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Investigation on viscosity of Fe_3O_4 nanofluid under magnetic field☆

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ABSTRACT

Thermal conductivity enhancement of base fluid by magnetic nano-particle under the magnetic field is a hot topic in science, but fewer studies focus on the viscosity properties which affect the thermal performance of base fluid. This article presents an experimental investigation on the viscosity of water based Fe_3O_4 nanofluid under different magnetic fields. Adjustable magnetic induction was got by improving the test region of SV-10 viscometer. By this improved viscometer the viscosity of Fe_3O_4 nanofluid in the magnetic field was tested. The ranges of magnetic induction, volume fraction and temperature are 0–30 mT, 0.5%–5% and 293–333 K. The results show that the viscosity of Fe_3O_4 nanofluid increases with the increase of magnetic induction and solid volume concentration, and decreases with the increase of temperature. Based on the experimental results, an empirical correlation was developed to predict the viscosity of Fe_3O_4 nanofluid at various temperatures, volume concentrations and magnetic inductions. The correlation presents an excellent agreement with experimental results. The proposed equation provides a useful engineering tool for analysis and thermal and fluid design applications of ferrofluid.

1. Introduction

Nanofluids are dilute colloidal suspension consisting of nanoparticles and carrier liquids. In general, nanoparticles are usually metal (Fe, Cu, etc.), metal oxides (Al_2O_3, CuO, etc.) and some other compounds (AlN, SiO_2, etc.), while carrier liquids are usually conventional fluids (water, engine oil, ethylene glycol, etc.) [1,2]. Because of superior performance on heat transfer improvement, nanofluids have attracted considerable attention over the past decades in various fields, such as thermal therapy, energy supply, chemical production, Heating, Ventilating and Air Conditioning (HVAC) and microelectronics [3–9] etc. Particularly, in recent years, there are many investigations implemented on heat transfer enhancement using nanofluids, including natural convection and forced convection. Hedayati et al. [10] investigated the effects of nanoparticle migration and asymmetric heating on forced convective heat transfer of Al_2O_3/water nanofluid in microchannels. Hedayati and Domairry [11] studied forced convection of laminar TiO_2/water nanofluid flow in a parallel plate micro channel. The laminar flow and convective heat transfer of Al_2O_3/water nanofluid in a micro channel under a uniform magnetic field were explored by Malvandi and Ganji [12,13]. Malvandi et al. [14] researched forced convective heat transfer of a magnetohydrodynamics (MHD) fully developed laminar nanofluid between two concentric horizontal cylinders in the presence of a radial magnetic field. The effects of nanoparticle migration on mixed convection of titania/water nanofluid inside a vertical micro channel have been numerically investigated by Hedayati and Domairry [15]. Sheikholeslami et al. [16] applied Lattice Boltzmann Method (LBM) to explore the effect of magnetic field on natural convection heat transfer of Al_2O_3/water nanofluid in a two-dimensional horizontal annulus. Ganji and Malvandi [17] conducted a theoretical investigation on natural convective heat transfer of nanofluids inside a vertical enclosure in the presence of an uniform magnetic field. Sheikholeslami and Ellahi [18] used LBM to investigate the natural convection heat transfer of Al_2O_3/water nanofluid in a cubic cavity under magnetic field.

Magnetic fluid, as one special nanofluids, is formed by dispersing the magnetic nanoparticles (Fe, Co, Fe_3O_4, Fe_2O_3, etc.) in base fluids. Over the last few decades, great achievements were made in the research of natural convection and forced convection heat transfer of ferrofluids [19]. Sheikholeslami et al. [20] investigated forced convection heat transfer of ferrofluid in the presence of non-uniform magnetic field using the Control Volume-based Finite Element Method (CVFEM). Bahiraeiand Hangi [21] evaluated the natural convection of $Mn_{0.6}Zn_{0.4}Fe_2O_4$/water magnetic nanofluid in a square cavity under a nonuniform magnetic field. The effect of MHD on ferrofluid flow and convection heat transfer using CVFEM was studied [22,23].

Meanwhile, teams of researchers are focused on thermophysical properties of ferrofluids. Philip et al. [24] observed that the maximum enhancement in the thermal conductivity of Fe_3O_4 ferrofluid was 300%

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Nomenclature

H	magnetic induction, mT ($1\ \text{mT} = 1 \times 10^{-3}$ Tesla)
T	temperature, K
ΔT	temperature difference, K
ΔH	magnetic induction difference, mT
U	uncertainly of experiments

Greek symbols

φ	volume fraction
μ	dynamic viscosity, mPa s ($1\ \text{mPa·s} = 1 \times 10^{-3}$ Pa·s)
$\Delta\mu$	viscosity difference, mPa s

Subscripts

nf	nanofluid
bf	base fluid
f	fluid

at a particle loading of 6.3 vol.%. Abareshi et al. [25] found that the thermal conductivity enhancement of a water based Fe_3O_4 nanofluid was 11.5% for 3 vol.% at 40 °C. Hong et al. [26] found that the thermal conductivity enhancement of ethylene glycol based Fe ferrofluid was increased to 18% for 0.55 vol.%. Zhu et al. [27] experimentally investigated the effect of volume fraction on the thermal conductivity enhancement of water based Fe_3O_4 magnetic nanofluids. Sundar et al. [28] investigated thermal conductivity of ethylene glycol and water mixture based Fe_3O_4 nanofluid and observed that the thermal conductivity was enhanced by 46% at 2.0 vol.% of 20%:80% ethylene glycol and water mixture. Bahiraei [29] obtained the effect of particle migration on the thermal conductivity enhancement of Fe_3O_4/water nanofluid.

Then, some other researchers examined the magnetic induction effect on the thermophysical properties of ferrofluids. For instance, Parrekh and Lee [30] observed a thermal conductivity enhancement of 30% at 4.7 vol.% for Fe_3O_4 nanofluid under transverse magnetic field. Gavili et al. [31] researched the thermal conductivity of water based Fe_3O_4 ferrofluid under magnetic field and found the maximum enhancement of thermal conductivity was more than 200%. Nkurikiyimfura et al. [32] investigated the thermal conductivity enhancement of engine oil based magnetite (Fe_3O_4) nanofluids. They found that the enhancement of thermal conductivity was related to nanoparticle diameter, volume concentration and direction of magnetic field.

Apart from thermal conductivity, viscosity is another important thermophysical property, which describes the internal resistance of fluid flow and is an important property for all thermal applications involving fluids [1]. However, most researchers focused on the thermal conductivity, few researchers engaged in the viscosity. Li et al. [33] experimentally explored the viscosity of magnetic nanofluid in either the absence or the presence of external magnetic field and found the viscosity of magnetic fluids increased with increasing mass concentration and magnetic induction. Effects of temperature, particles volume fraction on the viscosity of water based Fe_3O_4 were studied by Sundar et al. [34].

By comparison, it is shown the related work is rarely on the viscosity of magnetic fluid at various temperatures, volume concentrations and magnetic induction at the same time. Meanwhile, theoretical formulations to predict the dependence of temperature, volume concentration and magnetic induction on the viscosity of nanofluids are practically absent.

In this work, we present an experimental study on the viscosity of water based Fe_3O_4 nanofluid. Experiments are conducted with different Fe_3O_4 nanoparticles volume fractions (0.5%, 1.0%, 2.0%, 3.0%, 5.0%) and temperature ranged from 293 K to 333 K. A variable external magnetic field is applied in all tests. Magnetic induction ranges from 0 mT to 30 mT. A new correlation is developed to estimate the viscosity of Fe_3O_4 nanofluids based on experimental results. This work could provide a useful engineering tool for thermal and fluid design applications of ferrofluid.

2. Methodology

2.1. Materials

Fe_3O_4 nanoparticle was prepared by coprecipitation method. Transmission electron microscopy (TEM) images were obtained with a JEM-200 microscope, which is commonly employed by lots of researchers [35–37]. Samples were dispersed in water with an ultrasonic vibrator, and then a drop of water was placed on a carbon-coated copper grid and evaporated under ambient atmosphere. TEM image of dry nanopowder is presented in Fig. 1. It is found that Fe_3O_4 nanoparticles are uniform and the average particle diameter is about 7.5 nm.

Samples were prepared with different volume concentrations (0.5 vol.%, 1.0 vol.%, 2.0 vol.%, 3.0 vol.%, 5.0 vol.%). All additives were dispersed in deionized water with an ultrasonic vibrator (JP-031B, 180 W) for 1 h before tests.

2.2. Measurement of viscosity

The viscosity of nanofluids was measured by a sine-wave vibro viscometer SV-10 (A&D Company, Japan) with the range of measurement from 0.3 mPa s to 10,000 mPa s. A constant temperature bath controller was used to control the temperature of the test samples varying from 293 K to 333 K. Experimental data were taken with an interval of 5 K. Each experiment was performed two times and the average value was considered as the final value. Before the formal measurement of sample viscosity, it is necessary for the SV-10 viscometer to be calibrated. Deionized water was used as the standard solution.

2.3. Uncertainty analysis

All the measurements were performed under steady state conditions. The accuracy in temperature measurements is ±0.5 °C(20 °C–30 °C), ±2 °C (30 °C–100 °C) under magnetic field. Accuracy of viscometer is

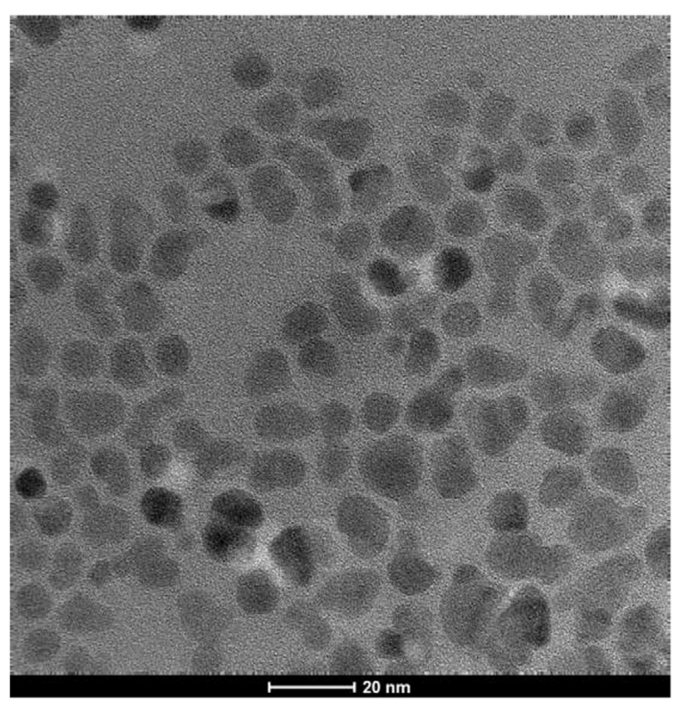

Fig. 1. TEM image of Fe_3O_4 nanoparticles.