady flow energy equation: } \frac{\partial(\rho u_i t)}{\partial x_i} = \frac{\partial\left(\frac{k}{C_p} \frac{\partial t}{\partial x_i}\right)}{\partial x_i} \tag{3}$$

Transport Equation:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial\left(\frac{\alpha_k \mu_{eff} \partial k}{\partial x_j}\right)}{\partial x_j} + G_k + \rho \varepsilon \tag{4}$$

Transport equation for dissipation:

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial\left(\frac{\alpha \varepsilon \mu_{eff} \partial \varepsilon}{\partial x_j}\right)}{\partial x_j} + \frac{G_k \varepsilon C_{1\varepsilon}^*}{k} - \frac{C_{2\varepsilon} \varepsilon^2 \rho}{k} \tag{5}$$

Where,

$$\mu_{eff} = \mu + \mu_t, \mu_t = \rho \frac{k^2}{\varepsilon} c_\mu, C_{1\varepsilon}^* = C_{1\varepsilon} - \frac{\eta \left(1 - \frac{\eta}{\eta_0}\right)}{1 + \beta \eta^3}, \eta = \frac{k}{\varepsilon} (E_{ij} 2E_{ij})^{0.5}, E_{ij} = \frac{1}{2} \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right]$$

The observed empirical values are as follows [31][32][33]:

$$C_{\mu} = \frac{845}{10,000}, C_{1\varepsilon} = \frac{142}{100}, C_{2\varepsilon} = \frac{168}{100}, \beta = \frac{12}{1000}, \eta_0 = \frac{438}{100}, \alpha_{\varepsilon} = \alpha_k = \frac{139}{100}$$

$$\text{Volume flow rate in Shell side} = \frac{\text{liter per minute}}{60 \times 1000} \frac{m^3}{s} \tag{6}$$

$$\text{Mass flow rate at Shell side} \left( \frac{kg}{s} \right) = \text{volume flow rate}$$

$$\left( \frac{m^3}{s} \right) * \text{Density} (\rho_s) \left( \frac{kg}{m^3} \right) \tag{7}$$

$$\text{Velocity of fluid in shell side [70]} V_s = \frac{\dot{m}_s}{\rho_s A_s} \frac{m}{s} \tag{8}$$

$$\text{Heat capacity rate at Shell side [187]} C_h = \dot{m}_h C_{p,h} \tag{9}$$

$$\text{Tube side volume flow rate} = \frac{\text{liter per minute}}{60 \times 1000} \frac{m^3}{s} \tag{10}$$

$$\text{Tube side mass flow rate} \left( \frac{kg}{s} \right) = \text{volume flow rate} \left( \frac{m^3}{s} \right) \times \text{Density} (\rho_t) \left( \frac{kg}{m^3} \right) \tag{11}$$

$$\text{Heat capacity rate can be expressed as [37]} C_c = \dot{m}_c C_{p,c} \tag{12}$$

$$\text{Capacity ratio [113]} C^* = \frac{(mC_p)_{\min}}{(mC_p)_{\max}} \tag{13}$$

$$\text{NTU is [113][187]} NTU = \frac{UA_0}{(mC_p)_{\min}} \tag{14}$$

$$\varepsilon = \frac{1 - e^{-NTU(1-C^*)}}{1 - C^* e^{-NTU(1-C^*)}} \tag{15}$$

Heat exchanger effectiveness expressed as follows:

$$\varepsilon = \frac{2}{\left[ 1 + C^* + \sqrt{1 + C^{*2}} \times \frac{1 + e^{-NTU \sqrt{1 + C^{*2}}}}{1 - e^{-NTU \sqrt{1 + C^{*2}}}} \right]} \tag{16}$$

$$\text{To calculate unknown parameter } \varepsilon = \frac{(mC_p)_{\min}}{T_{h,i} - T_{c,i}} = \frac{T_{c,2} - T_{c,i}}{T_{h,i} - T_{c,i}} \tag{17}$$

$$\text{Cold fluid outlet temperature } T_{c,o} = T_{c,i} + \varepsilon(T_{h,i} - T_{c,i}) \tag{18}$$

$$\text{The outlet temperature of hot fluid is } T_{h,o} = T_{h,i} - \left( \frac{(mC_p)_c}{(mC_p)_h} \times (T_{c,o} - T_{c,i}) \right) \tag{19}$$

$$\text{Hot fluid bulk temperature [34, 35, 36]} T_{h,b} = \frac{T_{h,i} + T_{h,o}}{2} \tag{20}$$

$$\text{Cold fluid bulk temperature [37, 38, 39, 40]} T_{c,b} = \frac{T_{c,i} + T_{c,o}}{2} \tag{21}$$

➤ *Boundary Condition:*

Tube side flow rates ranged from 0.23 to 0.43 kilogram per second. Shell side flow rates are measured in litres per minute, and the total heat transfer coefficient is assumed to be 1000 [41, 42, 43, 44].

- Fluid temperature on the shell side (hot).
- Fluid temperature on the tube side (cold).
- The fluid on the shell side is heated.
- Cold fluid on the tube side.

➤ *Data Reduction and Governing Equations*

The heat transfer rate was determined using the temperature differential and flow parameters. The heat transfer coefficient was calculated as follows [45, 46, 47]:

The heat transfer rate is computed as follows:

$$Q = \dot{m} C_p (T_{out} - T_{in})$$

The heat transfer coefficient is determined by:

$$h = Q / (A \Delta T_{lm})$$

The Nusselt number is computed as:

$$Nu = hD / k$$

The performance evaluation criteria (PEC) is evaluated as follows:

$$PEC = (Nu / Nu_0) / (f / f_0)^{1/3}$$

Where the subscript “0” refers to the baseline heat exchanger configuration without twisted tape inserts.

### III. RESULTS AND DISCUSSION

The numerical analysis of STHXs is performed using ANSYS Fluent R24/25, with fluid mass flow rates at the tube side ranging from 0.23 to 0.43 kg/s. hybrid nano fluids with 5% volume concentration is used as a coolant at tube side of heat exchanger. Also, a twist tape with pitch of 150mm is inserted at tube side to develop mixing strength of fluid which is caused for enhancement of heat transfer. It is assessed using

thermohydraulic metrics such as the heat transfer coefficient, Nusselt number, thermal efficiency, performance evaluation criteria, pressure drop, and friction factor.

➤ *Variation of Heat Transfer Coefficient and Nu with Mass Flow Rate:*

Figure 4 and 5, illustrates the variation of the heat transfer coefficient (HTC) and Nusselt number (Nu) with mass flow rate for a twisted tape pitch of 150 mm using hybrid nanofluids at a volume concentration of 5%. Both HTC and Nu increase consistently with increasing mass flow rate for all investigated nanofluid configurations due to enhanced turbulence intensity and improved convective heat transfer. Among the working fluids considered, the GO–TiO<sub>2</sub> hybrid nanofluid exhibits the highest HTC and Nu values, which can be attributed to its superior thermal conductivity combined with swirl-induced mixing generated by the twisted tape inserts.

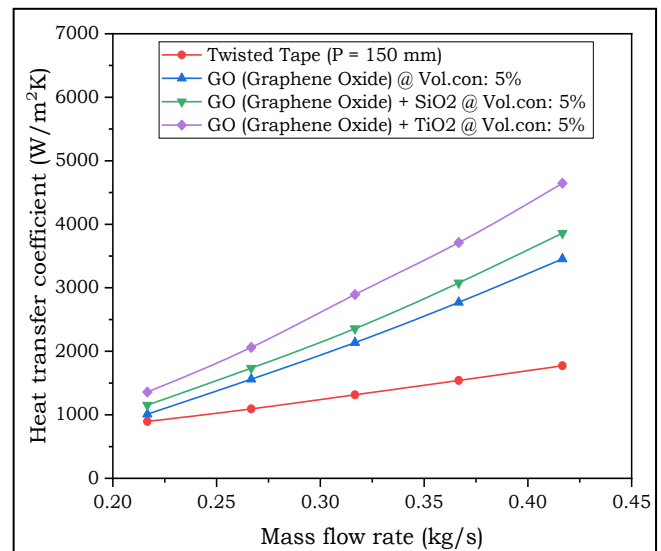


Fig 4 HTC vs Mass Flow Rate

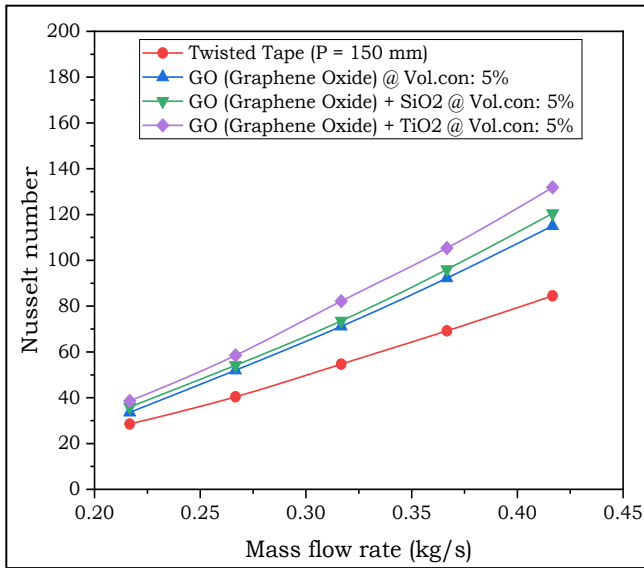


Fig 5 Nu vs Mass Flow Rate

➤ *Variation of Thermal Performance and Performance Evaluation Criterion:*

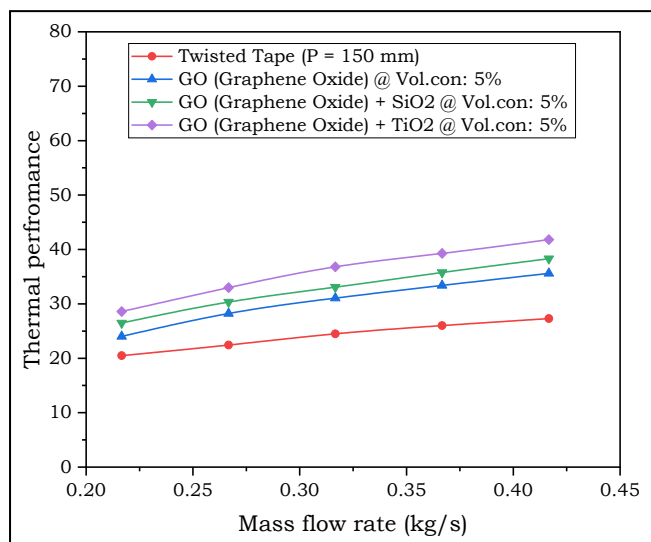


Fig 6 Thermal Performance vs Mass Flow Rate

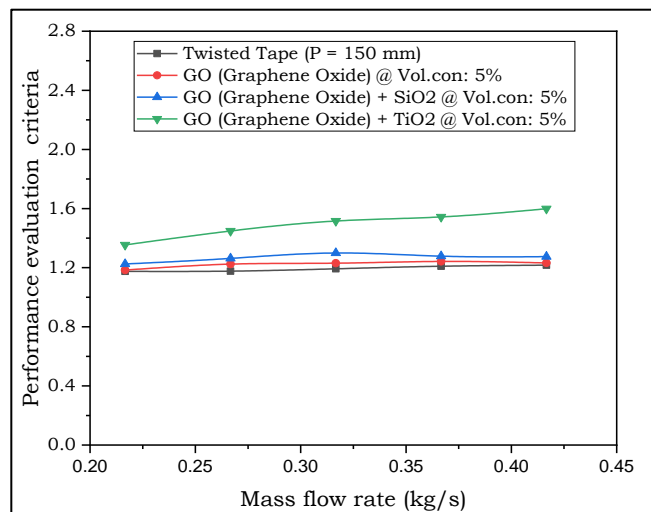


Fig 7 Performance vs Mass Flow Rate

Figure 6 and 7 shows the variation of thermal performance (TP) and performance evaluation criterion (PEC) with mass flow rate for the shell-and-tube heat exchanger. Both TP and PEC increase with increasing mass flow rate due to enhanced fluid mixing and stronger secondary flow generated by the twisted tape inserts at higher velocities. The application of hybrid nanofluids further improves TP and PEC, with the GO–TiO<sub>2</sub> nanofluid at a 5% volume concentration exhibiting the highest enhancement owing to its superior thermo-physical properties. Compared with the base fluid, the PEC increases by 1.31%, 5.08%, and 23.63% for GO, GO–SiO<sub>2</sub>, and GO–TiO<sub>2</sub> nanofluids, respectively. These results demonstrate the strong synergistic effect of twisted tape inserts and hybrid nanofluids on overall thermo-hydraulic performance.

➤ *Variation of Pressure Drop and Friction Factor Analysis:*

Figure 8 and 9 illustrates the variation of pressure drop and friction factor with mass flow rate for different hybrid nanofluids. Both parameters increase with mass flow rate due to higher fluid viscosity and intensified turbulence resulting from nanoparticle addition. Compared with the base fluid, the friction factor increases by 4.61%, 11.64%, and 18.29% for GO, GO–SiO<sub>2</sub>, and GO–TiO<sub>2</sub> nanofluids, respectively. Although the use of hybrid nanofluids leads to increased hydraulic resistance, the associated penalty is justified by the significant enhancement in heat transfer performance.

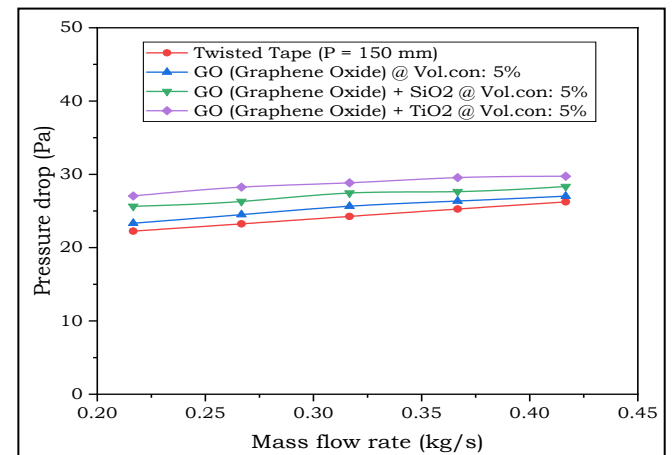


Fig 8 Pressure Drop vs Mass Flow Rate

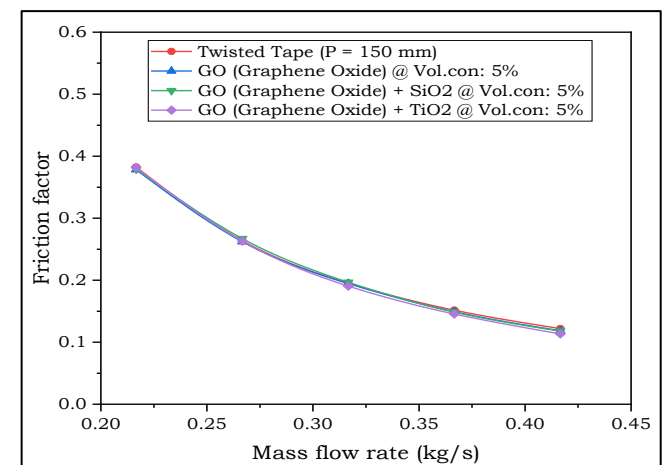


Fig 9 FF vs Mass Flow Rate

The observed trends are consistent with previous studies reported in the literature, confirming the reliability of the experimental results.

#### IV. CONCLUSIONS

An experimental investigation was conducted to evaluate the thermo-hydraulic performance of a shell-and-tube heat exchanger equipped with twisted tape inserts, hybrid nanofluids, and helical baffles. The following conclusions are drawn:

- The application of hybrid nanofluids significantly enhances heat transfer performance, with the GO–TiO<sub>2</sub> hybrid nanofluid exhibiting the highest enhancement at a volume concentration of 5%.
- Both the heat transfer coefficient and Nusselt number increase with increasing mass flow rate and nanoparticle concentration, while the associated increase in pressure drop remains within acceptable limits. It is due to the mixing of fluid.
- Twisted tape inserts effectively induce swirl flow and turbulence, resulting in substantial heat transfer enhancement compared with the plain tube configuration.
- Performance evaluation criterion (PEC) analysis indicates that a twisted tape pitch of 150 mm provides the optimal balance between heat transfer enhancement and hydraulic penalty.
- The combined implementation of helical baffles inclined at 40°, twisted tape inserts with a pitch of 150 mm, and a GO–TiO<sub>2</sub> hybrid nanofluid yields the highest overall thermo-hydraulic performance.

#### FUTURE SCOPE

Future research may focus on experimental validation of hybrid nanofluid performance under long-term operating conditions, including stability, fouling, and material compatibility. Further investigations could explore alternative hybrid nanoparticle combinations, lower volume concentrations for cost optimization, and the influence of twisted tape geometry variations. In addition, transient flow analysis and scale-up studies under industrial operating conditions would provide valuable insights for practical implementation.

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