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Heat Transfer Analysis and Friction Factor of Ternary Nanofluids with Twisted Tape Inserts

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ABSTRACT

This study investigates the heat transfer efficiency and friction factor of ternary nanofluids (Al_2O_3-TiO_2-SiO_2) in a simple tube equipped with a twisted tape. Ternary nanofluids, prepared using a volume-based composition ratio of 20:16:64, were tested at various volume concentrations ranging from 0.5% to 3.0%. Forced convection heat transfer experiments were conducted under varying Reynolds numbers (2,300 to 12,000) and a bulk temperature of 70 °C. The results indicate that the maximum viscosity occurs at a volume concentration of 3.0%. The highest increase in heat transfer for ternary nanofluids in a simple tube with twisted tape (H/D = 2.0) was achieved at a volume concentration of 3.0%, reaching 225.35%. Compared to a plain tube, the average thermal performance factor (TPF) of the twisted tape was significantly improved, with a further increase observed when the volume concentration rose from 2.73% to 3.22%.

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1. INTRODUCTION

Hybrid nanofluids are a new type of nanofluid that need additional research. Literature divides the language of hybrid nanofluids into two major research topics: binary and ternary nanofluids. However, in prior investigations, the word hybrid was used to describe binary nanofluids (Bahrami et al., 2016; Boroomandpour et al., 2020; Jung et al., 2011; Lee et al., 2010; Zeng & Xuan, 2018). Binary nanofluids are mostly used for heat transfer due to their ability to give ideal properties for the majority of their constituents. Binary nanofluids are thought to be an extension of mono nanofluids, in which two or more nanoparticles are suspended or dispersed in a single base fluid (Sarkar et al., 2015). In heat transfer applications, binary nanofluids perform better than conventional fluids and mono nanofluids due to their notable improvement in thermo-physical and heat transfer capacities (Akbaridoust et al., 2013; Goudarzi & Jamali, 2017; Guo et al., 2008; A. I. Ramadhan et al., 2022).

Mousavi, Esmaeilzadeh, and Wang (Mousavi et al., 2019) started the study of hybrid nanofluids by mixing three distinct nanoparticles into base fluids known as ternary nanofluids. Compared to current mono and binary nanofluids, ternary nanofluids are designed to enhance thermo-physical properties significantly more (Adun et al., 2021; Kashyap et al., 2021; Mousavi et al., 2019). In order to assess the heat transfer capacities for use in thermal engineering systems, a number of researchers looked at ternary nanofluids by examining their capacity to maintain improved stability, characterization, and thermo-physical properties (ADUN et al., 2021; Dezfulizadeh, Aghaei, Hassani Joshaghani, et al., 2021; Kumar & Sahoo, 2022; Kundan & Darshan, 2022; Mousavi et al., 2019; Sahoo, 2021). By distributing into multiple base fluids, the ternary nanofluid preparation employs a composition of three nanoparticles derived from metal and metal oxide.

In order to study the thermo-physical characteristics of ternary nanofluids, Mousavi, Esmaeilzadeh, and Wang (Mousavi et al., 2019) added three metal oxide nanoparticles that were distributed throughout a water base. Their research attempts to enhance the stability and thermal characteristics of nanofluids. In terms of stability behavior and thermal property enhancement, ternary nanofluids with distinct base fluids would perform better (Adun et al., 2021). Consequently, in order to be used in thermal engineering systems, the heating and cooling properties of ternary nanofluids need to be thoroughly investigated. According to Muzaidi, Fikri, Wong, Sofi, Mamat, Adenam, Yunin, and Adli (Muzaidi et al., 2021), the solar thermal system's heating speed was accelerated by the ternary nanofluids. The idea of ternary nanofluids has therefore emerged as a fascinating area of interest for ongoing and upcoming research projects (Abdalla & Shahsavar, 2023; Afrand et al., 2016; Ahmed & Elsaid, 2019; Allahyar et al., 2016; W. Azmi et al., 2021; Baby & Ramaprabhu, 2011; Dezfulizadeh, Aghaei, Joshaghani, et al., 2021; Hamid et al., 2017; Huminic & Huminic, 2018; Kumar & Sahoo, 2022; A. Ramadhan et al., 2021; Sahoo & Kumar, 2020; Shah et al., 2022; Sundar et al., 2014).

The thermo-hydraulic performance of twisted tape inserts with different laminar and turbulent flow channels was investigated by Saysroy and Eiamsa-Ard (Saysroy & Eiamsa-ard, 2017) using a computational model. For a Reynolds number of 2000, the numerical results showed that laminar flow had the highest thermal performance factor up to 7.28 using a tube with multichannel twisted tape with N = 2 and y/w = 2.5. A CuO/water nanofluid's pressure drop and heat transmission were examined by Eiamsa-Ard and Wongcharee (EIAMSA-ARD & WONGCHAREE, 2013) utilising tape inserts with a twisted surface. Using a CuO nanofluid with a twisted alternative axis improved Nusselt numbers and thermal performance. Furthermore, twisted tape with a twisted alternate axis was approximately 89% more efficient than ordinary twisted tape.

Based on physical properties like hollow widths and hole diameters, numerous researchers have looked at twisted tape designs that are hollow, double, perforated, and dimpled, among others (Abdolbaqi et al., 2016; Eiamsa-ard et al., 2010; He et al., 2018). According to earlier computational study, the system's heat transfer efficiency is impacted by various designs and tube geometries (Akbaridoust et al., 2013; Alosious et al., 2017; Azman et al., 2021; Bahremand et al., 2015). The goal of the study is to determine the Al_2O_3-TiO_2-SiO_2 ternary nanofluids' heat transfer performance, and friction factor in an experimentally tested plain tube with twisted tape inserts at a constant wall heat flux.

2. RESEARCH METHODOLOGY

2.1. Preparation of Al_2O_3-TiO_2-SiO_2 nanofluids

Three different kinds of nanoparticles—silicon dioxide (SiO_2), titanium oxide (TiO_2), and aluminium oxide (Al_2O_3)—are used in this investigation. The TiO_2 and SiO_2 nanofluids were provided by US Research Nanomaterials, Inc. (USA), whereas the Al_2O_3 nanoparticles were given by Sigma Aldrich (USA). The EG was provided by Polychem Indonesia, and water distiller equipment was used to produce distilled water. Nanoparticles of Al_2O_3, TiO_2, and SiO_2 had sizes of 13, 50, and 22 nm, respectively, and purity levels of 99.8%, 99%, and 99.99%. In this study, the characteristics of Al_2O_3, TiO_2, SiO_2, water, and are described in **Table 1** and **2**.

In this study, ternary nanofluids were prepared using a two-step process. In the first phase, a 60:40 volume ratio of water to EG was used to mix the base liquid. Next, separate Al_2O_3-TiO_2-SiO_2 nanofluids were combined with water/EG base fluid to create Al_2O_3-TiO_2-SiO_2 ternary nanofluids. Furthermore, to create ternary nanofluids, all mono nanofluids were combined at a composition ratio of 20:16:64 on a 100% volume scale. **Figure 1** shows the graphical process flow used to prepare samples of the ternary nanofluid Al_2O_3-TiO_2-SiO_2.

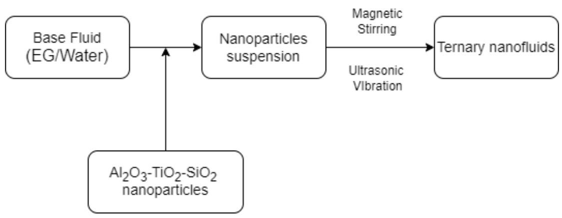


Figure 1. The ternary nanofluids (Al_2O_3-TiO_2-SiO_2) preparation

Table 1. Al_2O_3, TiO_2, and SiO_2 nanoparticle properties

Properties	Unit	Al_2O_3	TiO_2	SiO_2
Density (ρ)	kg m^{-3}	4000	4230	2220
Thermal conductivity (k)	W m^{-1} K^{-1}	40	8.4	1.4
Specific heat (C_p)	J kg^{-1} K^{-1}	773	692	745
Average particle diameter (d)	nm	13	50	22
Molecular mass (M)	g mol^{-1}	101.96	79.86	60.08

Table 2. Characteristics of Ethylene Glycol

Properties	Unit	Ethylene Glycol
Boiling point	°C	195–198
Melting point	°C	-13
Vapour pressure (20 °C)	mmHg	0.08
Density (25 °C)	g ml^{-1}	1.113

A total volume of 100 mL was created for the thermo-physical properties of ternary nanofluids in this study, and 20 L was utilized for forced convection tests.

The conversion from weight concentration to volume concentration is done using Equation 1. Equation 2 is also used to dilute the nanofluid to the established low volume concentration. The volume concentrations of ternary nanofluids are 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0%.

$$\phi = \frac{\omega \rho_{bf}}{\left(1 - \frac{\omega}{100}\right)\rho_p + \frac{\omega}{100}\rho_{bf}} \quad (1)$$

$$\Delta V = (V_2 - V_1) = V_1\left(\frac{\phi_1}{\phi_2} - 1\right) \quad (2)$$

2.2. Experimental setup

In order to assess forced convection heat transfer, a modified experimental setup based on earlier research by Azmi (W. H. Azmi, 2015) was used. In particular, forced convection heat transfer under turbulent flow conditions was investigated using a specially created experimental setup. This study's convective heat transfer experimental setup is based on Azmi's design (W. H. Azmi, 2015), with a few tweaks and enhancements. The first part to be created was the test portion, which is made up of a copper tube covered with glass wool and fiberglass insulators. **Figure 2** shows the schematic diagram. A thermocouple, data recorder, heater regulator, pressure transducer, flow rate meter, collecting tank, and chiller are some of the parts of the system.

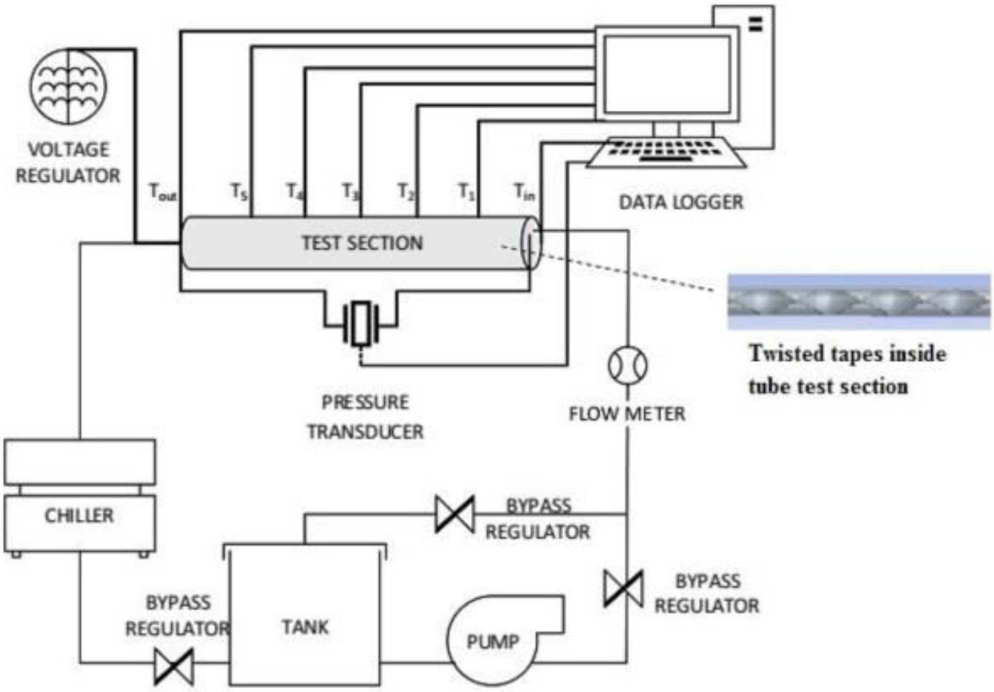


Figure 2. Experimental setup schematic for forced convection with twisted tape inserts

Table 3. Characteristic dimensions of the twisted tape

Twisted tape number	Width, *H* (mm)	Diameter, *D* (mm)	Twist ratio, *H/D* (mm/mm)
TT1	32	16	2.0
TT2	48	16	3.0
TT3	80	16	5.0

2.3. Design of Twisted Tape Inserts

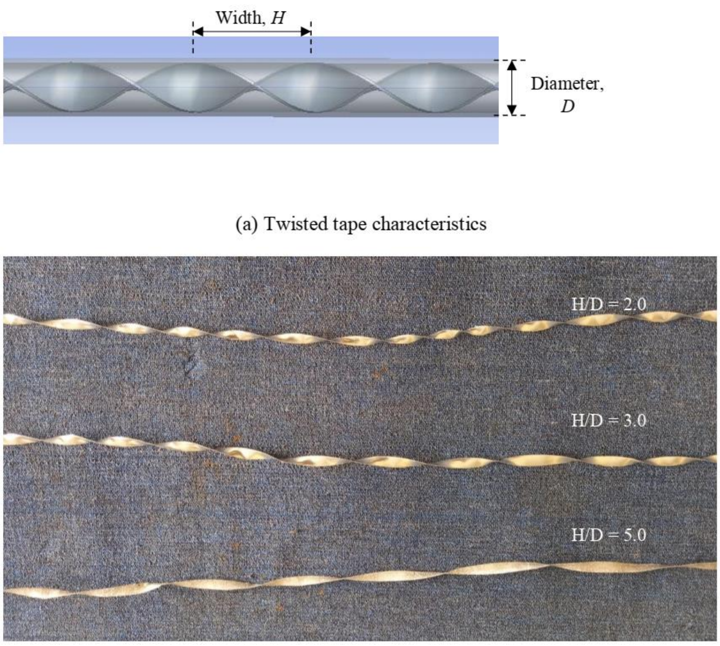
This study developed three inserts with varying twist ratios (2.0, 3.0, and 5.0). **Figure 3** illustrates how the twisted tape was made using aluminium strips that were 1 mm thick and 0.018 m wide. **Table 3** lists the twisted tape insert's manufacturing characteristics and procedure. In order to manufacture the twisted tape, the lab used a special device that, as explained in the methodology section, keeps the two ends of the strip on the lathe, one at the headstock end and the other at the tailstock end. The chuck was then manually turned to twist the strip.

2.4. Procedure for the experiment

In order to study forced convection heat transfer, the experimental inquiry started by validating the test equipment using a water:EG (60:40) mixture. After transferring 20 L of water and EG-based fluids to the collecting tank, the pump was turned on to move the fluids throughout the system. In addition to ensuring correct connections and preventing pipe leaks, the bypass valve regulator was employed to control the fluid flow in the system.

For this study, flow rates between 4 and 18 LPM were used. By activating the voltage regulator on the control screen, 750 W of input power was provided. A system chiller was employed to keep the working fluid's bulk temperature at 70 °C. To capture the temperature and pressure drop of the experimental data, the thermocouple and differential pressure transducer were attached to the data recording system. A regulator controlled the flowmeter, which measures the working fluid flow rate in liters per minute (LPM).

The experimental data was recorded using a LUTRON BTM-4208SD data logger to guarantee the data's correctness and accuracy.



(a) Twisted tape characteristics

(b) Twisted tape with different twist ratio (*H/D*)

Figure 3. Design of twisted tape inserts

Verifying that the test setup is reliable is the first step. The flow rate was initially set to its maximum in LPM while maintaining a steady operating temperature of 70 °C. At 70 ± 1 °C, the average intake and output temperatures are used to determine the flow or bulk temperature. Additionally, the working fluids' maximum LPM flow rate was lowered to a minimum. The data logger is configured to record the temperature and pressure drop for one minute following the stabilization of both the data logger's and the flow meter's temperatures under steady-state conditions.

Next, using ternary nanofluids in a simple tube, the experiment was conducted again. Various volume concentrations ranging from 0.5 to 3.0% were used to test the ternary nanofluids at 70 °C. Following the conclusion of a plain tube's forced convection heat transfer, the experiment was conducted again using wire coils and ternary nanofluids. The experiment was conducted at a bulk temperature of 70 °C for a broad range of Reynolds numbers, from 2,300 to 12,000. In simple tubes with twisted tape inserts, experiments were conducted with constant heat flux boundary conditions for flow (2.0 ≤ *H/D* ≤ 5.0).

2.5. Heat Transfer Analysis

Newton's rule of cooling states that the rate at which heat is transferred to or from a fluid flowing in a tube may be expressed using Equation 3.

$$Q = \mathrm{h}\ \mathrm{A}_s(T_s - T_b) \quad (3)$$

Where,

T_s is the average surface temperature and T_b is the bulk temperature.

Equation 4 expresses the power supply, Q in Watt, which is generated by the heater utilizing electrical energy.

$$Q = VI \quad (4)$$

In order to preserve energy balance, Equation 5 represents the heat from the tube as being equal to the heat in fluid flow under the assumption that there is no heat loss. Fluid flow heat is equal to the heat applied to the tube.

$$Q = \mathrm{h}\ \mathrm{A}_s(T_s - T_b) = \dot{m}C_p(T_{outlet} - T_{inlet}) = VI \quad (5)$$

Equations 6 and 7 thus express the derived Nusselt number and heat transfer coefficient.

$$h_{\mathrm{exp}} = \frac{Q}{A_s(T_s - T_b)} \quad (6)$$

$$Nu_{\mathrm{exp}} = \frac{h_{\mathrm{exp}}D}{k} \quad (7)$$

The average increase in heat transfer for nanofluids is calculated in percentage (%) using Equation 8.

$$\bar{h}_{enhanced} = \frac{\left[\sum_1^N \frac{h_{nf} - h_{W/EG}}{h_{W/EG}} \times 100\%\right]}{N} \quad (8)$$

Equations 9 to 11 describe the Reynolds number, the Prandtl number, and the Nusselt number, correspondingly (A. I. Ramadhan et al., 2024). Using the measurement and mixture relation, the values of *ρ*, *μ*, *k*, and *Cp* were estimated at the bulk temperature, T_b.

$$\mathrm{Re} = \frac{\rho v D}{\mu} \quad (9)$$

$$\mathrm{Pr} = \frac{\mu C_p}{k} \quad (10)$$

$$\mathrm{Nu} = \frac{hD}{k} \quad (11)$$

Equation 12 was used in this investigation to compute the experimental Darcy friction factor using the pressure transducer's pressure drop data. The results of the water/EG mixture were next verified by comparing the computed friction factor with the theoretical value obtained from the Blasius (Blasius, 1913) equation.

The Blasius (Blasius, 1913) equation, which is applied to Reynolds numbers between 3,000 and 5×10^6, is used in Equation 13 to estimate the friction factor for single phase flow in a tube. For the experimental setup to be reliable and the experimental results to be accurate, the experimental and theoretical friction factors must be compared.

$$f_{\text{exp}} = \frac{\Delta P_{\text{exp}}}{\left(\frac{L}{D}\right)\left(\frac{\rho v^2}{2}\right)} \quad (12)$$

$$f_{Bl} = \frac{0.3164}{\text{Re}^{0.25}} \quad (13)$$

Correlations presented by different scholars can be used to validate the heat transfer performance of flow in a tube with twisted tape inserts. For this reason, correlations proposed by Sarma, Subramanyam, Kishore, Rao, and Kakac (Sarma et al., 2002), Manglik and Bergles (Manglik & Bergles, 1993), and Smithberg and Landis (Smithberg & Landis, 1964) can be applied.

For flow across twisted tape inserts, Sarma, Subramanyam, Kishore, Rao, and Kakac's (Sarma et al., 2002) equation 14 is advantageous. This formula holds true between 10,000 < Re < 1.3×10^5 and 3 < Pr < 5. It makes an estimate of the Nusselt number, a dimensionless quantity that connects the fluid-to-wall temperature differential and thermal conductivity to the convective heat transfer rate. Correlations presented by different scholars can be used to validate the heat transfer performance of flow in a tube with twisted tape inserts.

$$Nu = 0.1012\left(1 + \frac{D}{H}\right)^{2.065} \text{Re}^{0.67}\ \text{Pr}^{1/3} \quad (14)$$

Equation 15 was presented by Manglik and Bergles (Manglik & Bergles, 1993) to calculate heat transport in a tube with twisted tape inserts. This formula works with twist ratios (*H/D*) between 3 and 6, Reynolds numbers larger than or equal to 10,000, and a Prandtl number of 5.2 for water.

$$Nu = 0.023Re^{0.8}\text{Pr}^{0.4}\left[1 + 0.769\frac{2D}{H}\right]\phi_2 \quad (15)$$

Where, $\phi_2 = [\pi/(\pi - 4\delta/D)]^{0.8}[(\pi + 2 - 2\delta/D)/(\pi - 4\delta/D)]^{0.2}$

The equation proposed by Smithberg and Landis (Smithberg & Landis, 1964) is a widely used correlation for determining the friction factor in turbulent flow through circular tubes with twisted tape inserts. It is based on the experimental data obtained from the tests conducted over a wide range of Reynolds numbers and twist ratios. The Smithberg and Landis equation is given by Equation 16 and is applicable for Reynolds numbers ranging from 10,000 to 100,000 and twist ratios ranging from 2 to 8.

$$f_{\text{SL}} = 4\left\{0.046 + 2.1\left[\frac{H}{D} - 0.5\right]^{-1.2}\right\}\left[\frac{Re}{1+2/\pi}\right]^{-n} \quad (16)$$

Where, $n = 0.2[1 + 1.7(H/D)^{-0.5}]$

Equation 17, which estimates the friction factor for the flow of water/EG mixture and nanofluids over tape inserts, was developed by Azmi, Sharma, Sarma, Mamat and Anuar (W. H. Azmi et al., 2014). The equation is valid for a range of conditions, including 6,800 < Re < 30,000, 5.00 ≤ Pr ≤ 7.24, ϕ ≤ 4%, and 5 ≤ H/D ≤ 15.

$$\frac{f_{\text{nf}}}{f_{\text{SL}}} = 1.4\left(0.001 + \frac{\phi}{100}\right)^{0.05} \quad (17)$$

The base fluid's friction factor for flow in tubes with twisted tape inserts was determined using Equation 13. Next, the friction factor's experimental value was contrasted with equations 16 and 17.

2.6. Thermal performance factor (TPF)

Heat transfer efficiency can be increased by using twisted tape. Similarly, the TPF was used to evaluate the overall efficacy of the twisted tape. The TPF parameter was utilized to assess the thermal-hydraulic performance of ternary nanofluids for flow with twisted tape. The TPF of twisted tape was calculated using Equation 18. In keeping with earlier studies, the 1/3 index is employed for comparison under the same pumping power (Chang et al., 2005; Sarma et al., 2003; Sharma et al., 2009). Compared to the increase in friction factor caused by the use of twisted tape, TPF with more than one (1) greatly improves heat transfer. As a result, for engineering purposes, a high TPF value is advised to reflect the optimal state of the twisted tape parameter.

$$\text{TPF (Twisted Tape)} = \frac{\frac{Nu_{nf,TT}}{Nu_{bf,PT}}}{\left(\frac{f_{nf,TT}}{f_{bf,PT}}\right)^{\frac{1}{3}}} \quad (18)$$

2.7. Uncertainty Analysis

Table 4 and **Table 5** provide a summary of the instrumentation and physical quantity uncertainty analysis results, respectively. The experiment's equipment had a maximum uncertainty of 0.73%, while the experimental parameters had a maximum uncertainty of 0.89%. All things considered, the uncertainty analysis offers crucial details on the precision of the experimental findings, and the minimal uncertainties discovered in this investigation imply that the measurements were accurate and trustworthy.

3. RESULTS AND DISCUSSION

3.1. Validation of Experimental

At a bulk temperature of 70 °C, the experimental Nusselt number and friction factor for the water/EG-based mixture were verified, as shown in **Figure 4(a)** and **(b)**, respectively. A comparison between the current experimental data and the estimation value by Sarma, Subramanyam, Kishore, Rao, and Kakac (Sarma et al., 2002), Manglik and Bergles (Manglik & Bergles, 1993), and Smithberg and Landis (Smithberg & Landis, 1964) confirms the dependability of the experimental setup with twisted tape inserts.

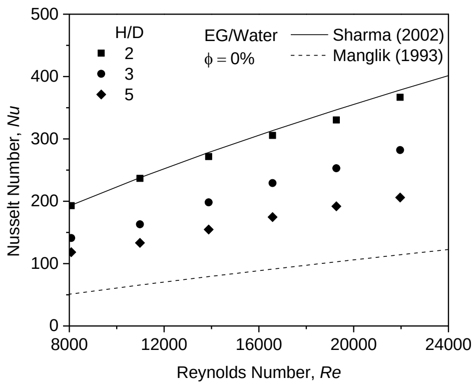
The validation in **Figure 4** shows that the present experimental value of the water/EG-based mixture agrees with the estimation by Sharma, Sundar and Sarma (Sharma et al., 2009), Manglik and Bergles (Manglik & Bergles, 1993), and Smithberg and Landis (Smithberg & Landis, 1964). The average deviation of the experimental Nusselt number was 1.61 and 7.24% compared to Sarma, Subramanyam, Kishore, Rao and Kakac (Sarma et al., 2002) and Manglik and Bergles (Manglik & Bergles, 1993), respectively.

Table 4. An overview of the uncertainty in the instruments

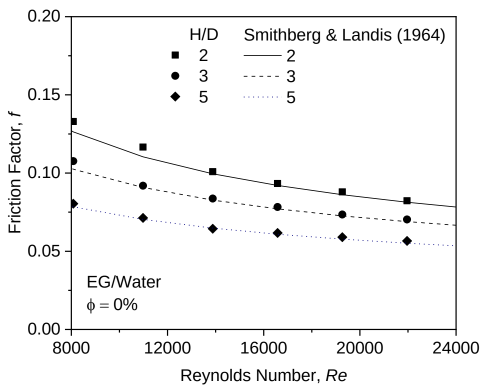
No	Instruments	Variables	Uncertainty (%)
1	Thermocouple, °C	Bulk temperature, T_b	0.19 – 0.48
2	Thermocouple, °C	Average surface temperature, T_w	0.29 – 0.73
3	Flow meter, LPM	Volume flow rate, $\dot{V}$	0.05 – 0.24
4	Voltage, *V*	Voltage, *V*	0.01
5	Current, *A*	Current, *I*	0.13
6	Pressure transducer, Psi	Pressure drops, *ΔP*	0.00014-0.0029

Table 5. An overview of the uncertainty in physical quantities

No.	Parameters	Uncertainty (%)
1	Reynolds number, *Re*	0.12 – 0.28
2	Heat flux, *q*	0.13
3	Heat transfer coefficient, *h*	0.38 – 0.89
4	Nusselt number, *Nu*	0.39 – 0.89
5	Friction factor, *f*	0.13 – 0.36



(a) Nusselt Number



(b) Friction factor

Figure 4. Validation for Nusselt number and friction factor of water/EG mixture with twisted tape

At the same time, the highest deviation of 3.25% was observed for the experimental friction factor of the water/EG-based mixture compared to Smithberg and Landis (Smithberg & Landis, 1964). Additionally, the point of reference for twisted tape setup validation using equations by Sarma, Subramanyam, Kishore, Rao and Kakac (Sarma et al., 2002), Manglik and Bergles (Manglik & Bergles, 1993), and Smithberg and Landis (Smithberg & Landis, 1964) also conducted by other researchers (W. H. Azmi et al., 2014; EIAMSA-ARD & WONGCHAREE, 2013; Sundar & Sharma, 2010).

3.2. Performance of heat transfer using twisted tape inserts

The greatest improvement in heat transfer performance was achieved with a ternary nanofluid volume concentration of 3.0%. With a twist ratio of 2.0, the ternary nanofluids rose up to 225.35% in comparison to the water/EG-based mixture in a plain tube. In the meantime, at 0.5% volume concentration, the heat transmission increment was the smallest for all twist ratios.

Table 6 summarizes the average enhancement in the heat transfer coefficient of ternary nanofluids for flow in a tube with twisted tape for a twist ratio of 2.0, 3.0 and 5.0. The heat transfer coefficient enhancement for the ternary nanofluid at each twisted tape ratio is presented in the table for all volume concentrations. The twisted tape significantly enhances heat transfer due to the following reasons. The eddy flow produced by the twisted tape in the tube causes the liquids to mix. In this condition, energy can be transferred more quickly (Sarma et al., 2003). Additionally, the mixing flow makes the temperature differential between the fluid and the wall steeper, according to Agarwal and Rao (Agarwal & Raja Rao, 1996). Furthermore, the temperature distribution in the tube is improved by the flow caused by the twisted tape.

For ternary nanofluids flowing in a tube with twisted tape inserts at all volume concentrations, **Figure 5** to **Figure 7** show the heat transfer coefficient, and **Figure 8** to **Figure 10** presented the Nusselt number. The Nusselt number and heat transfer coefficient of the twisted tape raise with increasing Reynolds number and are consistently higher than those of the water/EG-based mixture at every twist ratio. As the twist ratio of twisted tape decreases, the Nusselt number and heat transmission coefficient also rise.

Table 6. Twisted tape increases the heat transfer coefficient of ternary nanofluids on average for twist ratios of 2.0 ≤*H/D* < 5.0

Volume concentration, ϕ (%)	Twisted tapes twist ratio, *H/D*		
	2.0	3.0	5.0
0.5	128.78	123.92	103.71
1.0	139.91	128.77	107.43
1.5	150.76	138.45	117.18
2.0	169.55	142.34	121.80
2.5	178.08	163.16	130.66
3.0	225.35	199.83	134.31

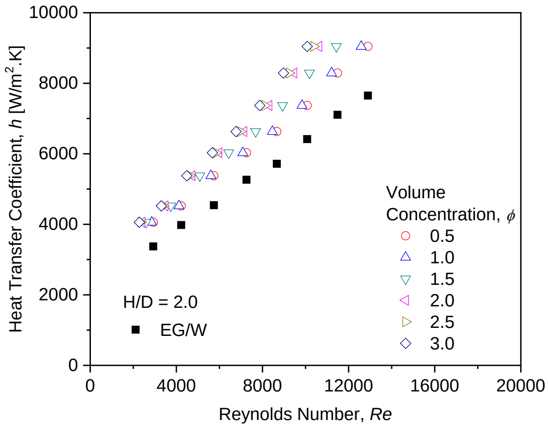


Figure 5. Heat transfer coefficient for ternary nanofluids with twisted tape for *H/D* = 2.0

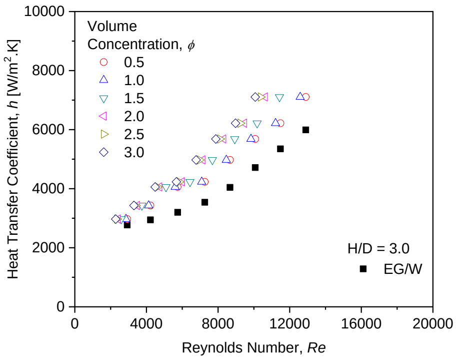


Figure 6. Heat transfer coefficient for ternary nanofluids with twisted tape for *H/D* = 3.0

The heat transfer coefficient increased most at a twist ratio of 2.0, and this effect held true for all ternary nanofluids volume concentrations. However, for every volume concentration of the ternary nanofluids, the twist ratio of 5.0 exhibits the least amount of heat transfer augmentation. In a tube without twisted tape, the heat transfer coefficient rose by over 100% when the twist ratio was reduced from 3.0 to 2.0.

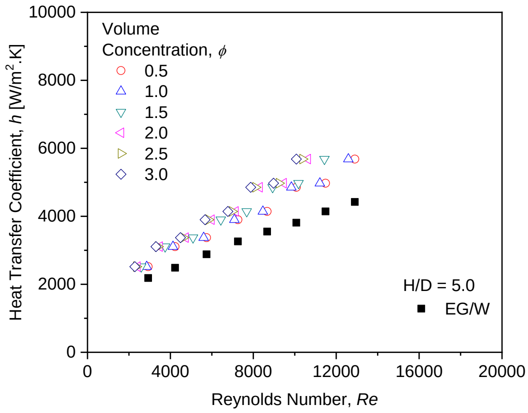


Figure 7. Heat transfer coefficient for ternary nanofluids with twisted tape for *H/D* = 5.0

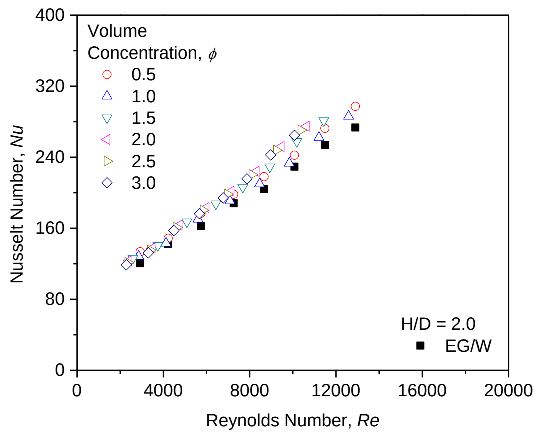


Figure 8. Nusselt number for ternary nanofluids with twisted tape for *H/D* = 2.0

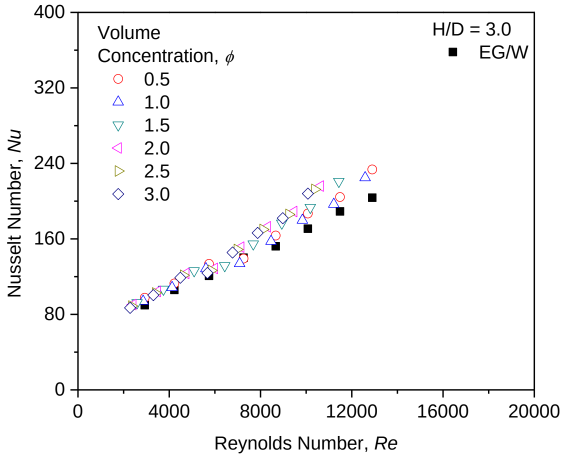


Figure 9. Nusselt number for ternary nanofluids with twisted tape for *H/D* = 3.0

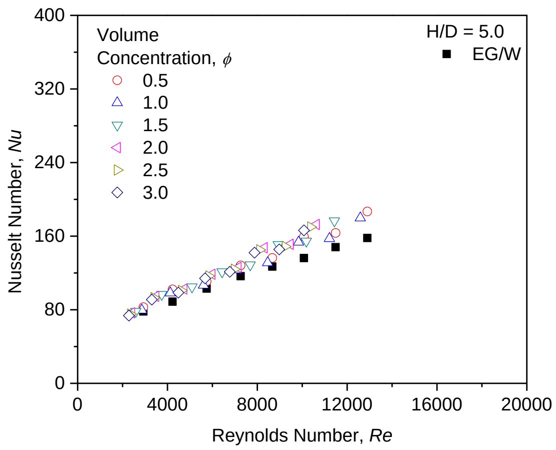


Figure 10. Nusselt number for ternary nanofluids with twisted tape for *H/D* = 5.0

3.3. Inserts of twisted tape for the friction factor

Figure 11 to **Figure 13** in the twist ratio range of 2.0 to 5.0 illustrates the impact of ternary nanofluid volume concentration on the friction factor. The water/EG pattern shows that the friction factor declines as the Reynolds number rises. The friction factor is evenly distributed across all composition comparisons on each twisted tape with no discernible differences. At all concentration volumes, the friction factor increases roughly similarly. A similar pattern was discovered when friction was discovered in plain tubes using twisted tape. However, the value of this increase grows as the twist ratio decreases.

The friction factor of the nanofluids increased at all concentration volumes as follows: The increase was approximately 2.6 and 3.2 times for twist ratios of 3.0 and 5.0 (compared to water/EG in a plain tube with inserts). The increase is approximately 6.1 times greater for a twist ratio of 2.0. The insertion of the twisted tape causes significant fluid friction due to the dynamic pressure dissipation of the fluid. Furthermore, as the number of twists increases, the surface area increases, as does the blockage of tape flow through the flow field, contributing to higher friction (W. H. Azmi et al., 2014).

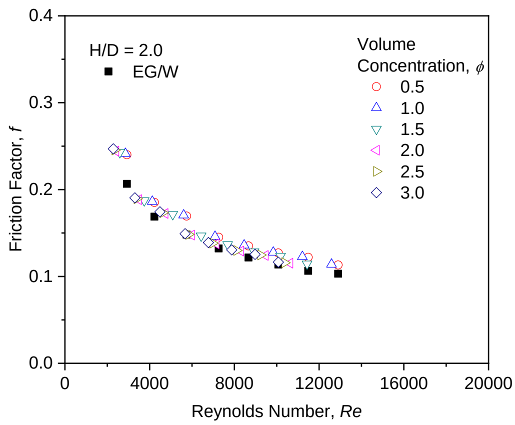


Figure 11. Friction factor of ternary nanofluids with twisted tape for *H/D* = 2.0

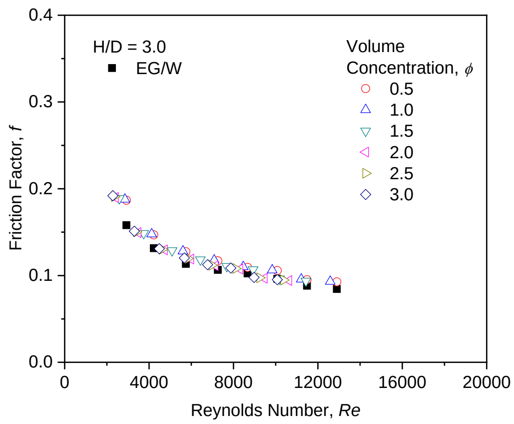


Figure 12. Friction factor of ternary nanofluids with twisted tape for *H/D* = 3.0

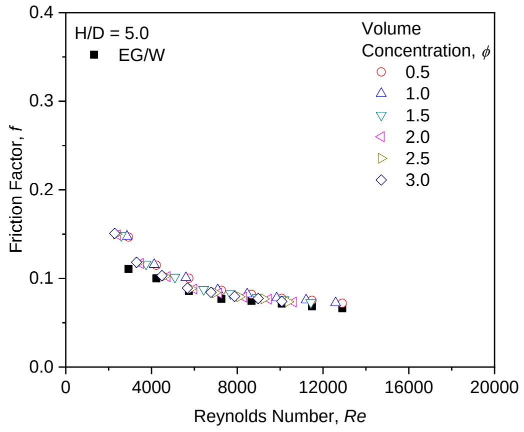


Figure 13. Friction factor of ternary nanofluids with twisted tape for *H/D* = 5.0

3.4. Thermal Performance Factor (TPF) Analysis

The local TPF of twisted tape for ternary nanofluids at different Reynolds numbers is shown in **Figure 14** together with the modification in volume concentration. Curiously, the local TPF for twisted tape is greater than 1.0 and performs better than the earlier simple tube and wire coil inserts. At a specific volume concentration, the local TPF fluctuation with Reynolds number is nearly constant, which is in line with the earlier findings. Additionally, when the volume concentration rises, so does the average TPF.

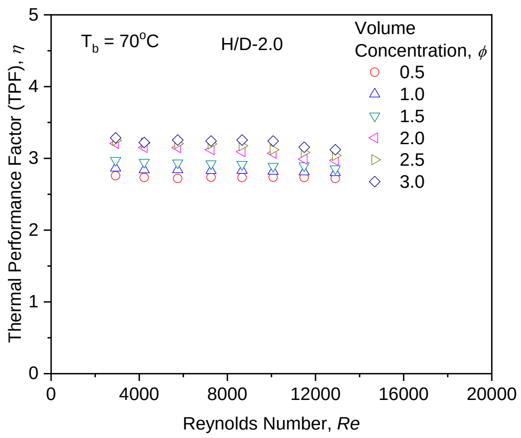


Figure 14. Thermal performance factor for local TPF for ternary nanofluids with twisted tape for H/D = 2.0

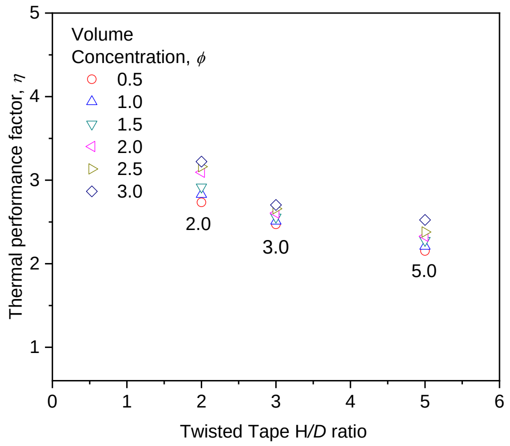


Figure 15. The ternary nanofluids' average thermal performance factor with the twisted tape for different twist ratio

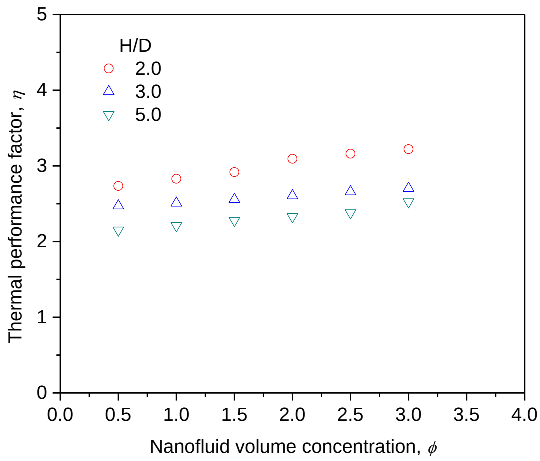


Figure 16. The ternary nanofluids' average thermal performance factor with the twisted tape for different volume concentration

The thermal performance factor for twisted tape at various volume concentrations and twist ratios is shown in **Figure 15** and **Figure 16. Figure 15** presented the variance of TPF for various twist ratios. This is true for all volume concentrations and twist ratios, and the TPF falls as the twist ratio rises above 2.0. Nevertheless, the TPF value decreases as the twist ratio increases. The maximum TPF for each volume concentration of ternary nanofluids was achieved at a twist ratio of 2.0. At the same time, for all wire coil twist ratios, the best performance is achieved with a volume concentration of 3.0%. **Figure 16** illustrates how the TPF affects volume concentration with a twist ratio modification.

The TPF marginally improved with increasing volume concentration for a specific twist ratio. Generally, the TPF for twisted tape is much higher than wire coil and plain tube. The following section discusses TPF comparison between ternary nanofluids in a tube, and with twisted tape.

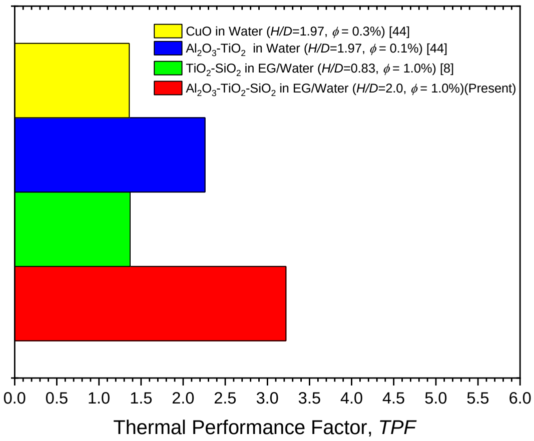


Figure 17. Comparison of thermal performance factors with literature

A similar finding also was observed by Naik, Fahad, Sundar and Singh (Naik et al., 2014). The TPF value for a mono nanofluid with twisted tape are 1.36. Likewise, Sarada, Raju, Radha and Sunder (Sarada et al., 2010) presented an increase in TPF ranging from 1.0 to 2.0 using twisted tape. In addition, Singh and Sarkar (Singh & Sarkar, 2020) observed the TPF of Al2O3-TiO2 binary nanofluid at 0.1% volume concentration and obtained in the range of 1.57 to 2.26. Hamza and Aljabair (Hamza & Aljabair, 2022) found that the TPF of binary nanofluid in a plain tube with twisted tape at 1.8% volume concentration and Reynolds number of 8,320 is 1.37. The TPF of this study and the TPF found in the literature are contrasted in **Figure 17**.

4. CONCLUSION

In this research, the viscosity was maximum at all temperatures in the current investigation at a volume concentration of 3.0%. When ternary nanofluids are concentrated in a simple tube with twisted tape (H/D-2.0), the largest increase in heat transfer is attained at a volume concentration of 3.0% to 225.35%. Comparing the twisted tape to the plain tube, the average TPF rose, and it increased even more as the volume concentration rose between 2.73 and 3.22. Using twisted tape, the lowest and maximum average TPF occurred at volume concentrations of 0.5 and 3.0% for ternary nanofluids.

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