Experimental Thermal and Fluid Science 77 (2016) 38–44

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Effects of temperature and nanoparticles concentration on rheological behavior of Fe_3O_4–Ag/EG hybrid nanofluid: An experimental study

Masoud Afrand [a,*], Davood Toghraie [b], Behrooz Ruhani [a]

[a] Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran
[b] Department of Mechanical Engineering, Khomeinishahr Branch, Islamic Azad University, Isfahan, Iran

ARTICLE INFO

Article history:
Received 22 January 2016
Received in revised form 30 March 2016
Accepted 7 April 2016
Available online 8 April 2016

Keywords:
Non-Newtonian hybrid nanofluid
Experimental study
Fe_3O_4 nanoparticles
Ag nanoparticles
Ethylene glycol

ABSTRACT

In this paper, the effects of temperature and nanoparticles concentration on the rheological behavior of Fe_3O_4–Ag/EG hybrid nanofluid have been experimentally investigated. Stable and homogeneous suspensions were prepared in solid volume fractions of 0.0375%, 0.075%, 0.15%, 0.3%, 0.6% and 1.2%. Viscosity measurements were performed at different shear rates (12.23–122.3 s^{-1}) under temperatures ranging from 25 °C to 50 °C. Results revealed 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, and followed the power-law model. Finally, the consistency index and power-law index were obtained from curve-fitting on shear stress–shear rate dependency. Curve-fitting results showed that all power-law indices were in the range of 0.5339–0.6706, indicating that the nanofluid samples possessed shear-thinning behavior at all temperatures considered.

1. Introduction

In recent decades, nanofluids applications have been recognized in various applications such as heat exchangers, solar collectors, heat pipes, microelectronics cooling, and biomechanics [1–6]. Nanofluids are suspensions of solid nanoparticles in fluids affecting the fluid flow and heat transfer rate. Examples of specialized applications of nanofluids have been shown in various researches. Mention may be made of the research studies conducted by Soltanimehr and Afrand [7], Akbar [8], Sheikholeslami and Ellahi [9,10], Akbar et al. [11–13], Zeeshan et al. [14], Sheikholeslami et al. [15–18], Ellahi et al. [19,20], Hemmat Esfe et al. [21–23], and Uddin et al. [24,25].

By adding the nanoparticles into liquids, other thermo-physical properties including viscosity are also affected [26–28]. Since viscosity is an important parameter for calculating the required pumping power, Reynolds, Prandtl and Rayleigh number values, it has attracted the researcher's attention. In this regard, many experimental investigations have been carried out to determine the rheological behavior of various nanofluids. For example, Chen et al. [29] investigated the rheological behavior of TiO_2/water nanofluids with solid volume fractions of 0.12%, 0.24% and 0.6%. Their experiments were performed at a shear rate ranging from 1 to 1000 s^{-1}. They reported that the nanofluid samples showed shear-thinning behavior. In another similar work, the rheological behavior of TiO_2/EG, TiO_2/water, TNT/water and TNT/EG nanofluids was examined by Chen et al. [30]. They measured the viscosity of the nanofluids at solid volume fractions ranging from 0% to 2%, and a shear rate ranging from 0.03 to 3000 s^{-1}. Their results revealed that TiO_2/EG exhibited Newtonian behavior, while TiO_2/water, TNT/water and TNT/EG nanofluids showed non-Newtonian behavior. Tamjid and Guenther [31] investigated the rheological behavior of Ag/EG in a solid volume fraction range of 0.11–4.38%. Their measurements, performed at a shear rate ranging from 1 to 200 s^{-1}, showed that the suspensions exhibited non-Newtonian (pseudoplastic) flow behavior. Hojjat et al. [32] dispersed various amounts of Al_2O_3, TiO_2 and CuO nanoparticles into aqueous solution (0.5 wt.%) of CMC. They measured the viscosity of the nanofluids at a shear rate ranging from 350 to 1000 s^{-1}. Their measurements indicated that the base fluid as well as all the suspensions exhibited non-Newtonian (shear-thinning) behavior. They also found that the relative apparent viscosity of TiO_2 and Al_2O_3 nanofluids increased with increasing the nanoparticles concentration, while for CuO nanofluid, it was almost independent of concentration. Cabaleiro et al. [33] studied the rheological behavior of TiO_2/EG nanofluids at nanoparticles mass concentrations up to 25% in a shear rate ranging from 0.1 to 1000 s^{-1}. Their experiments showed that the nanofluid exhibited non-Newtonian behavior

* Corresponding author.
E-mail addresses: masoud.afrand@pmc.iaun.ac.ir, masoud_afrand@yahoo.com (M. Afrand).

http://dx.doi.org/10.1016/j.expthermflusci.2016.04.007
0894-1777/

(Ostwald-de Waele model). Wang et al. [34] examined the viscosity of MWCNT/water at solid volume fractions of 0.05%, 0.24% and 1.27%. Their experiments were performed at a shear rate ranging from 1 to 120 s^{-1}. They found that, at a high solid volume fraction, nanofluids showed a clear shear-thinning behavior. Moghaddam et al. [35] measured the rheological properties of grapheme/glycerol nanofluids in a mass fraction range of 0.0025–0.02 and a shear rate ranging from 1 to 180 s^{-1}. Their results showed that the suspensions exhibited shear-thinning behavior at low shear rates. Shear-thinning behavior became more noticeable with an increase in nanoparticles concentration. Recently, Eshgarf and Afrand [36] examined the rheological behavior of MWCNTs-SiO_2/EG-water hybrid nano-coolant at temperatures ranging from 27.5 °C to 50 °C. They measured the viscosity of the suspensions with solid volume fractions ranging from 0.0625% to 2% at the shear rate range of 0.612–122.3 s^{-1}. Their results indicated that the base fluid exhibits a Newtonian behavior and the nano-coolant samples exhibit a pseudoplastic rheological behavior with a power law index of less than unity ($n < 1$).

In recent years, many researchers have become interested in the use of a new class of nanofluids containing various nanoparticles, called hybrid nanofluids, to improve the heat transfer rate [37–42]. On the other hand, despite the fact that Newtonian or non-Newtonian behavior of nanofluids plays an important role in fluid mechanics and convective heat transfer, few studies have been focused on the rheological behavior of hybrid nanofluids. Therefore, in this study, for the first time, the rheological behavior of Fe_3O_4–Ag/EG hybrid nanofluid is examined. For this purpose, nanofluid samples were prepared at several solid volume fractions and experimented under different temperatures.

Table 2
Characteristics of Fe_3O_4 and Ag nanoparticles.

Characteristic	Value	
	Fe_3O_4 nanoparticles	Ag nanoparticles
Purity	+98%	99.99%
Color	Dark Brown	Black
Size	20–30 (nm)	30–50 (nm)
Morphology	Spherical	Spherical
True density	4.8-5.1 (g/cm^3)	10.5 (g/cm^3)
Specific surface area (SSA)	40–60 (m^2/g)	16–20 (m^2/g)

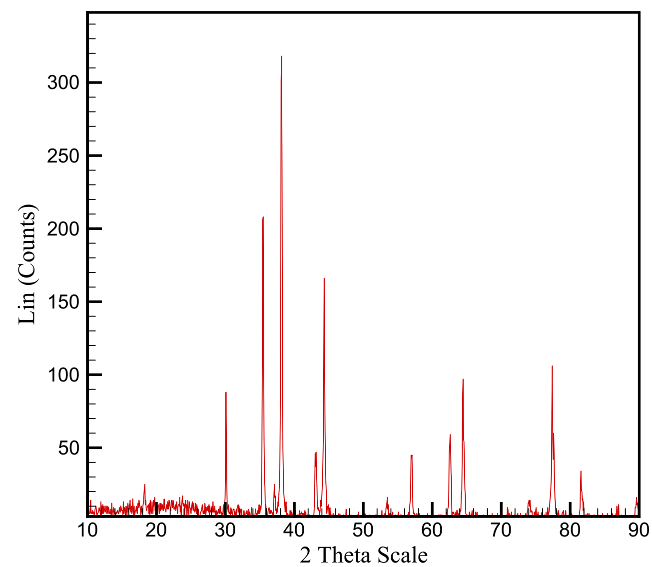

Fig. 1. XRD pattern of Fe_3O_4–Ag nanoparticles.

2. Experimental

2.1. Samples preparation

Nanofluid samples, with the solid volume fractions of 0.0375%, 0.075%, 0.15%, 0.6% and 1.2%, were prepared by a two-step method. In this way, equal volumes of Fe_3O_4 and Ag nanoparticles were dispersed in EG. The physicochemical properties of EG, Fe_3O_4 and Ag nanoparticles are presented in Tables 1 and 2. To evaluate the characterization of the hybrid nanoparticles, the structural properties of the dry Fe_3O_4–Ag nanoparticles were measured by using X-ray diffraction as shown in Fig. 1.

The quantities of Fe_3O_4 and Ag nanoparticles required for different solid volume fractions were obtained from the following equation [36],

$$\varphi = \left[\frac{\left(\frac{w}{\rho}\right)_{Fe_3O_4} + \left(\frac{w}{\rho}\right)_{Ag}}{\left(\frac{w}{\rho}\right)_{Fe_3O_4} + \left(\frac{w}{\rho}\right)_{Ag} + \left(\frac{w}{\rho}\right)_{EG}} \right] \times 100 \tag{1}$$

where φ is the solid volume fraction in %, ρ is the density in kg/m^3 and w is the mass in kg. Considering that 600 ml of nanofluid was required to measure the viscosity, the masses of nanoparticles and EG used for preparing a volume of 600 ml of nanofluid were calculated and presented in Table 3.

In this work, to prepare stable samples, after magnetic stirring for 2.5 h, in order to break down the agglomeration between the particles, the suspensions were exposed to an ultrasonic processor (Hielscher Company, Germany) with the power of 400 W and frequency of 24 kHz for 6 h. The photograph of the nanofluid sample (φ = 1.2%) is displayed in Fig. 2.

2.2. Viscosity measurement

The viscosity of the nanofluid samples were measured by using the Brookfield DV-I PRIME digital Viscometer equipped with a temperature bath as shown in Fig. 3. Measurements were performed in the temperatures of 25, 30, 35, 40, 45 and 50 °C in the shear rate range of 12.23–122.3 s^{-1}. To determine the Newtonian or non-Newtonian behavior of the nanofluid samples, all experiments

Table 1
Characteristics of ethylene glycol.

Characteristic	Value
Chemical formula	$C_2H_6O_2$
Molar mass	62.07 g/mol
Appearance	Clear, colorless liquid
Odor	Odorless
Density	1113.20 kg/m^3
Melting point	−12.9 °C
Boiling point	197.3 °C
Thermal conductivity	0.244 W/m K (@20 °C)
Viscosity	16.1 cP (@20 °C)

Table 3
Mass of nanoparticles and EG used for the preparing a volume of 600 ml of nanofluid.

Solid volume fraction (%)	Mass [±0.001] (g)		
	Fe_3O_4	Ag	EG
0	0.000	0.000	667.920
0.0375	0.563	1.181	667.670
0.075	1.125	2.363	667.419
0.15	2.250	4.725	666.918
0.3	4.500	9.450	665.916
0.6	9.000	18.900	663.912
1.2	18.000	37.800	659.905