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An Experimental Investigation of Thermal Conductivity of TiO_2 Nanofluid: Proposing a New Correlation

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In this study, TiO_2/Water nano fluids were prepared at different concentration by two step method. Zeta potential technique was used to investigate the stability of the colloidal solution of the titanium oxide in the base fluid (water).The effect of temperature (25-50°C) and solid volume concentration (0.5-3.0%) on the thermal conductivity of nanofluid was observed. Based on experimental observation and with curve fitting, a new empirical correlation was proposed for calculating the thermal conductivity of the nanofluid. It was observed that at higher temperature, enhancement in the thermal conductivity of nanofluid was more with an increase in solid volume fraction while at low volume fraction, the effect of raise in temperature on thermal conductivity was observed less. The highest enhancement of 15.69% in thermal conductivity observed with 3.0% volume concentration at 50°C.

Keywords: Nanofluid, thermal conductivity, solid volume fraction, empirical correlation

Introduction

In many industries such as power generation, air conditioning, automobiles and electronics, the performance of heat transfer devices used in different heating/cooling processes, depends on the thermo physical properties of working fluids in operation. The limited thermal conductivity of conventional fluid such as water, engine oil, ethylene glycols restricted the performance of the devices. In order to remove this restriction, the idea of suspending solid metallic particles possess much higher thermal conductivity, in the conventional heat transfer fluid is not new[1].However, all the drawbacks such as erosion of component, sedimentation, clogging associated with suspended particles of micro-millimeter size were eliminated with advancement of nanotechnology, which in turn reducing the suspended particles to nanometer sizes [14]. Choi[2] has been proposed a novel concept of nanofluid, prepared by dispersion of nanometer-sized (<100 nm at least in one direction) solid particles in conventional fluids. The high surface area to volume ratio of nanoparticles has resulted in superior thermal conductivity and better stability. In the past decade, several researchers have performed experiments to investigate the thermal properties of nanofluids which have been illustrated in the Table 1.

Experimentation

Preparation of nanofluid

In this experimental investigation, the different samples of nanofluid were prepared by two step method. The first step involves production of dry nanoparticles of nanomaterials in the form of powder. In the second step, the produced dry nanoparticles are dispersed in a base fluid by the use of magnetic stirrer, ultrasonic devices like ultrasonic probe. A titanium oxide (TiO2) nanoparticle, purchased from Alfa

Aesar, USA, was dispersed in the base fluid water. The physical properties of TiO_2 are presented in Table 2. The mass of TiO_2 nanoparticles required to prepare the samples of solid volume concentration (0.5-3.0%), was determine from Eq. 1 as follows:

$$C\% = \left[\frac{\left(\frac{w}{\rho}\right)_{TiO_2}}{\left(\frac{w}{\rho}\right)_{TiO_2}+\left(\frac{w}{\rho}\right)_{water}}\right] \quad \ldots 1$$

Where, C, w and ρ represents percentage of solid volume concentration, material weight in g and density in g/cm^3 respectively.

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Table 1 — Summary of the work done on TC of nanofluid.

Researcher	Measuring Technique	Nanoparticles	Base fluid	Particle size (nm)	Particle concentration (%)	Enhancement (%)
Murshed *et al.*[3]	Transient hot-wire method (THW)	TiO_2	water	15	0.50-5.00	30
Lee *et al.* [4]	THW	Al_2O_3	Water/EG	38.4	1.00-4.30	10
Turgut *et al.*[10]	THW	TiO_2	water	21	0.20-3.00	7.4
Kim *et al.*[11]	THW	ZnO	Water/EG	10/30/60	1.00-3.00	21
		TiO_2		10/34/70	1.00-3.00	15.4
Masuda *et al.*[12]	THW	Al_2O_3	Water	13	1.30-4.30	32.4
		SiO_2	Water	12	1.10-2.40	1.1
		TiO_2	Water	27	3.10-4.30	10.8
Azmi *et al.*[13]	THW	TiO_2	Water	22	0-3.0	7

Table 2 — Properties of TiO_2 nano particles

Description	True density	Particle size	Specific surface area	Crystallographic Structure	Atomic weight	Purity (%)
TiO_2	4.65g/cm^3	40-60 nm	220-240m^2/g	Spherical	79.865g/mol	≥ 99.9

Stability of nanofluid

In order to achieve homogeneity and dispersion stability, the each sample of nanofluid was stirred and exposed to a sonicator (VCX-500, 500W, 20 kHz) for 1 and 5 hours, respectively. The sonication processes was done to break the agglomeration of nanoparticles. To ensure the stability of the solution, Zeta potential was done on a Zetasizer (Nano-ZSP,Malvern).The average zeta potential value was observed as -28.0 mV. The zeta potential values higher than ±25.0 mV, shows the strong repulsion forces between oxide particles result in long term stability of nanofluids[5].

Measurement of thermal conductivity

A KD2 Pro (Decagon Devices Inc.) thermal property analyzer with maximum error of 3%, was used to measure the thermal conductivity (TC) of the samples for a temperature range of 25-50^{o}C. The KD2 pro instrument works on transient heat wire technique (THW). The three measurements of one sample at each temperature were taken and the average value is reported. To calibrate the measuring device, the measured thermal conductivity data for base fluid water were compared to available literature data [6]. The experimental result was validated with other theoretical classic models developed by many researchers [3, 7-9].

Results and Discussion

Effect of solid volume concentration

The variation in thermal conductivity ratio of nanofluid with respect to solid volume fraction at different temperature is shown in Figure 1. The TC ratio increases with increase in volume concentration

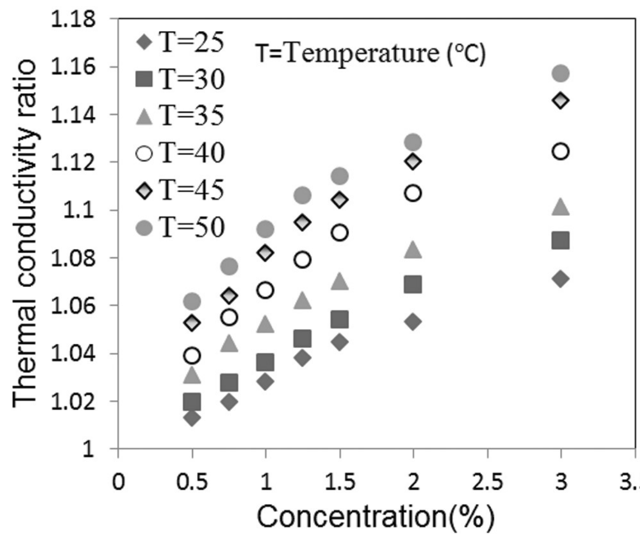

Fig. 1 — Thermal conductivity ratio variation in different solid volume fractions at different temperatures.

even at low temperatures. As the volume concentration increases, the chain of solid nanoparticles may form due to formation of clusters of nanoparticles. Heat can be transferred faster through these solid links which result in increase in thermal conductivity. The highest value of thermal conductivity ratio was observed at 50^{o}C with highest volume fraction. However the optimum value of solid volume fraction is limited with increase in viscosity and pumping power required for the nanofluid.

Effect of temperature

The variation in thermal conductivity ratio of nanofluid with respect to temperature at different solid volume fraction is shown in Figure 2. The TC ratio increases with increase in temperature. However

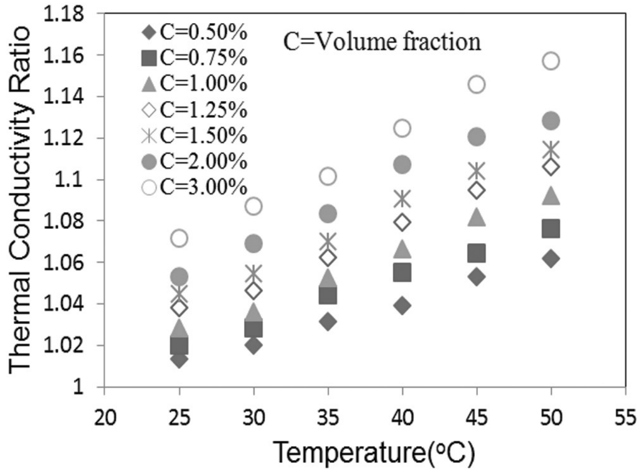

Fig. 2 — Thermal conductivity ratio variation by temperature at different solid volume fractions.

this increase in TC ratio was less at lower temperature, compared to high temperature. The rise in temperature attributed to the increased Brownian motion of nanofluid molecules and mixing of layers, increases in thermal conductivity of nanofluid and this phenomenon is amplified with increase in volume concentration of nanoparticles. Therefore highest enhancement of 15.69% in TC ratio was observed at 3.0% at 50°C.

Development of new correlation

In the current study, the thermal conductivity of TiO_2/water nanofluid was measured experimentally and also validated with already existing research models, as shown in Figure 4. A new empirical correlation for thermal conductivity based on curve fitting method has been developed in Eq. 2, as a function of two variables solid volume fraction and temperature. The R^2 value of the proposed correlation is 0.957, which is an indication of the accuracy of the correlation.

$$\frac{k_{nf}}{k_{bf}} = 0.761\ x\ C^{0.041}\ x\ T^{0.093} \qquad \ldots 2$$

Where k_{nf} and k_{bf} are represent the thermal conductivity of nanofluid and base fluid respectively. C is solid volume fraction (%) and T is the temperature in Celsius. Most of the points lie very close or on equality line in Figure 3, which demonstrate the comparison between the experimental result and the predicted values by developed correlation. The margin of deviation (MoD) was obtained using Eq. 3 as follows:

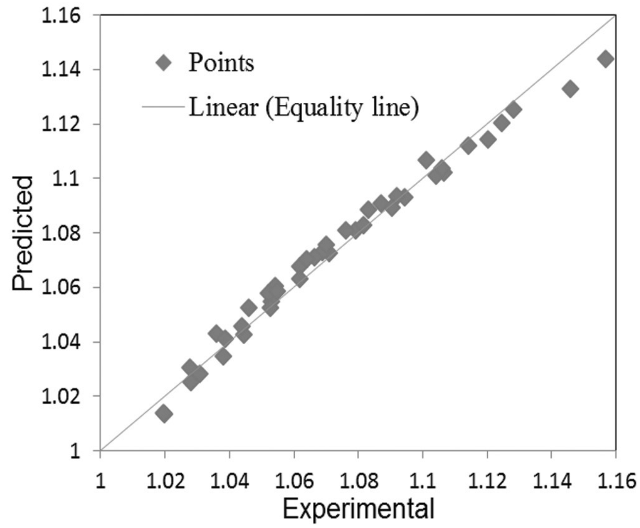

Fig. 3 — Comparison between the experimental results and predicted values obtained by correlation.

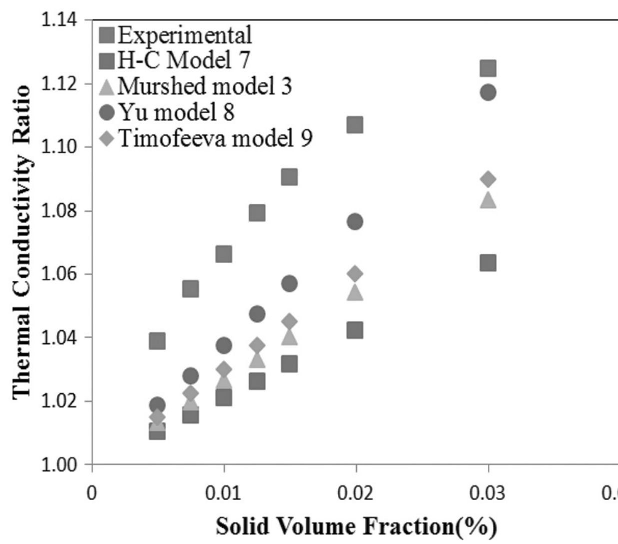

Fig. 4 — Comparison of experimental TC ratios with classic models.

$$MoD = \left[\frac{\left(\frac{k_{nf}}{k_{bf}}\right)_{exp} - \left(\frac{k_{nf}}{k_{bf}}\right)_{pred}}{\left(\frac{k_{nf}}{k_{bf}}\right)_{exp}}\right] x\ 100\% \qquad \ldots 3$$

The margin of deviation of the experimental thermal conductivity ratio values along with the predicted value at different data points was equal to 1.2%.

Conclusions

This experimental investigation, the effect of solid volume fraction and temperature on the thermal conductivity of TiO_2/water nanofluid has been observed and the results can be used to improve the performance of base fluids used in different heat transfer applications such as refrigeration, solar collectors, automobile cooling, electronic component cooling etc. The following conclusions are drawn:

1. The thermal conductivity of the TiO_2/water nanofluid enhanced with increase in Solid volume fraction and temperature.
2. The highest enhancement of the thermal conductivity was 15.69% that observed at 3.0% solid volume fraction and temperature of 50°C.
3. A new empirical correlation was proposed to predict the thermal conductivity ratio of TiO_2/water nanofluid.
4. The MoD between the experimental results and that of proposed correlation was equal to 1.2%.

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