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An experimental study on rheological behavior of hybrid nanofluids made of iron and copper oxide in a binary mixture of water and ethylene glycol: Non-Newtonian behavior

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ABSTRACT

This paper includes an experimental study on rheological behavior of hybrid nanofluids made of iron (Fe) and copper oxide (CuO) in a binary mixture of water and ethylene glycol. Nanofluid samples, with solid volume fractions of 0.05, 0.1, 0.25, 0.5, 1 and 1.5%, were prepared by dispersing an equal volumes of Fe and CuO nanoparticles in a binary mixture of water and ethylene glycol with the proportion of 20–80 vol. %. Viscosity measurements were performed at temperatures ranging from 25 °C to 50 °C and the shear rate range of 3.669–122.3 s^{-1} for all samples. Experimental findings revealed that the low concentration samples showed Newtonian behavior, while the high concentration samples had non-Newtonian behavior and followed the power law model. Moreover, the power law index and consistency index were obtained using curve-fitting on experimental shear stress-shear rate dependency. The curve-fitting results revealed that the power law index reduced to 0.36, indicating that the high concentration samples possessed shear-thinning behavior at all temperature considered.

1. Introduction

A binary mixture of water and ethylene glycol (EG) is frequently employed as an antifreeze working fluid in very cold regions. Depending on the percentage of water and EG in the mixture, it can withstand temperatures down to −50 °C without any frost. Accordingly, it can be used in many thermal systems such as solar collectors and heat exchangers. Despite the great advantage, the thermal conductivity of the binary mixture is very low [1]. According to many researchers claim, the addition of nano-sized solid materials to this mixture, called nanofluids, can improve its thermal conductivity [2–10]. These studies revealed that the thermal conductivity of nanofluids is a function of size, type and concentration of nanoparticles.

It is obvious that suspending nano-sized solid materials to the liquids varies their rheological behavior. It is a very important issue in calculating the pumping power and estimating the convective heat transfer rate. Therefore, it seems that the consideration of the rheological behavior of nanofluids is essential for the thermal and fluid science and applications. Numerous studies have been conducted on the rheological behavior of nanofluids. The researchers showed that the viscosity of nanofluids increasing with enhancing concentration of solid particles and decreasing temperature [11–15]. In order to evaluate the viscosity of nanofluids, Hojjat et al. [16] measured the viscosity of various nanofluids including Al_2O_3, TiO_2 and CuO nanoparticles dispersed in aqueous solution of Carboxy Methyl Cellulose (CMC). Their measurements showed that the base fluid as well as all the suspensions exhibited non-Newtonian (shear-thinning) behavior. Cabaleiro et al. [17] studied the effect of TiO_2 nanoparticles on the rheological behavior of ethylene glycol. They examined the viscosity of the nanofluid in the temperature range of 10–50 °C for nanoparticle mass concentrations up to 25%. Their experiments under various shear rates revealed that the nanofluid had non-Newtonian behavior. Phuoc et al. [18] investigated the viscosity of nanofluids containing multi-walled carbon nanotubes (MWCNTs). They used MWCNTs to enhance or reduce the base fluid viscosity. Their results revealed a reduction up to 20% in the viscosity-reduction case. They also observed a non-Newtonian behavior in the viscosity-enhancement case. Examination of the dynamic viscosity of single-wall carbon nanotubes (SWCNTs) in ethylene glycol was performed by Baratpour et al. [19]. They measured the viscosity of the nanofluid samples with solid volume fractions up to 0.1% at temperatures ranging from 30 °C to 60 °C. Their findings showed that nanofluid samples behaved as Newtonian fluid. Their results

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also revealed that the viscosity of the nanofluid increased to 3.18 times that of the base fluid.

Recently, hybrid nanofluids, made of two different types of nanoparticles in a base fluid, have been attracted the attention of some researchers [20–24]. Regarding the viscosity of hybrid nanofluids, Afrand et al. [25] presented an experimental study on the effects of temperature and concentration of SiO_2-MWCNTs hybrid particles on the dynamic viscosity of engine oil (SAE40). Their experiments were performed in the solid volume fraction range of 0–1.0% and temperatures ranging from 25 °C to 60 °C under different shear rates. Experimental findings showed that the nanofluid samples were Newtonian. Furthermore, their results showed that the maximum enhancement of viscosity of the hybrid nanofluid was 37.4%. Afrand et al. [26] also examined the effects of Fe_3O_4–Ag hybrid nanoparticles on the rheological behavior of ethylene glycol. They measured the viscosity at different shear rates (12.23–122.3 s^{-1}) under temperatures ranging from 25 °C to 50 °C. Their results demonstrated that the nanofluid samples with solid volume fractions of less than 0.3% had Newtonian behavior, while those with higher solid volume fractions (0.6% and 1.2%) had non-Newtonian behavior. The effect of SiO_2-MWCNTs hybrid particles on the viscosity of binary mixture of water and ethylene glycol with proportion of 50–50 vol.% was experimentally investigated by Eshgarf and Afrand [27]. They examined the rheological behavior of the nanofluid samples with solid volume fractions ranging from 0.0625% to 2% in the temperature range of 27.5–50 °C. Viscosity measurements under different shear rates showed that the base fluid was Newtonian, while nanofluid samples exhibit a pseudoplastic rheological behavior.

In the recent years, heat transfer and flow of magnetic fluids under various external magnetic fields have been attracted the attention of researchers. They reported the effects of the magnetic field on fluid flow and heat transfer rate [28–34]. However, the literature review showed that few studies focus on the effect of hybrid ferromagnetic nanoparticles on rheological behavior of a binary mixture of water and ethylene glycol. Therefore, as regards Newtonian or non-Newtonian behavior of nanofluids plays an imperative role in thermal and fluid flow applications, for the first time, the evaluation of the rheological behavior of hybrid nanofluids made of iron (Fe) and copper oxide (CuO) in a binary mixture of water and ethylene glycol with the proportion of 20–80 vol.% is presented.

2. Experimentation

2.1. Preparation of nanofluids

Stable samples, with volume fractions of 0.05, 0.1, 0.25, 0.5, 1 and 1.5%, were prepared by suspending an equal volume of Fe and CuO nanoparticles (50:50 vol.%) in a specified amount of the binary mixture of EG-water (80:20 vol.%). The characteristics of Fe and CuO nanoparticles are presented in Table 1. Characterizations of both nanoparticles were performed by using XRD as shown in Fig. 1. The average size of nanoparticles is obtained by using the data of XRD image (bruker-D8 Germany) and Debye–Scherrer equation [35]:

$$d = \frac{0.9\lambda}{\beta \cos\theta} \tag{1}$$

where d is particle diameter size, λ is wave length of X-ray (0.1541 nm), β is full width at half maximum and θ is the diffraction angle (from Fig. 1).

Based on the known percentage of solid volume fractions, the required masses of Fe and CuO nanoparticles for preparing 600 ml nanofluid samples were calculated from Eq. (2) [36] and presented in Table 2.

$$\varphi = \left[\frac{\left(\frac{w}{\rho}\right)_{Fe} + \left(\frac{w}{\rho}\right)_{CuO}}{\left(\frac{w}{\rho}\right)_{Fe} + \left(\frac{w}{\rho}\right)_{CuO} + \left(\frac{w}{\rho}\right)_{Water} + \left(\frac{w}{\rho}\right)_{EG}}\right] \times 100 \tag{2}$$

In Eq. (2), φ is the percentage of solid volume fraction, ρ is the density in kg/m^3, and w is the mass in kg.

In the present work, magnetic stirring should not be used, because the iron nanoparticles have a magnetic property. In order to make stable nanofluid, the solutions were exposed to an ultrasonic processor (Hielscher Company, Germany) with the power of 400 W and frequency of 24 kHz for 5–6 h. No particle sedimentation was observed up to 15 days. A summary of the process of preparing nanofluid samples is shown in Fig. 2.

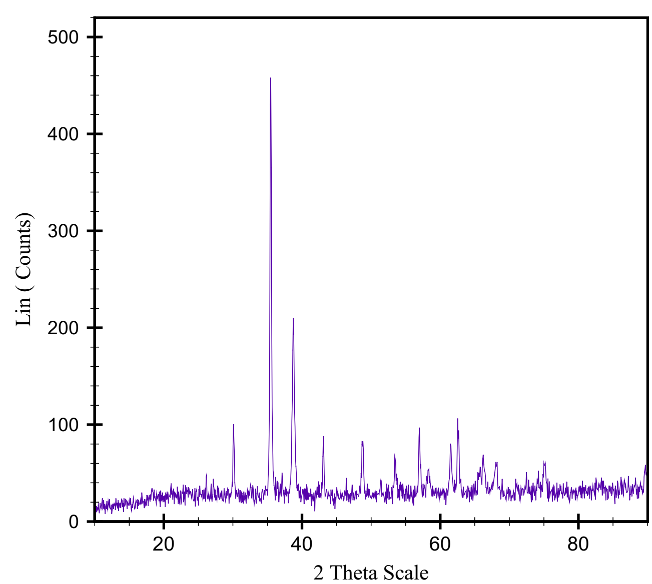

Fig. 1. XRD patterns for Fe-CuO hybrid nanoparticles.

Table 1
Characteristics of Fe and CuO nanoparticles.

Characteristic	Value	
	Iron (Fe)	Copper oxide (CuO)
Purity	>99.5%	>99.95%
Color	Black	Brown black
Size	35–45 (nm)	25–55 (nm)
Morphology	Spherical	Nearly spherical
Bulk density	0.45 (g/cm^3)	0.79 (g/cm^3)
True density	7.90 (g/cm^3)	6.4 (g/cm^3)
Specific surface area (SSA)	8–14 (m^2/g)	13.98 (m^2/g)

Table 2
Required masses of Fe and CuO used for the preparing a volume of 600 ml of hybrid nanofluids.

Volume fraction of samples (%)	Mass [±0.001] (g)	
	Fe	CuO
0.05	1.185	0.960
0.1	2.370	1.920
0.25	5.925	4.800
0.5	11.850	9.600
1	23.700	19.200
1.5	35.550	28.800