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Temperature and particle-size dependent viscosity data for water-based nanofluids – Hysteresis phenomenon

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Abstract

In the present paper, we have investigated experimentally the influence of both the temperature and the particle size on the dynamic viscosities of two particular water-based nanofluids, namely water–Al_2O_3 and water–CuO mixtures. The measurement of nanofluid dynamic viscosities was accomplished using a 'piston-type' calibrated viscometer based on the Couette flow inside a cylindrical measurement chamber. Data were collected for temperatures ranging from ambient to 75 °C, for water–Al_2O_3 mixtures with two different particle diameters, 36 nm and 47 nm, as well as for water–CuO nanofluid with 29 nm particle size. The results show that for particle volume fractions lower than 4%, viscosities corresponding to 36 nm and 47 nm particle-size alumina–water nanofluids are approximately identical. For higher particle fractions, viscosities of 47 nm particle-size are clearly higher than those of 36 nm size. Viscosities corresponding to water-oxide copper are the highest among the nanofluids tested. The temperature effect has been investigated thoroughly. A more complete viscosity data base is presented for the three nanofluids considered, with several experimental correlations proposed for low particle volume fractions. It has been found that the application of Einstein's formula and those derived from the linear fluid theory seems not to be appropriate for nanofluids. The hysteresis phenomenon on viscosity measurement, which is believed to be the first observed for nanofluids, has raised serious concerns regarding the use of nanofluids for heat transfer enhancement purposes.

Keywords: Nanofluid; Nanoparticles; Dynamic viscosity; Experimental data; Alumina–water nanofluid; Copper oxide–water nanofluid

1. Introduction

Nanofluids, two-phase mixtures composed of very fine particles in suspension in a continuous and saturated liquid (water, ethylene glycol, engine oil), may constitute a very interesting alternative for advanced thermal applications (Lee and Choi, 1996; Chein and Huang, 2005). It has been found that important heat transfer enhancement may be achieved by using nanofluids instead of conventional fluids; furthermore, some oxide nanoparticles exhibit excellent dispersion properties in traditional cooling liquids. In spite of their remarkable features, few results on nanofluids use in confined flow situations have been published (see Daungthongsuk and Wongwises (2007) for a partial review). Pak and Cho (1998) and Li and Xuan (2002) provided the first empirical correlation for computing Nusselt numbers in laminar and turbulent tube flows using water-based nanofluids. Others have considered the use of nanofluids in microchannel heat sinks (Chein and Huang, 2005). Recent publications (Ben Mansour et al., 2006; Maïga et al., 2005, 2006; Palm et al., 2004 and Roy et al., 2006a) confirmed the heat transfer enhancement due to nanofluids in tube flow and in radial flow between heated disks.

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Nomenclature

T	temperature (°C)	φ_m	maximum particle volume fraction
d_p	particle average diameter		
h	inter-particle spacing	*Subscripts*	
		bf	base fluid (distilled water)
Greek symbols		nf	nanofluid
μ	dynamic viscosity (cP)	p	particles
μ_r	relative viscosity (ratio of nanofluid-to-water viscosities)	r	'nanofluid/ base fluid' ratio
φ	volume concentration of particles		

Research efforts have mostly been concerned with the characterization of thermal and physical properties of nanofluids; a good proportion of published studies is of an experimental nature and focuses on the determination of effective thermal conductivities. A review of relevant literature (see in particular Eastman et al., 2004; Murshed et al., 2005; Roy et al., 2006b) has shown an important data dispersion for thermal conductivity obtained from various sources. Furthermore, these data were concerned only with low particle concentrations below 5% in volume. The data dispersion mentioned above may be attributed to various factors such as measuring techniques, particle size and shape, as well as particle clustering and sedimentation. In spite of this, it is clear that the thermal properties of nanofluids are considerably higher than those of the 'conventional' base fluids (Wang et al., 1999; Eastman et al., 1999, 2001). Apart from the pioneering works by Masuda et al. (1993), other relevant and important published results for nanofluid thermal conductivities include those by Choi (1995), Pak and Cho (1998), Lee et al. (1999), Xuan and Li (2000), Murshed et al. (2005) and Liu et al. (2006). Some of the researchers also considered the effect of particle aggregation and interfacial nanolayer (Xuan et al., 2003; Xie et al., 2005). It should be mentioned that there exist, so far, very limited data concerning the temperature effect on nanofluid thermal conductivities (Masuda et al., 1993; Das et al., 2003; Putra et al., 2003). Although the significant dependence of nanofluid thermal conductivity on temperature has clearly been shown, the amount of data remains very limited. The present authors have recently attempted to measure thermal conductivities for alumina–water nanofluids with particle concentrations ranging from 1% to nearly 9% (Roy et al., 2006b). Regarding the modeling of nanofluid effective thermal conductivity, one should mention the recent and interesting models proposed by Koo and Kleinstreuer (2005) and Chon et al. (2005), taking into account effects due to both temperature and particle size. It is worth noting that the differences in modeling nanofluid properties can lead to contradictory results regarding the thermal performance of nanofluids (Ben Mansour et al., 2007; Polidori et al., in press).

Regarding the nanofluid viscosity, the lack of data in the literature is even more striking. Masuda et al. (1993) were likely the first to measure the viscosity of several water-based nanofluids for temperatures ranging from room condition to 67 °C. Pak and Cho (1998) followed with viscosity data obtained for Al_2O_3–water nanofluid and two particle concentrations. Wang et al. (1999) obtained, using three different preparation methods, some data for Al_2O_3–water and Al_2O_3–ethylene glycol mixtures at ambient temperature. Putra et al. (2003) have also provided results showing the temperature effect on Al_2O_3–water nanofluid viscosity for two particle concentrations, namely 1% and 4%. Most recently, Maré et al. (2006), using a Brookfield viscometer with rotating cylinder, obtained some new temperature-dependent viscosity data for Al_2O_3–water at relatively high particle concentrations. To our knowledge, there exist no other data regarding nanofluids dynamic viscosity, a property of crucial importance for all thermal applications involving fluids.

In this paper, we present extensive measurements of the dynamic viscosities for three different water-based nanofluids, Al_2O_3–water with 36 nm and 47 nm particles, and CuO–water with 29 nm particles, for temperatures varying from room conditions to almost 75 °C.

2. Estimation of nanofluid viscosities

From the theoretical point of view, a nanofluid represents a fascinating new challenge to researchers in fluid dynamics and heat transfer because of the fact that it appears very difficult, if not practically impossible, to formulate any theory that can reasonably predict behaviours of a nanofluid by considering it as a multi-component fluid (Xuan and Roetzel, 2000). Yet, since a nanofluid is a two-phase fluid, one may expect that it would have common features with solid–fluid mixtures. The question regarding the applicability as well as the limitations of the classical two-phase fluid theory for use with nanofluids remains unanswered.

There exist few theoretical formulas that can be used to estimate particle suspension viscosities. Almost all such formulas have been derived from the pioneering work of Einstein (1906) which is based on the assumption of a linearly viscous fluid containing dilute, suspended, spherical particles. In that article Einstein calculated the energy dis-