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Rheological characteristics of non-Newtonian nanofluids: Experimental investigation ☆

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ABSTRACT

γ-Al_2O_3, TiO_2 and CuO nanoparticles were dispersed in a 0.5 wt.%. aqueous solution of carboxymethyl cellulose (CMC) to prepare three types of non-Newtonian nanofluids. Rheological characteristics of the base fluid and nanofluids with various nanoparticle concentrations at different temperatures were measured. Results show that all nanofluids as well as the base fluid exhibit pseudoplastic (shear thinning) behavior. The rheological characteristics of nanofluids and those of the base fluid are functions of temperature and particle concentrations.

1. Introduction

Numerous high-tech industries such as microelectronics, transportation, manufacturing, and metallurgy are often faced with the technical challenges of having higher cooling performance. Conventional methods leading to increased heat transfer rates such as extended surfaces and micro-channels, have the disadvantage to increase the required pumping power of the cooling fluid. The development of advanced fluids with improved flow and thermal characteristics are of paramount importance to achieve higher heat flux densities. Thermal conductivities of solids may be orders of magnitude greater than that of fluids and it is therefore expected that dispersion of solid particles will significantly improve the thermal behavior of fluids. Well dispersed and stable suspensions of nanoparticles in conventional heat transfer fluids were named nanofluids [1]. Many investigators have studied the various characteristics of fluid flow and heat transfer behavior of nanofluids over the past 15 years [2–4] and found that enhanced heat transfer coefficients were obtained with nanofluids. However, it is important that the enhanced heat characteristics of these new fluids are not counteracted by additional pumping power to circulate these fluids in the process. It is therefore necessary to also examine the rheological behavior of these fluids.

Rheological behavior is an important parameter in systems involving fluid flow. For calculating the required pumping power, the rheological behavior of flowing fluid is needed. Numerous investigations have been carried out on viscosity and rheological characteristics of various nanofluids [5–37]. All of these studies showed that viscosity of nanofluids was larger than that of the base fluid and increased with an increase in the nanoparticle concentration. For all these investigations, different types of base fluids were used but they were all Newtonian fluids. Based on the available data in the literature, the resulting dispersion of nanoparticles in Newtonian base fluids resulted in nanofluids exhibited Newtonian behavior [7,16,19,20,28], while many other nanofluids exhibited non-Newtonian, mainly shear-thinning, behavior [7–11,17,21,27,29–31,33]. The viscosity of nanofluids decreased with an increase in the nanoparticle size [12,14,34]. The effect of the temperature on the viscosity of nanofluids was also investigated. Results showed that, as most other fluids, the viscosity of nanofluids decreased with an increase in temperature [17–19,23,27,29,31,35,36,38]. Xinfang et al. [38] have studied the viscosity of Cu/water nanofluids, and their results showed that viscosity of nanofluids is independent of nanoparticle concentration. Tseng and Tzeng [15] have shown that aqueous nanofluids containing indium tin oxide nanoparticles over shear rate range of 10 to ~500 s^{-1} exhibited Newtonian behavior, but as shear rate increased their rheological behavior change into shear-thinning flow. Similar results were obtained by Alphonse et al. [39]. Some investigations showed that nanofluids with low nanoparticle concentrations exhibited Newtonian behavior, but at higher nanoparticle concentrations exhibited shear-thinning behavior [25,40]. Garg et al. [30] have reported the experimental results of a study on rheological behavior of MWCNT/water nanofluids. Their results clearly showed that nanofluids exhibited shear-thinning behavior.

The rheological behavior of nanofluids has often been modeled using the power law model with its two fitting parameters: the power law index and the consistency index. The power law index of nanofluids normally increases with an increase in temperature whereas the consistency index of nanofluids decreases with temperature. In this paper, the rheological behavior of suspensions of

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nanoparticles in a non-Newtonian fluid was experimentally studied. The base fluid used throughout this investigation was the solution of 0.5 wt.% CMC in de-ionized water (DIW). γ-Al_2O_3, TiO_2 and CuO nanoparticles were used in preparation of nanofluids.

2. Experimental

γ-Al_2O_3 (25 nm), TiO_2 (10 nm) and CuO (30–50 nm) nanoparticles (Nanostructured and Amorphous Material, Inc., USA) were used for this investigation. The base fluid was a 0.5 wt.% CMC solution in de-ionized water (DIW). The suspensions of nanoparticles in de-ionized water were subjected to ultrasonic vibration (Hielscher UP200S, Germany) for about 1 h to ensure a uniform nanoparticle dispersion was obtained. Then, appropriate amounts of concentrated CMC solutions were added to the suspensions and thoroughly mixed to achieve the desired concentration of nanofluids.

To investigate the effect of nanoparticle concentration, nanofluids of 0.1, 0.2, 0.5, 1.0, 1.5, 3.0, and 4.0% by volume were prepared. Measurements were carried out in the range of temperature varying from 5 to 45 °C. Rheological characteristics of nanofluids were measured using a rotational rheometer (HAAKE RV12). In order to change and control the temperature, the rheometer was connected to a constant temperature bath (Wisecircu WCL-P8/Korea) which was able to maintain temperature uniformity within ±0.1 °C. The schematic diagram of the experimental setup for the viscosity measurement is shown in Fig. 1. At least four measurements were taken at each temperature and an average value was caluclated.

3. Results and discussions

The base fluid was a 0.5 wt.% aqueous solution of CMC. The rheological behavior of aqueous solutions of CMC is well known. CMC solutions follow the power law model given in Eq. (1) with a flow behavior index or power law index of less than unity (n<1). CMC solutions therefore exhibit shear-thinning or pseudoplastic rheological behavior [41–45]. However, the type of CMC and its purity may affect the rheological characteristics of its aqueous solutions [46].

$$\eta = K\dot{\gamma}^{n-1} \tag{1}$$

In Eq. (1), η is the apparent viscosity, $\dot{\gamma}$ is the shear rate and Parameters K and n of the power law model are the consistency index and the power law index, respectively. The power law model predicts that the apparent viscosity decreases with increasing shear rate.

Fig. 2 presents the apparent viscosity of the base fluid and the nanofluids with two different nanoparticle concentrations as a function of the shear rate at 25 °C. Similar trends were observed for all nanofluids at all temperatures. These results clearly show that the three nanofluids used in this investigation possess shear-thinning behavior.

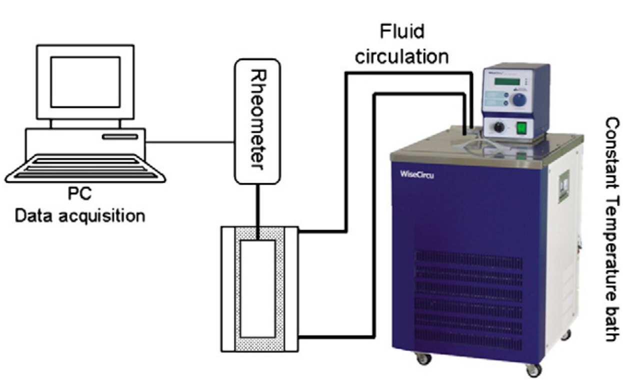

Fig. 1. Experimental setup for the viscosity measurement.

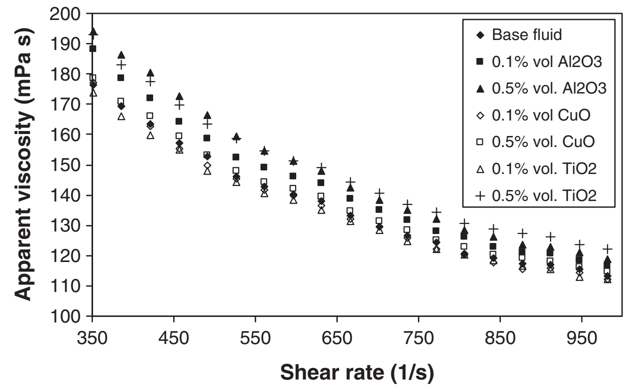

Fig. 2. Apparent viscosity of nanofluids as a function of shear rate at 25 °C.

In order to characterize the rheological properties of the base fluid and nanofluids, the logarithm of the shear stress was plotted against the logarithm of the shear rate. The slope and intercept of the fitted line yield the power law index (n) and the consistency index (K) of nanofluids respectively. Fig. 3 presents the logarithm of the shear stress as a function of the logarithm of the shear rate for the base fluid and 0.1 vol.% Al_2O_3 nanofluid. This Fig. shows that straight lines in a log–log plot can be used to depict accurately ($R^2 \approx 1$) the behavior of experimental data. Other prepared nanofluids exhibited similar behavior. These results clearly show that the power law index for a given fluid remains constant over the range of shear rate investigated.

Power law indices (n) of nanofluids as a function of the particle concentration for different temperatures are shown in Fig. 4. The power law index of Al_2O_3 and TiO_2 nanofluids generally decreases

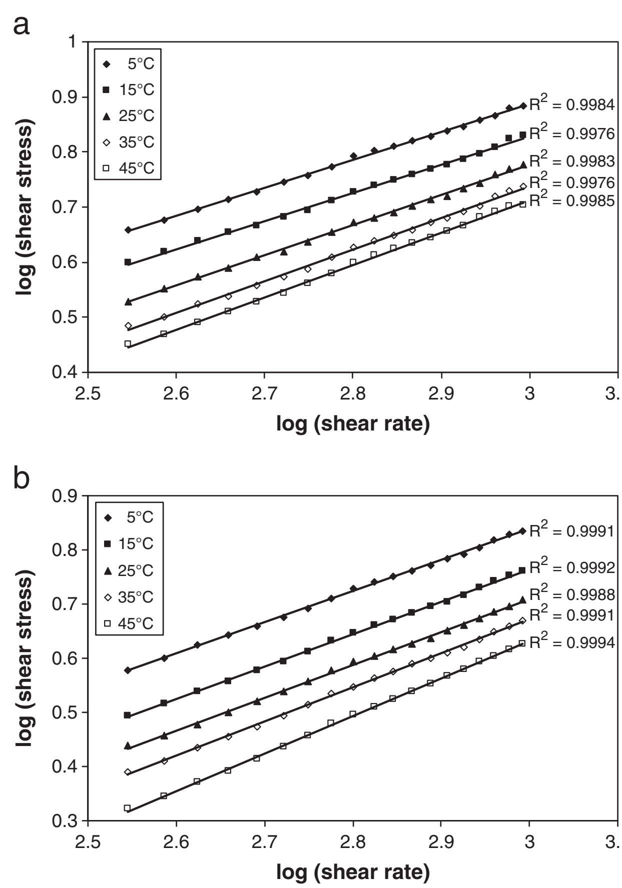

Fig. 3. (a–b): Logarithm the shear stress as a function of the logarithm the shear rate for (a) base fluid and (b) Al_2O_3 nanofluid.