



Experimental Investigation on Improving the Thermal Efficiency of a Double Pipe Heat Exchanger Utilizing ZnO

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ABSTRACT

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The study demonstrates that the compound outperforms the base fluids regarding heat transfer in heat exchangers with horizontal shells and tubes. However, the concentration of nanoparticles affects the friction factor because it increases the viscosity. According to this investigation, using nanofluids improves the heat exchanger's performance. Experimental investigations show that ZnO/distilled water nanofluids have increased heat transfer coefficients and thermal conductivity, making them appropriate for boosting heat exchanger efficiency. The studies were done at γ -ZnO concentrations of 0.0%, 0.05%, and 0.4%, temperatures of 65°C, and flow rates of 2, 4, and 6 LPM. Experimental results disclose that using double-pipe heat exchangers improves the heat transfer coefficient, offering significant insight into their performance under different operating situations. For instance, at a temperature of 65°C and a flow rate of 6 LPM, the heat transfer rate increased by 25% and the heat transfer coefficient increased by 20% when 0.4% ZnO was added. In contrast to distilled water, the Nusselt number for the ZnO nanofluid at 0.4% was 9% higher. The idea that thermal management in heat exchangers is boosted at the right concentrations of nanofluids is supported by this study. Thermal efficiency rises with Re to reach its maximum at $Re = 6000$. This study uses water-nanomaterial mixtures to advance heat transfer in double-tube heat exchangers.

1. INTRODUCTION

Heat transfer procedures are difficult when heat flow rates are high; thus, heat transfer processes require innovative technologies to increase efficiency. Metals and oxides have higher thermal conductivity coefficients than traditional heat transfer fluids [1]. Nanofluids, a blend of ordinary fluids and nanotechnology, have been utilized to improve heat transfer qualities. Nanofluids are nanoparticle suspensions in a base fluid that can increase heat transfer by increasing heat conductivity and convection coefficients. The goal of this research is to investigate the efficiency of nanomaterial-water solutions in double pipe heat exchangers. The performance of the heat exchangers was tested using various operating conditions as well as experimental data from the investigations [2]. The presence of nanofluid within the pipes, along with a rise in nanoparticle concentration, leads to a considerable improvement in thermal performance indices [3]. Many works were done in the twin pipe heat exchanger (DPHE). This work examined the thermal performance of a double-pipe heat exchanger using a ZnO-H₂O nanofluid stabilized by a surfactant. The experiments were done in the turbulent flow domain ($Re = 5500$ -16000). The results showed that raising the nanoparticle concentration to 0.06% increased the Nusselt number by 35% and the thermal performance factor to 1.15. These enhancements are due to the combined effects of

Brownian motion, the interfacial nanolayer, and the nanofluid's increased thermal conductivity. This work found that very low ZnO-distilled water nanofluid concentrations (up to 0.06%) stabilized with SDBS might result in significant thermal performance improvements. At $Re = 5500$, the Nusselt number increased by 35%, and the thermal performance factor increased by 1.15, demonstrating that effective heat transfer enhancement was feasible with little nanoparticle loading, decreased agglomeration, and better stability [4]. The research examined the performance of plate heat exchangers and double-pipe heat exchangers with the hot fluid being a 0.5% volume concentration of ZnO/water nanofluid. The results show that the nanofluid improves the heat transfer rate and coefficient when compared to the base fluid (water). Under the same working circumstances, the plate heat exchanger outperforms the double-pipe heat exchanger in terms of thermal efficiency. This research looked at the thermal performance of a 0.5% ZnO-water nanofluid in plate and concentric tube heat exchangers. It offered a systematic examination of heat transfer rates and coefficients at various hot and cold fluid flow rates, indicating that the nanofluid significantly increased heat transfer over the base fluid, with the plate heat exchanger outperforming. These discoveries gave significant information to improve nanofluid-based heat exchangers [5]. It was observed that the performance of a double-pipe heat exchanger with ZnO nanofluid

concentrations of 0.5%, 0.75%, and 1.25%. The results revealed that raising the nanoparticle concentration considerably improves the heat transfer rate, with a demonstrable improvement in thermal conductivity efficiency as the ZnO concentration in the base fluid increases [6]. It was found that the experiment examined a counter-flow double-tube heat exchanger with ZnO nanofluids (0.5% and 1% mass concentrations) as the cold fluid and pure water as the hot fluid. The results revealed that using nanofluid increased heat exchanger performance by up to 40% at 0.5% concentration and 54% at 1% concentration at a 2 lpm flow rate. Higher concentrations and flow rates of nanoparticles improved thermal performance. This study found that low-concentration (0.5-1%) ZnO-water nanofluids considerably increased thermal performance in a counter-flow double-pipe heat exchanger. The findings showed that low-concentration nanofluids were up to 54% more effective than pure water, demonstrating their practical utility for increasing heat transmission [7].

The studies were done utilizing a circular heat exchanger under continuous heat flow conditions to explore the thermal properties of ZnO and TiO₂ nanofluids. ZnO and TiO₂ mass concentrations of 0.025%, 0.05%, 0.075%, and 0.1% in distilled water were evaluated. All concentrations outperformed pure water in terms of thermal performance; however, 0.1% mass concentration demonstrated the highest performance, with a 36% increase in thermal conductivity and a 69% increase in convective heat transfer coefficient. As a result, 0.1% concentration is thought to be the most beneficial in terms of thermal characteristics [8]. ZnO- distilled water nanofluids of different mass concentrations (0.025%-0.1%) were used to improve the thermal performance of a heat exchanger. The greatest improvement was found at 0.1% mass concentration, when thermal conductivity rose by 52% and the Nusselt number increased by 47% as compared to distilled water. The geometric impact of the square heat exchanger structure, along with the steady dispersion of ZnO nanoparticles, is responsible for this increase [9].

The double pipe heat exchanger (DPHE) with nanofluid was thoroughly worked on. The research aims to improve the performance of a double-pipe heat exchanger by employing a nanofluid containing zinc oxide (ZnO) nanoparticles. The results revealed that adding 3% ZnO boosts the total heat transfer coefficient by 16% when compared to water alone. ZnO is distinguished by its excellent heat conductivity and ability to dissociate hydrogen bonds in water. However, it confronts issues with stability and particle sedimentation over time. The study advocates the use of ZnO nanofluids to increase heat exchanger efficiency, with a focus on dispersion and durability [10]. ZnO nanofluids dispersed in motor oil were employed to improve the thermal performance of a heat exchanger at 0.1% and 0.2% concentrations. At 0.2% concentration, ZnO nanofluids enhanced the Nusselt number by 19% and the heat transfer coefficient by 7% compared to SiO₂ nanofluids. Additionally, heat exchanger efficiency increased by roughly 16%. This illustrates the higher efficiency of ZnO nanoparticles in improving heat exchanger thermal performance [11]. The experiment had excellent results, improving both thermal and physical qualities. These unique features boost or aid with the heat conversion mechanism utilized using various amounts of zinc oxide nanoparticles. Zinc oxide nanoparticles are recommended in the literature due to their ability to break the hydrogen bond between water molecules. As a result, the portion of energy

that these bonds normally absorb is also passed through. Zinc oxide's insolubility in water reduces heat exchanger performance by settling to the bottom over time [12, 13]. It was observed how ZnO-water-ethylene glycol (EG) interactions impact factors such as volume fraction, particle size, and temperature. The nanofluid showed a 45% improvement in thermal conductivity at a volume percentage of 6.9% [14].

An experimental investigation was carried out on a double-pipe heat exchanger using a ZnO-water nanofluid to assess thermal performance and pressure decrease during turbulent flow. Four nanoparticle (0.005%, 0.02%, 0.04%, and 0.07%) volume fractions were examined, with the 0.07% volume fraction resulting in the greatest increase in Nusselt number (55.51%), as well as a 147.37% increase in friction. ZnO nanoparticles were also characterized, and new empirical correlations between Nusselt number and friction factor were generated [15].

This study looks at the performance of heat exchangers that use ZnO-water nanofluid combinations at concentrations of 0.0%, 0.05%, and 0.4%. Zinc oxide (ZnO) nanoparticles were chosen because they had a larger surface area, greater thermal conductivity, and superior dispersibility than other materials, resulting in increased heat transfer efficiency. The study focuses on double-pipe heat exchangers, investigating the effects of nanoparticle concentration, fluid flow rate, and temperature on thermal efficiency. It also compares ZnO-water nanofluids to traditional fluids to evaluate heat transfer gains. The goal is to create heat exchanger technologies that are both efficient and sustainable. This work is comparable to prior research on ZnO-water nanofluids in double-pipe heat exchangers in that it employs nanoparticles, assesses thermal performance in counter-flow configurations, and demonstrates a considerable increase in heat transfer and efficacy over pure water. This study is unique in that it provides experimental data at actual flow rates while also revealing significant performance increase with minimal nanoparticle loading, highlighting the promise of stable nanofluids for real-world applications.

2. EXPERIMENTAL WORK

This investigation sought to examine the heat transfer properties of a heat exchanger having two pipes utilizing water-based nanofluids. The process included designing and building the experimental apparatus, specifying operating parameters, carrying out tests, and analyzing results. The test apparatus was equipped with a heat exchanger having two pipes. The independent variables - flow rate, fluid temperature, and nanoparticle concentration - were systematically altered to investigate their influence on improving heat transfer. Improving heat exchange efficiency in applications in industry through the use of a systematic and analytical methodology was the primary objective of the study.

2.1 Experimental setup

The test system, as illustrated in Figure 1, contains two tanks for the cold fluid (filtered water) of 50-liter capacity, to which ice is added to keep the cold fluid's temperature at roughly 22°C, and the hot fluid (distilled water or nanofluid ZnO/water) of 6-liter capacity. It contains a 2400-watt variable electric heater with a safety thermostat that regulates the

temperature of the hot fluid. Two flow meters with a 2-18 LPM range, two electronic thermometers for temperature control (one for the hot fluid chamber and one for the cold-water chamber), and two metal valves are employed to regulate fluid flow, both hot and cold.

The test equipment has a twin concentric pipe heat exchanger. The PVC outer tube is sprayed with thermal insulating paint on the exterior to prevent heat loss, and the inner tube is composed of copper. Eq. (1) is employed for designing the heat exchanger that uses two pipes, which have the main characteristics listed in Table 1 [16].

$$\frac{L}{D} \sim 4.4 Re^{1/6} \quad (1)$$

Table 1. Parameters and dimensions

Parameters	Values (mm)
D1, Inner tube (copper), Outer diameter	25.5 mm
D2, Inner tube (copper), Inner diameter	23.5 mm
D3, Outer tube (PVC), Outer diameter	63 mm
D4, Outer tube (PVC), Inner diameter	57 mm
Double tube heat exchanger length	1160
Copper tube thickness	1 mm
(PVC), tube thickness	3 mm

The experimental heat exchanger system has a cold fluid temperature of 22°C. These parameters are chosen based on the conceivable, application-specific, and heat transfer-affecting circumstances. Because room temperature settings are used, it is feasible to duplicate in various climates without elaborate cooling. At a constant low temperature for the cold fluid, there is increased discrimination between the temperature and hot fluids, which improves heat transfer rates.

Twenty-four thermocouples were installed to track temperature variations at several places along the heat exchanger. Ten thermocouples were installed along the copper pipe carrying hot water, and eight were installed along the PVC pipe conveying cold water. The remaining thermocouples were positioned at the heat exchanger's outlet and inlet portions to correctly gauge the entrance and exit fluid temperatures. This configuration allows for complete thermal profiling and exact measurement of heat transfer performance throughout the system.

In addition, four thermocouples in the exterior tube gauge the cold fluid's temperature, i.e., filtered water, similarly to how a thermocouple measures the hot fluid's temperature. On the exterior surface of the copper tube. A constant-temperature bath was used to calibrate all of the thermocouples, and it was found that the maximum inaccuracy is 0.3°C.

Figure 1 Schematic diagram of the experimental arrangement.

The nanofluid is generated by applying the formula to compute the weight necessary to prepare 4 liters of nanofluid (ZnO/distilled water) for each concentration independently using an electronic scale with four numbers according to the following equation [17]:

$$m_{zno} = \left(\frac{\phi}{1-\phi} \right) \left(\frac{\rho_{zno}}{\rho_{water}} \right) m_{water} \quad (2)$$

Next, the zinc oxide powder is then dispersed in the distilled water utilizing a magnetic stirrer for 1 hour and many cycles at 1500 rpm. The produced combination is placed in an ultrasonic cleaning equipment for 4 hours, with a maximum power of 720 W.

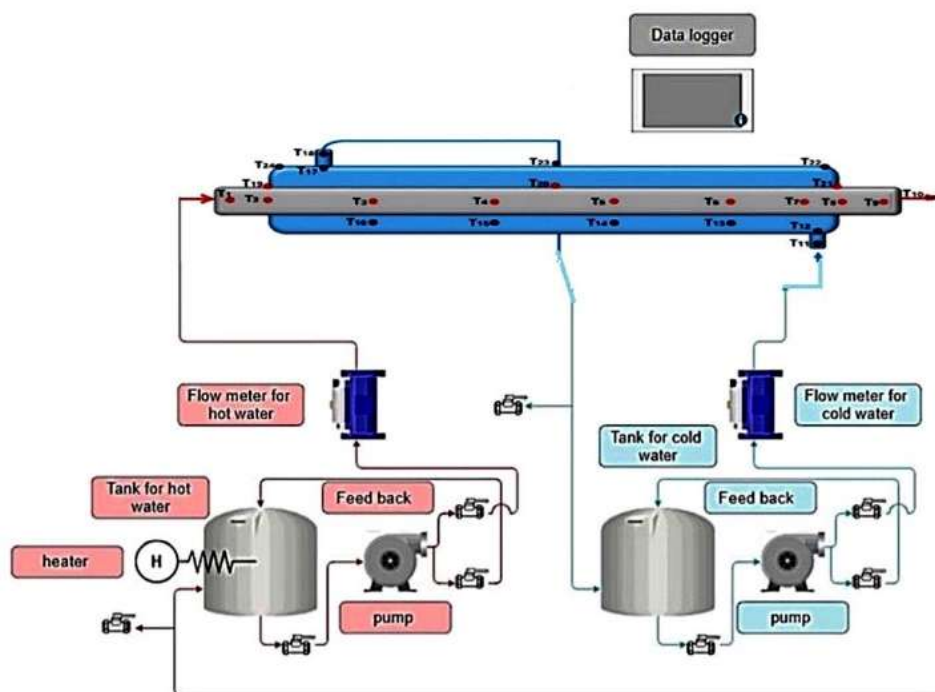


Figure 1. Schematics diagram

Table 2. Specification of ZnO used in this study [18]

Average Particle size/nm	Purity	Density/kg m ⁻³	Color	Morphology	Specific Heat/J·kg ⁻¹ ·k ⁻¹	Thermal Conductivity/W·m ⁻¹ ·k ⁻¹
10-30	>99%	5606	White to light yellow	Nearly spherical	495	60

The weights provided to ZnO powder are in grams or kilograms, whereas powders, particularly dry powders, are usually measured in grams or kilograms. This is attributable to factors such as density change, concentration calibration, and comparability during the study process. Density measurements can influence the quantity of nanoparticle-containing powders, whereas volume measurements can alter concentration levels. Weight measurements may also be used to determine the precise concentration of nanoparticles because the amount of solution is proportional to the mass of the nanoparticles. Furthermore, weight-based measurements are more replicable since another researcher may collect the same mass of ZnO regardless of whether the powder is thick or the sieving procedure utilized is different.

Once the nanofluid has been created, part of it is retained for macroscopical examination of its agglomerations. The experiments demonstrated that the fluid did not agglomerate over 24 hours (Figure 2). Specification of ZnO nanoparticles acquired from Sky Spring Nanomaterials, Inc., USA. Table 2 displays ZnO characteristics and particle size, while Figures 3 and 4 provide SEM and XRD test pictures, respectively.

The nanomaterial underwent X-ray diffraction (XRD) examination to identify the current phases and confirm its crystalline structure. The results revealed significant diffraction peaks, verifying the material's purity and conformance to the predicted crystal structure.

Several critical characteristics and dimensions are specified based on experimental results. Table 1 depicts them.



ZnO/distilled water 0.4%



ZnO/distilled water 0.05%

Figure 2. Samples of prepared nanofluid after 24 h

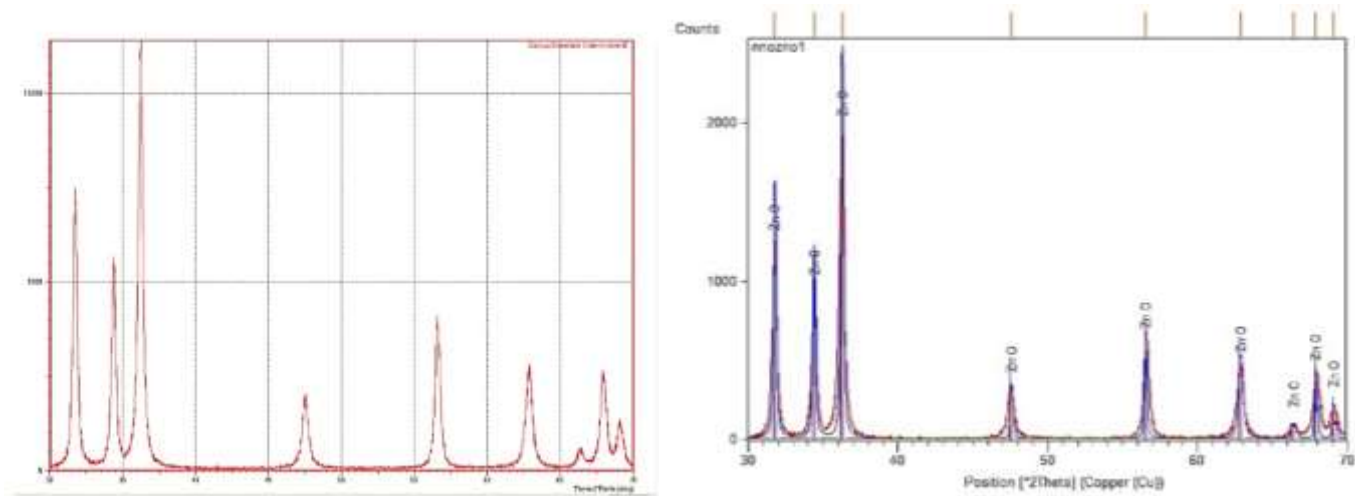


Figure 3. XRD test images

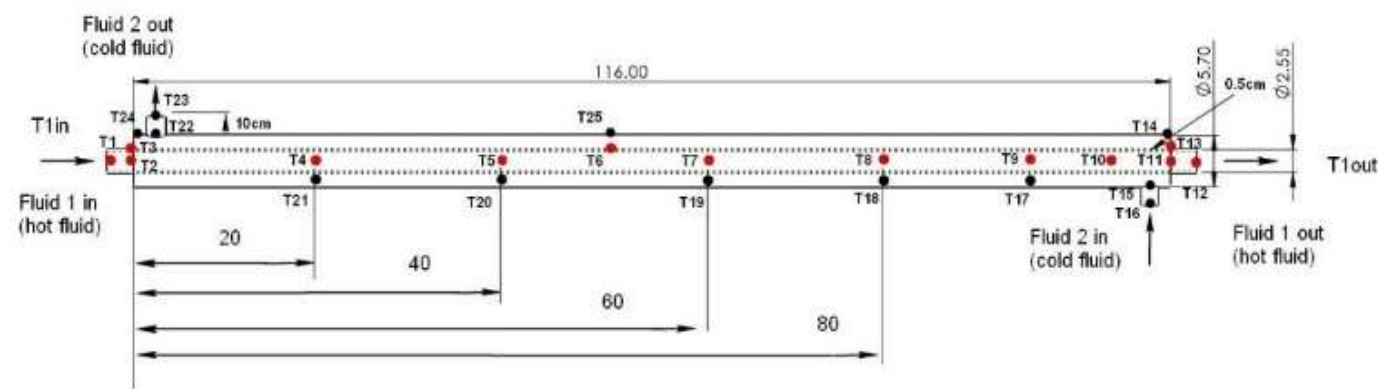


Figure 4. The location of the embedded

The outer PVC tube was used to filter water at 22°C with a flow rate of 12 LPM. The inner copper tube acted as a hot fluid channel, and three distinct fluid conditions were tested:

(1) The water samples to be utilized should be distilled water with flow rates of 6, 4, and 2 LPM at three different temperatures of 65°C, 55°C, and 45°C.

(2) Use 0.4% and 0.05% volume concentrations of nanofluid ZnO/distilled water, at similar temperature and flow rate as the buffer solution.

To achieve the maximum amount of heat transmission, the heat exchanger that uses two tubes was employed in counterflow mode. K-type thermocouples were placed in strategic spots on the heat exchanger to measure temperatures at various stages. Figure 4 illustrates the placements of the thermocouples.

2.2 Calculations

The gathered temperature data was used for the following calculations:

- Reynolds number (Re):

$$Re = \frac{\rho U_m d_i}{\mu} \quad (3)$$

- Nusselt number (Nu_{exp}) [19]:

$$Nu_D = \frac{(\frac{f}{8})(Re_D - 1000)Pr}{1 + 12.7(\frac{f}{8})^{\frac{1}{2}}(Pr^{\frac{2}{3}} - 1)} \quad (4)$$

- Prandtl number (Pr):

$$Pr = \frac{\mu C_p}{K} \quad (5)$$

- Friction factor [20]:

$$f = (0.79 \ln Re_D - 1.64)^{-2} \quad (6)$$

- Convective heat transfer coefficient (h) [21]:

$$h = \frac{Q}{A_s(T_{wt} - T_b)} \quad (7)$$

- The coefficient of overall heat transfer (U) [22]:

$$U = \frac{1}{\frac{1}{h_a} + \frac{1}{K} + \frac{1}{h_w}} \quad (8)$$

- Heat transfer rate (Q) [23]:

$$Q = \dot{m}_w C_{ph} (t_{h1} - t_{h2}) = \dot{m}_a C_{pc} (t_{c2} - t_{c1}) \quad (9)$$

$$Q = U A \theta_m \quad (10)$$

- The Number of transfer units (NTU) [24]:

$$NTU = \frac{UA}{C_{min}} = \frac{Q}{\Delta T_{LM} C_{min}} \quad (11)$$

where, $C_h = \dot{m}_h C_{ph}$, $C_c = \dot{m}_c C_{pc}$ and C_{min} . The minimum value of C_h and C_c .

- The effectiveness (ϵ) [24]:

$$\epsilon = \frac{1 - \exp[-NTU(1 - Cr)]}{1 - Cr \exp[-NTU(1 - Cr)]} \quad (12)$$

where, $Cr = \frac{C_{min}}{C_{max}}$.

- Thermal conductivity (k) [25]:

$$k_{nf} = k_{pf}(T)(1 + 4.5033\phi) \quad (13)$$

The mathematical models used were designed to conduct quantitative predictions of micro and macro factors in nanofluid heat transfer research, including the Nusselt number and friction factor. Every model is utilized for various studies, and the selection is based on the kind of flow and features of nanofluids, such as turbulent flow in heat exchangers.

The friction factor for turbulent flow of fluids with varying characteristics in a pipe is calculated using the Petukhov [20] correlation. It is most suited for complicated fluids, such as nanofluids, where flow resistance or friction loss is an important factor. Petukhov's model is useful for calculating flow resistance and the drop in pressure in a twin-pipe heat exchanger utilizing nanofluids, as flow resistance and friction loss are significant in this heat exchanger. When calculating the Nusselt number, the Dittus-Boelter formula, which is appropriate for turbulent flow circumstances, is employed, where fluid parameters are assumed to be equal to water or water-based fluids [19]. Because it employs water and ZnO-based nanofluids, this model is valuable for determining the system's heat transfer efficiency.

It applied Gnielinski's correlation to the coefficient of convective heat transfer to improve refinement in the transitional flow zone between laminar and turbulent flows. This model uses both Prandtl and Reynolds values, allowing for more accurate computations across a greater flow range. In the nanofluid inquiry procedure, it is used when the flow regime is unknown or a combination of both kinds.

2.3 Data analysis

Experimental data relationships are defined, including Reynolds number, Nusselt number, coefficients of local heat transfer of nanofluid and water along the axial distance, different flow rates for different temperatures with Nu and heat transfer rate, Reynolds number with friction factor, experimental Nu with Nu correlation, and experimental study results.

3. RESULTS AND DISCUSSION

Nanomaterials in water improve heat transport through a variety of mechanisms. Nanoparticles with high thermal conductivities improve the mixture's thermal conductivity, whilst Brownian motion boosts microconvection and heat transfer rates. Nanoparticles have bigger surface areas, resulting in more heat exchange points. This makes it possible to create heat exchangers that are both efficient. Although nanoparticles can be expensive, their improved heat transfer coefficient lowers total costs and enhances system performance. The number of nanoparticles used is critical for improving composite characteristics. Too low or too high concentrations might result in viscosity and increased pumping force. To prevent sedimentation and blockage, nanoparticles must be stable and evenly distributed.

3.1 Temperature distribution for 2 LPM, 65°C

The investigation revealed that a lower output temperature and a bigger reduction in temperature of the nanomaterial-water combination led to greater rates of heat transfer. The results show the temperature distribution along the x-axis for three distinct fluids: deionized water, ZnO in deionized water at 0.05% concentration, and ZnO in distilled water at 0.4%, as shown in Figure 5.

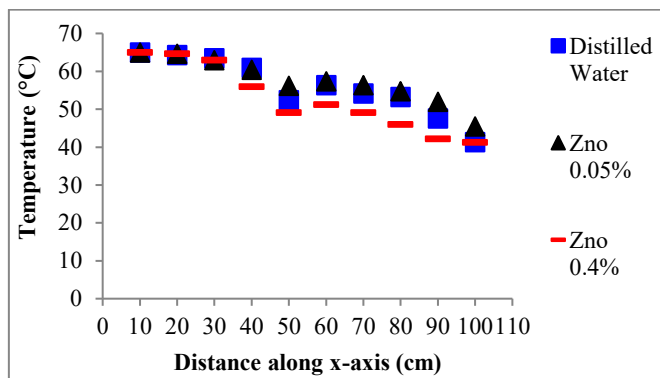


Figure 5. Temperature distribution along the x-axis: $T = 65^{\circ}\text{C}$ at 2 LPM

The data analysis shows that adding ZnO nanoparticles to distilled water causes a temperature reduction along the x-axis when compared to distilled water alone. The findings illustrated that the 0.4% ZnO concentration had the most effective thermal performance, retaining greater temperatures over the pipe length.

3.2 Temperature distribution for 4 LPM, 65°C

When added to water, they significantly improve the heat transferability of the combination. This improves convective heat transport and micro-convection in the fluid, as seen in Figure 6.

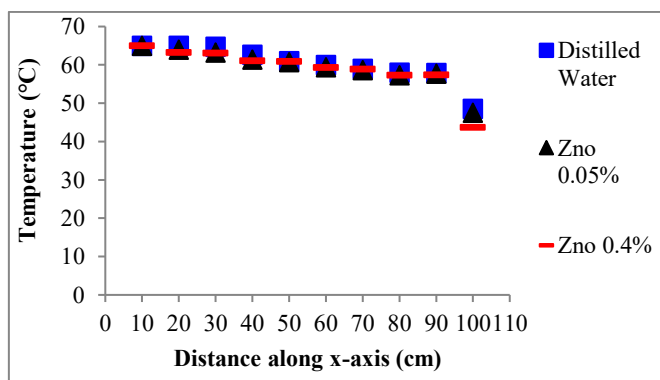


Figure 6. Temperature distribution along the x-axis: $T = 65^{\circ}\text{C}$ at 4 LPM

Figure 6 depicts the temperature distribution for ZnO/distilled water nanofluids and distilled water at concentrations of 0.4% and 0.05%, respectively, in relation to axial distance. The temperature gradually declines along the axial direction, and the presence of ZnO nanoparticles exhibits a substantial influence on thermal behavior, independent of the beginning temperature.

The 0.4% concentration of ZnO nanofluid causes higher

temperatures throughout the pipe, indicating a rise in the coefficient of convective heat transfer. Furthermore, raising the rate of volumetric flow results in a higher temperature decrease across the heat exchanger.

3.3 Temperature distribution for 6 LPM

In Figure 7, see that raising the flow rate can substantially lower the temperature more than other flow rates, confirming that increasing the flow rate causes a reduction in temperature along the exchanger. In the case of nanofluid, the decline is larger than that of distilled water, with the greatest percentage loss occurring at a concentration of 0.4%, as shown in Figure 7.

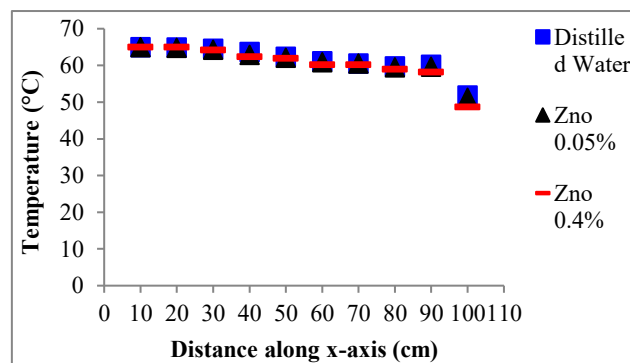


Figure 7. Temperature distribution along the x-axis: $T = 65^{\circ}\text{C}$ at 6 LPM

We appreciate the reviewer's feedback. The data recorder took immediate measurements from one hot-water temperature sensor, one cold-water temperature sensor, one hot-water flow meter, and one cold-water flow meter throughout a 30-minute period for each operational point. After removing the initial transient, 20 minutes of consistent data were averaged. Temperature and flow rate had mean variations of $\pm 1\%$ and $\pm 1.2\%$, respectively. The computed heat-transfer coefficient has an overall error of around $\pm 5\%$. The amended paper now includes a remark on repeatability and uncertainty, as well as appropriate error bars in Figures 5-7.

3.4 Heat transfer rate vs. Reynolds number

The heat exchanger's overall efficiency may be assessed using criteria, including the rate of overall heat transfer, effectiveness (ϵ), and NTU symbolizing the number of transfer units. When evaluating heat exchanger performance utilizing a nanomaterial-water solution, the Reynolds number factor and the rate of heat transfer are important. The rate of heat transfer for all three fluids rises with increasing Reynolds number, as higher Reynolds numbers result in faster flow rates and convective heat transfer [22]. Distilled water cools the heated wall more slowly than nanomaterial-water mixes, and its efficiency decreases as the Reynolds number increases. The water combination containing 0.4% ZnO and distilled water had the maximum heat transfer rate at all Reynolds numbers. Although an increase in nanoparticle concentration may marginally limit heat transfer rate owing to higher viscosity, both nanofluid mixes outperform pure water in terms of thermal performance. This shows that the use of nanoparticles improves both thermal conduction and convective heat transmission, as indicated in Figure 8.

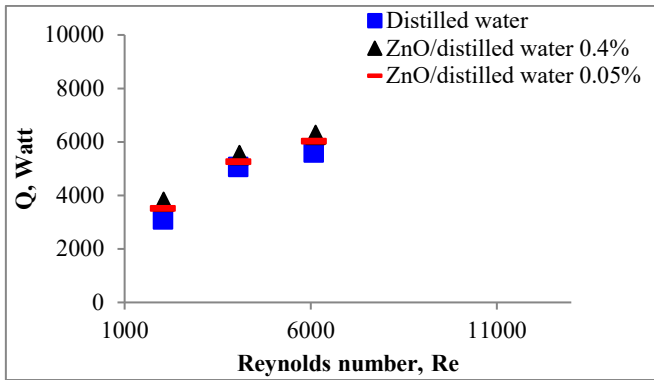


Figure 8. The heat transfer rate vs. Reynolds number

3.5 The Nusselt number vs. volumetric flow rate

The results of this investigation show that 0.4% ZnO/water has greater Nusselt numbers than purified water for all Reynolds values. The largest Nusselt numbers are recorded in 0.4% ZnO/water, followed by 0.05% ZnO combination and pure water. Nusselt numbers were found to increase with increasing concentrations of ZnO nanoparticles. When comparing the findings obtained from both the 0.4% and 0.05% ZnO-water mixes, it can be determined that the 0.4% mixture has a higher influence on increasing Nusselt numbers; this is plainly obvious in Figure 9.

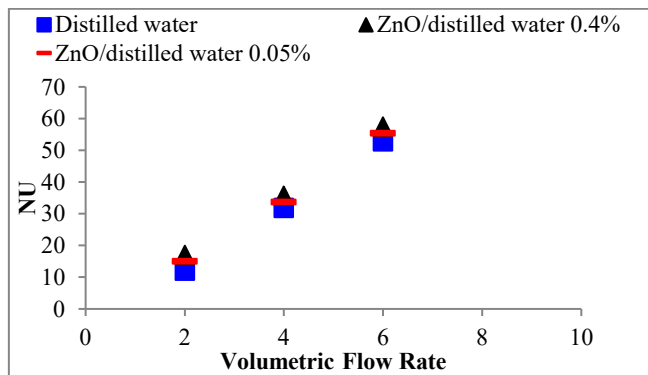


Figure 9. The experimental Nusselt number vs. volumetric flow rate

3.6 The heat transfer coefficient vs. volumetric flow rate

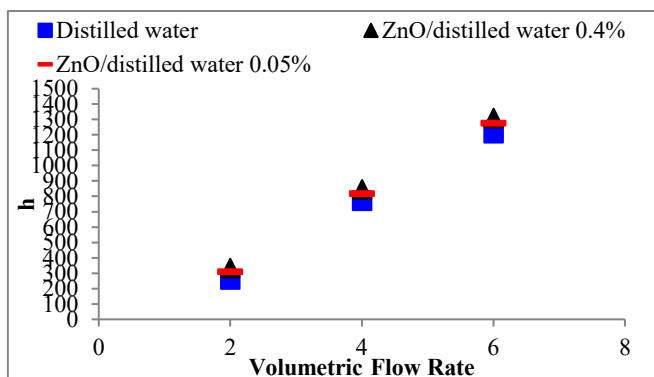


Figure 10. The heat transfer coefficient vs. volumetric flow rate

The water combination had the greatest heat transfer coefficients in all Re numbers of the three fluids studied. The

0.4% ZnO/dis. Water mixture outperforms the 0.05% ZnO/dis. water mixture, demonstrating that the concentration of nanoparticles is increased as the coefficient of heat transfer is improved, as presented in Figure 10.

3.7 The number of transfer units vs. Reynolds number

An essential metric for studying heat exchanger performance is the NTU, symbolizing the number of transfer units, which indicates the efficiency of the thermal transmission process between fluids. As the Reynolds number rises, it typically rises as well, which is determined by the fluid type and larger flow rates develop the coefficient of convective heat transfer, resulting in larger NTU values. Because of enhanced convective heat transmission, NTU values rise with nanoparticle concentration. Higher Reynolds numbers can be used to achieve higher NTU values, which can improve heat exchanger performance. Heat exchangers may be optimized to function in turbulent flow regions, increasing heat transfer coefficients [26]. Figure 11 represents the connection between Re, which symbolizes the Reynolds number, and NTU, which symbolizes the number of transfer units, for ZnO-based nanofluids and distilled water at 0.4% and 0.05% concentrations, respectively. A substantial improvement in heat transfer efficiency is observed with rising ZnO concentration, according to the results. Furthermore, NTU grows gradually with increasing Re values in all circumstances.

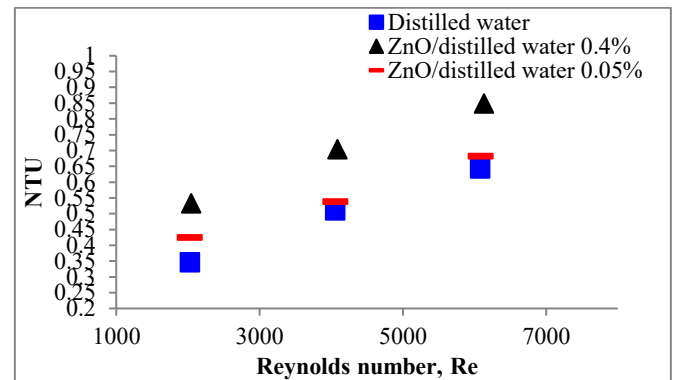


Figure 11. The number of transfer units vs. Reynolds number

3.8 The effectiveness vs. Reynolds number

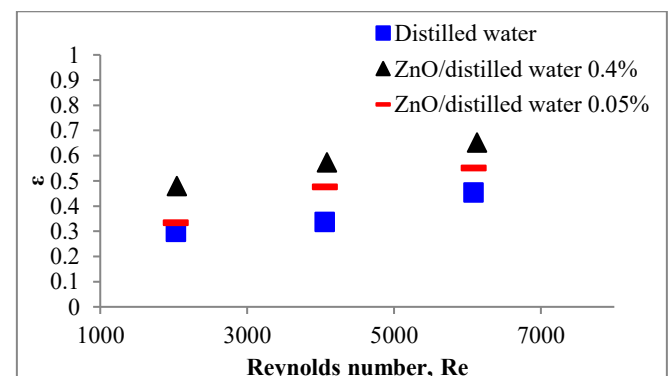


Figure 12. Effectiveness vs. Reynolds number

As a consequence, 0.4% ZnO/water is shown to be more efficient than distilled water for all Reynolds numbers. Figure 12 shows that the improvement in efficacy is more significant at higher Reynolds numbers, as one would expect. According

to the data, 0.4% ZnO/water is the most effective of the three fluids utilized in the study. It is proposed that because the nanoparticles are denser, there is improved heat transmission capability.

3.9 The friction factor vs. Reynolds number

Figure 13 plots the friction factor (f) vs Reynolds number (Re) for three water solutions: Distilled water, ZnO nanofluid/distilled water at 0.4% concentration, and ZnO nanofluid/distilled water at 0.05% concentration.

In all three fluid compositions, the friction factor falls as the Reynolds number rises. At low Reynolds numbers, ZnO dispersions have somewhat greater friction factors than pure water. All friction factors diminish as the Reynolds number increases, and at extremely high Reynolds numbers, they are nearly identical. As the Reynolds number increases, the friction factor lowers, resulting in lower frictional losses. ZnO dispersions have somewhat greater friction factors due to improved thermal conductivity, making them more appropriate for applications of heat transfer. These qualities are useful for designing cooling systems, pipelines, and heat exchangers since they affect efficiency and performance.

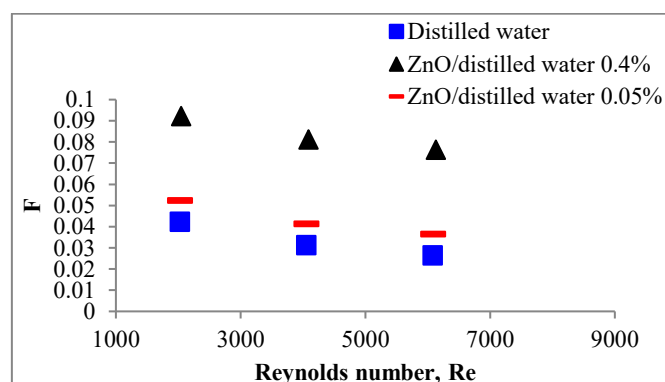


Figure 13. Friction factor vs. Reynolds number

In the study of Hassanein et al. [27], an analysis was done on the thermal performance of Al_2O_3 /distilled water nanofluid at a concentration of 0.5% under comparable operating circumstances as employed in the current work. As illustrated in Figure 14, a comparison with ZnO/distilled water nanofluid at a lower concentration of 0.4% revealed a significant thermal advantage for ZnO, despite the lower nanoparticle loading. At $Re \approx 6000$, the ZnO nanofluid had an enhancement factor (ϵ) of around 0.61, compared to 0.42 for the Al_2O_3 nanofluid, representing an almost 45% improvement. ZnO outperformed Al_2O_3 in the turbulent flow regime ($Re = 6000-8000$), with ϵ values ranging from 6.5% to 8.7% higher. This improved heat transfer behavior is primarily due to ZnO nanoparticles' superior thermophysical properties, which include higher thermal conductivity and greater dispersion stability, making ZnO nanofluids more effective for thermal enhancement under comparable flow conditions. The current study and [27] used the same experimental conditions: cold water at 22°C, hot water at 65°C, cold water flow of 12 L/min, and hot water fluxes of 2, 4, and 6 L/min. and the tests were carried out using the identical heat exchanger shape and dimensions as described by Hassanein et al. [27], ensuring a fair comparison. The primary differences between the experiments are the kind of nanofluid employed and the inclusion of fins in the reference heat exchanger [27], whereas the current study's heat

exchanger lacks fins.

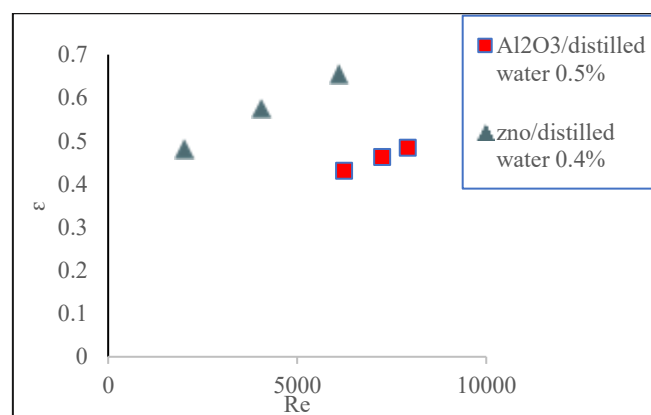


Figure 14. Al_2O_3 /distilled water and ZnO/distilled water effectiveness vs. Reynolds number

4. CONCLUSIONS

The experimental inquiry into improving heat transfer utilizing ZnO-water nanofluids in a heat exchanger with two pipes provides essential insight into how nanofluids contribute to increased thermal performance. In the early phases, the rise in the factor of convective heat transfer with flow velocity increased the thermal transfer rate of all three working fluids by around 25% with the Reynolds number. When Reynolds numbers approached 6000 and hot fluid temperatures reached 65°C, all examined fluids had significantly higher NTU values - up to 20% - with ZnO nanofluids exceeding pure water.

Among the concentrations tested, the 0.4% ZnO nanofluid improved overall thermal performance by around 25%, demonstrating that increasing nanoparticle concentration can improve thermal behavior even further. Furthermore, at 0.4% concentration, the Nusselt number increased by almost 9%, demonstrating the beneficial effect of ZnO nanoparticles. These findings show that the addition of ZnO nanoparticles increases the thermal conductivity and heat transfer efficiency of the working fluid. The statistics clearly demonstrate that nanofluid concentration is a significant component in increasing heat exchanger performance. The use of ZnO nanofluid in water improves heat transfer performance, which can increase the efficiency of industrial heat exchangers, reduce energy consumption, and optimize cooling systems in the Heating, Ventilation, and Air Conditioning, chemical, and food processing sectors.

The current study was confined to a double-pipe heat exchanger arrangement and used ZnO/water nanofluid at low concentrations, which may limit the broader application of the findings. To better represent commercial applications, future research should look at a broader variety of nanofluids and concentrations, as well as more sophisticated heat exchanger designs like shell-and-tube, plate, or spiral kinds. Furthermore, long-term performance studies under varied operating and heating circumstances would offer further information on the dependability and practicality of nanofluid-based heat exchangers.

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NOMENCLATURE

A_s	specific heat capacity at constant pressure, J/(kg.K)
C_h, C_c	heat capacity rate of hot and cold fluid, W/K
C_{min}	minimum heat capacity rate, W/K
C_p	specific heat capacity at constant pressure, J/(kg.K)
C_r	heat capacity ratio (C_{min}/C_{max}), dimensionless
d_i	inner diameter of the pipe, m
f	friction factor, dimensionless

h	convective heat transfer coefficient, W/(m ² .K)
k	thermal conductivity, W/m.K
k_{nf}	thermal conductivity of nanofluid, W/m.K
k_{pf}	thermal conductivity of base fluid, W/m.K
$\dot{m}$	mass flow rate, kg/s
NTU	number of transfer units, dimensionless
Nu	Nusselt number, dimensionless
Pr	Prandtl number, dimensionless
Q	heat transfer rate, W
Re	Reynolds number, dimensionless
T_b	bulk fluid temperature, °C or K
T_w	wall temperature of pipe, °C or K
U	overall heat transfer coefficient, W/(m ² .K)
U_m	mean velocity of fluid, m/s

Greek symbols

ϕ	volume fraction of nanoparticles, dimensionless
θ_m	log mean temperature difference (LMTD), K
μ	dynamics viscosity, Pascal.sec
ρ	density of fluid, kg/m ³
ε	heat exchanger effectiveness, dimensionless