EXPERIMENTAL STUDY ON THE VISCOSITY OF Al_2O_3-WATER NANOFLUID

F.C. Motta, fran@sc.usp.br
G.Ribatski, ribatski@sc.usp.br

Department of Mechanical Engineering, Escola de Engenharia de São Carlos (EESC).
University of São Paulo (USP), 13566-590 São Carlos - SP, Brazil.

Abstract. *Al_2O_3 nanoparticles dispersed in deionized water at different volume concentration (0.1 - 1%) were produced and characterized. The average diameter of Al_2O_3 spherical particle is 15 nm. A steady suspension was acquired by means of ultrasonic agitation. The transport property measured in this work was the viscosity with a disk-rheometer. Viscosity measurements were carried out over temperature ranges from 20 to 40 °C. The effect of the nanoparticle concentration on viscosity was analyzed in this paper. Viscosity measurements show that the Al_2O_3–water nanofluid viscosity increases with increasing the nanoparticle volume concentration and decreases with increasing temperature. Results for viscosity had been compared against results from predictive methods.*

Keywords: *Nanofluids; Viscosity; Nanoparticles.*

1. INTRODUCTION

The interest for sustainable energy use and sources has grown in the last few decades. In this scenario, the heat transfer studies in molecular or atomic level may play an important role.

In the past, numerous studies on thermal conductivity and viscosity of suspensions containing solid millimeter- or micrometer sized particles have been conducted. The problems with the use of these conventional large size particles in heat exchangers are the following: (i) rapid settling; (ii) heat transfer surface abrasion; (iii) and clogging. To minimize such problems, Choi (1995) has proposed the dispersion of metallic and nonmetallic nanoparticles smaller than 100 nm in base fluids as water, oil and ethylene glycol. Recently, Wen and Dig (2005) showed that the transport properties and thermal hydraulic behaviors of nanofluids depend on the particle concentration, size and morphology, as well as the presence of dispersants. It should be highlighted that surfactants and/or dispersants, often used in order to achieve a stable suspension, have significant influence on the nanofluid transport properties. As pointed out by Namburu et al. (2007a), the accurate knowledge of the viscosity is crucial in order to estimate the pressure drop and the heat transfer rate in most thermal systems, since the Prandtl and Reynolds numbers are both functions of the dynamic viscosity, and the correct knowledge of the pressure drop and heat transfer rate are essential to predict the necessary pumping power as well as the overall heat transfer area of the heat exchanger.

Wang et al. (1999) measured the viscosity of Al_2O_3–water and Al_2O_3–ethylene glycol nanofluids. Their results showed that the relative viscosity increases with increasing volume concentration of nanoparticles for both nanofluids. Das et al. (2003) also measured the viscosity of Al_2O_3–water nanofluids against shear rate. Their results showed an increase of viscosity with increasing particle concentration. Lee et al (2008), presented results for different nanoparticle concentrations showing the variation of the Al_2O_3–water viscosity. They found viscosity increments up to 2.9% at a concentration of 0.3 vol.%. According to the results of Chandrasekar et al. (2010) for Al_2O_3-water nanofluid, the viscosity increases almost linearly with increasing the nanoparticle concentration up to 2 vol.% and can be predicted quite well by Einstein´s equation. Investigators have also studied the rheology of Al_2O_3 nanoparticles in ethylene glycol as Wang et al. (1999) and of CuO nanoparticles in water as Namburu et al. (2007b). Viscosity of SiO_2-water and TiO_2 particles in ethylene glycol and water mixture were investigated by Pak and Cho (1998) and Duangthongsuk and Wongwises (2008), respectively. Wang and Mujundar (2007) recommended further experimental studies on developing new accurate viscosity models for nanofluids so they can be used in simulation studies.

There exist few correlations and models that can be used to estimate particle suspension viscosities. Almost all existing predictive methods were derived from the Einstein's pioneering work (Einstein, 1956). His model is based on the assumption of a viscous fluid that contains dilute suspended spherical particles. Then, he calculated the energy dissipated by the fluid flow around a single particle by associating that energy with the work done for moving this particle relatively to the surrounding fluid. In which, he obtained:

$$\mu_{\mathrm{nf}} = (1 + 2.5\phi)\mu_{\mathrm{bf}} \tag{1}$$

were μ_{nf}, μ_{bf}, and ϕ are the viscosity of the nanofluid, the viscosity of the base fluid, and the volume concentration, respectively.

Einstein proposed his viscosity correlation for particle suspensions with volume concentration lower than 2%.

Based on the work of Einstein, Brinkman, 1952 proposed a new correlation to predict the dynamic viscosity of solutions of a base fluid and moderate concentrations of solid particles. His correlation is given as follow:

$$\mu_{\mathrm{nf}} = \frac{1}{(1-\phi)^{2.5}}\mu_{\mathrm{bf}} \qquad (2)$$

Batchelor, 1977 considered the effect of the Brownian motion of particles on the bulk stress of an approximately isotropic suspension of rigid and spherical particles obtaining a correlation given by:

$$\mu_{\mathrm{nf}} = (1 + 2.5\phi + 6.5\phi^2)\mu_{\mathrm{bf}} \qquad (3)$$

Furthermore, Wang et al. (1999), based on his own measurements, proposed a correlation to predict the viscosity of nanofluids given by:

$$\mu_{\mathrm{nf}} = (1 + 7.3\phi + 123\phi^2)\mu_{\mathrm{bf}} \qquad (4)$$

Nguyen et al. (2008) suggested that these correlations can be used when the nanofluid viscosity is affected only by the fluid viscosity and the particle volume fraction.

In this paper, dynamic viscosities of Al_2O_3/water nanofluid were measured. Nanoparticles with average diameter of 15 nm and volume concentration ranging from 0.1 to 1% were used in order to produce the nanofluids. The effects of the nanoparticle concentration and nanofluid temperature on the viscosity were investigated.

2. EXPERIMENTS

2.1. Nanofluids Preparation

In the literature, there are two fundamental methods to obtain nanofluids namely *single-step method* and *two-steps method*. In the *single-step method*, the dispersion of nanoparticles is obtained by direct evaporation of metallic nanoparticles and their condensation in a base liquid. Yu et al. (2008) pointed out that for nanofluids containing high-conductive metals such as copper; the one-step technique is preferable to the two-step process since it prevents the oxidation of the particles. In the two-steps method, first the nanoparticles are obtained by different methods and then they are dispersed into the base liquid. The suspensions obtained by either case should be well mixed and uniformly dispersed and stable in time (Mamut, 2006). Making nanofluids using the two-step processes is challenging because individual particles tend to quickly agglomerate before achieving a uniform dispersion.

In the two-steps method, the dispersion of nanoparticles in water is obtained by mixing the Al_2O_3 nanoparticles and water. The solution is homogenized by using, generally, ultrasonic vibration. To obtain uniform dispersion and stable nanoparticle suspensions in the liquid are key aspects in most nanofluid applications according to Chandrasekar, 2009. The equipments used to disperse dry nanoparticles include ultrasonic agitator, magnetic stirrer, high-shear mixer, homogenizer among others. The time can significantly influence the dispersion since nanoparticles have a strong tendency to agglomerate due to the London van der Waals force among the particles.

In the present study, the nanofluid was obtained by dispersing in water alumina nanoparticles with averages diameter of 15 nm and density of 3,500 kg/m^3 (Nanum Nanotecnologia S.A, 2009). Nanofluids with volume concentrations of 0.1%, 0.3%, 0.5%, 0.7% and 1% were dispersed in deionized water without any stabilizer. Sample preparation was carried out using a sensitive mass balance with an accuracy of 0.1 mg. After mixing the alumina nanoparticles and water, this solution is agitated during 1 hour with an ultrasonic agitator (CP 505, Cole-Parmer Instruments) at a frequency of 20 kHz.

In order to obtain data under stable conditions in case of nanofluids produced without any stabilizer or surfactant, as suggested by Wen, et al. (2009), the viscosity measurements were performed just few minutes after the nanofluid preparation. The measures were carried out after a few minutes of agitation.

Figure 2 from Nanum Nanotecnologia S.A shows a SEM photograph of Al_2O_3 nanoparticles dispersed in water.

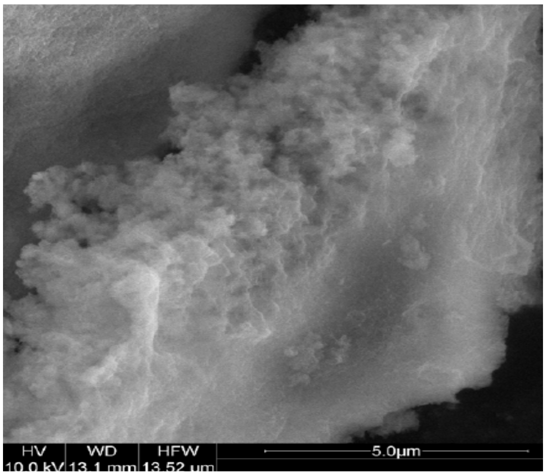

Figure 1. SEM photographs of Al_2O_3 particles produced by Nanum Nanotecnologia S.A.,

2.2. Viscosity measurement

The dynamic viscosity was measured through a cone/plate type viscometer manufactured by Brookfield model (LVDV-III U/CPE). This equipment allows performing measurements under temperature controlled conditions. In this viscometer, the cone is connected to the spindle drive while the plate is mounted in the sample cup (Fig. 2). In the present measurements, the CPE-40 spindle was used. For this spindle type, the cone/plate geometry requires a sample volume of only 0.5 ml. The spindle type and speed combinations will produce satisfactory results when the applied torque is between 10% and 100%. The spindle speeds available with this viscometer falls in the range of 0 to 200 rpm and the shear rate range is 0 - 1250 s^{-1}. In order to validate the measurements, experimental results for deionized water were also obtained. The viscometer is benchmarked with distilled water. A dynamic viscosity of 1.01 was measured for deionized water at a temperature of 20 °C. This result agrees with the literature value of 1.008 (Bejan, 1993).

Dynamic viscosity measurements were performed for Al_2O_3-water nanofluids with concentrations from 0.1 to 1% and for a temperature range of 20 to 40 °C.

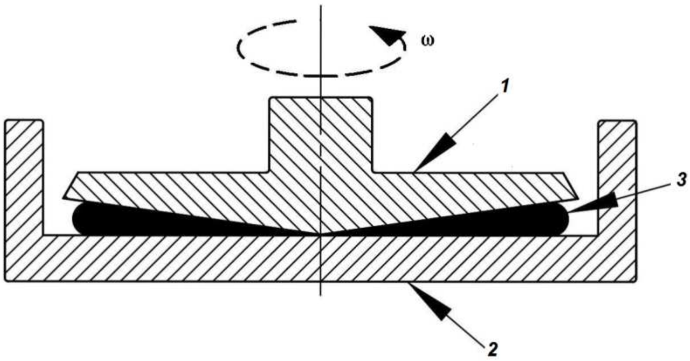

Figure 2. Schematic of cone and plate geometry. 1 – Cone, 2 – Plate and 3 – Sample.

3. RESULTS AND DISCUSSION

One of the goals of the present study is to verify if the nanofluid behaves as a Newtonian or a non-Newtonian fluid. The equation governing the behavior of Newtonian fluids is given as follow:

$$\tau = \mu \dot{\gamma} \tag{5}$$

where τ is the shear stress, μ is the dynamic viscosity and $\dot{\gamma}$ is the shear strain rate. In case of a Newtonian fluid, μ is independent of $\dot{\gamma}$. Fig. 3 presents a plot of the shear rate as a function of shear stress for various volume concentrations. In this figure, the angular coefficients of the curves are constants what imply a constant dynamic viscosity and consequently a Newtonian behavior. Moreover, as expected, the curve slope as well as the viscosity, increases with increasing the nanoparticle concentration.

In Fig. 4, it can be figured out that the viscosity increases almost linearly with increasing the nanoparticle concentration. The uncertainties bars displayed in Fig. 4 were calculated as the standard deviation of viscosity measurements of different nanofluid samples and different shear strain rates.

Fig. 5 illustrates the effect of the nanofluid temperature on its dynamic viscosity for different nanoparticle concentrations. According to this figure and as expected, the viscosity of the nanofluid decreases with increasing its temperature. The difference between the viscosity of the nanofluid and pure water also increases with increasing temperature. This behavior can be explained through the fact that the water viscosity decreases with increasing temperature. So, its relative effect on the overall viscosity becomes less important and the effect of nanoparticle concentration becomes more prominent.

Fig. 6 shows the variation of the nanofluid viscosity with the nanoparticle volume concentration. This figure also shows a comparison between the measured data and the predictive methods of Einstein, Brinkman and Wang. According to Fig. 6, the correlation proposed by Wang et al. (1999) predicted quite well the present data while the predictive methods of Einstein and Brinkman worked poorly. It should be highlighted that the method of Wang was developed based on his database the includes Al_2O_3-water nanofluids and Einstein and Brinkman correlations were developed based on theoretical assumptions for solid particles, no necessary nano sized ones dispersed in a base liquid. So, it is not surprising that Wang worked the best.

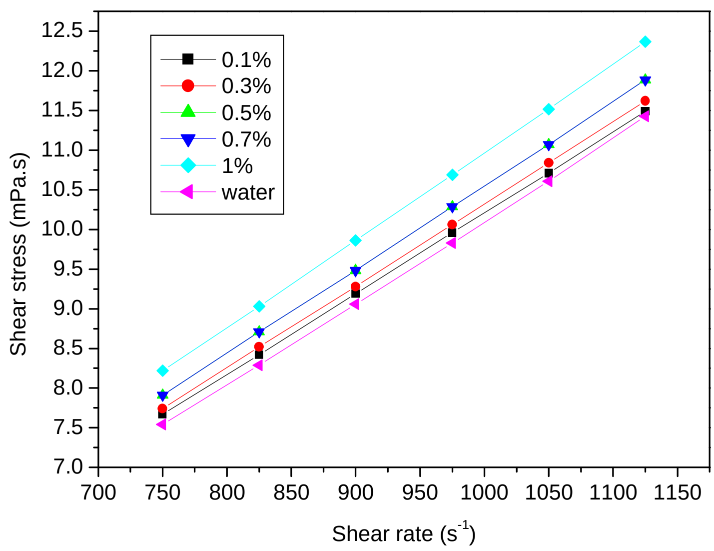

Figure 3. Shear stress as a function of the shear rate at 20 °C for different volume concentrations.

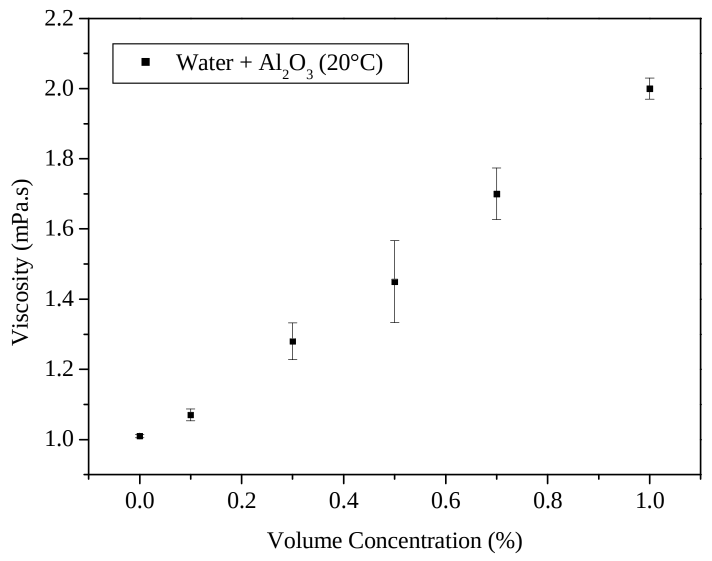

Figure 4. The variation of the Al_2O_3-water nanofluid (15 nm) viscosity with volume concentrations for a solution temperature of 20 °C.

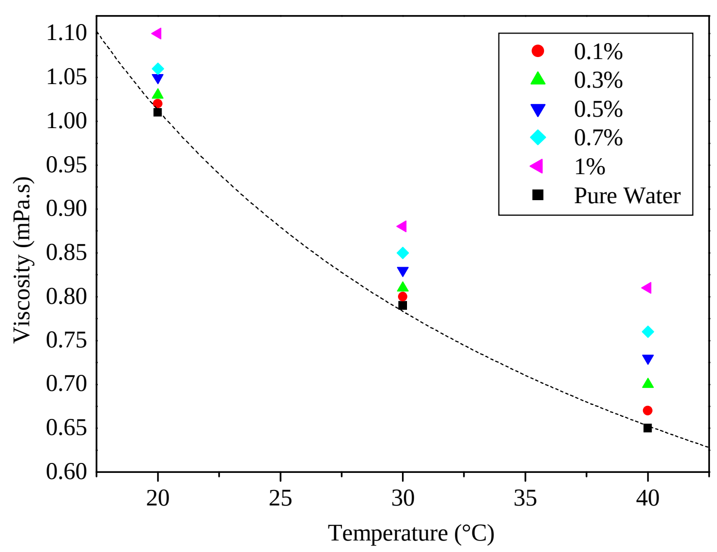

Figure 5. Dynamic viscosities of Al_2O_3-water nanofluids as a function of temperature.

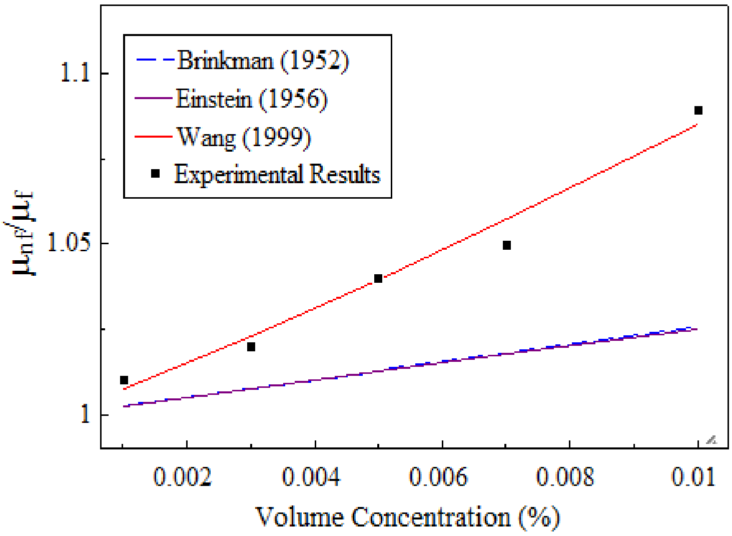

Figure 6. Comparison between measured and predicted viscosities of Al_2O_3-water nanofluids.

5. CONCLUSIONS

In this paper, an experimental study on the dynamic viscosity of water-based-nanofluids containing Al_2O_3 nanoparticles with average diameter of 15 nm is presented. Al_2O_3-water nanofluid by two step method with ultrasonication and without any surfactant was produced. A Brookfield cone/plate viscometer was used in order to measure the nanofluid dynamic. For concentrations varying from 0.1 % to 1 % and solution temperatures ranging from 20 to 40 °C, the alumina nanofluids exhibited a Newtonian behavior. As expected, the nanofluid viscosity increases with increasing the volume concentration and decreasing the nanofluid temperature. Wang et al. (1999) correlation predicted relatively well the present database.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledged the funding of this work by the National Council for Scientific and Technological Development (CNPq) (Young Researcher on Nanotechnology, contract number 576982/2008-3) and Brazilian Federal Agency for Support and Evaluation of Graduate Education (CAPES) (Nanobiotec and Pró-Engenharias, contracts numbers 23038.019131/2009-85 and 1224-2008, respectively). The authors would also like to thank Prof. Dr. Sergio Rodrigues Fontes from Thermal and Fluids Engineering Group at EESC-USP, for his technical contributions who made this study possible.

7. REFERENCES

Batchelor, G.K., 1977, "The effect of Brownian motion on the bulk stress in a suspension of spherical particles", J. Fluid Mech, Vol. 83, No. 1, pp. 97–117.
Bejan, A., *Heat Transfer*, Wiley, New York, 1993
Brinkman, H.C., 1952, "The viscosity of concentrated suspensions and solution", J. Chem. Phys, Vol. 20, pp. 571–581.
Chandrasekar, M., Suresh, S. and Bose, A.C., 2010, "Experimental investigations and Theoretical Determination of Thermal Conductivity and Viscosity of Al_2O_3/water nanofluid", Experimental Thermal and Fluid Science, Vol. 34, pp. 210–216.
Chandrasekar, M., Suresh, S., 2009, "A Review on the Mechanisms of Heat Transport in Nanofluids", Heat Transfer Engineering, Vol. 30, No. 14, pp. 1136–1150.
Choi, S.U.S, 1995, "Developments and Applications of non-Newtonian Flows", ASME FED. Vol.66, pp. 99–105
Das, S.K., Putra, N., Thiesen, P., Roetzel, W., 2003, "Temperature dependence of thermal conductivity enhancement for nanofluids", ASME Trans. J. Heat Transfer, Vol. 125, pp. 567–574.
Duangthongsuk, W., and Wongwises, S., 2008, "Effect of thermophysical properties models on the predicting of the convective heat transfer coefficient for low concentration nanofluid", International Communications in Heat and Mass Transfer, Vol. 35, pp. 1320–1326.
Einstein, A., 1956, "Investigations on the Theory of the Brownian Movement", Dover Publications, New York.
Lee, J. H., Hwang, K. S., Jang, S. P., Lee, B. H., Kim J. H., Choi, S. U. S. and Choi, C. J., 2008, "Effective viscosities and thermal conductivities of aqueous nanofluids containing low volume concentrations of Al_2O_3 nanoparticles", International Journal of Heat and Mass Transfer, Vol. 51, pp. 2651–2656.

Mamut, E., 2006, “Characterization of Heat and Mass Transfer Properties of Nanofluids”, Romanian Journal of Physics, Vol. 51, No. 1–2, pp. 5–12

Namburu, P. K., Kulkarni, D. P., Misra, D. and Das, D. K., 2007a, “Viscosity of copper oxide nanoparticles dispersed in ethylene glycol and water mixture” Experimental Thermal and Fluid Science, Vol. 32, pp. 397–402.

Namburu, P.K., Kulkarni, D.P., Dandekar, A. and Das, D.K., 2007b, “Experimental investigation of viscosity and specific heat of silicon dioxide nanofluids”, Micro & Nano Letters, Vol. 2, No. 3, pp. 67–71.

Nanum Nanotecnologia S.A, 2009, Belo Horizonte, MG, Brazil, http://www.nanum.com.br

Nguyen, C.T., Desgranges, F., Galanis, N., Roy, G., Maré, T., Boucher, S. and Mintsa, H. A., 2008, “Viscosity data for Al_2O_3–water nanofluid—hysteresis: is heat transfer enhancement using nanofluids reliable?” International Journal of Thermal Sciences, Vol. 47, pp. 103–111.

Pak B. C., and Cho Y. I., 1998, “Hydrodynamic and Heat Transfer Study of Dispersed Fluids with Submicron Metallic Oxide Particles”, Experimental Heat Transfer, Vol. 11, pp. 151–170.

Wang, X., Xu, X., and Choi, S.U.S., 1999, “Thermal conductivity of nanoparticles–fluid mixture”, J. Thermophys. Heat Transf., Vol. 13, No. 4, pp. 474–480.

Wang, X.Q. and Mujumdar A.S., 2007, “Heat transfer characteristics of nanofluids: a review”, International Journal of Thermal Sciences, Vol. 46, pp. 1–19.

Wen, D. and Ding, Y., 2005, “Formulation of nanofluids for natural convective heat transfer applications”, International Journal of Heat and Fluid Flow, Vol. 26, pp. 855–864.

Wen, D., Lin, G., Vafaei, S., and Zhang, K., 2009, “Review of nanofluids for heat transfer applications”, Particuology, Vol. 7, pp. 141–150.

Wen, D.S. and Ding, Y.L., 2004, “Experimental investigation into convective heat transfer of nanofluids at entrance area under laminar flow region” International Journal of Heat and Mass Transfer, Vol. 47, No.24, pp. 5181–5188.

Yu, W., France, D. M., Routbort, J. L., and Choi, S. U. S., 2008, “Review and Comparison of Nanofluid Thermal Conductivity and Heat Transfer Enhancements”, Heat Transfer Engineering, Vol. 29, No. 5, pp. 432–460.