IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Heat and Technology
Vol. 41, No. 5, October, 2023, pp. 1383-1388
Journal homepage: http://iieta.org/journals/ijht

Friction Factor and Heat Transfer Enhancement of Hybrid Nanofluids in a Heated Circular Tube

Firas Aziz Ali[1*], Adnan M. Alsaffawi[2]

[1] Department of Power Mechanics Technology Engineering, Northern Technical University, Mosul 41001, Iraq
[2] Department of Mechanical Engineering, Mosul University, Mosul 41002, Iraq

Corresponding Author Email: firasaziz@ntu.edu.iq

https://doi.org/10.18280/ijht.410530

Received: 3 April 2023
Revised: 19 September 2023
Accepted: 10 October 2023
Available online: 31 October 2023

Keywords:
hybrid nanofluids, performance, Nusselt number, heated tube

ABSTRACT

This work investigates the potential of hybrid nanoparticles suspended in pure water to enhance the thermal performance of heat exchangers at minimal weight fractions. A hybrid nanofluid consisting of 50% ZnO and 50% Al_2O_3 nanoparticles dispersed in pure water at weight fractions of 0.1%, 0.3%, and 0.5% was prepared. An experimental rig, featuring a straight horizontal tube with a constant wall heat flux, was equipped with eight thermocouples positioned at the inlet, outlet, and along the tube's surface. The study focuses on the impact of the hybrid nanofluid on the friction factors and heat transfer coefficients within a Reynolds number range of 5000 to 20000. Observations indicate that the Nusselt number escalates with an increase in the Reynolds number through the horizontal tube, while the friction factor exhibits a converse relationship. The peak Nusselt number and friction factor were observed at a 5% mass fraction of the hybrid nanofluid. Specifically, enhancements in the Nusselt number were recorded at 9%, 11.8%, and 16.7% for the weight fractions of 0.1%, 0.3%, and 0.5% respectively. Additionally, the deviation in the friction factor was noted at 2.3%, 3.6%, and 4.1% in comparison to pure water. This study thus provides critical insights into the role of hybrid nanofluids in optimizing heat transfer in heat exchangers.

1. INTRODUCTION

Techniques for enhancing heat transfer in tubes have been developed to improve thermal performance across a range of industrial applications. Active methods of heat transfer enhancement, encompassing techniques such as jet cleaning, mechanical assistance, fluid vibration, electrostatic fields, and surface vibration, necessitate the utilization of external power to modify flow and augment heat transfer.

Conversely, several methods eschew the need for an external power source, integrating strategies such as surface roughness, flow swirl equipment, modified walls, displacement enhancements, surface fixtures, enlarged surfaces and fasteners, and the addition of solid nanopowder. The application of nanofluids for heat transfer enhancement in order to meet specific cooling challenges is widespread in diverse fields, including photonics, transportation, semiconductors, and electricity generation [1-8].

One such passive method, involving the use of tube ribs, has been demonstrated to foster heat transmission, albeit at the cost of increasing the pressure drop [9-13]. Certain studies suggest that the heat transfer and friction factor under laminar conditions are not significantly influenced by an increase in the number of tubes [9, 10, 14]. Similar findings have been reported [15-17] in relation to the rise in the friction factor and Nusselt number due to turbulent flow through improved tubes.

Luciu et al. [18] presented both experimental and numerical investigations of the application of nanofluid aluminum oxyhydroxide for the modification of a heat exchanger tube in a coaxial arrangement using solar radiation. In a similar vein, Prajapati and Rajvanshi [19] conducted a study to examine the convective heat transfer of turbulent nanofluid flow utilizing alumina with H_2O in the outer tube under varying surface temperatures. The presence of small solid materials in the fluid was found to enhance heat transfer.

Bozorgan [20] examined a horizontal tube-in-tube heat exchanger, employing both numerical and experimental methods to investigate the impact of turbulent flow in the opposite direction. For both experimental and simulated purposes, FLUENT was used. Their findings corroborated that nanofluid significantly boosted heat transmission and concurred with previous experimental data. Rostamani et al. [21] quantitatively investigated nanoparticle turbulence in two-dimensional models using copper oxide, titania, and alumina in varying fractions flowing in channels under steady conditions of constant heat flux.

Numerous investigators have conducted experiments related to convective heat transfer in turbulent and laminar nanofluid flows through tubes [22-24]. These studies employed water and nanoparticles of copper oxide (CuO), aluminum oxide (Al_2O_3), and titanium dioxide (TiO_2), and proposed correlations of the Nusselt number. It was observed that the heat transfer efficiency was enhanced in comparison to the base fluid at the selected Reynolds number.

Wen and Ding [25] reported on experimental results for the laminar flows of water nanofluids suspended with 30 nm alumina nanoparticles in a heated pipe. A substantial increase in the Nusselt number was noted in the inlet region, which was found to diminish with increasing axial distance.

Numerical and experimental studies focusing on the influence of 1-10% weight fractions of alumina solid nanoparticles in H_2O/EG base fluid were conducted [26]. It was revealed that as the nanoparticle fractions increased under the Reynolds numbers, there was a corresponding rapid increase in the heat transfer rate.

Li et al. [27] illustrated the technique of heat transfer using finned helical tubes. It was observed that bubbles arranged themselves in parabolic patterns during laminar flow. However, this pattern was disrupted in the turbulent flow regime due to the random separation of vortices.

Liu and Jensen [28] extended their previous research by examining two finned helical tubes under fully developed turbulent single-phase flow. Raja et al. [16] indicated that the friction factor and Nusselt number of micro fin tubes marginally exceeded those of conventional pipes, recommending against the use of micro fin tubes under laminar flow conditions.

Further research by Yang et al. [29] involved the investigation of four corrugated spiral tubes by measuring the pressure drop and heat transfer. It was determined that the heat transfer coefficient did not rise due to friction under the regime of turbulent flow.

Hussein et al. [30] conducted computational fluid dynamics studies to investigate the flow of alumina nanofluid with water through a flat tube. It was demonstrated that the variations in behavior between the base fluid and nanofluid are sensitive to the comparative parameters chosen. At the same Reynolds number, a higher Nusselt number and pressure drop were found to correspond with a higher concentration of nanoparticles.

Azeez et al. [31] explored the efficiency of thermal energy using carbon nanotube nanofluids in a tube. The enhancement in heat transfer was observed to be due to an improvement in effective thermal conductivity.

In light of the literature survey, the behavior of the Nusselt number and friction factor in a circular pipe under fixed heat fluxes with hybrid nanofluids weight fractions of 0.1, 0.3, and 0.5% was studied. The objective of the undertaken study was to enhance the heat transfer of a heated tube using a hybrid nanofluid. An experimental method was employed to examine the heat transfer rate from hybrid nanoparticles of 50% ZnO and 50% Al_2O_3 in a simple tube, with the wall heat flux maintained constant.

2. EXPERIMENTAL WORK

2.1 Preparation

This investigation, US Research Nanomaterials, Inc. (USA) supplied the suspended 50%ZnO–50%Al_2O_3 nanoparticles with concentrations of 0.1%, 0.3% and 0.5% individually. The starting weight fractions of ZnO and Al_2O_3 single nanofluids was estimated using Eq. (1). Additionally, both single nanofluids were diluted from their initial form. The optimal ZnO/water and Al_2O_3/water nanofluid heat transfer capability, according to earlier studies [31-34], was noted at 1% weight fraction. The hybrid nanofluids are put through the stirrer procedure utilizing a mechanical mixer for 60 min as part of the preparation as shown in Figure 1(a). To create a stable final solution, the solutions underwent additional sonication using an ultrasonic bath for various sonication periods, up to 45 min as indicated in Figure 1(b).

(a) Mechanical stirrer (b) Ultra sonication stirrer

Figure 1. Preparation of hybrid nanofluid

2.2 Thermal properties

The thermal conductivity (k_{nf}), viscosity (μ_{nf}), specific heat capacity (C_{nf}) and density (ρ_{nf}) of hybrid nanofluids can be evaluated as [35]:

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

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

$$\rho_{nf} = (1-\emptyset)\rho_{bf} + \emptyset(\rho)_{ZnO} + \emptyset(\rho)Al_2O_3 \quad (3)$$

$$C_{nf} = \frac{(1-\emptyset)\rho_{bf}C_{bf} + \emptyset(R\rho)_{ZnO} + \emptyset(R\rho)Al_2O_3}{\rho_{nf}} \quad (4)$$

$$\frac{k_{nf}}{k_{bf}} = \left(1+\frac{T}{70}\right)^{0.077}\left(1+\frac{\emptyset}{100}\right)^{5.58} \quad (5)$$

$$\frac{\mu_{nf}}{\mu_{bf}} = 0.081\exp\left(0.35\frac{T}{70} + 0.11\emptyset\right) \quad (6)$$

Both friction factor and Nusselt number can estimated as:

$$f = \frac{0.316}{Re^{0.25}} \quad (7)$$

$$Nu = \frac{h}{k}D_h = 0.023\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \quad (8)$$

Since the weight fraction of the hybrid nanofluids is less than 5%, it is assumed that they act like Newtonian fluids, the nanofluids characteristics are summarized in Table 1.

Table 1. Hybrid nanofluids thermophysical properties

ϕ(%)	ρ(kg/m^3)	μ(mPa.s)	Cp(J/kg.K)	k(W/m.K)
0.1	1099	2.99	3339	0.62
0.3	1155	3.03	3201	0.66
0.5	1220	3.18	3042	0.72

2.3 Test rig and experimental test

We take the stream to be a Newtonian fluid that is both incompressible and turbulent, with no axial heat conduction and influence of gravity. In order to perform the turbulent flows, the k-ε turbulence model is employed, which can be implemented by wall heating. Comparison of pressure drop and heat transfer from experimental tests of a plain tube containing a hybrid nanofluid with those from Equation of

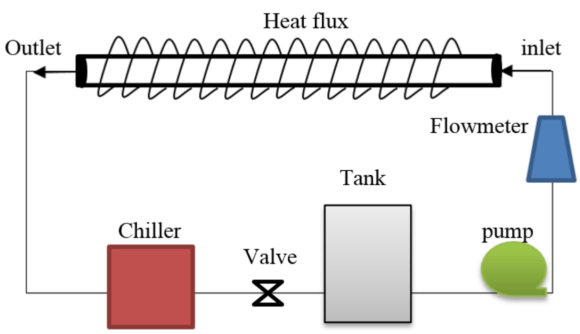
Blasius Eq. (7) and Dittus-Boelter Eq. (8), respectively. Assuming that at weight fractions of 0.1, 0.3, and 0.5%, nanofluids behave as Newtonian fluids. The friction factor can be expressed by Ding et al. [32] under conditions of dynamic equality for two streaming media, liquids and nanoparticles through the pipes.

The system shown in Figure 2 is set up to measure the inlet and outlet temperatures and drop of pressure to estimate heat transfer coefficient and friction factor. The experimental system setup contains of a tank for reserving cold fluid, water heater, one centrifugal pump, a flow meter, valves, tubes, eight digital K type thermocouples and oil manometer tube. A flow meter was in the range of 7-22 liter per min with control valve to measure the flow rates. The 0.5 hp centrifugal pump was fixed between the flow meter and the reservoir tank.

Two thermocouples joined at the outlet and inlet of the inner tube to measure the fluid temperature. The thermocouples were calibrated using a mercury thermometer and water baths of varying temperatures, achieving an accuracy of ±0.5℃.

In order to measure the pressure drop, 8 mm diameter small tube providing with oil as a U-tube manometer has been connected. Cleaning of the experimental test rig has been performed before running to eliminate scale or particles. After creating the nanofluid and filling the cold container while the hot water was setting as seventy degrees Celsius, start the experimental testing and adjust each loop flow rate and allow sufficient time for steady state system.

(a) Photograph of test rig



(b) Schematic of test rig

Figure 2. Experimental system

3. DISCUSSION OF RESULTS

3.1 Results validation

To verify outcomes utilizing the experimental work with data of other researches available in the literature, the validation step is conducted. This is seen on Figure 3, where the friction coefficient reduces as Reynolds number increase of the with turbulent regime. Results are shown as dashed black lines in Blasius Eq. (7) for base fluid and other data of researches [11] between the present results and their equivalence with the equation, there seems to be some agreement.

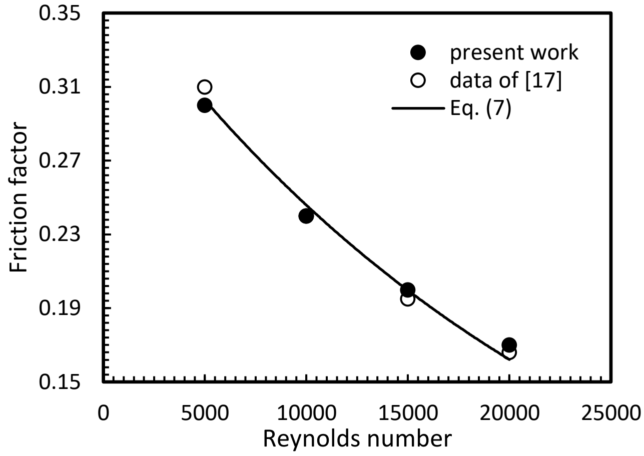


Figure 3. Validation of experimental friction factor results for pure water

The comparison of the Dittus-Boelter Eq. (8) and data from others [13] and the recorded data of temperature to compute the Nusselt number values for hybrid solid nanoparticles suspended in pure water, is shown in Figure 4. As can be seen, a significant amount has been acquired using experimental tests evaluated values for in different Reynolds numbers.

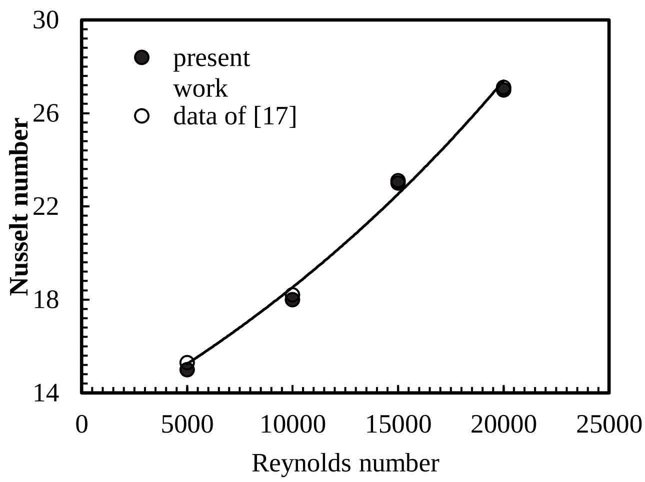


Figure 4. Validation of experimental Nusselt number results for pure water

3.2 Nusselt number

Figure 5 shows Nusselt number results for hybrid nanofluids with weight fractions of 0.1, 0.3 and 0.5% at the Reynolds numbers 5000 to 20000 experimentally. In general, Nusselt number is increased as Reynolds Number increases in the same way experimentally.

The impact of nanofluid weight fractions appears to be substantial, where the increase of volume fraction has led to increase of heat transfer. Since it is favorable to raise weight fractions, the improve should take pumping strength into consideration.

Additionally, it is evident that as the nanoparticles volume fraction rises, Nusselt increases as well as Reynolds number, the base liquid thermal conductivity, and Brownian motion of solid nanoparticles. The outcomes match those of the experiment conducted by Hussein et al. [17]. The medium's thermal conductivity heat transfer has a significant impact on the Nusselt number.

Solid nanoparticles are disseminated for pure water to boost the final thermal conductivity because thermal conductivity of solid particles is increased. For of 0.1, 0.3, and 0.5%, weight fractions respectively, the average variance between the experimental results and the other data showed good agreement at approximately 4%.

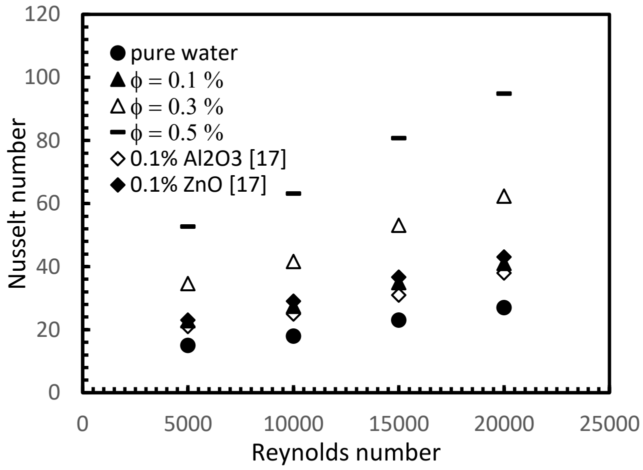


Figure 5. Nusselt number from experimental result and data of Hussein et al. [17]

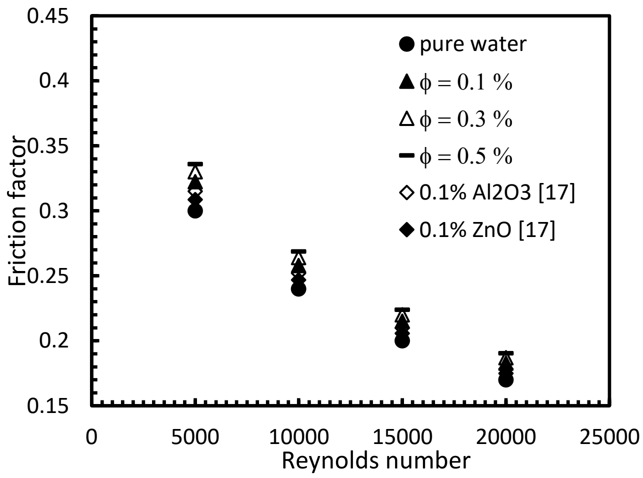


Figure 6. Friction factor against Reynolds number comparing with experimental data of with data of Hussein et al. [17]

3.3 Friction factor

In an experimental tests of plain tube, Figure 6 indicates the relation between nanofluids friction factor and Reynolds number with various concentrations from 0.1% to 0.3%. The weight fraction of 0.3%, followed by 0.2 and 0.1%, has the biggest rise due to friction factor which is visible. Similar findings were previously reported by Hussein et al. [17]. The average deviation value of the experimental data illustrates a respectable level of correspondence with the outcomes of the data available in the literature. For the weight fractions of 0.1, 0.3, and 0.5%, the average deviation is 2.2, 2.5 and 2.9%, respectively.

4. CONCLUSIONS

In the current study, an experimental research of a circular heated straight tube has been performed with forced convection of hybrid nanofluids under turbulent flow condition. The 50% ZnO+50% Al_2O_3 suspended in water is kind of hybrid nanofluid that is utilized. The weight fractions 0.1, 0.3, and 0.5% were employed under 5000 to 20000 range of Reynolds number. This work describes the impact of hybrid nanofluids on Nusselt number and friction factor. The findings demonstrate the experimental heat transport in a simple heated straight tube is increased as Reynolds number increases. The maximum Nusselt values were found for 50% ZnO+50% Al_2O_3 suspended in water hybrid nanofluids at weighted fraction of 0.5%, and the highest friction coefficient was followed by 0.3%, finally 0.1%. The average variation for the weight fractions of 0.1, 0.3, and 0.5% in this investigation was determined to be 6.5, 7.2, and 8.3% when experimental findings were compared to pure water. It was observed that the average deviation of the friction factor is 2.3, 2.8 and 3.3% for 0.1, 0.3, and 0.5% concentrations respectively.

ACKNOWLEDGMENT

Acknowledgement to all staff of Mosul technical engineering due to support the authors.

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NOMENCLATURE

C	Specific heat
D_h	Hydraulic diameter (m)
h	Coefficient of heat
k	Thermal conductivity
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
V	Velocity of nanofluid (m/s)
N	Nusselt number

Greek symbols

ϕ	Weight fractions (%)
ρ	Density (kg/m^3)
μ	Dynamic viscosity (mPa.s)
p	Nanoparticle
nf	Nanofluid
bf	Base fluid