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Synthesis and experimental investigation of the electrical conductivity of water based magnetite nanofluids

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ABSTRACT

In this study, magnetite, Fe_3O_4, nanoparticles were synthesized by chemical co-precipitation technique at different conditions. The products were characterized using X-ray diffraction, transmission electronic microscopy, and Fourier transform infrared spectroscopy. The electrical conductivity of nanofluids was nvestigated at different volume fractions and temperatures. Experimental measurements indicated considerable enhancement of electrical conductivity of Fe_3O_4 nanofluids with increase in both volume fraction and temperature under our experimental conditions. The results were compared with Shen's model, an electrical conductivity model previously developed for nanofluids. Survey results indicated that this model is largely able to explain the mechanism of Fe_3O_4 nanofluid electrical conductivity especially at low concentrations.

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1. Introduction

Nanofluids are a new group of fluids containing suspended metallic or non-metallic nanoparticles in a base fluid [1]. Recently, nanofluids have attracted great interest for both experimental and theoretical researches due to many important applications such as electrical power and microelectronic cooling, seals and lubricants materials, contrast medium at magnetic resonance imaging [1–4].

Recent studies have shown that thermal conductivity of some nanofluids is considerably larger than their base fluids [5–7]. Some different models such as those of Maxwell [8], Hamilton and Crosser [9], Xue [10] and Mehata et al. [11] were proposed to describe the thermal behavior observed in nanofluids. Also several articles were published considering the rheological behavior of nanofluids such as viscosity [12]. Although the thermal and rheological properties of the nanofluids are the subject of intense studies there is little data in the literature concerning their electrical properties. Ganguly et al. [13] and Minea et al. [14] investigated the electrical conductivity of Al_2O_3 nanofluids at different volume fractions and temperatures. They illustrated the insufficiency of the Maxwell model for explaining the electrical conductivity mechanism in the alumina nanofluids. White et al. [15] studied electrical conductivity of the propylene glycol-based ZnO nanofluids for several volume fractions and offered a model based on the electrophoresis and sedimentation of colloidal suspensions of spherical particles. Shen et al. studied the electrical conductivity of ZnO-insulated oil nanofluids [16] and oil based AlN nanofluids [17] in terms of the volume fraction as well as with respect to the temperature. They also proposed a new model to describe the electrical conductivity mechanism of nanofluids. Sikdar et al. [18] proposed a correlation to show the dual effect of temperature and volume fraction on electrical conductivity of titanium dioxide-water nanofluid. Further investigations by Sarojini et al. [19] evaluated the electrical conductivity of nanofluids containing metallic and ceramic particles (Cu, Al_2O_3, and CuO) with different volume fractions. They investigated the influence of various physico-chemical factors on the electrical conductivity of nanofluids and compared their experimental results with the O'Brien model.

Various investigations have been carried out for the physical mechanism and mathematical modeling to describe the electrical conductivity of nanofluids which is depending on many factors, such as volume fraction, size and shape of the nanoparticles, temperature and physicochemical properties of the medium, etc. Several mechanisms for strange enhancement of electrical conductivity of a nanofluid as compared to its base fluid have been already discussed. Among them, Brownian motion and interfacial layer of particles have been talked about comprehensively [15–19]. Literature survey shows that understanding the mechanism of effective electrical conductivity of nano-scale colloidal suspensions still continues to be an active research area. Based on effective medium theory, Maxwell model [8] was the first theoretical approach used to calculate the effective electrical conductivity of solid-in-liquid

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suspensions. This model is based on a static analysis for diluted and randomly distributed, non-interacting spherical components included in a homogenous medium. The electrical conductivity of nanofluids in the Maxwell model, σ_M, as a function of the volume fraction of nanoparticles, φ, is given by

$$\frac{\sigma_M}{\sigma_0}=1+\frac{3(\alpha-1)\varphi}{(\alpha+2)-(\alpha-1)\varphi} \tag{1}$$

where σ_0 is the electrical conductivity of the base fluid, and $\alpha=\frac{\sigma_p}{\sigma_0}$ is the conductivity ratio of the nanoparticles, σ_p, to the base fluid. This model does not include the particle surface charge effects, and motion of particles, which are considered important factors for the enhancement of the electrical conductivity of nanofluids. Considering the movement of nanoparticles as one kind of the carriers under the electric field, the electrophoretic conductivity σ_E, can be given by [16,17]:

$$\sigma_E=\frac{2\varphi\varepsilon_r^2\varepsilon_0^2U_0^2}{\eta r^2}. \tag{2}$$

Here ε_r is the relatively dielectric constant of the base fluid, ε_0 the dielectric constant of the vacuum, U_0 the nanoparticle Zeta potential, η the dynamic viscosity of the fluid and r the nanoparticles radius. For the usual volume fractions (less than 10%), the viscosity in Eq. (2) at a given temperature in Kelvin can be expressed in terms of temperature and volume fraction as [16,17]:

$$\eta=\rho\upsilon\left(1+25\varphi+625\varphi^2\right)e^{-\lambda(T-T_0)} \tag{3}$$

where ρ and υ are the density and the kinematic viscosity of the fluid in temperature T_0, respectively, and λ is the decreasing rate of the viscosity when the temperature is increasing. Substituting Eq. (3) into Eq. (2) leads to Eq. (4).

$$\sigma_E=\frac{2\varphi{\varepsilon_r}^2{\varepsilon_0}^2U_0^2}{\rho\upsilon(1+25\varphi+625\varphi^2)r^2}e^{\lambda(T-T_0)} \tag{4}$$

The Brownian motion of nanoparticles, as another dynamic mechanism of conductivity, is responsible for enhancement of electrical conductivity. The electrical conductivity of nanofluids based on this mechanism, σ_B, as a function of temperature and volume fraction can be defined as [16]:

$$\sigma_B=\frac{3\varphi\varepsilon_r\varepsilon_0U_0}{r^{\frac{3}{2}}}\left(\frac{RT}{L}\frac{e^{\lambda(T-T_0)}}{3\pi\rho\upsilon(1+25\varphi+625\varphi^2)}\right)^{\frac{1}{2}}. \tag{5}$$

Here R and L are the thermodynamic and Avogadro's constant, respectively.

Recently, Shen et al. [16,17] proposed a new model to describe the electrical conductivity of nanofluids based on the Maxwell model and considering the Brownian motion of particles and electrophoresis. Based on Shen's model, the electrical conductivity of nanofluids, σ, can be written as the following [16]:

$$\begin{aligned}\sigma=\sigma_M+\sigma_E+\sigma_B=\sigma_{0(T)}(1+3\varphi)\\ +\frac{2\varphi{\varepsilon_r}^2{\varepsilon_0}^2U_0^2}{\rho\upsilon(1+25\varphi+625\varphi^2)r^2}e^{\lambda(T-T_0)}\\ +\frac{3\varphi\varepsilon_r\varepsilon_0U_0}{r^{\frac{3}{2}}}\left(\frac{RT}{L}\frac{e^{\lambda(T-T_0)}}{3\pi\rho\upsilon(1+25\varphi+625\varphi^2)}\right)^{\frac{1}{2}}.\end{aligned} \tag{6}$$

The first sentence is the approximated form of Maxwell's equation for $\sigma_p \gg \sigma_0$, as in magnetite nanofluid.

To the best of our knowledge, there exists no report in the literature concerning the electrical conductivity of Fe_3O_4 nanofluids. Hence, the main purpose of this study includes two parts: (1) the electrical conductivity of Fe_3O_4 nanofluids is measured at different volume fractions and temperatures after preparation; (2) the experimental results are compared with Shen's model [16]. This issue is not yet theoretically settled and the relevant experimental data are scarce, so we will not discuss this aspect further.

2. Experimental method

2.1. Materials

The initial chemicals for preparing the Fe_3O_4 nanopowders were ferric chloride hexahydrate ($FeCl_3$-$6H_2O$), ferrous chloride tetrahydrate ($FeCl_2$-$4H_2O$), aqueous ammonia solution, and tetramethyl ammonium hydroxide ($N(CH_3)_4OH$). All the chemicals were used as received.

2.2. Nanofluid preparation

Magnetite (Fe_3O_4) nanoparticles were synthesized by a facile chemical co-precipitation method. The details of synthesis have been reported by Abareshi et al. elsewhere [5]. In order to obtain the best conditions for the formation of Fe_3O_4 nanoparticles, several experiments were performed (see Table 1). In this table, initial pH is the pH of iron salt solution and final pH is the pH of the product. After finding the best sample, the Fe_3O_4 nanoparticles dispersed uniformly into deionized water using tetramethyl ammonium hydroxide (TMAH) as a surfactant and intensive ultrasonic vibration. Finally, four nanofluid samples were prepared with 0.1, 0.2, 0.3, 0.4 and 0.5% volume fractions.

2.3. Characterization

XRD measurements were carried out with a diffractometer using Mo-Kα radiation ($\lambda = 0.7092$ Å) in the range of 2θ diffraction angles between 5.0° and 40.0° by a step of 0.02°. Morphological features of the samples were analyzed by TEM (PHILIPS CM-120). Fourier transform infrared spectra were recorded using Shimadzu 4300 spectrometer over the range from 400 to 1500 cm^{-1} using a KBr pellet.

2.4. Electrical conductivity measurement

The DC electrical conductivity of the nanofluids was measured using Wagtech Ec-meter model Con 11 (Fig. 1a) which is a microprocessor-based device, and includes two cylindrical electrodes of radius 5 mm with built-in temperature sensor (Fig. 1b). The instrument gives both temperature and conductivity values simultaneously at a given instant with a measuring conductivity and temperature ranges of 0.01 μS/cm to 199.99 mS/cm (±1%) and 0 °C to 100 °C (±0.5 °C), respectively. In the measurements, 100 mL nanofluid was used with above-mentioned volume fractions at temperatures of 10, 20, 30, 40, 50 and 60 °C. The response time, the time to reach steady state current for each measurement was within 10 s. The instrument was calibrated with an aqueous KCl solution (0.01 M) and the consistency of data was checked by repeating the measurements. At least five measurements were taken for each case to ensure the uncertainty of measurements within 5%. The electrical conductivity of deionized water as the base fluid is measured to be $\sigma_0 = 2.5$ μS/cm at

Table 1
Different conditions in the synthesis of magnetite nanoparticles.

Sample	pH (initial)	pH (final)	Synthesis temperature (°C)
I	6	4	30
II	6	10	30
III	1	10	30
IV	1	10	70

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