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Experimental investigation on convective heat transfer and hydrodynamic characteristics of magnetite nanofluid under the influence of an alternating magnetic field

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ABSTRACT

An experimental study has been carried out on the laminar forced convective heat transfer of Fe_3O_4/water nanofluid (ferrofluid) under an external magnetic field. Here, the ferrofluid flows into a long uniformly heated parallel plate channel and is influenced by an external magnetic field generated by four electromagnets. The efficient arrangement of the electromagnets is obtained by numerical simulations and primary experiments. Effects of magnetic field intensity and frequency on the convective heat transfer and pressure drop have been investigated at different concentrations (1, 1.5, and 2 Vol%) and flow rates ($200 \le Re \le 1200$). It is observed that the convective heat transfer has a direct relation with the Reynolds number and ferrofluid concentration. Moreover, at a constant Reynolds number, the magnetic field intensity increases the heat transfer. Note that there exists an optimum frequency for every single Reynolds number which increases by Reynolds number. Our results also show a maximum heat transfer enhancement of 16.4% by the use of ferrofluid, in the absence of a magnetic field. This value is increased up to 24.9% and 37.3% by application of constant and alternating magnetic field, respectively.

1. Introduction

Augmentation of heat transfer is a key challenge for many industrial applications. Among several methods which have been proposed for heat transfer enhancement, using of nanofluids has achieved growing interest by many researchers recently. Several experimental and numerical studies have been carried out on the transport properties and heat transfer characteristics of different nanofluids [1–10]. A number of these studies have concentrated on the magnetic nanofluids (ferrofluids).

Ferrofluid is a synthesized colloidal mixture of nonmagnetic carrier liquid, typically water or oil, containing single domain permanently magnetized nanoparticles, typically magnetite [11]. Similar to the other nanofluids, the thermal conductivity of the base fluid can be enhanced noticeably due to addition of the magnetic nanoparticles [12–16]. 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 [17–20]. For example Philip et al. [17] and Gavili et al. [20] 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 the intensity of the magnetic field [17].

Furthermore, the forced convection heat transfer of the ferrofluids has also been investigated in the absence and presence of an external magnetic field [21–27]. Sundar et al. [21] 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.

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Motozawa et al. [25] 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. [26] 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. Azizian et al. [27] 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.

Above mentioned works apply a constant magnetic field to increase the ferrofluid convective heat transfer. Application of an alternating magnetic field for heat transfer enhancement was first introduced by Murray [28] for *a particle laden fluid*. He employed time varying magnetic field to cause the iron filings in mineral oil to be attracted to and released from a heated pipe wall. He demonstrated a 267% increase in heat transfer coefficient against a 48% increase in flow differential pressure.

With a similar mechanism to that used by Murray [28], the current research investigates the effect of an alternating magnetic field on the heat transfer and pressure drop of ferrofluid flow in a channel. Specifically, ferrofluid flows into a channel with uniformly heated top and bottom copper plates and is influenced by a magnetic field generated by four electromagnets. The efficient arrangement of the electromagnets is obtained by the numerical simulations and primary experiments. All the heat transfer experiments are configured based on the numerically designed arrangement. The convective heat transfer coefficients are then measured at both thermally developing and fully developed regions at different Reynolds numbers, nanoparticle concentrations, magnetic field intensities, and frequencies. The results have been compared with those of ferrofluid flow without external magnetic field and deionized water alone.

2. Experimental method

2.1. Experimental apparatus

The experimental set-up is shown schematically in Fig. 1. The main components are: parallel plate channel test section, a closed loop for circulating the nanofluid, pressure drop measurement device, magnetic field generation and control system, and data acquisition system for temperature recording.

The studied geometry is a parallel plate channel with a flow passage size of 40 mm (W) × 4 mm (H) × 2500 mm (L). The channel consists of a hydrodynamic entry section and a heat transfer section with lengths of 500 mm and 2000 mm, respectively. The length of entry section is selected such that the hydrodynamically fully developed flow is ensured at the heat transfer section for all the Reynolds numbers. Convective heat transfer coefficients are measured on the heat transfer section. Cross section of the heat transfer section is also shown in Fig. 1. It consists of two copper top and bottom plates which are fixed in a very low thermal conductivity polyethylene housing. A small mixing chamber is located at the exit of the heat transfer section for purpose of the proper measurement of fluid mean exit temperature.

A constant surface heat flux is maintained on both copper plates by passing electric current through the two strip heaters which are pressed to the back of copper plates.

The surface temperature of each copper plate is measured by 21 calibrated thermocouples. Two thermocouples are also inserted in the inlet and outlet of the test section to measure the inlet and exit temperatures of the fluid. The thermocouples are connected to two data loggers and all the temperatures can be monitored and recorded simultaneously during the tests.

The pressure drop of the heat transfer section is measured by Endress Hauser differential pressure transducer with operation range of 0–250 kPa (0–2500 mbar) and 1% accuracy, as calibrated by the manufacturer.

Ferrofluid is circulated in a loop from a reservoir tank by a DC pump. The 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. A constant temperature bath is located upstream of the pump to control the inlet temperature.

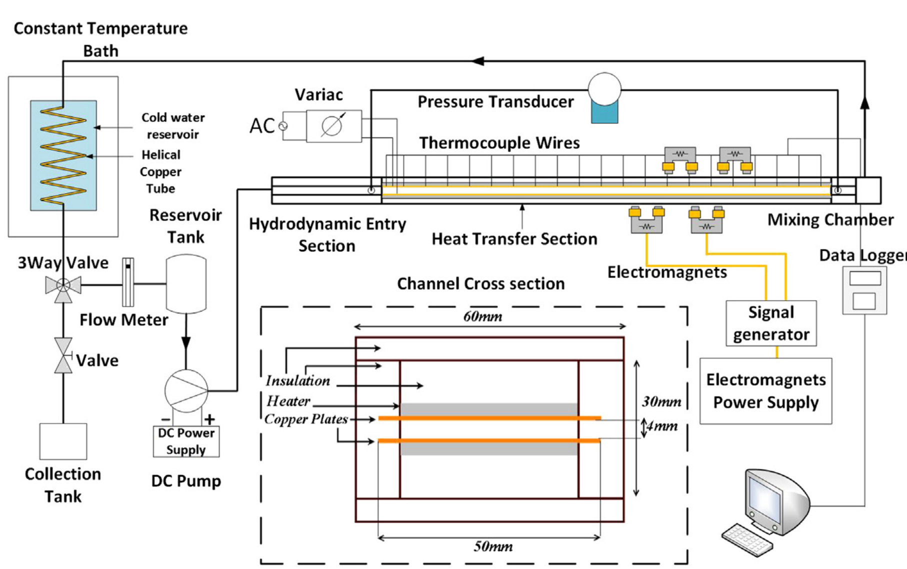

Fig. 1. Schematic diagram of the experimental setup.