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Enhancement of thermal conductivity and kinematic viscosity in magnetically controllable maghemite (γ-Fe_2O_3) nanofluids

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ABSTRACT

The objective of this study is to investigate the thermal conductivity and kinematic viscosity enhancement of maghemite nanofluids at various particle volume fractions (0.1%, 0.2%, 0.3%, 0.4%, 0.5% and 0.6%) under the influence of an external magnetic field in different orientations (parallel and perpendicular). The effect of magnetic field strength and orientation on these properties is investigated at two temperatures of maghemite nanofluids (25 and 30 °C). The results show that the thermal conductivity enhancement of maghemite nanofluids increases with an increase in the magnetic field strength. The highest thermal conductivity enhancement (39.09%) is attained at the following experimental conditions: (1) particle volume fraction: 0.6%, (2) magnetic field strength: 300 Gauss, (3) temperature of maghemite nanofluid: 30 °C and (4) magnetic field orientation: parallel. The results also show that the kinematic viscosity enhancement of the maghemite nanofluids increases with an increase in the magnetic field strength. Likewise, the highest kinematic viscosity enhancement (31.91%) is attained at the above-mentioned experimental conditions. Based on the results, it can be concluded that both the magnetic field strength and orientation has a significant effect on the thermal conductivity and kinematic viscosity enhancement of maghemite nanofluids.

1. Introduction

Nanofluids have received much attention in recent years due their unique characteristics such as high thermal conductivity and convective heat transfer efficiency. Nanofluids offer exciting possibilities due to their enhanced heat transfer performance compared to conventional fluids. The properties of nanofluids, particularly the thermal conductivity and kinematic viscosity, play a significant role in thermal engineering applications. Hence, a fundamental understanding of the heat transfer behavior of nanofluids and the measurement of their transport properties is important.

Several researchers have investigated the thermo-physical properties of nanofluids and most studies have shown that the thermal conductivity of nanofluids increases with an increase in the particle concentration and temperature [1,2]. However, the kinematic viscosity of nanofluids increases with an increase in particle concentration but it decreases with an increase in temperature [3–5]. Several researchers have also investigated the thermal conductivity of nanofluids using a statistical approach [6] while others used artificial neural networks [7–10].

Magnetic nanofluids are unique liquids with magnetic properties. The physical properties of these nanofluids can be tuned by varying the magnetic field. Maghemite nanofluids (γ-Fe_2O_3) have received much attention in recent years due its interesting magnetic properties such as superparamagnetic behavior [11]. These smart materials have been used extensively for dynamic sealing [12,13], heat dissipation [14], drug delivery [15] and environmental applications [16,17]. These nanofluids have also been used as magnetic recording media [18] and magnetic resonance imaging media [19,20]. The energy flow in maghemite nanofluids can be controlled using external magnetic field and therefore, these nanofluids can be used effectively in thermal engineering applications [21].

In general, the thermal conductivity and kinematic viscosity of nanofluids are dependent on the properties, volume fraction, temperature, particle size as well as the morphology of the nanoparti-

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cles in the base fluid [22–25]. However, most of these studies are carried out in the absence of an external magnetic field.

Even though a number of studies have been conducted regarding the effect of magnetic field strength on the thermal conductivity and kinematic viscosity of magnetic nanofluids, these studies are centred on magnetite nanofluids. Li et al. [26] discovered that the presence of an external magnetic field has remarkable effects on both the thermal conductivity and kinematic viscosity of magnetite nanofluids. Philip [27] observed a dramatic thermal conductivity enhancement in magnetite-based nanofluids under the influence of an external magnetic field along the direction of heat flow. This thermal conductivity enhancement was within the predicted value of parallel mode conduction. In another study [28], the results showed that the thermal conductivity of engine oil-based magnetite nanofluids increases with particle size and volume fraction under the influence of an external magnetic field. However, to date, there is a lack of studies on the kinematic viscosity of magnetic fluids in the literature.

Even though there are several important studies pertaining to magnetic nanofluids available in the literature, little is known regarding the thermo-physical properties of these nanofluids. Hence, the objective of this study is to investigate the thermal conductivity and kinematic viscosity of water-based maghemite nanofluids under the influence of an external magnetic field in parallel and perpendicular orientations to the flow direction. The primary advantage of the water-based maghemite nanofluids is that maghemite nanoparticles inherently more chemically stable than magnetite nanoparticles. In addition, surfactant is not used during the synthesis.

2. Experiments

The maghemite nanoparticles were synthesized using the chemical co-precipitation method [29]. The thermal conductivity and kinematic viscosity measurements were carried out for maghemite nanofluids at low particle volume fractions in parallel and perpendicular magnetic fields in order to investigate the effect of magnetic field strength and orientation on the thermal conductivity and kinematic viscosity of maghemite nanofluids.

2.1. Preparation of nanofluids

Maghemite nanofluids were prepared by diluting stock solution at a known concentration in a 100 ml volumetric flask at different particle volume fractions (0.1%, 0.2%, 0.3%, 0.4%, 0.5% and 0.6%) using deionized water. The concentration of the nanofluids in volume percent (vol.%) was determined using Eq. (1).

$$\phi = \frac{\frac{m_p}{\rho_p}}{\frac{m_p}{\rho_p} + \frac{m_f}{\rho_f}} \times 100\% \quad (1)$$

where ϕ is the particle volume fraction, m_p is the mass of the nanoparticles, m_f is the mass of the base fluid, ρ_p is the density of nanoparticles and ρ_f is of the density of the base fluid.

Fig. 1 shows the physical appearance of the maghemite nanofluids at various particle volume fractions. It can be observed that the maghemite nanofluids have a clear, light brown color at low particle volume fractions (0.1%, 0.2% and 0.3%). In contrast, the maghemite nanofluids have a dark brown color at high particle volume fractions (0.4%, 0.5% and 0.6%). It is apparent that there is no sedimentation in any of the solutions.

2.2. Thermal conductivity measurements

The thermal conductivity measurements of the maghemite nanofluids were conducted using KD2 Pro thermal properties analyser (Decagon Devices Company, USA) based on the transient hot wire method. The KD2 Pro instrument consists of a hand-held controller and sensor which will be inserted into the medium. The KS-1 single-needle sensor (diameter: 1.3 mm, length: 60 mm) connected to a microprocessor was used to detect and measure the thermal conductivity of the nanofluids. The sensor consists of a heating element and thermo-resistor in its interior. The accuracy of the instrument is specified by the manufacturer to be within ±5%.

The measurements were recorded for each sample (volume: 30 ml) whereby the needle probe was inserted into the sample bottle. The sample bottle was placed into a water jacketed glass vessel and the temperature of the vessel was kept constant at 25 and 30 °C using JEIO TECH benchtop circulating and refrigerating water bath (Model: VTRC-620, Korea). The sample was left in the vessel for 30 min until it reaches the desired temperature. The external magnetic field was generated using a pair of Helmholtz coils, whereby each coil consists of 5000 windings of copper wire wrapped around an iron core pipe. A direct current (DC) power supply was used to supply current to the Helmholtz electromagnetic coils. The magnetic field strength was measured using a hand-held DC Gaussmeter (Model: GM-1-ST, AlphaLab Inc., USA). The measurements were carried out for different particle volume fractions (0.1%, 0.2%, 0.3%, 0.4%, 0.5% and 0.6%) and magnetic field strength (50, 100, 150, 200, 250 and 300 Gauss). The meter was calibrated prior to the measurements using standard solutions of known thermal conductivity. The thermal conductivity was recorded five times with an interval of 15 min for each sample and the mean thermal conductivity value was determined. The schematic diagram of the experimental set-up is shown in Fig. 2.

2.3. Kinematic viscosity measurements

The kinematic viscosity of the maghemite nanofluids was measured using Cannon–Fenske calibrated glass capillary viscometer (Model: 960 B, No. 50, Cannon, USA). The measurements were conducted for both parallel and perpendicular magnetic fields. The temperature of each sample was kept constant at 25 and 30 °C using JEIO TECH bench-top circulating and refrigerating water bath (Model: VTRC-620, Korea). Each sample was placed in the viscometer and left in the water jacketed glass vessel for 30 min until the sample reaches the desired temperature. The external magnetic field was generated using a pair of Helmholtz coils, whereby each coil contains 5000 windings of copper wire wrapped around an iron core pipe. A DC power supply was used to supply current to the Helmholtz coils. The magnetic field strength was measured using a hand-held DC Gaussmeter (Model: GM-1-ST, AlphaLab Inc., USA). The kinematic viscosity measurements were conducted for various particle volume fractions (0.1%, 0.2%, 0.3%, 0.4%, 0.5% and 0.6%) and magnetic field strength (50, 100, 150, 200, 250 and 300 Gauss). The kinematic viscosity was recorded five times for each sample and the mean kinematic viscosity was determined.

2.4. Uncertainty analysis

The term 'uncertainty' refers to the range of possible values that an error may have. In reality, both the measurement system and measurement process are not perfect and therefore, it can be expected that the measured values are subject to errors. However, it is not possible for one to know the exact value of the error for the measured parameter and for this reason, the error is known as uncertainty. There are two types of uncertainties, namely systematic (fixed) and random uncertainties. Systematic