Advances in Engineering and Technology
An International Journal

Experimental Analysis of Fluid Flow and Heat Transfer of Al_2O_3-Water Nanofluids in Turbulator Tube

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Abstract

Nanofluids have attracted huge attention due to their improved thermal properties. One prominent application of nanofluids is enhancing the thermal performance of heat exchangers. In this research work, experimental investigations were conducted to evaluate the effect of adding Al_2O_3-water nanofluids on the overall heat transfer coefficient in a shell and tube heat exchanger fitted with helical coil turbulators. Al_2O_3 nanoparticles were uniformly dispersed in water to create nanofluids with concentrations of 0.2% and 0.4% by weight. These nanofluids were used in the tube of the shell and tube heat exchanger having helical coil turbulators with pitches of 16 mm and 20 mm induced turbulence to enhance heat transfer. The study examined various parameters including nanofluid concentration and turbulator pitch, analyzing their effects on heat transfer and found that using Al2O3 - water nanofluids significantly enhances the thermal efficiency of the shell and tube heat exchanger. The maximum increase in the overall heat transfer coefficient was observed with 0.4% Al_2O_3-water nanofluid combined with a 16mm pitch helical coil.

Keywords: *Nanofluid, Turbulator, Helical Coil Pitch, Heat Transfer*.

1. Introduction

Heat exchangers are used in many industries to facilitate heat transfer between different fluids, aiming to recover waste heat and minimize utility costs [1]. Various techniques have been used to improve heat transfer, including magnetic fields, geometric modifications, ribs and baffles, surface roughness, and the incorporation of nanoparticles. Pimsarn et al. investigated the use of serrated-ring turbulators in heating tubes, finding that these devices enhance heat transfer by disrupting the laminar sub-layer, creating reversing flows, and delaying boundary layer development [2]. Similarly, Kamboj et al. optimized turbulator pitch in double-pipe heat exchangers to maximize heat transfer efficiency while minimizing power consumption [3].

In heat exchangers, fluid selection is critical for optimizing heat transfer efficiency and operational performance. The ideal fluid must have excellent thermal conductivity, a suitable specific heat capacity to absorb and release heat effectively, and a viscosity that allows for smooth flow through the heat exchanger. Nanofluids, which are fluids containing a base fluid (like oil, ethylene glycol or water) with dispersed nanoparticles, leverage these properties to significantly enhance the base fluid's thermal performance. This enhancement is due to the nanoparticle's high surface area to volume ratio, which boosts both convective heat transfer coefficients and thermal conductivity. A review by Apmann et al. explores how factors like base liquid, temperature, surfactants, nanoparticle concentration, size, shape, and material affect the thermal conductivity and viscosity of nanofluid [4]. They found that higher nanoparticle concentrations generally enhance the thermal conductivity and viscosity than larger nanoparticles which affect conductivity and viscosity differently. Hussein et al. experimentally measured the thermal properties of nanofluids including aluminum oxide (Al_2O_3), (TiO_2), and silicon oxide (SiO_2) dispersed in water at various concentrations [5]. The study revealed enhanced thermal conductivity compared to the base fluid, with Al_2O_3 exhibiting the highest thermal conductivity among the tested nanoparticles. Lee et al. conducted experimental research on the thermal conductivity of nanofluids using a transient hot wire method. They examined four different nanofluids Al_2O_3-water, Al_2O_3-ethylene glycol, CuO-water, and CuO-ethylene glycol [6]. Their findings indicated consistently higher conductivity enhancements in ethylene glycol-based nanofluids compared to water-based ones. Additionally, Rohit S. Khedkar et al. investigated the impact of copper oxide (CuO) nanoparticles on the thermal conductivity of monoethylene glycol and water. Both fluids showed increased conductivity with higher nanoparticle concentrations and longer sonication times [7]. Shahrul et al. conducted an analytical study on a shell and tube heat exchanger using nanofluids containing Fe_3O_4, ZnO, TiO_2, CuO, and Al_2O_3 nanoparticles [8]. Their findings highlighted that the highest heat transfer coefficient was of Al_2O_3-water among the tested nanofluids.

Shell and tube heat exchangers are known for their mechanical strength and durability, essential for withstanding the operational stresses in experimental setups involving high flow rates [9]. Turbulent flow has been extensively researched for its profound impact on enhancing heat transfer rates in fluids. It is widely acknowledged that turbulent flow can significantly augment heat transfer compared to laminar flow. This disturbance of the thermal boundary layer significantly enhances the heat transfer coefficient [10]. Kia et al. investigated heat transfer and pressure drop in helical tubes using Al_2O_3 and SiO_2-base oil nanofluids at various concentrations [11]. They found that Al_2O_3 nanofluid significantly enhances heat transfer coefficients, and various helical tube geometries improve heat transfer compared to straight tubes. Suresh et al. experimentally investigated heat transfer and pressure drop in circular tubes using spiraled rod inserts and Al_2O_3-water nanofluids [12]. They found that nanoparticles significantly enhanced heat transfer, increasing Nusselt numbers compared to plain tubes. Akyurek et al. conducted experimental research using nanofluids in a concentric tube heat exchanger with wire coil turbulators [13]. They observed that higher nanoparticle concentrations enhanced the total heat transfer coefficient. Furthermore, they found that elevated Reynolds numbers and the turbulent flow induced by the turbulators boosted heat transfer rates but pressure drop also increased across the heat exchanger. Chandrasekhar et al. investigated friction factor and heat transfer in a horizontal tube in turbulent flow conditions [14]. They noted that while turbulent flow enhances heat transfer rates, it also results in higher friction factors. This trade-off between improved heat transfer and increased flow resistance is an essential consideration in heat exchanger design. Murugesan et al. studied turbulent flow in a circular tube equipped with twisted tape inserts [15]. They found that both heat transfer rates and friction factors escalate by increasing Reynolds numbers. Shabi et al. examined Al_2O_3-water nanofluid in a shell and helical coiled heat exchanger, finding that higher nanoparticle concentrations improved both heat transfer coefficient and pressure drop [16]. T. Salameh et al. conducted experimental and numerical analyses on concentric counter flow tube heat exchangers using different nanofluids, highlighting significant performance improvements over base fluids [17]. A. K. Tiwari et al. explored the effects of nanoparticle concentration in plate heat exchangers, discovering that increased concentrations led to enhanced heat transfer rates [18]. These studies collectively underscore the significant potential of nanofluids to enhance heat transfer efficiency in various heat exchanger designs.

However, there is a notable gap in comprehensive experimental data concerning the Al_2O_3-water nanofluid's performance in shell and tube heat exchangers equipped with helical coil turbulators. Thus, the primary objective of this research is to investigate how varying concentrations of Al_2O_3 nanoparticles and the use of helical coil turbulators with different pitches influence the overall heat transfer coefficient in shell and tube heat exchangers. Additionally, comparative analyses involving pure water and nanofluids without turbulators are essential to isolate and quantify the benefits and drawbacks of these enhancements. Accordingly, this research aims to provide deeper insights into these factors to facilitate the design and optimization of a more efficient heat exchange system.

2. Materials and method

2.1 Synthesis of Aluminium Oxide Nanoparticle

Ten grams of aluminum nitrate nonahydrate ($Al(NO_3)_3 \cdot 9H_2O$) were dissolved in 100 milliliters of distilled water to form an aluminum nitrate nonahydrate solution. Additionally, a solution of ethanol was prepared by dissolving 3.35 grams of ethanol in 50 milliliters of distilled water. The synthesis process commenced by stirring the aluminum nitrate nonahydrate solution and the ethanol solution together at room temperature for approximately ten minutes, ensuring the formation of a homogenous mixture. The mixture was subsequently heated to 80 °C for one hour to yield a viscous liquid. The temperature was further elevated to 350 °C, and combustion occurred over 45 minutes, leading to a significant evolution of gases and a voluminous reaction. The resulting burned materials were subsequently ground and subjected to calcination in a muffle furnace for one hour at 1000 °C, resulting in the formation of Al_2O_3 nanoparticles [19].

2.2 Characterization using X-Ray Diffraction (XRD)

XRD analysis was employed for the characterization of the synthesized Al_2O_3 nanoparticles. This technique offers insights into the lattice structure of crystalline substances, providing information about chemical composition, bond angles, unit cell dimensions, and crystallographic structure of materials. The basis of this method lies in the X-rays constructive interference when interacting with crystalline samples. The Scherrer's formula was employed to calculate the particle size based on the broadening of X-ray diffraction lines (β) corresponding to specific (hkl) reflections [19].

$$D = \frac{K\,\lambda}{\beta cos\theta} \tag{1}$$

where,

D = Particle size (nm)

λ = 0.15406 nm (X-ray wavelength)

K = 0.9

θ = Peak position (radian)

β = FWHM, Full Width at Half Maximum (radian)

The particle size (D) can be smaller or equal to grain size. Diffraction patterns were recorded using Cu Kα radiation (λ = 1.5418 Å).

2.3 Preparation of Nanofluid

The procedure for preparation of Nanofluid:

- Mass of Al_2O_3 nanoparticles are measured using a digital electronic balance.
- Gradually introduce the measured Al_2O_3 nanoparticles into distilled water while continuously agitating the mixture.
- Utilize an ultrasonicator device (400W, 24 kHz) to sonicate the mixture continuously for one hour. This step ensures the nanoparticles are uniformly dispersed in the water.
- Nanofluid can be prepared at varying concentrations, such as 0.2% and 0.4%.

2.4 Mathematical Calculations

The mathematical calculations used in this research work to calculate the properties of Al_2O_3-water nanofluid and the overall heat transfer coefficient are shown. Physical properties of the Al_2O_3-water nanofluid are calculated based on the proportion of Al_2O_3 nanoparticles to water, following the method described by M. Fares et al. [1].

2.4.1 Density

Density of the Al_2O_3-water nanofluid (ρ_{nf}) is calculated using the mixture rule, which takes under account densities of base fluid (ρ_{bf}) and nanoparticles (ρ_{np}). Calculation is as follows:

$$\rho_{nf} = \phi\rho_{np} + (1 - \phi)\rho_{bf} \tag{2}$$

where,

ϕ = proportion of Al_2O_3 nanoparticle in water.

The density of Al_2O_3 nanoparticles is assumed to be independent of temperature within the operating range. Conversely, the density of water varies with temperature. The change in water density, while keeping a volumetric flow rate constant, affects the calculated heat transfer between the cold and hot sides of the heat exchanger.

2.4.2 Specific Heat Capacity

Similarly, the specific heat capacity of the nanofluid is determined by the proportions of Al_2O_3 nanoparticles and water.

$$(\rho Cp)_{nf} = \phi\,(\rho Cp)_{np} + (1 - \phi)(\rho Cp)_{bf} \tag{3}$$

2.4.3 Thermal conductivity

Various models in the literature provide methods for predicting the thermal conductivity of nanofluids. These models consider numerous factors, including the thermal conductivities of both the base fluid and the nanoparticles, the surface area and geometry of the nanoparticles, their fractions, and the temperature. Maxwell model is employed to predict the thermal conductivity of Al_2O_3-water nanofluid.

$$k_{nf} = \frac{k_{bf}\left(k_{np} + 2k_{bf} + 2\phi\left(k_{np} - k_{bf}\right)\right)}{\left(k_{np} + 2k_{bf} - \phi\left(k_{np} - k_{bf}\right)\right)} \tag{4}$$

k_{bf}, k_{nf} and k_{np} represent the thermal conductivities of base fluid, nanofluids, and nanoparticles, respectively.

2.4.4 Overall convective heat transfer coefficient

The overall convective heat transfer coefficient of heat exchanger is determined using the following:

$$U = \frac{Q}{A \times LMTD} \tag{5}$$

where,

A = heat transfer area (m^2)

Q = Average heat transfer (W)

LMTD = Logarithmic mean temperature difference (K).

$$Q_h = V\,(\rho Cp)_{bf}\ (T_{h1} - T_{h2}) \tag{6}$$

$$Q_c = V\,(\rho Cp)_{nf}\ (T_{c2} - T_{c1}) \tag{7}$$

$$Q = \frac{Q_h + Q_c}{2} \tag{8}$$

$$LMTD = \frac{(T_{h1} - T_{C2}) - (T_{h2} - T_{C1})}{ln\left(\frac{T_{h1} - T_{C2}}{T_{h2} - T_{C1}}\right)} \tag{9}$$

Where, V is flowing rate, $T_{h1,}$ and T_{h2} are inlet and outlet temperatures of hot fluid and T_{C1} and T_{C2} are inlet and outlet temperatures of cold fluid respectively

2.5 Nanofluid Properties

The properties of different concentrations of Al_2O_3-water nanofluid and pure water are given in Table 1.

Fluid	ρ (kg/m³)	Cp (J/kg.K)	k (W/m.K)	μ (Pa.s)
Water	998	4182	0.598	0.001
0.2% Al_2O_3-Water	1004	4155	0.600	0.00244
0.4% Al_2O_3-Water	1010	4128	0.602	0.00314

Table 1: Properties of nanofluid

2.6 Experimental Setup

The experimental setup comprises three primary components: the primary heat exchanger, the data acquisition system and the water bath section, as shown in the figure 1 and 2. The main test loop includes a pump, flow sensor, pressure gauge, Arduino UNO, K-type thermocouple, computer, power supply unit, and the heat exchanger. The test section consists of shell and tube heat exchanger. Shell is made of PPR pipe and Tube is made of aluminum material. The external and internal diameter of shell were 40 mm and 32 mm respectively. External and internal diameter of tube were 15 mm and 13 mm respectively and a wall thickness of 1 mm. The total length of test section is 1180 mm. Two K-type thermocouples are installed at both ends of the aluminum pipe with a diameter of 2.5 mm, and two more are placed at both ends of the PPR pipe to measure inlet and outlet temperatures of cold and hot fluid, respectively. These K-type thermocouples was calibrated in a thermostat with a deviation of ±0.1 °C before use. Temperature readings were recorded via a computer connected to an Arduino, with the average values used for analysis. Heat transfer from the hot fluid increases the temperature of the cold fluid, consequently decreasing the temperature of the hot fluid. An additional heat exchanger is utilized to maintain the cold fluid at a constant inlet temperature. The water tank of 24 L (46x23x23 cm) is used. An electrical geyser heats the hot fluid, keeping the temperature steady at 68 °C. A pressure gauge measures the pressure across the test section. A pump is used to circulate hot fluid through the outer side of the tube, while the flow rate of hot and cold fluid is measured by a flow sensor. To examine the effects on heat transfer, two types of turbulators with pitches of 16mm and 20mm each measuring 1000mm in length are used in a shell and tube heat exchanger. These turbulators were designed to be inserted into the testing area through removable elements located at both ends of the shell and tube heat exchanger. For this experiment, a nanofluid was circulated through the system by a pump. Hot water at 68°C then flows through the outer side of the tube. The flow rates of both the nanofluid and the hot water were adjusted accordingly, with the hot water inlet flow rate set at 132 l/hr and the cold-water inlet flow rate varying between 470 and 620 l/hr. As the Al_2O_3-water nanofluid flowed through the tube, its temperature increased. Once a steady state was reached, the temperatures of both the nanofluid and the hot water were measured [13] .

Figure 1: Experimental Setup

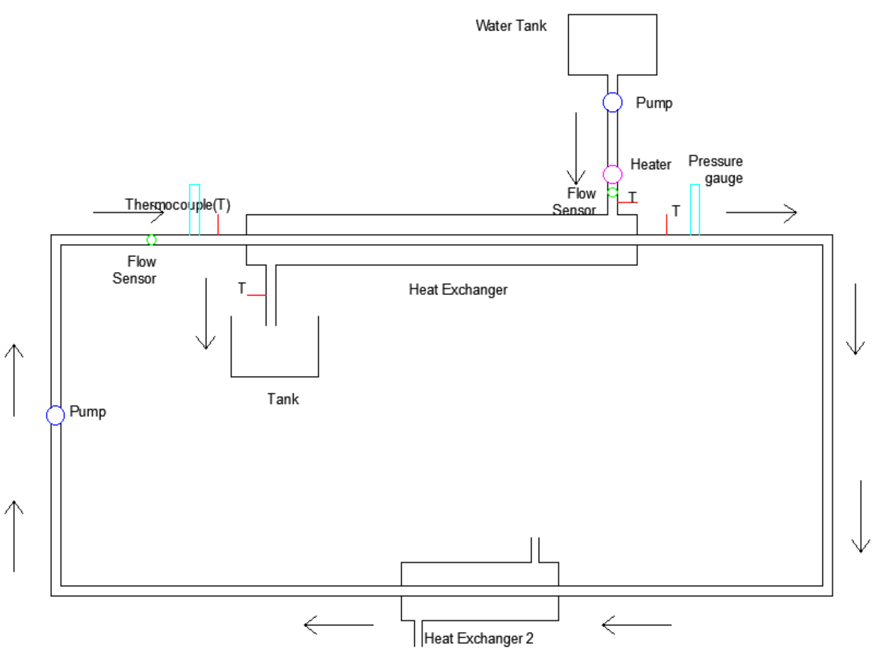

Figure 2: Schematic diagram of Experimental setup

2.7 Materials, Equipment, and Measuring Devices

2.7.1 Materials and Equipment

- **Nanofluids**: These are engineered colloidal suspensions containing nanoparticles dispersed in a base fluid, typically oil, ethylene glycol or water. Al_2O_3-water nanofluid was used.

- **Pipes**: Shell was made of PPR Pipe of external diameter 40mm. The tube was made of aluminum with an external diameter 15mm. Other pipes for the circulation of fluid are of CPVC material.

- **Mild steel pipes**: For making the support structure of the experiment, square and rectangular mild steel pipes were used.

- **Hydraulic pump**: Two pumps were used for the circulation of hot fluid and cold fluid in the shell and tube heat exchanger. The capacity of the pump was 0.37 kW.

- **Electric Geyser**: To supply hot fluid to the system, an electric geyser was used to heat water. The electric power of the geyser was 3000 watts.

- **Heat exchanger**: One main heat exchanger and one secondary heat exchanger were used in this experiment. The secondary heat exchanger was used to maintain the temperature of the outlet cold fluid.

- **Other fittings**: Other fittings like CPVC L-bow, CPVC Tee, CPVC male and female socket, CPVC Tee socket, and CPVC union were used to make the experimental setup.

2.7.2 Measuring devices

- **Flow sensor**: Measured the flow rate of the fluid.

- **Pressure gauge**: Measured the pressure.

- **Temperature Sensors**: Measured the temperatures at the outlet and inlet of the tube.

3. Results And Discussion

The Miller Indices obtained from XRD data of Al_2O_3 nanoparticles are 012, 104, 110, 113, 024, 116, 118, 024, 030, and 119 as shown in Figure 3 is close to the data obtained by Joseph Owalabi and Pius Ojadi [19]. The average size of the nanoparticle obtained was 35 nm.

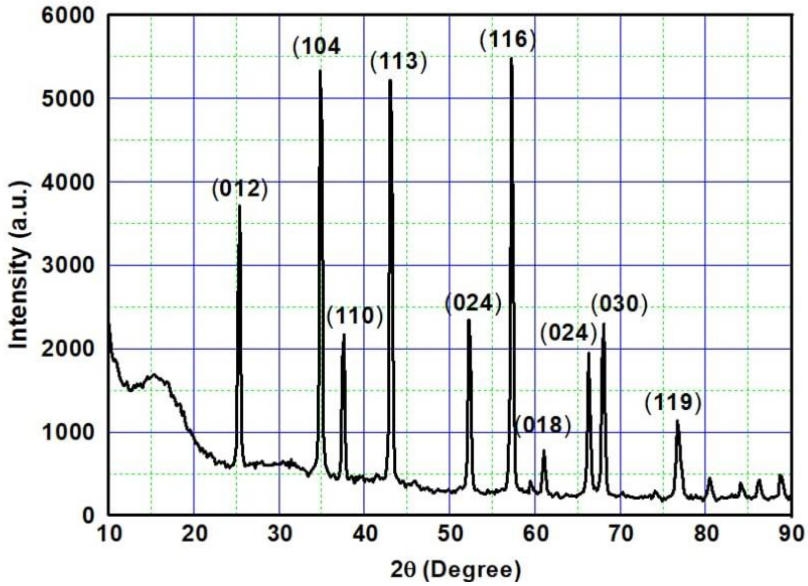

Figure 3: XRD of Al_2O_3 Nanoparticle

3.1 Comparison of Overall heat transfer coefficient with different parameters

Overall heat transfer coefficients for 0.2% and 0.4% Al_2O_3-water nanofluids without turbulator increase by 11.47% to 19.5% and 20.77% to 34.66%, respectively, across flow rates ranging from 470 to 620 l/hr compared to pure water is shown in figure 4. This improvement is due to enhanced thermal conductivity and increased surface area provided by the nanoparticles, as reported in previous works on graphene nanofluid concentrations [1].

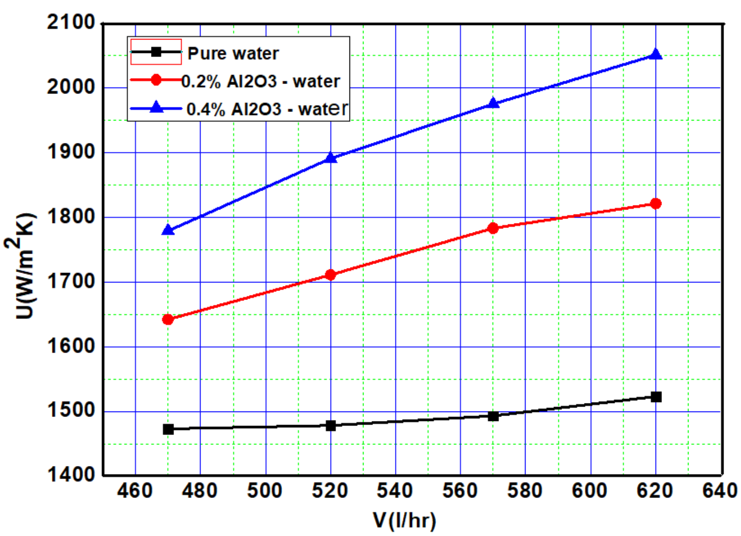

Figure 4: Overall heat transfer coefficient vs flow rate for different concentration nanofluid

In adding a 16 mm helical coil turbulator inside the tube of the heat exchanger, the overall heat transfer coefficient increased by 47.09% to 54.76% compared to pure water without turbulator as shown in Figure 5. Similarly, incorporating a 20 mm helical coil turbulator, the overall heat transfer coefficient increased by 26.7% to 34.66% compared to pure water conditions without turbulators. These turbulators create significant turbulence, thereby enhancing heat transfer from the hot water to the nanofluids in the heat exchanger. The helical coil turbulator acts as turbulence promoter when in contact with the pipe wall and increases heat transfer. Smaller pitch sizes in the helical coils intensify turbulence, resulting in enhanced heat transfer, consistent with findings in previous literature [13].

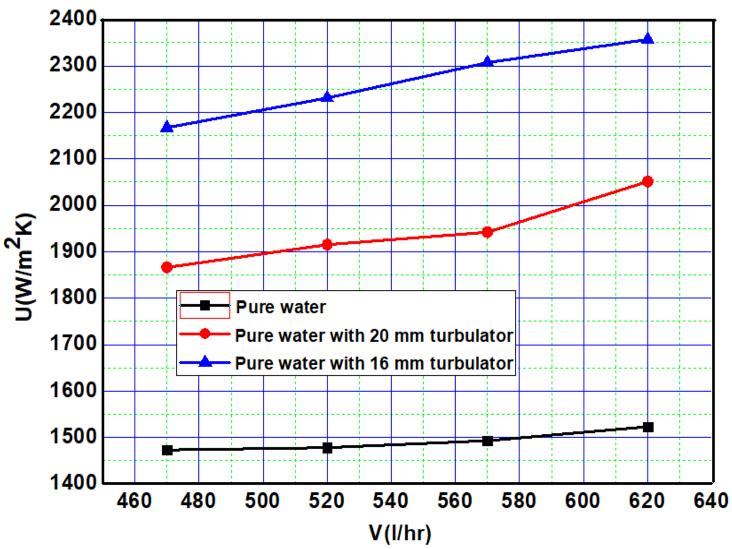

Figure 5: Overall heat transfer coefficient vs flow rate for pure water with different turbulator

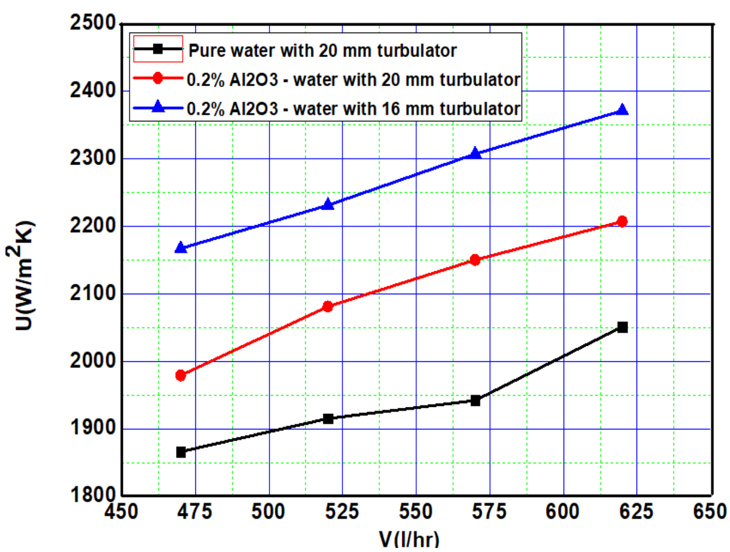

Figure 6: Overall heat transfer coefficient vs flow rate of 0.2% nanofluid with different turbulator

Figure 6 shows the increase in the overall heat transfer coefficient of 0.2% Al_2O_3-water nanofluids with different turbulator. Specifically, using a 16 mm pitch helical coil turbulator in 0.2% Al_2O_3-

water nanofluids, overall heat transfer coefficient increases from 42.51% to 39.78%, whereas adding 20mm helical coil turbulator in the same nanofluid led to an increase between 20.52% and 21.26% compared to using the nanofluid without any turbulators in the heat exchanger.

Figure 7 shows the increase in the overall heat transfer coefficient of 0.2% Al_2O_3-water nanofluids with different turbulator. Employing a 16 mm pitch helical coil turbulator in 0.4% Al2O3-water nanofluids, the overall heat transfer coefficient increased by 51.48% to 44%. Similarly, adding 20mm helical coil turbulator in the same nanofluid led to an increase of 21.81% to 15.6% compared to using the nanofluid without any turbulators.

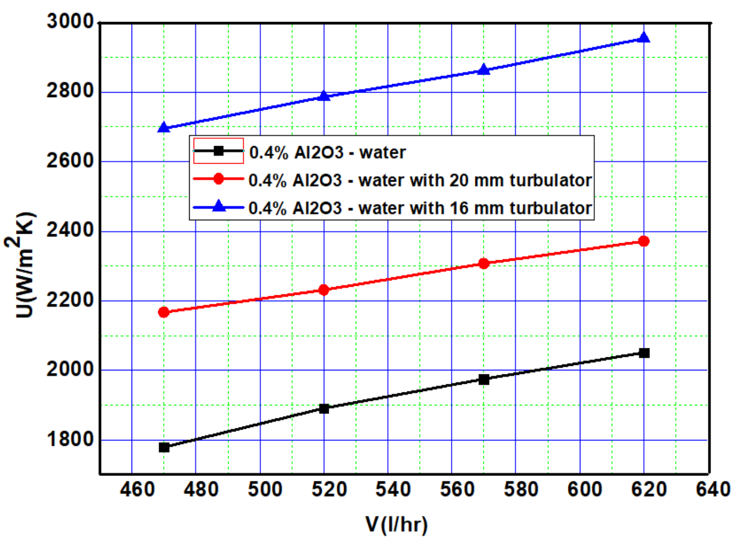

Figure 7: Overall heat transfer coefficient vs flow rate of 0.4% nanofluid with different turbulator

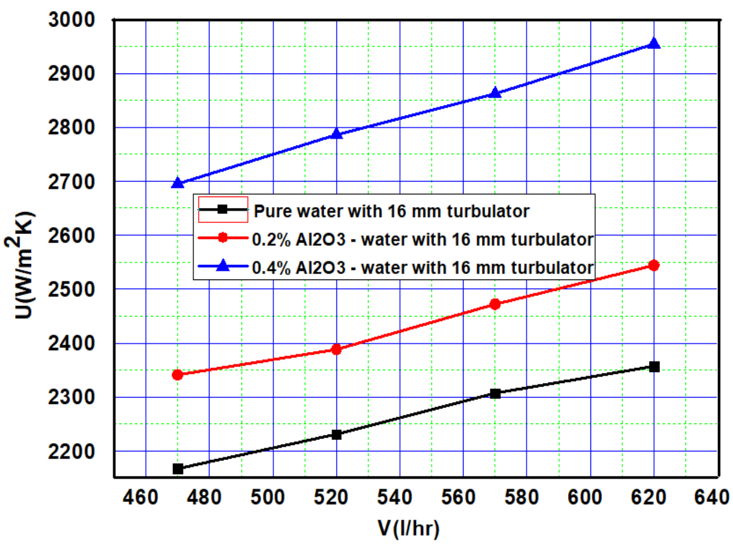

Figure 8: Overall heat transfer coefficient vs flow rate for different concentration nanofluid with 16mm turbulator

Comparison of the overall heat transfer coefficient of 16 mm pitch helical coil turbulator for pure water and different concentrations of nanofluid are shown in figure 8. The use of a 16 mm pitch helical coil with 0.2% and 0.4% nanofluid results in increasing the heat transfer coefficient by 7.93% and 25.32%, respectively, over using a 16 mm trubulator in the case of water.

A comparison of the overall heat transfer coefficient of a 20 mm pitch helical coil turbulator for pure water and different concentrations of nanofluid is shown in Figure 9. The use of a 20mm pitch helical coil with 0.2% and 0.4% nanofluid results in increasing the heat transfer coefficient by 7.6% and 15.6%, respectively, over using a 20 mm trubulator in the case of water.

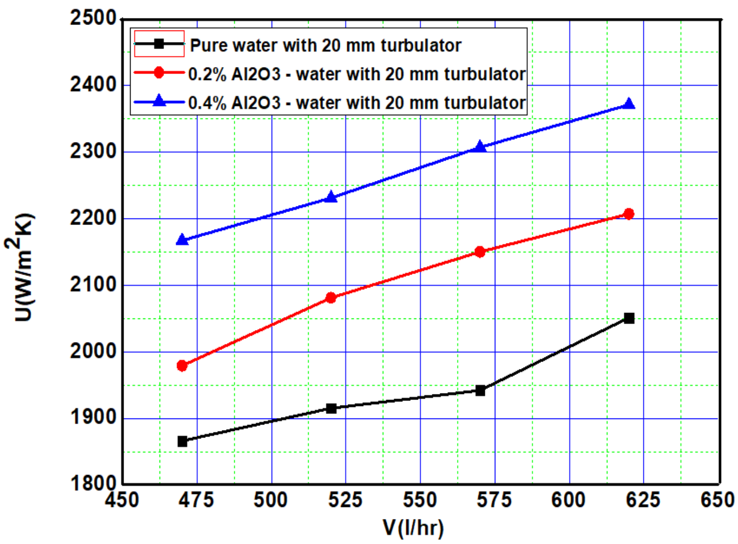

Figure 9: Overall heat transfer coefficient vs flow rate for different concentration nanofluid with 20 mm turbulator

4. Conclusions

This research investigates the impact of Al_2O_3-water nanofluids and helical coil turbulators on the overall heat transfer coefficient in shell and tube heat exchangers. The study explores nanofluid concentrations of 0.2% and 0.4%, along with helical coil turbulators of 16mm and 20mm pitches, aiming to optimize heat exchanger performance. Experimental findings reveal significant enhancements in convective heat transfer coefficient and thermal conductivity due to inclusion of Al_2O_3 nanoparticles in pure water. Specifically, Al_2O_3-water nanofluids demonstrate marked improvements in heat transfer efficiency compared with pure water. Additionally, use of helical coil turbulators intensifies these enhancements by inducing turbulence, thereby increasing the overall heat transfer coefficient. Furthermore, comparative analyses with pure water and nanofluids without turbulators confirm that combining nanofluids and turbulators yields superior thermal performance. Adding 0.2% and 0.4% Al_2O_3-water nanofluids without turbulators increases the overall heat transfer coefficient by 11.47% to 19.5% and 20.77% to

34.66%, respectively, compared with pure water. Introducing 16mm and 20mm helical coil turbulators in pure water, increases the overall heat transfer coefficient by 47.09% to 54.76% and 26.7% to 34.66%, respectively, compared with pure water without turbulator.

Acknowledgment

The authors are thankful to the Department of Mechanical and Aerospace Engineering, Pulchowk Campus for providing this opportunity. The auhothrs are also thankful to the Research Centre for Applied and Technology (RECAST), Tribhuvan University, Nepal Academy of Science and Technology (NAST), and Nepal Oil Corporation for providing the necessary laboratory facilities and testing.

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