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Experimental investigation of viscosity and thermal conductivity of suspensions containing nanosized ceramic particles

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ABSTRACT

Purpose: In this study we report measurements of effective thermal conductivity by using 3ω method and effective viscosity by vibro-viscometer for SiO_2-water and Al_2O_3-water nanofluids at different particle concentrations and temperatures.

Design/methodology/approach: The effective thermal conductivity of nanofluids is measured by a technique based on a hot wire thermal probe with ac excitation and 3ω lock-in detection. There is presented an experimental study of thermal conductivity and viscosity of nanofluids. It was investigated Alumina and Silica nanoparticles in water with different particle concentrations.

Findings: Measured results showed that the effective thermal conductivity of nanofluids increase as the concentration of the particles increase but not anomalously as indicated in the majority of the literature and this enhancement is very close to Hamilton-Crosser model, also this increase is independent of the temperature. The effective viscosities of these nanofluids increased by the increasing particle concentration and decrease by the increase in temperature, and can not be predicted by Einstein model.

Practical implications: The results show that for our samples, thermal conductivity values are inside the limits of (moderately lower than) Hamilton-Crosser model.

Originality/value: Experiments at different temperatures show that relative thermal conductivity of nanofluids is not related with the temperature of the fluid.

Keywords: Thermal conductivity; Viscosity; 3ω method; Nanofluids; Nanoparticles

PROPERTIES

1. Introduction

Nanofluids are suspensions consisting of solid nanoparticles with sizes generally less than 100nm. Nanofluid technology becomes a new challenge for the heat transfer fluid since it has been reported that the thermal conductivity of nanofluid is anomalously enhanced at a very low volume fraction [5]. This group observed an increase up to approximately two times in the thermal conductivity of the fluid by the addition of a nanoparticle less than 1% volumetric concentration [6]. The effect of particle inclusions on the effective thermal conductivity of liquid has attracted a great interest experimentally and theoretically. Very recent papers [16, 19] provides a detailed literature review of nanofluids including synthesis, potential applications, experimental and analytical analysis of effective thermal conductivity, effective thermal diffusivity and convective heat transfer.

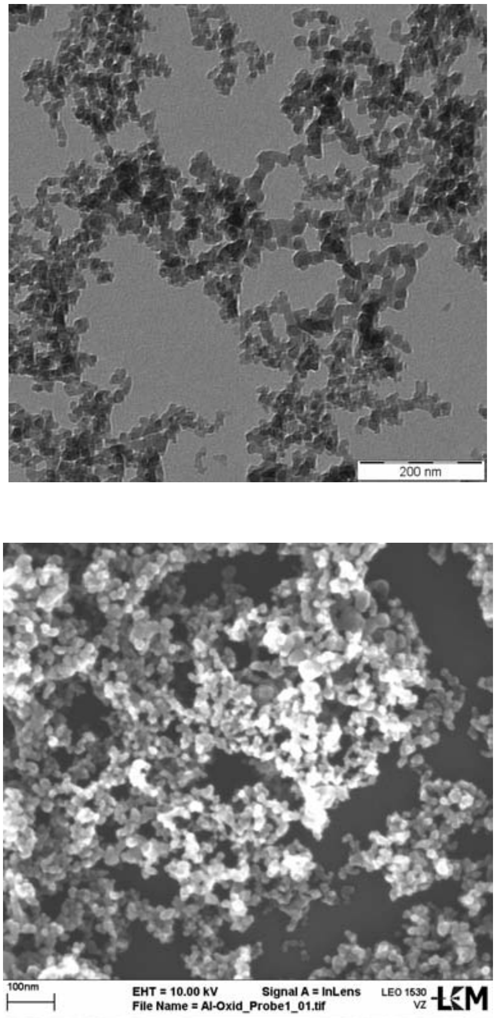

Fig. 1. TEM images of (a) SiO_2 , (b) Al_2O_3 nanoparticles in de-ionized water

Experimental results in the literature show that, thermal conductivity enhancement increases with increased particle concentration, this enhancement in thermal conductivity of nanofluids can not be predicted by any of the classical models [15], [9] which consider the effect of particle concentration, particle and fluid thermal conductivity and particle shape. Several attempts have been performed to model this anomalous enhancement, which take into consideration the particle size and temperature effect on effective thermal conductivity of nanofluids [12] and [10] proposed models which take in to account particle size and temperature effects. Effect of particle size for enhancement is not clear, where a group of results show increase in the thermal conductivity by increase in diameter, some other groups report just the contradictory results. Similar contradiction is valid for fluid temperature effect. For industrial applications one should also know the viscosity characteristics of the nanofluids, since for heat transfer applications pump costs are important.

In this study we report measurements of effective thermal conductivity by using 3ω method and effective viscosity by vibro-viscometer for SiO_2-water and Al_2O_3-water nanofluids. Measured results showed that the effective thermal conductivity of nanofluids increase as the concentration of the particles increase but not anomalously as indicated in the majority of the literature and this enhancement is very close to Hamilton-Crosser model and also this increase is independent of the temperature. Also effective viscosity of these nanofluids found to be very high that can not be predicted by Einstein model.

2. Material and method

2.1. Production and dispersion characteristics of nanofluids

Thermal conductivities of SiO_2 and Al_2O_3 nanoparticles are 1.38 and 46 W/mK. respectively. De-ionized water used as a base fluid. A two-step method was used to produce water based nanofluids with concentrations of SiO_2 nanoparticles 0.45, 1.85 and 4 vol.% and Al_2O_3 nanoparticles with concentration 0.5 and 1.5 vol.%, without any surfactant. In the first stage dry nanoparticles, average primary particle size 12 nm and 30 nm in diameter respectively for SiO_2 and Al_2O_3 manufactured by Degussa Co. mixed in de-ionized water. The next step was to homogenize the mixture using ultrasonic vibration (UIP 1000S, Dr. Hielscher GmbH), to break down the agglomerations. The TEM images of the samples given in Figure1.

2.2. Measurements of the effective thermal conductivity

The effective thermal conductivity of nanofluids is measured by a technique based on a hot wire thermal probe with ac excitation and 3ω lock-in detection. Since the principle and procedures of the technique have been described in details previously[18],[2] only a brief description is given here. We consider a thermal probe (ThP) consisting of a metallic wire of length $2l$ and radius r immersed in a liquid sample, acting simultaneously as a heater and as a thermometer. The sample and probe thermophysical properties are the volume specific heat ρc and the thermal conductivity k, with the respective subscripts (s)

and (p). The wire is excited by ac current at frequency $f/2$ and we assume that it is thermally thin in the radial direction so that the temperature θ (f) is uniform over its cross section. Since the electrical resistance of the wire is modulated by the temperature increase, the voltage across the wire contains a third harmonic $V_{3\omega}$ proportional to θ (f). It is convenient to use a normalized (reduced) 3ω signal, $F(f)$ [4]. For r/μ_s<<1, the temperature increase $\theta(f)$ generated by a modulated line heat source P in an infinite and homogeneous medium can be approximated by (Carslaw and Jaeger, 1959) and [1]:

$$F(f) \propto \theta(f) = -\frac{P/l}{2\pi k_s}\left(\gamma + \ln\frac{\sigma_s r}{2}\right) = -\frac{P/l}{2\pi k_s}\left(\ln\frac{1.26r}{\mu_s} + i\frac{\pi}{4}\right) \quad (1)$$

where $\gamma = 0.5772$ is the Euler constant. The complex quantity σ_s is given by $\sigma_s = (1+i)/\mu_s = (i2\pi f/\alpha_s)^{1/2}$ with μ_s the thermal diffusion length at frequency f and $\alpha_s = k_s/\rho_s c_s$ the thermal diffusivity.
In this work we are concerned with the measurement of thermal properties of water-based nanofluids, relative to pure water (subscript w). From Eq.(1) one has:

$$\frac{k_s}{k_w} = \frac{\mathrm{Im}(F_w)}{\mathrm{Im}(F_s)}$$

and

$$\cot\varphi_s - \cot\varphi_w = \frac{\sin(\varphi_w - \varphi_s)}{\sin\varphi_s \sin\varphi_w} = -\frac{2}{\pi}\ln\frac{\alpha_s}{\alpha_w} \quad (2)$$

For small diffusivity difference the phase yields:

$$\frac{\alpha_s}{\alpha_w} = 1 + \frac{\pi(\varphi_s - \varphi_w)}{2\sin^2\varphi_w} \quad (3)$$

In principle, Eqs. (2) give frequency-independent results of, but in practice there is an optimum frequency range such that r/μ_s<1 in which k_s and α_s have stable and low noise values as a function of frequency.

The first harmonic in the voltage signal is dominant and must be cancelled by a Wheatstone bridge arrangement. The selection of the 3rd harmonic from the differential signal across the bridge is performed by a Stanford SR850 lock-in amplifier tuned to this frequency, Figure 2 [3]. The thermal probe (ThP) is made of 40 μm in diameter and $2l$=19.0 mm long Ni wire. The temperature amplitude θ in water was 1.25 K. The minimum sample volume for equation (1) to apply is that of a liquid cylinder centered on the wire and having a radius equal to about $3\mu_s$. At $2f$=1 Hz, this amounts to 25 μl. The method was validated with pure fluids (water, methanol, ethanol and ethylene glycol), yielding accurate k-ratios within ±2% (equation 2) and absolute α value for water within ±1.5% (equation 3).

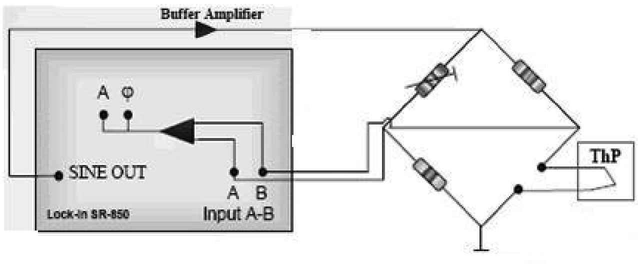

Fig. 2. Experimental set up for 3ω hot wire measurements consisting of thermal probe (ThP), Wheatstone bridge, lock-in amplifier and buffer amplifier

2.3. Measurements of the effective viscosity

The experimental setup for measuring the effective viscosity of nanofluids, consists of a Sine-wave Vibro Viscometer SV-10 and Haake temperature-controlled bath with 0.1C. The SV - 10 viscometer has 2 thin sensor plates that are driven with electromagnetic force at the same frequency by vibrating at constant sine-wave vibration in reverse phase like a tuning-fork. The electromagnetic drive controls the vibration of the sensor plates to maintain constant amplitude. The driving electric current, which is an exciting force, will be detected as the magnitude of viscidity produced between the sensor plates and the sample fluid. The coefficient of viscosity is obtained by the correlation between the driving electric current and the magnitude of viscidity. Since the viscosity is very much dependent upon the temperature of the fluid, it is very important to measure the temperature of the fluid correctly. By this viscometer we can detect accurate temperature immediately because the fluid and the detection unit (sensor plates) with small surface area/thermal capacity reach the thermal equilibrium in only a few seconds. It’s measurement range of viscosity is 0.3 – 10.000 mPa.s.

3. Results and discussion

3.1. Effective thermal conductivity of nanofluids

The effective thermal conductivity of SiO_2-water nanofluids with concentration 0.45, 1.85, 4.0 vol.% and Al_2O_3 – water nanofluids with concentration 0.5 and 1.5 vol.% were measured at temperatures 20°C, 35°C and 50°C. In Figure 3 we compared our results with classical effective thermal conductivity model, known as Hamilton – Crosser model [9]:

$$\frac{k_{eff}}{k_l} = \frac{k_p + (n-1)k_l - (n-1)(k_l - k_p)\phi}{k_p + (n-1)k_l + (k_l - k_p)\phi} \quad (4)$$

where n is the shape factor given by $n=3/\psi$ with ψ the sphericity, $\psi=1$ for spherical particles, k_l and k_p are the thermal conductivities of the base fluid and particles, respectively. Our experimental results for water based SiO_2 and Al_2O_3 nanofluids are lower than the model. Relative thermal conductivity is the ratio of effective thermal conductivity of nanofluids to thermal conductivity of base fluid.

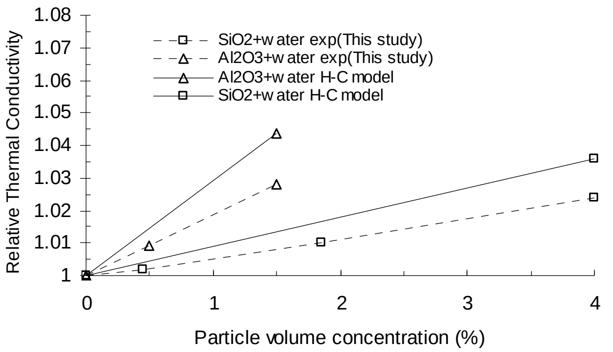

Fig. 3. Effect of volumetric fraction on the relative thermal conductivity for water-SiO_2 and water–Al_2O_3 nanofluids

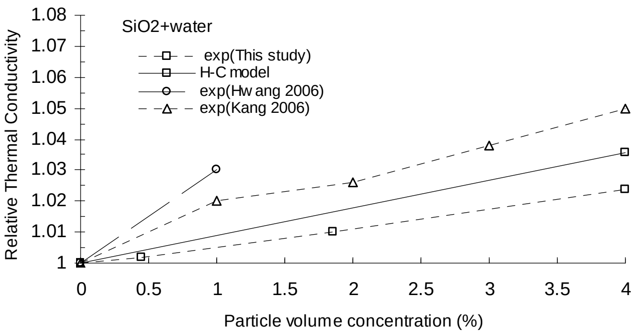

Fig. 4. Comparison of our experimental results with selected results from literature for the relative thermal conductivity of water-SiO_2 nanofluids

In Figure 4, comparison of our experimental results with selected results from literature for the relative thermal conductivity of water-SiO_2 nanofluids, are given. From this comparison one can see that our results are at the lower end of the selected data from literature. Effect of temperature on the enhancement of thermal conductivity of nanofluids is given in figure5 for Al_2O_3 – water nanofluids. Figure5 compares our data for 1.5% volumetric concentration of nanoparticles and the data reported by [17] for 1%, [7] for 1% and for %1.3 volumetric loading of nanoparticles. For the measurements at 20°C, our results are similar with [7] and [16]. But with the increase of temperature, relative thermal conductivity of our nanofluids is not increasing, which is in contradiction with the data of [7] and [16].

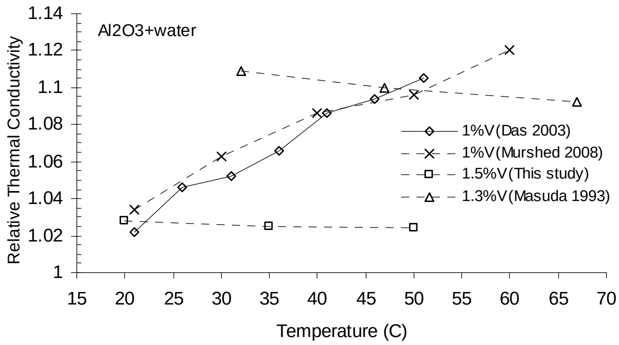

Fig. 5. Effect of temperature on the relative thermal conductivity for water- Al_2O_3 nanofluids

3.2. Effective viscosity of nanofluids

To verify the accuracy of our system, the viscosity of water was measured before and after from each experiment. The obtained results were compared with the data from literature [14]. After we performed the calibration, viscosity of nanofluids were measured for different particle concentrations, with varying temperature between 20°C to 50°C. The results of these measurements are shown in Figure 6 for SiO_2 – water nanofluids and in Figure 7 for Al_2O_3 – water nanofluids. Effective viscosity of these nanofluids, show a similar behavior as water with the increase in temperature.

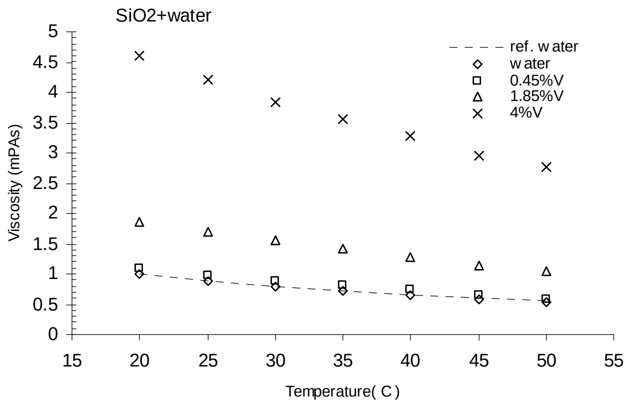

Fig. 6. Effective viscosities of SiO_2 – water nanofluids for 0.45, 1.85 and 3 vol.% concentrations as a function of temperature

Figure 8 gives the relative viscosity $(\mu_r) = (\mu_{eff})/(\mu_l)$, defined as the ratio of effective viscosity of nanofluid and the pure base fluid, as a function of volumetric particle concentration. Einstein proposed a viscosity correlation for non-interacting particle suspension in base fluid when the volume concentration is lower than 5%.

$$\mu_{eff} = \mu_l(1+2.5\phi) \quad (5)$$

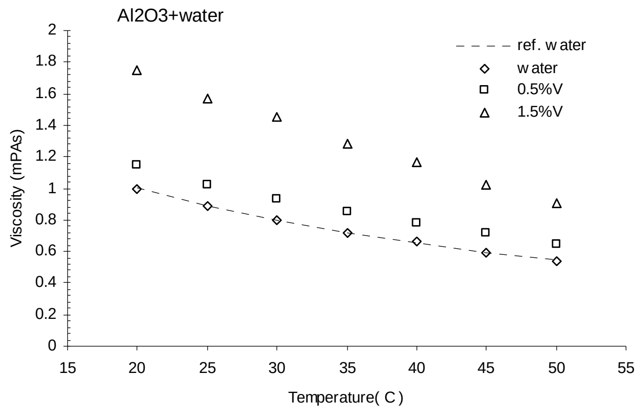

Fig. 7. Effective viscosities of Al_2O_3 – water nanofluids for 0.5 and 1 vol.% concentrations as a function of temperature

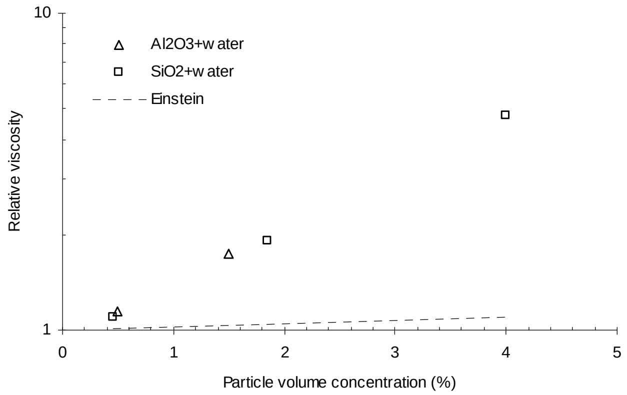

Fig. 8. Relative viscosity of water-SiO_2 and water–Al_2O_3 nanofluids as a function of nanoparticle volume fraction

Measured viscosity of nanofluids is much higher than that predicted by the Einstein equation, which shows strong effect of interactions of the nanoparticles. Viscosity of nanofluids increases dramatically, with increase in particle concentration which may be related with not using any surfactant or chemical additives while producing the nanofluids.

4. Conclusions

We have presented an experimental study of thermal conductivity and viscosity of nanofluids. We have investigated Alumina and Silica nanoparticles in water with different particle concentrations. Our results show that for our samples, thermal conductivity values are inside the limits of (moderately lower than) Hamilton-Crosser model. Our experiments at different temperatures show that relative thermal conductivity of nanofluids is not related with the temperature of the fluid. Viscosity of our nanofluids increase dramatically with the increase in particle concentration, Einstein model is found to be unable to predict this increase.

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