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Convective heat transfer characteristics of magnetite nanofluid under the influence of constant and alternating magnetic field

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ABSTRACT

The effects of constant and alternating magnetic field on the laminar forced convective heat transfer of water based magnetite (Fe_3O_4) ferrofluid in a heated tube are studied experimentally. The ferrofluid flows in a uniformly heated tube with 9.8 mm diameter and 2680 mm length and is influenced by a magnetic field generated by four electromagnets. The local convective coefficients are measured at both thermally developing and fully developed regions for three different volume fractions of $\varphi = 1$, 1.5 and 2 % and in the Reynolds number range of 400–1200. The magnetic field and the resulting magnetic force distributions are also simulated to get further insight into the heat transfer augmentation. In the absence of a magnetic field, results show that using magnetite ferrofluid with $\varphi = 2$ % improves the average convective heat transfer up to 13.5% compared to the DI-water at Re = 1200. This value grows up to 18.9% and 31.4% by application of constant and alternating magnetic field with intensity of $B = 500$ G, respectively. The heat transfer is shown to be increased with the Reynolds number, ferrofluid concentration, and the intensity of the magnetic field. Under the constant magnetic field, migration of nanoparticles to the tube surface increases the local thermal conductivity and consequently the heat transfer near the electromagnets. Moreover, disruption of the thermal boundary layer and increased flow mixing seem to be the possible reasons for the heat transfer enhancement by the alternating magnetic field.

1. Introduction

Ferrofluid is a synthesized colloidal mixture of non-magnetic carrier liquid, such as water or oil, containing single domain permanently magnetized nano particles, typically magnetite [1]. Several studied have been carried out on the thermal conductivity of the nanofluids including ferrofluids and effects of different parameters such as nanoparticle and base fluid type, dimension and concentration of the nanoparticles, and temperature have been investigated [2–10]. These studies indicate that the thermal conductivity of the base fluid is enhanced noticeably due to the addition of the nanoparticles. Thus, similar to the regular nanofluids, ferrofluids can be used as working fluids of heat exchangers in many industrial applications. Moreover, the distinctive characteristic of the ferrofluid is the ability to respond to an external magnetic field. Recent studies show the significant increase of the ferrofluid thermal conductivity in the presence of an external magnetic field [11–14]. Among them are, Philip et al. [11] and Gavali et al. [14] who observed 300% and 200% thermal conductivity enhancement for Fe_3O_4 ferrofluid, respectively. The enhancement of the thermal conductivity is attributed to the formation of chainlike structures in the ferrofluid which grow with intensity of the magnetic field [11].

Furthermore, a number of studies have concerned the forced convection heat transfer of the ferrofluids in the absence and presence of an external magnetic field [15–19]. Sundar et al. [15] studied turbulent forced convection heat transfer and friction factor of Fe_3O_4 magnetic nanofluid in a tube in the absence of magnetic field and obtained correlations for estimation of the Nusselt number and friction factor. Their results show that the heat transfer coefficient is enhanced by 30.96% and friction factor by 10.01% at 0.6% volume fraction compared to the base fluid. Motozawa et al. [16] studied the effect of magnetic field on heat transfer of water-based magnetic fluid named W-40 in a rectangular duct. It is shown that heat transfer coefficient increases locally in the region where magnetic field exists and has a direct relation with magnetic field intensity. They reported a maximum of 20% heat transfer enhancement for their studied case. Lajvardi et al. [17] studied the convective heat transfer of ferrofluid flowing through a heated copper tube in the laminar flow regime in the presence of a magnetic field. They attributed the enhancement of the heat transfer to the improvement of thermophysical properties of ferrofluid under the influence of the magnetic field. Ghofrani et al. [18] investigated the effects of constant and alternating magnetic fields on the forced convection heat transfer in a short tube. They observed that applying a constant magnetic field adversely affects or has a negligible effect on the heat transfer enhancement. However, it

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increases up to 27.6% at low Reynolds numbers by an alternating magnetic field.

Recently, Azizian et al. [19] studied the effect of a constant magnetic field on the laminar convective heat transfer and pressure drop of magnetite nanofluid in a vertical tube and reported large enhancement in the local heat transfer coefficient against only a 7.5% increase of pressure drop. They also showed that the convective heat transfer enhancement increases with the magnetic field intensity and gradient.

The aim of this paper is to experimentally investigate the effects of constant and alternating magnetic field on forced convective heat transfer of Fe_3O_4 nanofluid in a long heated tube. For this purpose, the convective heat transfer coefficients have been measured at both thermally developing and fully developed regions at different Reynolds numbers, magnetic nanoparticle concentrations, and magnetic field intensities. The results will be compared with those of no magnetic field.

2. Experimental method

2.1. Ferrofluid synthesis procedure

The ferrofluid samples are synthesized using the conventional coprecipitation process. Briefly, stochiometric amounts of $FeCl_2.4H_2O$ and $FeCl_3.6H_2O$ equivalent to the chemical composition of Fe_3O_4 are dissolved in DI-water and degassed via argon gas purging. Then, NH_4OH solution is gradually added into the iron solution under the mechanical stirring until pH reaches 12. The black precipitate is removed from the liquid phase via centrifugal and magnetic separation and washed several times by acetone and DI-water. The obtained solid product is redispersed in DI-water and TMAH is added to the solution under stirring in a manner that the desired volume fraction values of 1%, 1.5% and 2% are achieved. The stirring process is continued for an additional 1 h until the stable ferrofluid is obtained. SEM image of the synthesized sample is presented in Fig. 1.

As seen in Fig. 1, nanoparticles with various shapes are aggregated and formed larger agglomerates. The mean particle size is 30 nm.

2.2. Experimental apparatus

An experimental setup has been designed, implemented, and used to study the effects of constant and alternating magnetic fields on laminar forced convection characteristics of *Fe_3O_4* ferrofluid in a heated circular tube. The setup is presented schematically in Fig. 2. The main components are: a constant temperature bath in a closed loop for circulating the nanofluid, tube test section, magnetic field generation and control system, and data acquisition system for temperature recording.

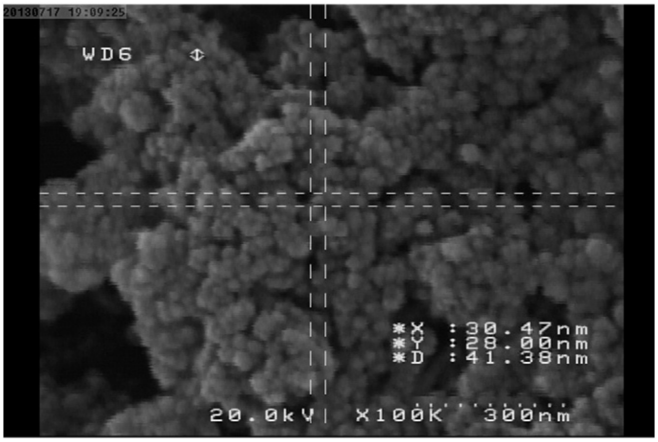

Fig. 1. SEM image of the synthesized sample.

2.2.1. Fluid circulation system

Ferrofluid is circulated in a loop from a reservoir tank by a 24 V DC pump driven by a DC power supply. Volumetric flow rate passing through the loop is measured using a calibrated flow meter, and can be varied by changing the voltage of the DC power supply of the pump. There is also a fluid collection tank for measuring and calibrating flow rates. The constant temperature bath (F10-Hc Julabo) is located upstream of the pump to control the inlet temperature. The exit heated ferrofluid from the tube passes through a spiral copper tube which is submerged in the thermal bath reservoir. Ferrofluid is cooled due to the heat transfer to the cold water inside the constant temperature bath. Therefore, nanofluid inlet temperature to the tube can be controlled by the thermal bath reservoir temperature.

2.2.2. Tube test section

The main part of the tube test section is a 2680 mm long straight aluminum tube with inner and outer diameters of 9.8 mm and 11.8 mm, respectively. The tube has a heat transfer section of 2380 mm. The 100 mm entry and 200 mm exit lengths of the tube are unheated in order to eliminate the end effects in the measurements. A constant heat flux is provided by passing electric current through a 3 mm thick flat-wire element. The heater is wounded on the entire tube surface and is connected to an AC power supply through a variac. It does not contain any ferric material to prevent the distortion of the inner magnetic field in the tube. The tube and heater are insulated with low thermal conductivity elastomeric foam of 10 mm thickness. Two polyurethane bushings are lathed and placed on the inlet and outlet of the aluminum tube to diminish the heat flow in the axial direction. A small mixing chamber is located at the exit of the heat transfer section for the purpose of the accurate measurement of fluid exit temperature.

The surface temperature of the tube at the heat transfer section is measured by 20 thermocouples coated with a compound of copper powder and thermal paste. The thermocouples are installed on the aluminum tube surface with an equal spacing of 125 mm. Also, located in the inlet and outlet of the test section are two K-type thermocouples to measure the inlet and exit temperatures of the fluid. All the thermocouples used in this study are calibrated and the uncertainty of the temperature measurement is estimated to be less than 1%. The thermocouples are connected to two data connected to a PC such that all the temperature values can be monitored and recorded simultaneously.

2.2.3. Magnetic field generation and control system

The magnetic field generation system includes four electromagnets, a high voltage DC power supply, a signal generator and an oscilloscope, as shown in Fig. 3(a). Four electromagnets are used to generate the magnetic field. The first one is located below the tube at the distance $x = 1625$ mm from the tube entrance and the other three electromagnets are placed in a staggered configuration with equal distances of 30 mm from each other. Dimensions of the electromagnets are shown in Fig. 3(b).

Each electromagnet consists of a U core and two copper windings. The core material is made of electrically insulated iron powder and alternatively iron alloys with low hysteresis and a high saturation flux density, which is required for producing an alternating magnetic field. The windings have $N = 3000$ turns of 0.5 mm diameter copper wire with a total electric resistance of 35Ω.

An eight-channel DC power supply with variable voltage of 0–90 V has been designed to provide the required current density in all the eight windings of the electromagnets.