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Ferrofluids for heat transfer enhancement under an external magnetic field

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ABSTRACT

Overheating of power electronic devices has become a significant issue due to their continued miniaturization and increased heat flux that needs to be dissipated. Ferrofluids (magnetic nanofluids) have been shown to have higher thermal conductivity than their base aqueous or oil based fluids due to the solid magnetic nanoparticles that make up the ferrofluid. This allows higher convective heat transfer rates and, importantly, the ability to externally effect the flow using a magnetic field. In this paper, we focus on material characterization of ferrofluids and measurement of heat transfer rates for single-phase ferrofluidic forced convective flow in microchannels. We show that heat transfer properties of the flow are enhanced with the use of ferrofluids and that the material make-up of the ferrofluid affects these properties. In this paper, we argue that generally, convective heat transfer rates for ferrofluids are increased by increasing the solid volume concentration of magnetic particles (~0.2–0.4%). Interestingly, increasing magnetic flux was shown to decrease heat transfer enhancement. This was due to a reduction in the thermal conductivity of the bulk fluid caused by magnetic nanoparticles being drawn out of the isotropic mixture and becoming pinned to the channel wall in the region of strongest magnetic field. We show that there is good correlation between both theory and experimental visualization of this phenomenon.

1. Introduction

Miniaturization and increased processing capabilities are the two technological trends of electronic devices, thus greater energy efficiency is desired whilst reducing their size. However, two major barriers to improve performance of such devices are the system interconnects and heat removal techniques [1]. System interconnect deals with integrating the front-side electronic device and the back-side cooling system, while heat dissipation techniques deal with enhancing heat transfer rates to the cooling system, or improving heat removal rates of the device [1]. One solution to this is to integrate cooling into the electronic chips. However, to obtain high heat fluxes, integrated liquid cooling typically utilises microchannels for increased surface area to transport fluid volume, which are characterised by very low Reynolds numbers (*Re*) and hence laminar flow. These characteristics limit the convective heat transfer coefficient to about $h \leq 790\,W/cm^2$ [2]. One way to enhance heat transfer, is to increase the thermal conductivity of the working fluid. Nanofluids offer the ability to significantly enhance heat transfer by embedding nanoparticles of higher thermal conductivity than the carrier fluid. The high surface area to volume ratio inherent with nanoparticles provides excellent contact surface area for conductive heat transfer between the fluid and the solid particle, which acts to elevate the effective conductivity of the nanofluid mixture [3]. Ferrofluids are a subclass of nanofluids made of superparamagnetic nanoparticles that allow them to be easily manipulated by an external magnetic field [4]. Ferrofluids have been commonly used in audio loudspeakers to improve its audio response, increasing sound amplitude while reducing distortion. They have also been used in fluid seals for devices such as rotating shaft seals, where they allow for the almost complete elimination of frictional losses compared to traditional mechanical seals, or for high-speed computer disk drives to prevent the ingress of dust particles and impurities [4]. Therefore, manufacturing technologies of commercial ferrofluids are advanced, reliable, and cost effective.

Ferrofluids are essentially made up of three components – solid magnetic nanoparticles, a surfactant coating which helps prevent agglomeration of the particles, and a dispersion fluid medium [5]. Ensuring the particles remain dispersed in the carrier fluid is critical in achieving higher thermal conductivity compared to

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larger scaled suspensions [4]. The concentration by mass/volume, size and type of magnetic nanoparticle, surfactant, and dispersion medium, including the method of synthesis dictates the thermophysical properties of ferrofluids. These in turn influence the transport properties and thus, the convective heat transfer rates [4,6–9].

An additional means to enhance heat transfer is introducing mixing in the microfluidic flow. Rapid mixing can be induced within microchannel flow either by active or passive methods [10,11]. Active methods require an external force such as electroosmosis, magnetism, acoustics, thermocapillary, pulsating flow or mechanical stirring with moving parts [10]. Due to the magnetic nature of ferrofluids, rapid mixing can be easily produced by the application of an external magnetic field using permanent magnets, as has been demonstrated in this work.

In this paper, we aim to explain the behaviour of ferrofluids under the effect of an external magnetic field to enhance heat transfer properties of laminar microfluidic channel flow.

1.1. Thermal conductivity

Table A1 in the appendix compiles past experimental results of ferrofluid thermal conductivity. Generally, the published results demonstrate that thermal conductivity increases with an increase in solid volume fraction (ϕ) and magnetic flux (B), and thermal conductivity decreases with an increase in temperature of the ferrofluid. Philip et al. [12,13] found that enhancement in thermal conductivity compared to the base fluid occurs when solid volume fraction is more than 1.7%. The maximum thermal conductivity enhancement observed was 300% when ϕ = 6.3% at a magnetic flux of 8.2 mT, at 25 °C, where the magnetic field was applied parallel to the temperature gradient for a kerosene-based ferrofluid. The team observed that the maximum enhancement occurred when the value of magnetic flux matched the value of saturation magnetization of the ferrofluid. Past this value, thermal conductivity decreases with increasing magnetic flux. They attribute this to the cross-linking of the chains and subsequent distortion in the nematic-like order [12].

Gavili et al. [14] recorded a maximum thermal conductivity enhancement of 65.5% when ϕ = 5% at a magnetic flux of 60 mT, at 25 °C, where the magnetic field was applied perpendicular to the measurement apparatus for a water-based ferrofluid. It must be noted that for both Gavili et al. [14] and Philip et al. [13] the test area used for measurements might be too small to record accurate results according to the manufacturer's specifications – a minimum of 15 mm of material parallel to the sensor in all directions is necessary for accurate measurements. Altan et al. [15,16] observed that thermal conductivity decreases with increasing solid mass concentration (which translates to an increase in solid volume concentration). Jiang et al. [9] and Pastoriza-Gallego et al. [17] recorded an increase in thermal conductivity with an increase in temperature. However, Jiang et al. [9] prepared the water-based ferrofluid using thermal decomposition with phase transfer method as compared to co-precipitation adopted by other researchers who report a decrease in thermal conductivity with an increase in temperature, and Pastoriza-Gallego et al. [17] prepared ethylene glycol-based ferrofluids. As explained earlier, the difference in method of synthesis and dispersion fluid medium alters thermophysical characteristics of the ferrofluid. Hence, we cannot directly compare these two studies. Furthermore, this highlights the need for each ferrofluid type to have its properties carefully measured.

1.2. Viscosity

Minimising viscosity is important in minimising the pumping power required for the system.

Table A2 in the appendix compiles past experimental results for ferrofluid viscosity. Past experimental results have agreed that viscosity increases with an increasing solid volume concentration and magnetic flux strength, and viscosity decreases with increasing temperature [8,18–21]. Li et al. [18] and Wang et al. [19] found that the rate of increase in viscosity is reduced with increasing solid volume concentration, magnetic flux strength and temperature. However, Li et al. [18] uses solid magnetic nanoparticles that are greater than 16 nm – the prescribed theoretical size limit for magnetite (Fe_3O_4) nanoparticles to remain superparamagnetic [4].

As explained above, an increase in viscosity is unfavourable for the cost of pumping. However, while an increase in solid volume concentration and magnetic flux increases viscosity, and thus pressure drop, it also increases the thermal conductivity of the ferrofluid. Hence, an optimal solid volume concentration percentage and magnetic flux strength should be found to enhance heat transfer of the magnetofluidic flow whilst limiting the increase in viscosity; the aim being to increase the ratio of $Nu/\Delta P$.

2. Materials and experimental methods

2.1. Material characterization

Commercial water-based ferrofluids (Domain Detection Kit, Ferrotec), containing fluid types EMG308, EMG408, EMG707, EMG708 and EMG807, were used to make diluted samples of 5% and 10% ferrofluid content for each EMG series, with de-ionized water (DIW). The initial properties given by the supplier are shown in Table 1. This gives a volume ratio of ferrofluid:DIW as 0.05:0.95 for 5% dilution, and 0.10:0.90 for 10% dilution. Thermophysical properties of the diluted samples were measured and compiled in Table 2.

Density of the diluted samples was measured at room temperature (RTP) (~22 °C) using a density bottle, also known as a pycnometer (Calibrated 25.102 cm^3, BLAUBRAND®). DIW was used as the calibration standard. Measurements were repeated three times and averaged.

Contact angle of the diluted ferrofluid samples on a flat polydimethylsiloxane (PDMS) surface (the material of the microchannel) was captured using a Canon EOS 700 digital single-lens reflex (DSLR) camera at RTP, then evaluated using ImageJ software.

2.1.1. Particle sizing

It is well known that the size, shape, and composition of the magnetic nanoparticles strongly influence the thermophysical profile of the ferrofluid, and thus, their transport and flow properties. Since all the diluted samples contain Fe_3O_4 magnetic nanoparticles, the only variable is size. Depolarized dynamic light scattering (DDLS) and transmission electron microscopy (TEM) were employed to size the particles. Size distribution of the magnetic nanoparticles was obtained using DDLS, performed on an ALV-5022F spectrometer. Four measurements of 2-min duration were performed, and the average of the data sets were taken. Morphology of the diluted samples were observed on a JEOL 1010 TEM (100 kV) equipped with a CCD camera (Orius SC600A, Gatan).

2.1.2. Transport properties

Viscosity and thermal conductivity are dependent on the type and concentration of magnetic nanoparticles, and surfactant make-up of the ferrofluid. The type and strength of external magnetic field applied also affects these properties.

2.1.2.1. Viscosity. Kinematic viscosity of the diluted ferrofluid samples was measured at 25 °C using a capillary viscometer (Micro-Ubbelohde 531 10, SCHOTT) along with a viscosity