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Experimental Investigations on the Viscosity of Magnetic Nanofluids under the Influence of Temperature, Volume Fractions of Nanoparticles and External Magnetic Field

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ABSTRACT

This article investigates the effect of magnetic field on the viscosity of Fe_3O_4-water magnetic nanofluid experimentally. Experiments were done in the volume fraction range 0 to 1 vol% and the temperature ranges from 25 to 45 ˚C. The results showed that the viscosity increased with increasing of nanoparticle volume fractions and decreased with temperature enhancement with or without of magnetic field. Also, it is observed that the viscosity of the magnetic nanofluid increases with enhancement of magnetic field strength. Thus, magnetic field is a basic factor that influences the viscosity of the magnetic nanofluids and magnetic nanofluid flow can be controlled by applying a magnetic field.

Keywords: Viscosity; Ferrofluids; Magnetic nanofluids; Magnetic field.

NOMENCLATURE

m	mass, kg	**Subscript**	
v	volume, m^3	bf	base fluid
ρ	density, kg/m^3	np	nanoparticle
φ	volume fraction of nanoparticles		

1. INTRODUCTION

Magnetic nanofluid is a colloidal suspension consisting of magnetic nanoparticles and a carrier liquid phase. Due to its remarkable features, the magnetic fluid behaves as an intelligent or functional fluid and has applications in a variety of fields such as electronic packing, mechanical engineering, aerospace, and bioengineering (Li *et al.* 2005). Magnetic fluid exhibits some unique characteristics such as magneto-viscous effect in the presence of magnetic field. Since the control and handling of the flow and energy transport processes in the magnetic fluid are possible by using an external magnetic field, the magnetic fluid expanded into thermal engineering during the past decade besides these applications (Li and Xuan 2009), but very few research are available about the viscosity of different nanofluids and ferrofluids. Some investigations measured the viscosity of the magnetic fluids (Graham 1981; Timko *et al.* 1994; Wagh and Avashia 1996; Patel *et al.* 2003; Li *et al.* 2005; Hong *et al.* 2007; Ren *et al.* 2008). They exposed that the viscosity of the magnetic fluid is greater than that of the base liquid in both the absence and presence of the external magnetic field. The magnetic field strength performs an important role in the viscosity of the magnetic fluid. Some other researchers investigated the effect of nanoparticles volume fraction and temperature on the viscosity of nanofluids. Li *et al.*(2005) found that the viscosity of the magnetic fluids increases with the suspended magnetic particles. They reported that the viscosity increased with the magnetic field until it reached a constant value as the magnetization of the magnetic fluid arrived at a saturation state. Zeinali Heris *et al.*(2006) studied the viscosity of nanofluids containing CuO and Al_2O_3-water.They reported that both nanofluid systems behave as newtonian fluid at volume fractions to 3.0vol%.Nguyen *et al.* (2007) investigated experimentally the effect of both the temperature and the particle size on the dynamic viscosity of two particular nanofluids, namely Al_2O_3-water and CuO-water. They found that the application of Einstein's formula seems not to be suitable for nanofluids. Ren *et al*. (2008) proposed a comprehensive relation that express the viscosity of ferrofluid based on various parameters such as magnetic field strength, temperature and volume fraction of the nanoparticles. Murshed *et al*. (2008) investigated the viscosity of TiO_2-water and Al_2O_3-water nanofluids. They observed that TiO_2-water nanofluid displayed an increase of 60% over the viscosity of the base fluid for volume fraction up to 4.3% and for Al_2O_3-water nanofluid the increase was found to be about 82% at volume fraction of 5%.Corcione (2011) works on nanoparticle alumina, copper oxide, titania and copper in water and ethylene glycol based fluid and proposed a correction for dynamic viscosity of nanofluids. Sundar *et al.* (2013) studied the thermal conductivity and viscosity of Fe_3O_4-water based nanofluidin the volume fraction range 0.0% to 2.0% and the temperature range 20 to 60 ˚C. They reported that the viscosity of Fe_3O_4-water nanofluid decreased with temperature and increased nonlinearly with volume fraction of nanoparticles. Patra *et al.* (2014) studied the variation of velocity and shear stress in the presence of magnetic field. They found that the heat effects on the magnetic field.

In the present study, the temperature and nanoparticles volume fraction dependent viscosity of magnetic nanofluid in both the absence and the presence of an external magnetic field have been considered. In this work, a rotary viscometer (model LVDV- II+Pro, Brookfield) is used to measure the viscosity of the magnetic nanofluid. The effects of temperature, volume fraction ofthe nanoparticles and magnetic field strength on the viscosity of nanofluid are considered simultaneously.

2. EXPERIMENTAL PROCEDURE

2.1. Particle Characterization

Magnetite nanofluids were prepared by dispersing Fe_3O_4 nanoparticles in distilled water as a base fluid. In this work, Fe_3O_4 nanoparticles were manufactured by U.S. Research Nano materials, Inc. with true density of 5180 kg/m^3 and bulk density of 840 kg/m^3. The morphology of the Fe_3O_4 nanoparticles as spherical and their sizes less than 100 nm (about 20-30 nm) were reported by the company.

2.2. Preparation of Nanofluid

Prepared nanoparticles were dispersed in distilled water to get the water based ferrofluid. Nanoparticles volume fraction was estimated from equation 1:

$$\varphi = \frac{V_{np}}{V_{bf}} \times 100 = \frac{m_{np}/\rho_{np}}{V_{bf}} \times 100 \qquad (1)$$

Where φ is the volume fraction of the nano particles in the nanofluids, v_{bf} is the base fluid volume. v_{np}, m_{np} and ρ_{np} are the volume, mass and bulk density of the nanoparticles, respectively. Due to high difference between densities of nanoparticles and water, the nanoparticles should be prohibited from sedimentation in water. Therefore, at first, nanoparticles dispersed in water using an ordinary agitator (model MJ-176NR-Japan) for 30 minutes at 11500 rpm and then pH was adjusted at 12.8.pH is an important parameter in nanofluid stability which is related to the electrostatic charge on the particle surfaces. In this experimental work, 0.1 vol% Fe_3O_4-water nanofluid samples were prepared from pH=2 to 13.Amount of pH of samples were adjusted with HCl and NaOH solutions and measured using a pH meter (model pH7110, WTW).After investigation of the magnetic nanofluid stability at different amounts of pH, the value of pH=12.8 was characterized as the best value for the magnetic nanofluid stability.

2.3. Viscosity Measurement

Viscosity is a measure of the trend of a liquid to resist flow and is the ratio of the shear stress to shear rate ($\mu = \tau/\dot{\gamma}$). In this work, the rotating viscometer (model LVDV- II+Pro, Brookfield) was used to measure the viscosity of the aqueous magnetic fluid with and without magnetic field. This viscometer consists of two cylindrical coaxial involute that the inner cylinder rotates at a constant speed and the outer cylinder is fixed. Between the two cylinders was filled with a fluid. Calculation of the fluid viscosity is based on measuring the torque of the inner cylinder. The outer cylinder of viscometer was connected to a circulator water bath with cooling and heating system (model TC-502, Brookfield). Temperature of water bath was controlled during measurements with accuracy 0.1 ˚C and the temperature of the fluid in viscometer is equaled with the temperature of the fluid in the circulator.

When the viscosity is constant at different shear rates, the liquid is known as Newtonian. The liquid is non-Newtonian, when the viscosity varies as a function of shear rate. In these experiments, the nanofluids contain spherical particles at modest volume fraction (φ<3 vol%), thus the nanofluid samples show Newtonian behaviors(Lee et al. 2011). The viscosity of various volume fractions of Fe_3O_4nanofluids were measured in the range of temperature 25 to 45 ˚C. Before measurement of the viscosity of the magnetic nanofluids, the rotating viscometer was calibrated by measuring water viscosity in the absence of the external magnetic field. Comparison between experimental data with literature (Baehr andStephan2006), showed 3-5% error at 45 and 25 ˚C temperatures.

3. RESULTS AND DISCUSSION

In this section, experimental results on viscosity of nanofluids containing magnetic Fe_3O_4 nanoparticles dispersed in deionized water with and without magnetic field were presented. Figure1 shows the viscosity of different volume fractions of

Fe_3O_4nanofluid versus temperature, without applying magnetic field. It can be seen that the viscosity of nanofluid increased with increasing of nanoparticle volume fractions at different temperatures. For example, at 25 ˚C, the viscosity for volume fraction of 0.1 and 1 vol% increases 1.2% and 14.0% compared to the base fluid, respectively. The reason is that by adding nanoparticles to the base fluid and increasing nanofluid concentration, the interaction between solid particles in the base fluid rises and causes to enhance the viscosity. Also, by increasing temperature the viscosity of the nanofluid decreases. For example, at 1 vol% the viscosity of nanofluid from 0.98 at 25 ˚C decreases to 0.67 at 45 ˚C. On the other hand, increasing of the temperature causes to enhancement of collisions between nanoparticles and thus leads to enhancement of the viscosity of nanofluids. In other word, the viscosity of the base fluid decreases with increasing temperature. The second effect is dominant factor and leads to decrease suspension viscosities.

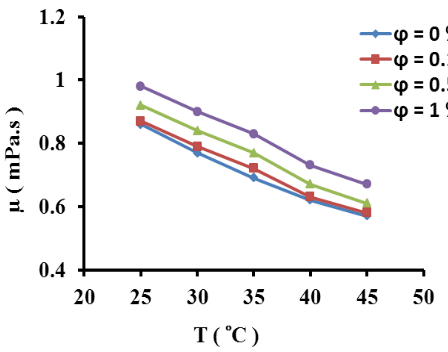

Fig. 1. Experimental viscosity of nanofluid versus temperature at different volume concentration.

Figure 2 indicates the effects of temperature on the viscosity of the Fe_3O_4-water magnetic nanofluids, with and without application of the external magnetic field. Temperature and magnetic field ranges were 25 to 45 ˚C and 0 to 550 Gauss, respectively. As expected, in all of used volume fractions and magnetic fields, the viscosity decreased with increasing temperature. Application of magnetic field had no effect on the decreasing rate of viscosity. Reduction in viscosity due to increase of temperature in the presence of magnetic field had the same reason as the case of without magnetic field. It can be said that as the temperature increased, the bond between the fluid molecules were broken and fluid layers tend to slip and fluid motion become smoother and caused to decrease the viscosity. Also, it is seen that the effect of the magnetic field is more evident at higher volume fractions. This will be explained more in the following paragraph.

Influence of magnetic field on the viscosity of Fe_3O_4-water nanofluid has been shown in Figs. 3 and 4. Figure 3 shows the viscosity variations with magnetic field at different volume fractions of nanoparticles. The experimental results indicated that adding Fe_3O_4 nanoparticles enhanced the viscosity of the fluid in the absence or presence of magnetic field. For example, in the absence of magnetic field, with increasing nanoparticle volume fraction from 0.1 to 1 vol% at 30 ˚C, the viscosity increased from 0.79 to0.90 m Pa.s and changed from 0.63 mPa.s to 0.73 mPa.s at 40˚C. As stated, the reason is that adding nanoparticles to the base fluid and increasing volume fraction of nanoparticles caused to decrease the distance and increase the interaction between added solid particles. Therefore, the viscosity of nanofluid increased.

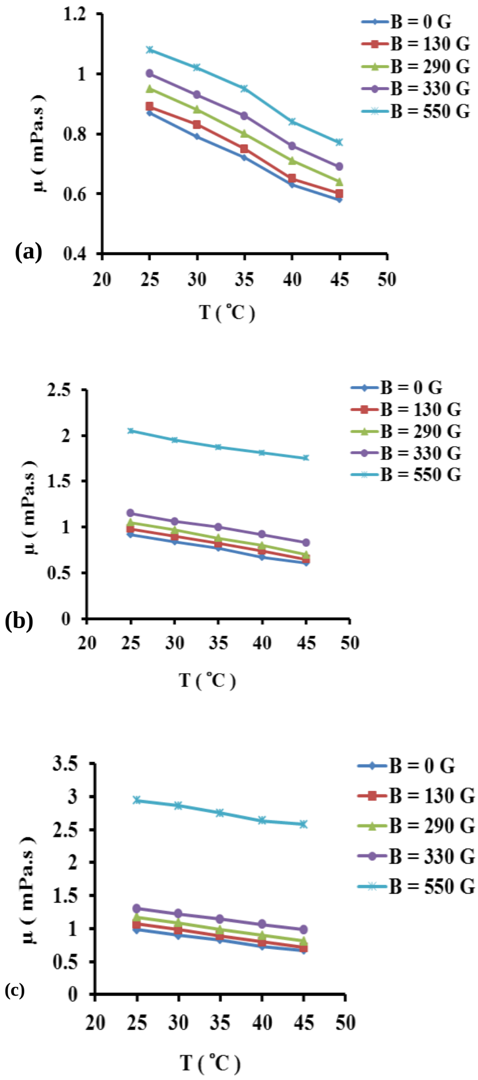

Fig. 2. Viscosity versus temperature at different magnetic field (a) 0.1 vol%, (b) 0.5 vol%, (c) 1 vol %.

Figure 4 shows the variation of the viscosity ratio of magnetite fluid versus the magnetic field intensity at temperature 25 and 35 ˚C. The relative viscosity is defined as the ratio of the viscosity of a magnetic fluid in the presence of an external magnetic field to that of the magnetic fluid in the absence of an external magnetic field. It can be found that the viscosity of Fe_3O_4-water magnetic fluid increased by enhancement of the magnetic field intensity.

This enhancement in viscosity is more obvious for volume fraction of 0.5 and 1 vol% and field strength more than 300 Gauss. In other word, in order to achieve a significant increase in viscosity, both the magnetic field intensity and the nanoparticle volume fractions should be more than the certain values. For example, at temperature 25 ˚C and magnetic field intensity 130 Gauss, the relative viscosity for volume fraction of 0.1 and 1 vol% are 1.023 and 1.092, while with increasing field intensity to 550 Gauss, these values increase to 1.241 and 3.000, respectively.

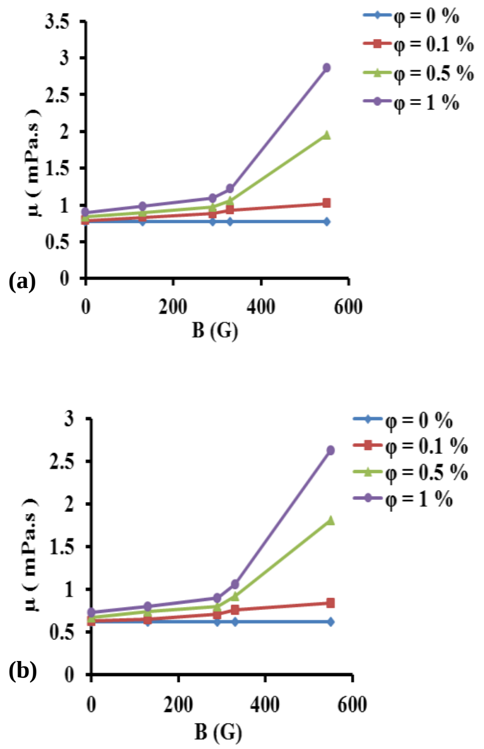

Fig. 3.Viscosity variations with magnetic field at different volume fraction of nanoparticles (a) 30 ˚C, (b) 40 ˚C.

Experimental results presented in Figs. 3 and 4 showed that the external magnetic field had a significant effect on the viscosity of ferrofluid, as the viscosity of the magnetic fluid increased with the magnetic field strength. Thus, magnetic field is a key factor affecting on the viscosity of the ferrofluids. The reason was that the viscosity of the nanofluids depends on both the base fluid and the suspended nanoparticles. Figures 3 and 4 clearly showed that the magnetic field did not have effect on the viscosity of pure water, and with increase in magnetic field no obvious effect on the viscosity of base fluid was found which showed the accuracy of the experimental work. This result was also confirmed with report of Ghauri and Ansari (2006). On the other hand, applying magnetic field to nanoparticles leads to formation of magnetic dipoles along the direction of magnetic field. Therefore, the particles created chainlike clusters along the direction of the applied magnetic field in ferrofluid which caused to increase friction between the fluid layers and block the flow stream. As a result, the viscosity of ferrofluids increased under external magnetic field. As the magnetic field further increased and/or the number of suspended particles in the fluid increased, more number of particles oriented in direction of magnetic field. Consequently, number of clusters and their length increased. Hence, the obstruction against the flow became more evident and the viscosity increased more.

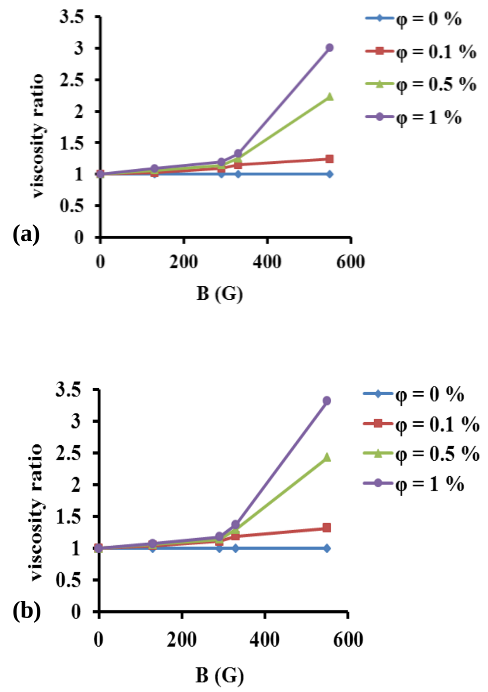

Fig. 4. Variation of viscosity ratio with the magnetic field intensity at different concentration of nanoparticles (a) 25 ˚C (b) 35 ˚C

4. CONCLUSION

In this work, the viscosity of ferrofluid containing Fe_3O_4 magnetic nanoparticles was investigated experimentally. The rotating viscometer was used to measuring the viscosity of Fe_3O_4-water and effects of parameters of ferrofluid temperature, nano particles volume fraction and external magnetic field were considered. The results showed that the viscosity variations depend on the nanoparticle volume fractions and nanofluid temperature. Higher nanoparticle volume fractions and lower nanofluid temperatures exhibited higher viscosity. By application of the external magnetic field, viscosity of the magnetic nanofluid increased. For example, with increasing magnetic field strength from 130 to 550 Gauss, the viscosity increased about 20% and 175% for φ=0.1vol% and φ=1vol%, respectively. Applying magnetic field had no effect on the rate of decreasing in viscosity with increasing temperature. With increasing in both the nanoparticle volume fractions and applied external magnetic field, more number of particles oriented in direction of magnetic field and number of chainlike clusters and their length increased and caused to increase the viscosity.

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