Thermal Conductivity and Viscosity Measurements of Water-Based Silica Nanofluids

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ABSTRACT

Nanofluids are a new class of thermal vectors potentially able to drastically increase the heat transfer properties of base fluids such as water, glycol and oil. Nanoparticles of various materials, size (<100 nm), shapes and concentrations can be added to the base fluid to enhance the transport properties. In particular, the knowledge of thermal conductivity and viscosity is essential to study the effect of nanoparticles on the heat transfer coefficient of the fluid. Here, thermal conductivity and viscosity of nanofluids based on water and SiO_2 are measured at nanoparticles concentrations ranging from 1% to 54% by weight and temperatures between 10°C and 70°C. After a discussion of the results obtained, the experimental data are used to evaluate the thermal heat transfer capability of water-SiO_2 nanofluids in comparison with the base fluid, i.e. water, through the Mouromtseff figure numbers for laminar and turbulent flow.

Keywords: nanofluids, water, SiO_2, thermal conductivity, viscosity

1 INTRODUCTION

Nanofluids are a new class of fluids that could significantly improve the thermal properties of fluids used as thermal vectors. They are obtained by dispersing in common fluids (water, glycol, oil) solid nanoparticles (diameter <100 nm) of different materials (metal oxides, metals, carbon nanotubes) [1]. Also at relatively low nanoparticle concentrations, it is possible to get an unproportional increase in thermal conductivity and heat transfer coefficient [2-3], with a correspondent increase of the energy efficiency of plants or components using such fluids. In general, the higher the concentration, the higher the heat transfer enhancement. Other important parameters influencing the enhancement are material, dimension and shape of the nanoparticles [4], Zeta potential, pH, type and concentration of dispersants [5-6]. However, nanofluids can be actually applied in technological systems only if the addition of nanoparticles does not determine a significant viscosity enhancement, because the increase of energy required to pump the nanofluid could nullify the advantages obtained in terms of thermal properties.

In the literature, several papers present measurements of thermal properties and/or viscosity for water based nanofluids and various kinds of added nanoparticles showing different behaviors [7, 8, 9].

However, the results are frequently not coherent, probably due to different methods of nanofluids preparation and insufficient information on the nanoparticles characteristics. To evaluate the reasons for these discrepancies, within the International Nanofluid Property Benchmark Exercise (INPBE), thermal conductivity of identical samples of colloidally stable dispersions of nanoparticles was studied at ambient temperature by over 30 organizations worldwide, using a variety of experimental approaches [10]. The authors concluded that differences observed among the various experimental approaches tend to disappear when the data are normalized to the measured thermal conductivity of the base fluid. Moreover, classic effective medium theory for well-dispersed particles [11] was found to be in good agreement with the experimental data, suggesting that no anomalous enhancement of thermal conductivity was achieved in the nanofluids tested in the exercise.

However, the measurements were performed at ambient temperature only, not taking into account the influence of temperature on thermal conductivity enhancement.

Considering that oxide nanoparticles can be of particular interest for industrial applications because of their low cost, high stability, easy production, here the same nanofluid belonging to set 3 in [10] was considered to perform a series of measurements with the following aims:

1. to check the accuracy of our thermal conductivity apparatus by comparing our results with those of INPBE;
2. extend the temperature range of the measurements and consider various nanoparticles concentrations to evaluate the enhancement also at temperature different from ambient;
3. measure viscosity as a function of temperature to evaluate the viscosity enhancement;
4. estimate the effects of thermal conductivity and viscosity enhancements on heat transfer performance through the Mouromtseff (Mo) number [12].

2 EXPERIMENTAL

2.1 Materials

The nanofluid object of the present study is formed by silica nanoparticles of spherical shape monodispersed in deionized water. It was supplied by Grace & Co. (Ludox TM-50) at a nanoparticles nominal concentration of 50% by mass. The real concentration was evaluated by measuring the density of the nanofluid at 20°C, assuming a linear dependence of density from the volumetric fraction of nanoparticles and a density of 2100 kg/m^3 for SiO_2. The actual SiO_2 mass fraction resulted to be 54%.

Bidistilled water (CARLO ERBA, CAS Nr 7732-18-5) was added to the commercial nanofluid to obtain other three compositions: 1 wt%, 5 wt% and 27 wt%. Each nanofluid obtained in this way was further sonicated in order to completely disperse the nanoparticles in the water.

2.2 Nanofluids stability characterization

The nanoparticles size declared by the supplier was 22 nm. A Zetasizer Nano ZS (Malvern), based on Dynamic Light Scattering (DLS), was used to check the actual average dimension of the nanoparticles in solution and verify the dependency of the diameter size from the concentration of the solution. The mean particle diameter, measured 3 times for each sample, was around 30 nm for the 1 wt% solution, 25 nm for 5 wt% and 20 nm for 27 wt%, showing a slight dependence of size on nanoparticles concentration. The forth fluid (54 wt%) was not measured since this concentration is too high, giving problems of multiple scattering. The measured diameters were practically constant for more than 20 days after preparation at all the concentrations, demonstrating the strong stability of the various nanofluids.

Also the Zeta potential of nanofluids was measured, again with the Zetasizer Nano (Malvern), by electrophoresis light scattering technique and M3-PALS method. Water-SiO_2 nanofluids Z potential was in the range between -35 mV and -45 mV for all the nanoparticles concentrations, corresponding to strong repulsive interactions and reduced tendency to form aggregates, then confirming the stability of the nanofluids.

Also pH value of a colloidal solution is one of the main parameters influencing particle aggregation and stability of the suspension. The pH of each nanofluid has been measured with a pocket-Sized pH Meter with Replaceable Electrode (HANNA instruments). It was almost independent from nanoparticles concentration, ranging from 9.1 at 54 wt% to 9.9 at 1 wt%.

2.3 Thermal Conductivity apparatus

Thermal conductivity data were measured by means of a TPS 2500 S, based on the hot disk technique. In case of liquids, the sensor is immersed in the fluid within a specifically built aluminium box, made up of two parts containing a cylindrical cavity. The filled box is put in a water thermostatic bath to reach the test temperature. The stability is achieved in at least 2 hours. The power supplied for each measurement was 40 mW and the time of the power input was 4 s. The declared instrument uncertainty is 5%.

2.4 Viscosity apparatus

The dynamic viscosity was measured by means of an AR-G2 (TA Instruments) rotational rheometer endowed with a plate-cone geometry. In order to stabilize the measurement temperature, an Upper Heated Plate (UHP) was used. Before the measurements, the rheometer was carefully calibrated at each temperature.

All the measurements were performed at constant temperature and variable shear rate, from 80 1/s to 1200 1/s, at constant step of about 124 1/s (except for the isotherm at 70 °C, at which faster measurements had to be performed due to the water evaporation). A conditioning step of 2 seconds and a pre-shear rate at 80 1/s were performed before the measurements to remove any possible fluid "memory" due to the sample preparation, storage and loading.

3 RESULTS AND DISCUSSION

3.1 Thermal conductivity experimental data

Thermal conductivity of all selected water-SiO_2 nanofluids was measured at ambient pressure as a function of temperature in the range between 10 °C and 70 °C, with steps of 10 °C, ≤for all the selected nanoparticles concentrations, in order to evaluate the enhancement with respect to pure water.

To assess the accuracy of the measurements, water thermal conductivity was measured at each temperature and compared with Refprop 8.0 database assumed as the reference [13]. The average absolute deviation between experimental data and expected values was around 0.7%

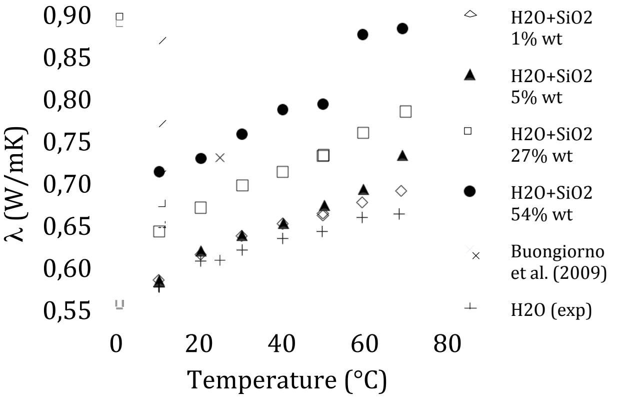

Figure 1: thermal conductivity of water-SiO_2 nanofluids as a function of temperature

with a maximum of 1.3%.

Figure 1 shows nanofluids thermal conductivity as a function of temperature, while Figure 2 presents the ratio between the thermal conductivity of nanofluids and that of water (enhancement). First of all, the thermal conductivity measured at 20 °C and 50% wt is compatible, within the experimental accuracy, with that measured at the same conditions by [10]. Thermal conductivity increases almost linearly with temperature at concentrations higher than 1% wt. Some instability is observed at temperatures higher than 50 °C, probably due to some evaporation of the sample. For this reason, in Figure 2 the enhancement is represented only up to 50 °C. The enhancement is strongly dependent on concentrations, even if it is less than proportional to concentration (e.g.: enhancement below 25% for 54% wt nanofluid at any temperature). Moreover, it is less sensitive to temperature than thermal coinductivity, with an increase of only few percent between 10 °C and 50 °C at all concentrations.

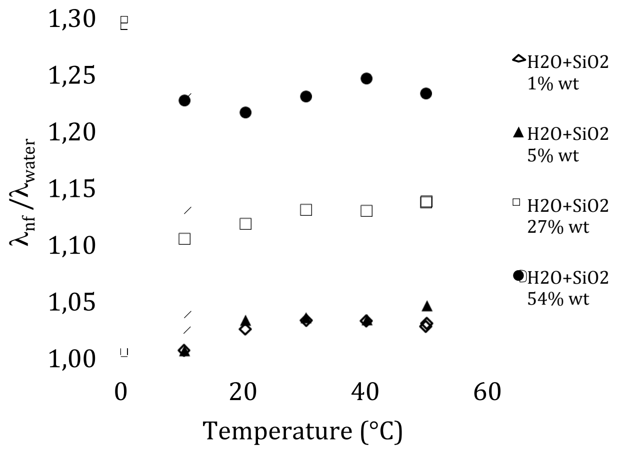

Figure 2: thermal conductivity ratio between water-SiO_2 nanofluids and water as a function of temperature

3.2 Viscosity experimental data

Dynamic viscosity data of pure water and water based nanofluids were measured from 10 °C to 70 °C by increments of 20 °C per step.

The measurement accuracy has been evaluated by measuring the viscosity of a well known fluid like water at each temperature. The experimental data have been compared with Refprop 8.0 database calculations as reference [13]. Data for water are very close to reference values, being the percentage absolute average deviation below 1% at any temperature except at 70 °C, at which the measurements are less stable, probably due to sample evaporation and arising of convective motions inside the sample.

At concentrations between 1% wt to 27% wt, the ratio between shear stress and shear rate was constant in the shear rate range of measurements at all the temperatures, highlighting a newtonian behaviour of the nanofluids. Figure 3 shows that viscosity values, taken at a constant shear rate of 550 (1/s), decrease with lower declination at increasing temperatures. Viscosity at concentrations below 5% wt is practically the same as that of water. This can be seen even better in Figure 4, were the ratio between nanofluids viscosity and water viscosity is reported. At given concentration, the viscosity ratio is practically constant with temperature, except at 70 °C, at which the ratio is increased, probably due to some aggregation phenomena. Viscosity for the 27% wt nanofluid is more than twice the viscosity of water.

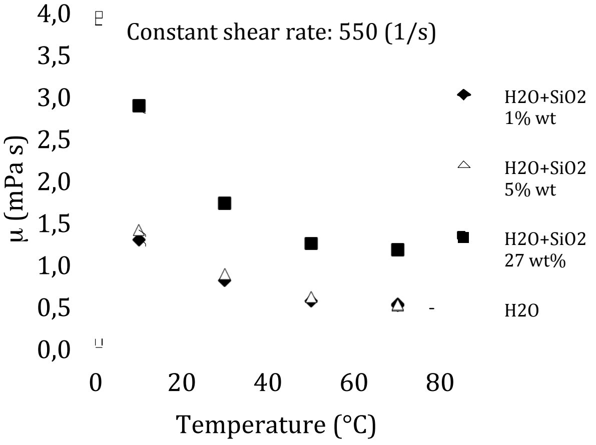

Figure 3: viscosity of water-SiO_2 nanofluids as a function of temperature

Nanofluid with 54% wt SiO_2 nanoparticles showed a non-newtonian behaviour and a viscosity one order of magnitude higher than that at other concentrations. Moreover, the viscosity increased with temperature at temperatures higher than 50 °C. This behaviour is probably due to strong aggregation of nanoparticles. For these reasons, the viscosity behaviour at this concentration was not included in the figures.

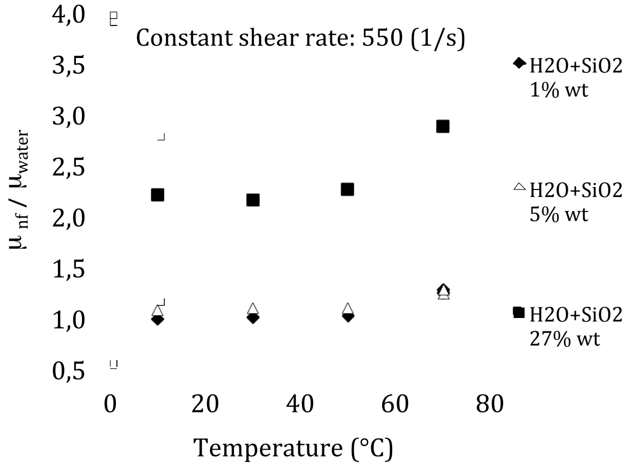

Figure 4: viscosity ratio between water-SiO_2 nanofluids and water as a function of temperature

3.3 Mouromtseff number analysis

The Mouromtseff number (Mo) is a figure of merit to evaluate and compare the heat transfer capability of alternative thermal fluids [12]. With reference to a flow inside a fixed geometry at a given velocity, the highest heat transfer rate is achieved by the liquid coolant with the highest Mouromtseff number.

In case of full developed internal laminar flow, it can be shown that the ratio of the Mouromtseff number (*Mo*) for each nanofluid to that of water is equal to the ratio of the respective thermal conductivities:

$$\frac{Mo_{nf}}{Mo_{water}} = \frac{\lambda_{nf}}{\lambda_{water}} \qquad (1)$$

The value of *Mo* as a function of temperature and concentrations is then the same as that of thermal conductivity ratio shown in Figure 2. In any case, it is higher than 1 and increases with SiO_2 concentrations. Then, the heat transfer capability of water-SiO_2 nanofluids is potentially higher than that of water if the flow is developed laminar.

For internal turbulent flow, *Mo* is given by:

$$Mo = \frac{\rho^{0.8}\lambda^{0.67}c_p{}^{0.33}}{\mu^{0.47}} \qquad (2)$$

The behaviour of *Mo* as a function of temperature for turbulent flow is shown in Figure 5. The number is only slightly higher than 1 at low SiO_2 concentrations and temperatures below 60 °C. In all other cases, Mo is clearly lower than 1 with a minimum of 0.75 for 27% wt nanofluid at 70 °C. This means that in turbulent flow (the most significant for technological applications) water-SiO_2 nanofluids could be penalised in terms of heat transfer efficiency with respect to water, mostly due to the increase of viscosity produced by the addition of nanoparticles.

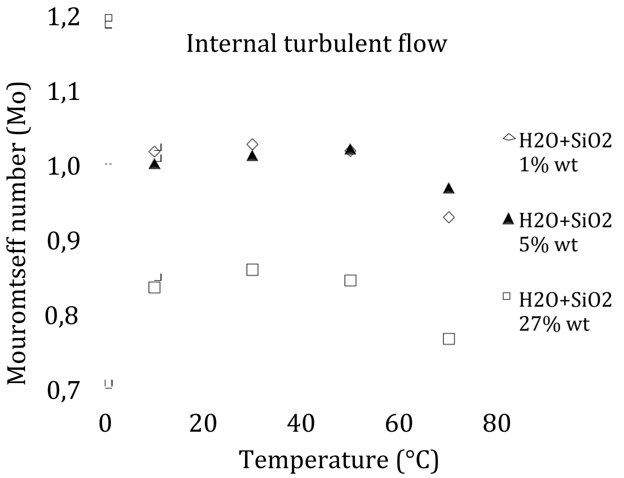

Figure 5: Mouromtseff number (Mo) for water-SiO_2

4 CONCLUSIONS

Viscosity and thermal conductivity for nanofluids formed by water and SiO_2 nanoparticles with concentration from 1% to 54% by mass were measured in the range of temperatures between 10 °C and 70 °C. The thermal conductivity clearly enhanced with reference to water, but only at the higher concentrations with a weak dependence on temperature. At the same time, viscosity increases even more significantly. The effect of these properties on thermal transfer capability has been analysed through the Mouromtseff number, showing that water based nanofluids with silica nanoparticles could be profitable only in laminar flow, while their capability could be lower than that of water in turbulent flow.

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