Journal of Mines, Metals and Fuels, *73(1): 165-172; 2025. DOI: 10.18311/jmmf/2025/47225*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Enhancement in Heat Transfer with Nanofluids in Double-Pipe Heat Exchangers

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Abstract

This study investigates the potential of using nanofluids, specifically those composed of water and Titanium Dioxide (TiO_2) nanoparticles, to enhance the thermal performance of a double-pipe copper heat exchanger. By incorporating varying concentrations of TiO_2 nanoparticles (0.1%, 0.3% and 0.5%) into water, the researchers aimed to improve the fluid's thermal conductivity and viscosity. The experimental results demonstrated that the addition of TiO_2 nanoparticles led to a significant increase in the overall heat transfer rate. The highest heat transfer rate was achieved at a nanoparticle concentration of 0.3%, indicating an optimal balance between enhanced thermal properties and potential flow resistance. However, a slight decrease in heat transfer rate was observed at a concentration of 0.5%, suggesting that higher concentrations may not necessarily lead to further improvements. The study further revealed a substantial 23% improvement in the efficiency of the heat exchanger when using the 0.3% TiO_2 nanofluid. This enhancement is attributed to the improved thermal conductivity of the nanofluid, which allows for more efficient heat transfer between the hot and cold fluids. In conclusion, the findings of this research strongly suggest that TiO_2/water nanofluids can significantly enhance the performance of double-pipe heat exchangers. By carefully optimising the nanoparticle concentration and flow conditions, it is possible to achieve substantial gains in thermal efficiency while minimising potential drawbacks such as increased pressure drop.

Major Findings: *This study explored the use of TiO_2/water nanofluids to enhance heat transfer in a double-pipe heat exchanger. The addition of TiO_2 nanoparticles significantly improved heat transfer, with an optimal concentration of 0.3% leading to a 23% increase in efficiency. However, higher concentrations, while improving thermal conductivity, may lead to increased pressure drop, potentially offsetting the benefits.*

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Keywords: *Double-Pipe Heat Exchanger, Nanofluid, NTU, Thermal Conductivity*

1.0 Introduction

To reduce the temperature difference between the fluids, a larger heat exchanger may be employed. However, this increases both the system's size and cost, making it necessary to find a balance between these factors during the design phase. Nanofluids, which enhance the thermal conductivity of fluids, were first introduced by Choi at Argonne National Laboratory. A "nanofluid" is a fluid that contains nanoparticles (less than 50nm in diameter) suspended within it, which notably improves the fluid's heat transfer characteristics and flow behaviour[1,2]. The thermal performance of a nanofluid is influenced by the uniformity of nanoparticle distribution, which can be achieved with the use of ultrasonic mixers or homogenizers operating at frequencies between 20 and 40kHz. The concentration and size of the nanoparticles determine the nanofluid's thermal properties. Finer nanoparticles, with their larger surface area, contribute to a more stable suspension with reduced pressure drop in the system. Key parameters, such as the Nusselt, Peclet and Res, are used to calculate heat transfer rates, with the Nusselt and Peclet numbers being inversely related to the h and rate. Collaborative work by various authors[3,4] led to the development of models that predict the effective thermal conductivity of nanofluids under specific boundary conditions. Boundary layer effects and Brownian motion in the fluid further enhance heat transfer. As the volume concentration of nanoparticles increases, the Nu rises, indicating improved heat transfer performance. The performance of a heat exchanger is affected by both technical aspects and external factors, such as available space and production costs. The need for more efficient energy transfer has driven engineers to design heat exchangers that balance thermal performance with cost-effectiveness. Altering the physical and thermodynamic properties of fluids is vital for improving heat transfer[5]. Standard fluids generally exhibit lower thermal conductivity compared to nanomaterials like copper oxide, alumina and metals such as copper and aluminium. Therefore, the inclusion of nanoparticles can significantly enhance heat transfer efficiency. Recent advancements in nanofluid technology now allow for stable nanoparticle dispersion without blockages in channels, further improving thermal properties[6]. Factors such as the type of nanofluid, its concentration and the type of heat exchanger are critical to optimising performance. Research suggests that nanofluids have substantial potential to improve heat transfer efficiency, making them a promising solution for future heat exchanger applications[7]. This study fills a research gap by investigating the effects of TiO_2/water nanofluids on double-pipe heat exchangers. Effect of substrate thermal conductivity on electronic component temperature control, Phase Change Material (PCM) cooling for smartphone circuits, Computational Fluid Dynamics (CFD) for Integrated Circuit (IC) chip thermal management, AI-based IC chip placement for efficient cooling and water-saving hygienic faucets for public places[8-14]. The research, Heat transfer enhancement in tubular heat exchangers using jet impingement, twisted tape inserts, and nanofluids: A review and experimental investigation[15-23] explores thermal management strategies for electronic devices in harsh environments. Topics include optimising aerofoil design, predicting heat transfer enhancement with twisted tape inserts and analysing the impact of wavy corrugated twisted tape inserts and circular holes on heat transfer in double-pipe heat exchangers. Additionally, the research investigates the thermal performance of electronic components on various substrate materials and the effect of heat transfer on symmetric and asymmetric IC chips mounted on SMPS boards with and without PCM[24-32]. By addressing these research gaps, this study aims to provide valuable insights into the practical application of TiO_2/water nanofluids in double-pipe heat exchangers, contributing to the development of more efficient and sustainable thermal systems.

2. Methodology

2.1 Experimental Procedure

The experimental setup consists of a double-pipe heat exchanger with a test section, pumps, rotameters, a U-tube manometer, a heater and a storage tank, as shown in Figure 1. This 1850mm long section is insulated with glass wool, cotton rope and Plaster of Paris (POP). Temperature measurements are taken using Platinum Resistance

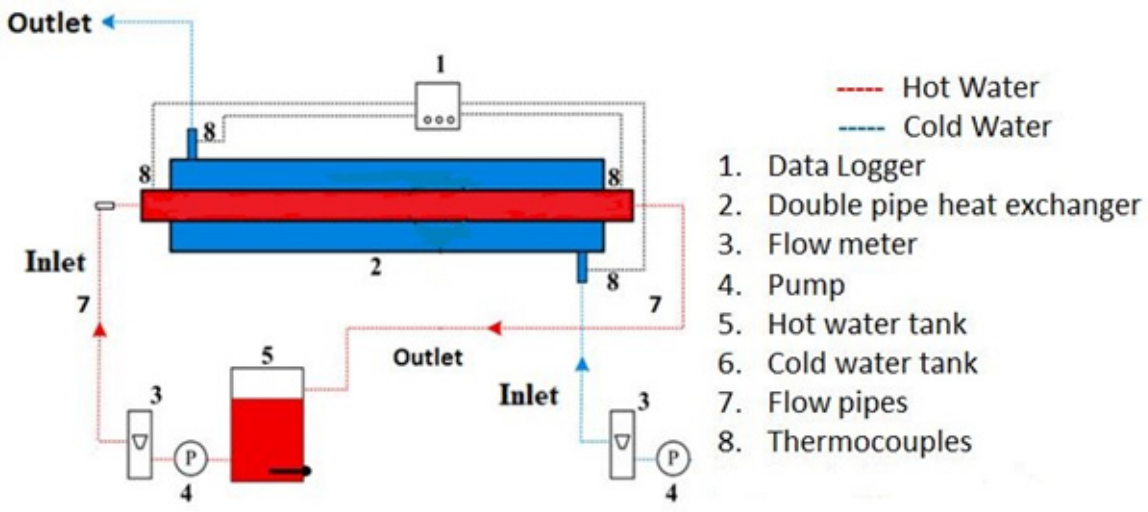


Figure 1. Test Section.

Table 1. Thermal properties of TiO_2 nanoparticles and water

Material	Specific Heat Capacity (J/kg.k)	Thermal Conductivity (w/m.k)	Density (kg/m^3)	Temperature (^{0}C)
Pure Water	4186	0.59	998	26
TiO_2	690	8.2	4170	26

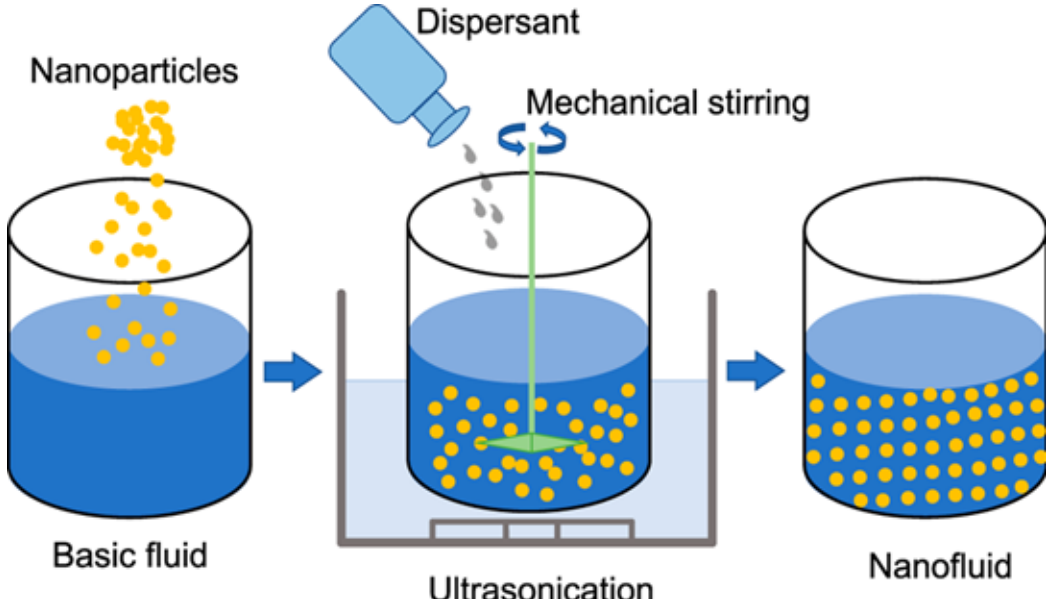


Figure 2. Two-step method.

Thermometer (PT)-100 Resistance Temperature Detector (RTD) sensors and T-type thermocouples. A data logger records these readings. Pressure drop is monitored using a U-tube manometer. A temperature controller and ultrasonicator regulate hot water temperature. Hot and cold fluids are pumped through rotameters and

ball valves to control flow rates. The Re ranges from 5500 to 16000, with a 1500 interval. Cold water inlet temperature is ambient, and hot water inlet temperature is 60°C.

Nanoparticles were dispersed evenly in 3 litres of water through 40-50 minutes of mixing using an electric mixer. This was done in four phases due to the mixer's 1-litre capacity. An ultrasonic device was used for 50-55 minutes to further ensure uniform dispersion, as shown in Figure 2. The prepared nanofluid was then transferred to the test device's reservoir, which had a built-in electric mixer to maintain nanoparticle suspension. Table 1 shows the thermal properties of nanoparticles at 26°C.

2.2 Experimental Test

Keep the electric mixers running in the nanofluid tank to maintain uniform nanoparticle dispersion. Heat the second basin's water to 70°C using an electric coil and thermostat. Account for nanoscale water temperatures and flow rates within the heat exchanger tubes. Regulate hot water flow at 4 L/min and nanofluid flow at 2, 4 or 6 L/min using pyloric valves. Install flow meters to measure flow rates. Monitor temperatures at the exchanger's input and output. Record temperature readings every 10 minutes. This research focuses on a single-phase fluid in turbulent conditions. Data was collected under steady-state conditions after the inlet temperature reached 60°C and remained stable for two hours.

The following steps were involved in data reduction:

Bulk mean temperature

$$T_b = \frac{T_i + T_o}{2}$$

Wall temperature of the inner pipe

$$T_w = \frac{T_1 + T_2 + \cdots + T_{10}}{10}$$

The convective heat transfer rate

$$Q = \dot{m} c_p (T_i - T_o)$$

$$Q_{ave} = \frac{Q_h + Q_c}{2}$$

Overall h ( )

$$Q_{ave} = U_i A_i \Delta T_{LMTD}$$

Logarithmic Mean temperature difference ($\Delta TLMTD$)

$$\Delta T_{LMTD} = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln((T_{h,i} - T_{c,o})/(T_{h,o} - T_{c,i}))}$$

H (h0) for cold fluid

$$Q_c = h_0 A_0 (T_w - T_{b,c})$$

Average convective h (hi)

$$\frac{1}{U_i A_i} = \frac{1}{h_i A_i} + \frac{\ln(d_o/d_i)}{2\pi k_{ip} L} + \frac{1}{h_o A_o}$$

Average Nu for hot fluid

$$Nu_i = \frac{h_i d_i}{k_i}$$

Pressure drop in the inner pipe

$$\Delta P = P_i - P_o$$

Frictional loss in the inner pipe (friction factor)

$$f = \frac{\Delta P}{(\rho u^2/2)(L/d_i)}$$

Thermal performance factor

$$\eta = \frac{\left(Nu_t/Nu_0\right)}{\left(f_t/f_0\right)^{(1/3)}}$$

3.0 Uncertainty Analysis

The Kline and McClintock equation was used to estimate this uncertainty.

$$\frac{\delta R}{R} = \left[a\left(\frac{\delta X_1}{X_1}\right)^2 + b\left(\frac{\delta X_2}{X_2}\right)^2 + c\left(\frac{\delta X_3}{X_3}\right)^2 + \cdots + m\left(\frac{\delta X_M}{X_M}\right)^2\right]^{0.5}$$

Tables 2 and 3 show the obtained uncertainty in measured quantities and calculated quantities.

Table 2. Obtained uncertainty in measured quantities

Sr. No.	Parameters	Uncertainty
01	Test Tube Surface Area	0.007215
02	Inner Pipe Cross Sectional Area	0.012
03	Outer Pipe Cross Sectional Area	0.0126
04	Hot Water Mass Flow Rate	0.0347
05	Velocity of hot fluid in the tube	0.0361

Table 3. Obtained uncertainty in calculated quantities

Sr. No.	Parameters	Uncertainty
01	Hot Water Heat Transfer Rate	0.03842
02	Cold Water Heat Transfer Rate	0.0051
03	Cold Water Heat Transfer Coefficient	0.013
04	Hot Water Heat Transfer Coefficient	0.0442
05	LMTD	0.005
06	Average Heat Transfer	0.03866
07	Overall Heat Transfer Coefficient	0.0413
08	Reynolds Number	0.0387
09	Nusselt Number	0.0447
10	Pressure Drop	0.0044
11	Friction Factor	0.0359

4.0 Results and Discussion

Figure 3 illustrates the relationship between Nu and Re for various volume concentrations (0.12% to 0.52%). As both numbers increase, it indicates an increase in fluid velocity leading to improved heat transfer. Furthermore, higher nanofluid concentrations result in increased Nus, attributed to a higher h.

Figure 4 illustrates the relationship between Reynolds No. (Re) and h for various volume concentrations. As the concentration increases, the h also increases, attributed to the enhanced thermal conductivity of the nanofluids. This is due to the improved thermal and physical properties of the fluid at higher concentrations.

Figure 5 illustrates the relationship between Re and friction factor for three different volume concentrations. A high friction factor was observed at low Res (around 500). As the Re increases, the friction factor of the nanofluids decreases.

Figure 6 illustrates the relationship between the Number of Transfer Units (NTU) and Re for different nanofluid concentrations. The optimal NTU is observed at a Re of 500 and a nanofluid concentration of 0.5%. As the volume concentration of the nanofluid increases from 0.12% to 0.52%, the NTU also increases.

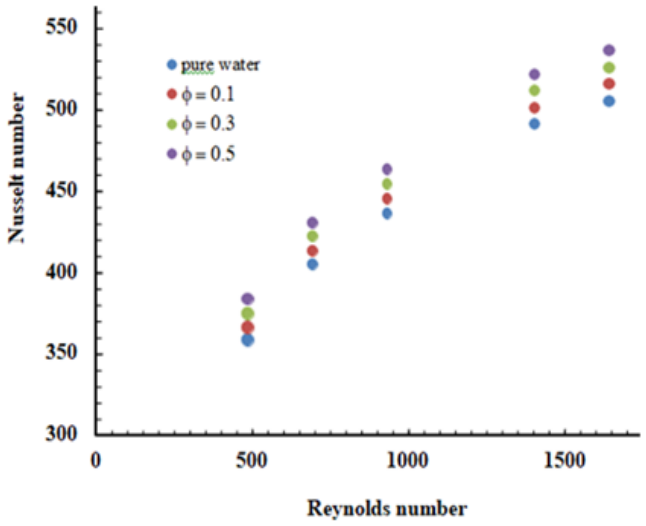


Figure 3. Shows the Nusselt-Reynolds correlation as volume concentration increases.

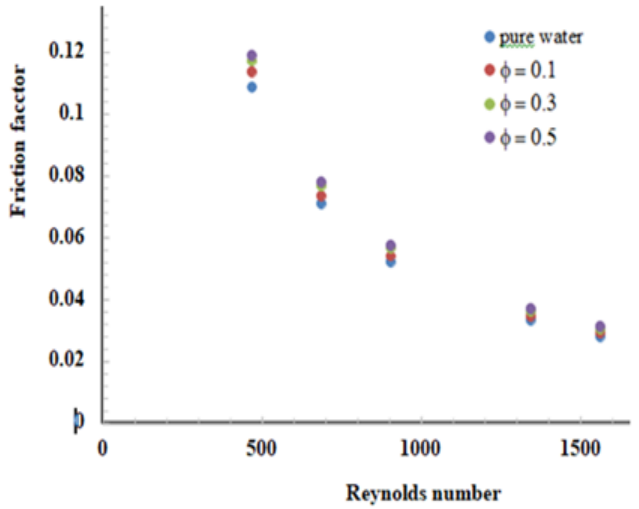


Figure 5. F Vs Re.

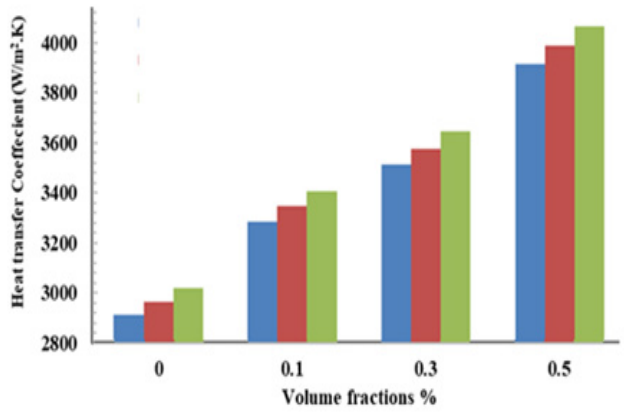


Figure 4. h and nanofluid volume fractions.

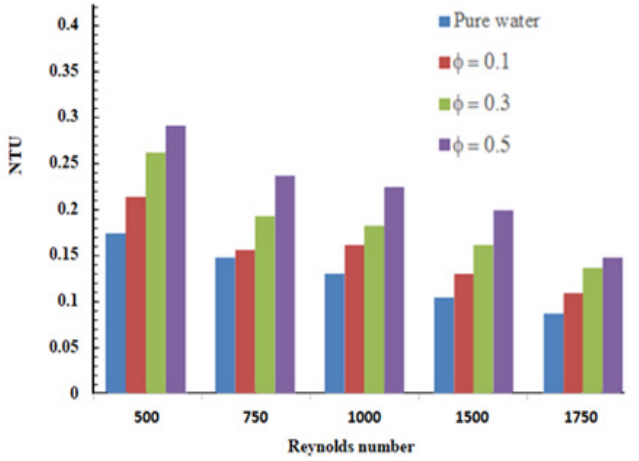


Figure 6. NTU with different Re and volumetric concentrations.

5.0 Conclusion

As the concentration of titanium dioxide (TiO_2) nanoparticles in the water-based nanofluid increased from 0.12% to 0.52%, the heat transfer coefficient also increased. This indicates that the addition of nanoparticles enhanced the thermal conductivity of the fluid. A notable 21% improvement in the overall heat transfer rate was observed when a 0.5% nanofluid was used at a flow rate of 2 litres per minute. The optimal performance of the heat exchanger, characterised by the highest NTU, was achieved at a Re of 500 and a nanofluid concentration of 0.5%. This suggests that at this specific combination of flow conditions and nanoparticle concentration, the heat exchanger was most effective in transferring heat between the two fluids. The maximum effectiveness of the heat exchanger, which measures the actual heat transfer achieved compared to the maximum possible heat transfer, was found to be 38%. This value was obtained using a 0.5% nanofluid at a flow rate of 2 litres per minute. This result highlights the significant potential of TiO_2/water nanofluids to improve the performance of heat exchangers.

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