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Viscosity measurements of multi-walled carbon nanotubes-based high temperature nanofluids

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ABSTRACT

Experimental measurements of the viscosity of molten salts nanofluid containing multi-walled carbon nanotubes were performed for a wide range of the shear rate and various nanotube concentrations. In addition, the effect of nanoparticle aggregation is also investigated in the present study. The high temperature nanofluid showed the non-Newtonian behavior in low shear rate region but it was extended to high shear rate region by increasing the nanoparticle concentration. The viscosity of the nanofluid is significantly enhanced up to 93% in the concentration of 2 wt%. The results are well matched with the Krieger–Dougherty equation using a nanoparticle aggregation factor.

1. Introduction

A large number of studies have been dedicated to investigate outstanding thermal properties of nanofluids [1–6]. However, relatively a little work has been published on the nanofluid viscosity. In most of the studies, limited fluids (e.g. water and ethylene glycol) which are not applicable to be used in high temperature applications were chosen as base fluid of the nanofluids. The motivation for performing these measurements is to resolve the issue of considerable engineering significance. Rheological properties of nanofluids are important for determining the efficacy of materials for thermal energy storage in energy harvesting applications such as in concentrating solar power (CSP) plants. Recently molten salt eutectics have also gained attention because utilizing them as thermal energy storage materials enhances the overall efficiency of the CSP plant [7]. Since, furthermore, recent studies [8–12] reported that the specific heat capacity of the nanofluids is significantly enhanced by dispersing small amount of nanoparticles into molten salts, the molten salt-based nanofluid is effective to reduce the cost for electricity generation. Present study aims at examining rheological behaviors and the viscosity of the carbon nanotube-based high temperature nanofluid.

2. Experimental

An alkali carbonate eutectic is used as a base fluid which is composed of lithium carbonate (Sigma-Aldrich) and potassium carbonate (Sigma-Aldrich) by molar ratio of 62:38. Multi-walled carbon nanotubes (MWCNT, Meliorum Technologies) with 10–30 nm in diameter and 1.5 μm in length were dispersed into the eutectic. All chemicals were used as received in this work.

Fig. 1(a) shows the synthesis procedures of the high temperature nanofluids. First, MWCNT are added to water-Gum Arabic (GA, Sigma-Aldrich) solution with 0.1 wt% of GA, where GA was employed for the homogeneous dispersion of MWCNT into distilled water, and then, the suspension is subjected to sonication in an ultra-sonic bath for 1 h (Step 1). The eutectic and extra distilled water are added to the aqueous MWCNT nanofluid, and the suspension is sonicated again for 1 h (Step 2). Finally, water in the suspension is evaporated out on a hot-plate (Step 3). A Transmission Electron Microscope image of the high temperature nanofluid is shown in Fig. 1(b).

A rotational rheometer and a cone-and-plate test section were used for the viscosity measurements over a wide range of shear rate from 1 to 1000 s^{-1}. The temperature was fixed at 550 °C for ensuring the molten salt eutectic to be in the homogeneous liquid state. The temperature of the samples was controlled by an external convection–radiation oven. Nanoparticle mass concentrations were fixed at 1%, 2%, and 5%. The mass concentration of GA was fixed at 1 wt% with respect to the eutectic. To examine the effect of agglomeration of the nanotubes on the rheological behavior of nanofluids, another sample was also synthesized by

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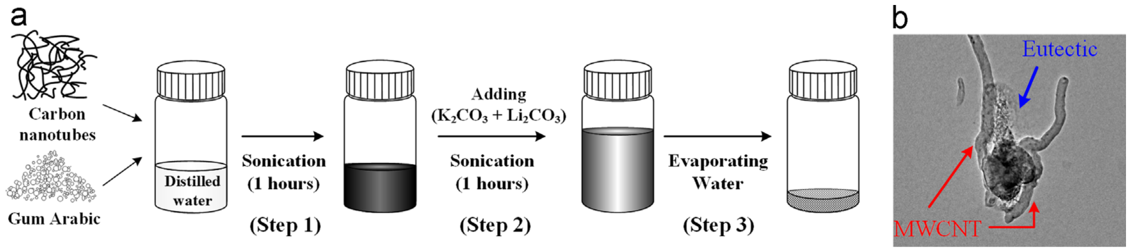

Fig. 1. (a) Schematic of high temperature nanofluid synthesis and (b) TEM image of the nanofluid.

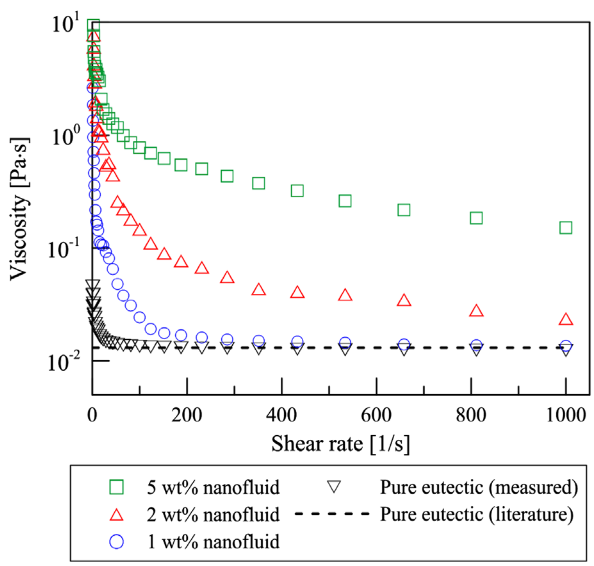

Fig. 2. Viscosity of nanofluids as a function of shear rate for various nanotube concentrations at 550 °C.

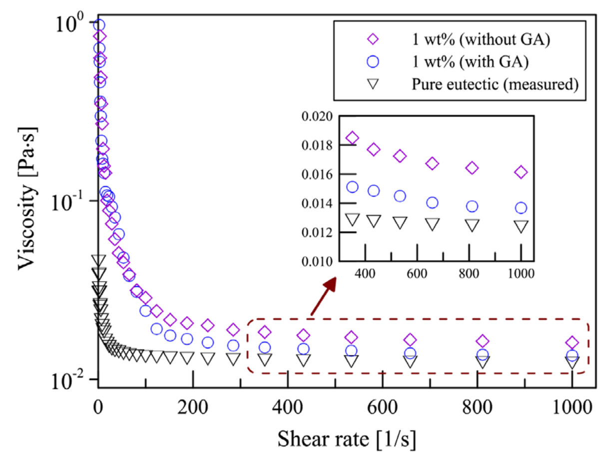

Fig. 3. Effect of nanoparticle dispersion on the viscosity of nanofluids.

mixing the nanoparticles without GA. The rheological properties of all the samples were measured for identical test conditions in the rheometer. The cone–plate configuration enabled the imposition of uniform shear rates throughout the volume of the test samples.

3. Results and discussion

Fig. 2 shows the viscosity of the pure carbonate eutectic and the MWCNT nanofluids as a function of the shear rate for the various nanotube concentrations. It was observed that the results for the pure eutectic are in good agreement with the literature data [13]. For the measurements at low shear rate, the exceptionally high viscosity values for both the pure eutectic and the nanofluids can be attributed to the high measurement uncertainty associated with the small torque in the instrument. As shown in Fig. 2, highly non-linear rheological behavior was observed for the nanofluids which is akin to properties of shear thinning liquid. The shear thinning behavior was more pronounced for higher mass concentrations of the nanoparticles. In other words, the non-Newtonian behavior was extended to higher shear rates with increase in the mass concentration of the nanoparticles in the nanofluids. At a shear rate of 1000 s^{-1} where asymptotic value for the viscosity values was observed, the increase of the viscosity values was 11%, 93%, and 1130% for the MWCNT mass concentrations of 1%, 2%, and 5%, respectively.

In recent reports [14–16], the enhancement in the viscosity of nanofluids was attributed to the level of agglomeration of the nanoparticles. In this study the effect of agglomeration of nanoparticles on rheological characteristics of the nanofluids was examined for a mass concentration of MWCNT (1%). The viscosity of two nanofluids was measured as a function of shear rate at 550 °C. The results from the measurement for the two different nanofluids (with GA and without GA) are compared in Fig. 3. It was observed that the viscosity of the nanofluids synthesized without using GA is about 18% higher than the viscosity of the nanofluid synthesized by using GA. GA was used to ensure better uniformity in dispersing the MWCNT in the aqueous solution of the eutectic salt mixture. GA was reported in the literature for its effectiveness in obtaining homogeneous dispersion of MWCNT in distilled water [17,18]. It was observed that GA was effective to make uniformly dispersed MWCNT–molten salt nanofluids [8], even though it was decomposed at lower than 550 °C [19]. It was, moreover, observed that the carbon nanotubes in the nanofluid with GA were mixed with the eutectic whereas the carbon nanotubes in the nanofluid without the surfactant were agglomerated with themselves as shown in Fig. 4.

Einstein suggested a simple model [20] in Eq. (1) to estimate the viscosity of fluids containing spherical particles at very low concentrations. However, it failed to explain experimental results in the nanofluid viscosity [21]. The Brinkman model [22] which is a generalized form of the Einstein model for higher concentrations is introduced as shown in Eq. (2). However, both models could not give a good estimation of the enhanced viscosity for the high temperature nanofluid used in this study

$$\eta_r = \frac{\eta_{nf}}{\eta_{bf}} = 1 + 2.5\,\phi \qquad (1)$$

$$\eta_r = \frac{1}{(1-\phi)^{2.5}} \qquad (2)$$

In these equations, η indicates the viscosity, ϕ is the volume concentration of the nanoparticle, and subscripts, *r*, *nf*, and *bf*, refer to the relative ratio, nanofluid, and base fluid, respectively. As mentioned before, the nanoparticle agglomeration can significantly