Experimental and Numerical Study of Heat Transfer in Double-Pipe Heat Exchanger Using Al_2O_3, and TiO_2 Water Nanofluid

Abhishek Mund, Bikash Pattanayak, J. S. Jayakumar, Kajal Parashar and S. K. S. Parashar

Abstract Nanofluid is a two-phase fluid of solid-liquid mixture. Nanofluid provides higher effective thermal conductivity when compared with the base fluid. Thermal properties of heat transfer fluid are one of the important topics of concern for research in heat transfer analysis. In recent years, there are stances about the study of agglomeration of two or more nanoparticles in base fluid, i.e., hybrid or composite nanofluid, and they also have good heat transfer characteristics. In this experiment, Al_2O_3 and TiO_2 and hybridized Al_2O_3, TiO_2 nanoparticles were prepared by using high-energy ball milling technique. These nanoparticles were characterized by using XRD, SEM, and TEM. It was found that crystalline size is 30 nm. Polyvinyl alcohol of 3% was used in 1:10 ratio of the mass of the nanoparticle for preparing stable nanofluid. The stability was observed for 32 h which was good to conduct an experiment. The densities, viscosity, thermal conductivity, and the specific heat of the nanofluid were calculated. The overall heat transfer coefficient, logarithmic mean temperature difference, friction factor, and effectiveness of the hybrid double-pipe heat exchanger using the nanofluid were calculated by NTU method. The data obtained using ANSYS (FLUENT) 18.2 were compared with the experimental result. An optimized volume concentration of the nanofluid was found out to be used as an effective cooling fluid in the hybrid heat exchanger.

Keywords XRD · ANSYS · NTU · Nanofluid

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Nomenclature

A	Surface area (m^2)
C_p	Specific heat (J/kg K)
k	Thermal conductivity (W/mK)
m	Mass flow rate (kg/s)
T	Temperature (°C)
U	Overall heat transfer coefficient (W/m^2 K)

Greek Symbols

ρ	Density (kg/m^3)
μ	Dynamic viscosity (kg/ms)
ϵ	Effectiveness
φ	Volume concentration

Subscripts

c	Cold fluid
ci	Cold fluid inlet
co	Cold fluid outlet
h	Hot fluid
hi	Hot fluid inlet
ho	Hot fluid outlet
i	Inner
nf	Nanofluid
p	Nanoparticle
1	Al_2O_3 nanopowder
2	TiO_2 nanopowder
w	Water

1 Introduction

Nanofluid is a two-phase fluid, basically a colloidal suspension of nanoparticles in base fluids like oil and water. Hybrid nanofluids are engineered fluids of two different nanoparticles dispersed into base fluid. A hybrid material combines the properties (physical and chemical) and exhibits them homogeneously [1]. The thermo-physical properties of hybrid nanofluid are comparatively higher than single-particle nanofluid and base fluid [2]. An instrument devised to make the exchange of heat between two fluids at different temperature without mixing them is known as a heat exchanger. In this experiment, a counterflow double-pipe heat exchanger was used. It is found that the processes of double-pipe heat exchangers are being widely in use for industrial as well as commercial purposes [3]. From the analysis of various research papers, it has been inferred that a material does not inherit all the properties needed for a specific purpose. Hybrid nanofluids have a wide application in the field of electro-mechanical, HVAC, automotive cooling, etc. So in this experiment, hybrid nanofluid has been used in hybrid double-pipe heat exchanger, and it has been compared with a single material nanofluid, and the usage of these fluids to enhance the effectiveness of the heat exchanger has been analyzed. Chopkar et al. analyzed that the thermal conductivity was enhanced by using Al_2O_3-Cu/water hybrid nanofluid in electronics cooling through a heat sink by comparing the results obtained with base fluid and single-particle nanofluid [4]. An experiment was conducted using a tubular heat exchanger for Cu/TiO_2 hybrid water-based nanofluid, and it was observed that the overall heat transfer has increased to 30.4% at a volume concentration of 0.7% [5]. Suresh et al. conducted an experiment for Al_2O_3–Cu/water hybrid nanofluid in a tube and suggests that at Reynolds number of 1730, Nusselt number enhanced by 13.56% [6]. Madhesh et al. conducted an experiment in a tube-type counter flow heat exchanger using Cu–TiO_2 deionized double-distilled water hybrid nanofluid and observed that thermal conductivity enhanced as compared to base fluid [7]. Basically, nanofluids exhibit higher thermal conductivity and enhance the heat exchanger's effectiveness. The reason behind such enhancement may be the increase in surface area and heat capacity of the fluid by suspending particles [8]. In this experiment, the thermo-physical properties of the nanofluids and their role in enhancing the effectiveness of the heat exchanger have been discussed.

2 Experimental Analysis

2.1 Synthesis of Nanoparticles

The nanometer-sized powder of titanium dioxide and aluminum oxide was prepared by HEBM technique at 300 rpm with the ball to powder ratio 10:1. The powders of 25 microns and 99.8% purity were mechanically milled in tungsten carbide jars with tungsten carbide balls for 15 h, with 60 min milling time and 30 min gap to avoid overheating. The density, specific heat, and thermal conductivity values of the TiO_2 and Al_2O_3 powders are 4010 kg/m^3, 690 J/kg K, 8.3 W/mK and 3880 kg/m^3, 703 J/kg K, 25.6 W/mK, respectively. The TiO_2 and Al_2O_3 nanopowders are shown in Fig. 1a, b. It was clearly observed from Fig. 1a, b that the color of the Al_2O_3 nanoparticle is white and that of the TiO_2 nanoparticle is gray.

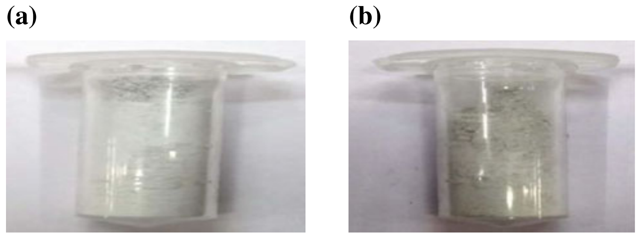

Fig. 1 **a** Al$_2$O$_3$ and **b** TiO$_2$ nanopowders

2.2 Characterizations of Nanoparticles

The X-ray diffraction (XRD) patterns were obtained using PANalytical X'Pert PRO machine for TiO$_2$ and Al$_2$O$_3$ nanoparticles analyzed for this work and were plotted in Fig. 2a, b. The peaks were indexed as (012), (104), (110), (006), (113), (024), (116), (018), (214), (300) for TiO$_2$ and (012), (104), (110), (006), (113), (024), (116), (018), (214), (300), for Al$_2$O$_3$. In case of Al$_2$O$_3$, the powder was of rhombohedral crystal system with a lattice constant (A^0) $a = 4.751$, $b = 4.751$, $c = 12.97$. These data match well with JCPDS card (Joint committee on Powder Diffraction Standard) reference code 00-003-1033 for TiO$_2$ and 00-003-1033 for Al$_2$O$_3$. The strong intensity and sharp narrow width peaks indicate that the nanopowders were of high crystalline. SEM images were taken using JEOL JSM-6510 machine at ×10,000 resolution and 1 μm reference size. The particles are uniform and spherical in nature shown in Fig. 3a, b. However, TiO$_2$ nanoparticles are smaller than the Al$_2$O$_3$ nanoparticles. The confirmation of nanoparticles was done by FEI, Tecnai TEM. It was found that the synthesized 15-h dry ball-milled powder of TiO$_2$ and Al$_2$O$_3$ was at 30–40 nm shown in Fig. 4a, b. The particles are uniform and spherical in nature.

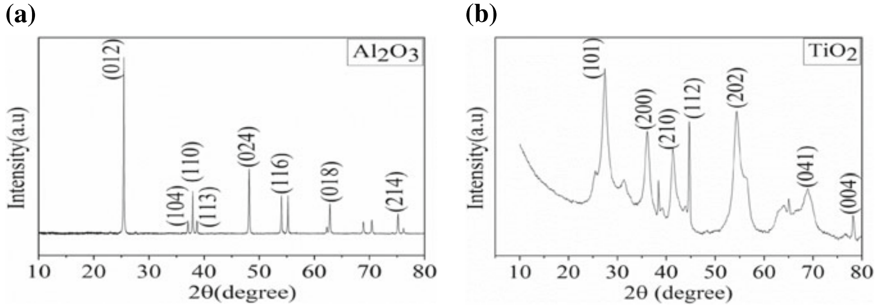

Fig. 2 XRD patterns of **a** Al$_2$O$_3$ and **b** TiO$_2$ nanoparticles

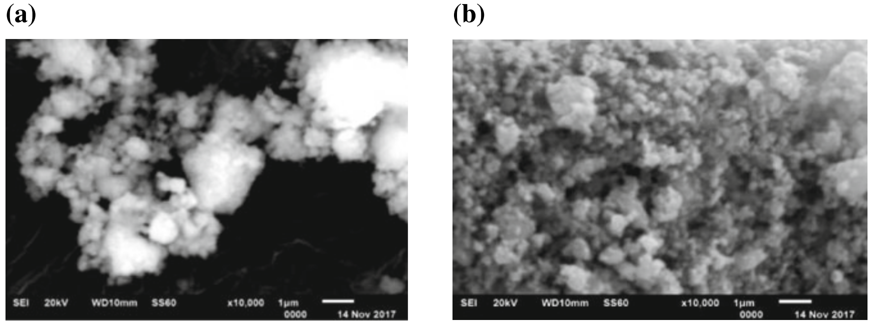

Fig. 3 SEM micrographs of **a** Al_2O_3 and **b** TiO_2 nanoparticles

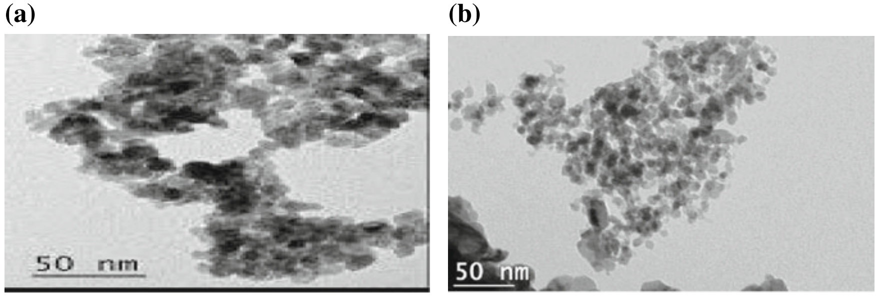

Fig. 4 TEM images of **a** Al_2O_3 and **b** TiO_2 nanoparticles

2.3 Preparation of Nanofluids

The nanofluids were prepared by using two-step method [9]. The methodologies followed to prepare the nanofluids were same. Different concentrations of nanofluids were prepared by mixing a quantified volume concentration of nanopowder (0.025, 0.05, 0.075, and 0.1%) in water. The nanopowder-added fluid was then magnetically stirred at 1000 rpm speed for 6 h and then was ultrasonically agitated for 2 h. The stability of the nanofluid was maintained up to 12–18 h by adding 3% PVA in one-tenth ratio to the mass of the nanoparticle. In the experimental practice, some nanofluid without surfactant was taken in a petri dish, and after sometimes, cluster formation occurs, and it settles down. The petri dish was then heated, and the residue was measured. The same methodology was applied with the PVA-added nanofluid, and it was observed that after 12 h, cluster formation started, and after 18 h, it stopped. The residue was heated and measured. The mass was comparatively low, so it has been concluded that the fluid is stable.

2.4 Experimental Setup and Procedures

In this experiment, a hybrid double-pipe heat exchanger was used where the inner tube is of copper and the outer pipe is of unplasticized polyvinyl chloride (UPVC). The TiO_2 water nanofluid and Al_2O_3 water nanofluid were made to flow into the annulus section with the mass flow rate of 21.95 L/H; hot water is made to flow into the copper pipe with the mass flow rate of 31.57 L/H. The LMTD, U, and effectiveness of all the nanofluids at different volume concentrations keeping same inlet temperature were calculated. Basically, double-pipe heat exchanger consists of two metallic concentric tubes and some insulating materials externally applied on the outer pipe to restrict the heat flow. In this experiment, hybrid heat exchanger consists of a concentric tube of metal and plastic, no insulating material being used because plastic tube itself behaves as an insulator to heat flow shown in Fig. 5. The thermo-physical properties obtained were given as input in the ANSYS 18.2. The k-epsilon and SIMPLE method were followed during the simulation. In this experiment, the models used to measure thermo-physical properties have certain limitations such as they can be used for spherically shaped nanoparticle and the volume concentration is limited to 4%. The temperature of the hot water and nanofluids at the inlet and outlet was measured by using digital temperature display TPM-10 with reference accuracy ±0.1 °C.

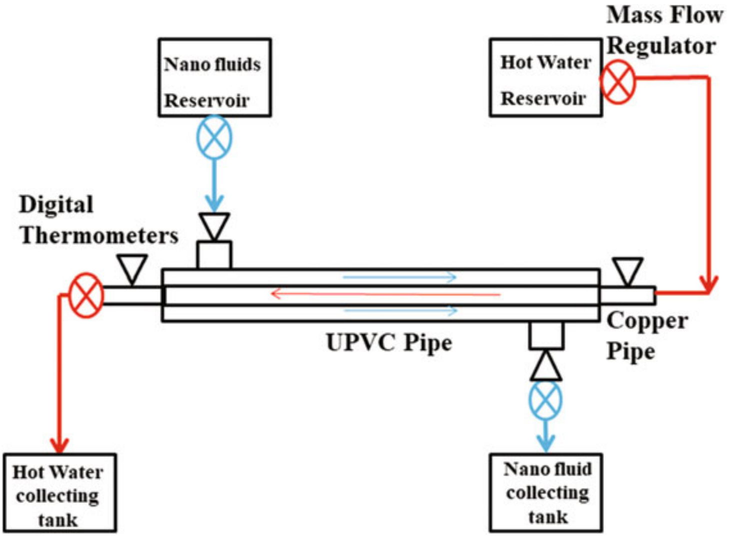

Fig. 5 Schematic diagram of double-pipe heat exchanger

3 Results and Discussions

3.1 Calculation of Various Thermo-physical Properties

The density, thermal conductivity, viscosity, and specific heat of the nanofluids were calculated using various models. It was observed that volume concentration increases, the density, viscosity, thermal conductivity increases, but specific heat decreases. In nanofluids, thermal conductivity can be enhanced by the collision between the solid particles. By increasing the volume concentration, the number of collision between the solid particles increases, and the internal energy of the particle increases resulting in the increase in effective thermal conductivity of the nanofluid [10]. Nanofluids are dual-phase dispersion system having high surface energies; therefore, they are thermodynamically unstable. Due to the strong Brownian motions, agglomeration of nanoparticles increases and dispersion of nanoparticles in the fluids may deteriorate with time because of van der Waals forces [11]. For this reason, with an increase in volume concentration, the viscosity increases. Equations 1, 2, 3, and 4 represent Pak and Choi model, Wasp model, LS Sundar model, and homogeneous mixture specific heat formula used to determine density, thermal conductivity, viscosity, and specific heat, respectively. The data obtained were tabulated in Table 1.

$$\rho_{\mathrm{nf}} = \varphi_1\rho_1 + \varphi_2\rho_2 + (1 - \varphi_1 - \varphi_2)\rho_{\mathrm{w}} \tag{1}$$

$$k_{\mathrm{nf}} = k_{\mathrm{w}} \frac{k_{\mathrm{p}} + 2k_{\mathrm{w}} - 2\varphi\left(k_{\mathrm{w}} - k_{\mathrm{p}}\right)}{k_{\mathrm{p}} + 2k_{\mathrm{w}} + \varphi\left(k_{\mathrm{w}} - k_{\mathrm{p}}\right)} \tag{2}$$

Table 1 Thermo-physical properties of the nanofluids

Nanofluid	Volume concentration	Density	Viscosity	Thermal conductivity	Specific heat
Al_2O_3-water	0.025	1074.6	0.00088	0.673	3862.6
	0.05	1149.2	0.00093	0.721	3583.7
	0.075	1223.8	0.00096	0.771	3335.8
	0.1	1298.5	0.00099	0.823	3117.7
TiO_2-water	0.025	1075.2	0.00088	1.041	3860.9
	0.05	1150.5	0.00093	1.094	3577.5
	0.075	1225.7	0.00098	1.145	3328.9
	0.1	1301.0	0.00107	1.196	3109.1
TiO_2-water Al_2O_3-doped	0.025	1147.2	0.00191	0.671	3587.6
	0.05	1294.5	0.00356	0.717	3124.6
	0.075	1441.7	0.00575	0.765	2756.2
	0.1	1589.0	0.00850	0.816	2456.1

$$\mu_{\mathrm{nf}} = \mu_{\mathrm{w}}\left(1 + 39.11\varphi + 533.9\varphi^2\right) \tag{3}$$

$$C_{\mathrm{p\,nf}} = \frac{(\varphi_1 \rho C_{\mathrm{p}})_1 + (\varphi_2 \rho C_{\mathrm{p}})_2 + \left((1 - \varphi_1 - \varphi_2)\rho C_{\mathrm{p}}\right)_{\mathrm{w}}}{\rho_{\mathrm{nf}}} \tag{4}$$

3.2 Determination of the Effectiveness of the Counter Flow Heat Exchanger Using NTU Method

The effectiveness of the hybrid double-pipe heat exchanger is calculated using the number of transfer units (NTU) method. Calculation for effectiveness using ANSYS is tabulated in Table 2, and calculation for effectiveness by the experimental method is tabulated in Table 3. LMTD (°C) is logarithmic mean of temperature difference of the fluids flowing in heat exchangers. The temperature difference is the driving force for heat transfer. For the counter flow heat exchanger, LMTD is given by:

$$\mathrm{LMTD} = \frac{(T_{\mathrm{hi}} - T_{\mathrm{co}}) - (T_{\mathrm{ho}} - T_{\mathrm{co}})}{\ln(T_{\mathrm{hi}} - T_{\mathrm{co}})/(T_{\mathrm{ho}} - T_{\mathrm{co}})} \tag{5}$$

The heat lost by the hot fluid, heat gained by the cold fluid (nanofluids), and the net transfer were estimated using the following expressions, respectively

$$Q_{\mathrm{h}} = m_{\mathrm{h}} Cp_{\mathrm{h}} (T_{\mathrm{hi}} - T_{\mathrm{ho}}) \tag{6}$$

$$Q_{\mathrm{c}} = m_{\mathrm{c}} Cp_{\mathrm{c}} (T_{\mathrm{co}} - T_{\mathrm{ci}}) \tag{7}$$

$$Q = 0.5(Q_{\mathrm{h}} + Q_{\mathrm{c}}) \tag{8}$$

The overall heat transfer coefficient and NTU is given by:

$$\begin{aligned} U &= \frac{Q}{A_{\mathrm{i}} \times \mathrm{LMTD}} \\ A_{\mathrm{i}} &= \pi d_{\mathrm{i}} L \end{aligned} \tag{9}$$

Table 2 Calculation of effectiveness using ANSYS

Nanofluids	T_{hi}	T_{ci}	T_{ho}	T_{co}	LMTD	NTU	C	ϵ
Al_2O_3 (0.1)	60	26	48.03	28.94	26.28	0.5217	0.5170	0.3723
TiO_2 (0.1)	60	26	47.49	27.24	26.73	0.4674	0.5156	0.3440
Al_2O_3-doped TiO_2 (0.1)	60	26	52.96	39.26	23.71	0.6108	0.4073	0.4239

Table 3 Calculation of effectiveness by the experimental method

Nanofluids	T_{hi}	T_{ci}	T_{ho}	T_{co}	LMTD	NTU	C	ϵ
Al_2O_3 (0.1)	60	26	42.3	34.7	20.47	1.048	0.5170	0.5770
TiO_2 (0.1)	60	26	38.4	31.9	19.19	1.245	0.5156	0.6308
Al_2O_3-doped TiO_2 (0.1)	60	26	35.5	33.1	16.71	1.344	0.4073	0.6726

$$\text{NTU} = \frac{(U * A)}{\left(mC_{\text{p}}\right)_{\text{small}}} \tag{10}$$

$$\epsilon = \frac{1 - \exp^{-(1-c)\text{NTU}}}{1 - c\exp^{-(1-c)\text{NTU}}} \tag{11}$$

3.3 Contours Obtained Using ANSYS 18.2

From the experiment, the obtained input temperatures and thermo-physical properties were given as the input value to obtain the following contours using ANSYS 18.2 workbench. A turbulence effect came into the picture near the nanofluid inlet when vector velocity graph was obtained (Fig. 6).

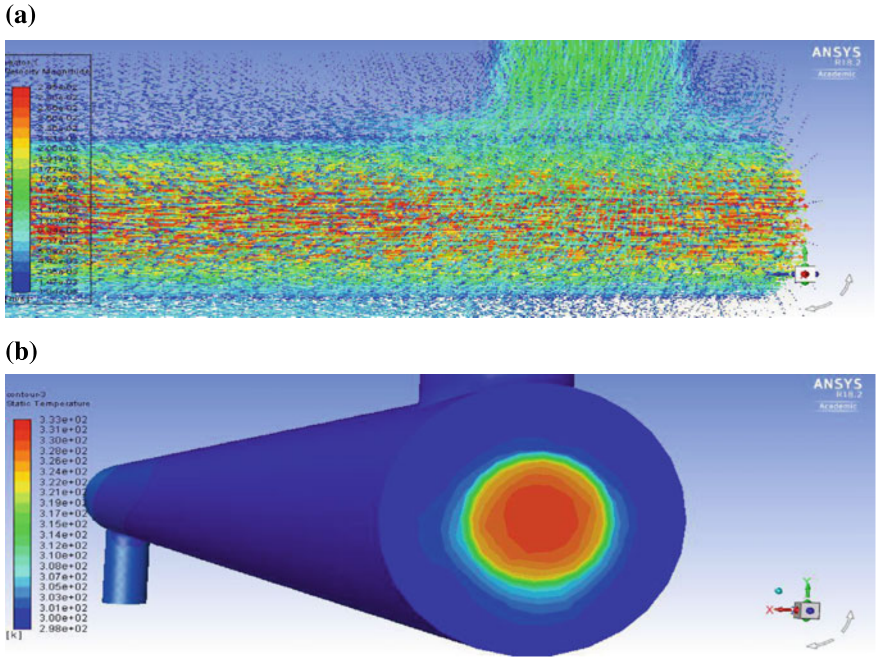

Fig. 6 **a** Velocity vector, **b** static temperature of Al_2O_3-doped TiO_2 nanofluid

4 Conclusions

It was inferred from the experiment that for both experimental and numerical analysis, aluminum oxide-doped titanium dioxide nanofluid provides higher effectiveness. So it can be used as a cooling fluid for heat transfer application. It was observed that at the inlet of the nanofluid, vortex formation takes place, and it can be considered as a factor for heat transfer enhancement.

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