Experimental Thermal and Fluid Science 76 (2016) 1–11

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Experimental investigation on laminar forced convective heat transfer of ferrofluid loaded with carbon nanotubes under constant and alternating magnetic fields

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ARTICLE INFO

Article history:
Received 25 January 2016
Received in revised form 2 March 2016
Accepted 6 March 2016
Available online 11 March 2016

Keywords:
Ferrofluid
Carbon nanotubes
Convective heat transfer
Alternating magnetic field

ABSTRACT

In this paper, the effects of both constant and alternating magnetic fields on the laminar forced convective heat transfer of a hybrid nanofluid containing tetramethylammonium hydroxide (TMAH) coated Fe_3O_4 nanoparticles and gum arabic (GA) coated carbon nanotubes (CNTs) flowing through a heated tube were investigated experimentally. The experiments were carried out over wide range of parameters such as Reynolds number (548–2190), volume concentrations of Fe_3O_4 (0.5–0.9%) and carbon nanotube (0.25–1.35%) nanoparticles, magnetic field strength (300–700 Gauss) and alternating magnetic field frequency (10–50 Hz). In present study, the experimental observations in the case without magnetic field revealed that by using Fe_3O_4/CNT hybrid nanofluid, the convective heat transfer has been improved significantly. The maximum enhancement of 62.7% was achieved in the local Nusselt number for hybrid nanofluid containing 0.5 vol.% Fe_3O_4 and 1.35 vol.% CNT at Reynolds number equals to 2190. Additionally, the results showed that the heat transfer of the studied hybrid nanofluids has been improved in the presence of constant and alternating magnetic fields and the amount of heat transfer increment due to a constant magnetic field was much more significant compared with an alternating magnetic field. Moreover, the effects of magnetic field were more noticeable in the hybrid nanofluids with higher volume concentrations and lower Reynolds number. Eventually, the highest increment of 20.5% in comparison with the case without field was reported in the local Nusselt number for hybrid nanofluid containing 0.5 vol.% Fe_3O_4 and 1.35 vol.% CNT at Reynolds number equals to 548.

1. Introduction

A ferrofluid is a stable colloidal suspension of sub-domain magnetic particles (magnetite, ferric oxide, iron nickel oxide, etc.) with a particle size in the range of 5–15 nm dispersed in a liquid carrier [1]. The ferromagnetic nano-particles are coated with a surfactant to prevent their agglomeration (due to van der Waals forces and magnetic forces). Although the name may suggest otherwise, ferrofluids do not display ferromagnetism, since they do not retain magnetization in the absence of an externally applied field. In fact, ferrofluids display paramagnetism, and are often described as "superparamagnetic" due to their large magnetic susceptibility.

Most published studies on ferrofluids have focused on the thermal conductivity [2–6] and viscosity [5,7–10]. Up to now only very few attempts have been made to investigate the convective heat transfer of ferrofluids through a pipe in either presence or absence of a magnetic field. Forced convective heat transfer of Fe_3O_4/water ferrofluid with 5% solid volume concentration passing through a heated tube under a constant magnetic field is investigated for the forced time by Lajvardi et al. [11]. Their results showed that the use of Fe_3O_4 magnetic nanoparticles as the dispersed phase in water cannot enhance the convective heat transfer in the laminar flow regime in the absence of a magnetic field. They also concluded that the enhancement of heat transfer coefficient is particularly significant under the influence of an applied magnetic field. The convective heat transfer characteristic of Fe_3O_4 ferrofluid for turbulent flow in a circular tube in the absence of a magnetic field is evaluated experimentally in the volume concentration range of 0–0.6% by Sundar et al. [12]. They found that the heat transfer coefficient is enhanced by 30.96% at 0.6% volume concentration compared to flow of water at similar operating conditions. Ghofrani et al. [13] presented an experimental investigation on

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http://dx.doi.org/10.1016/j.expthermflusci.2016.03.010
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forced convective heat transfer of an aqueous ferrofluid flow passing through a circular copper tube in the presence of constant and alternating magnetic fields. They used water based Fe_3O_4 magnetic nanofluid with three different solid volume concentrations of 0.6%, 1% and 2% in the investigation. Their results showed that the application of a ferrofluid leads to enhancement in the average convective heat transfer along the copper tube in the laminar flow regime in the absence of a magnetic field. They also found that applying a constant magnetic field, based on Reynolds number and axial distance from the entrance adversely affects or has low enhancement in the convective heat transfer. Additionally, their results showed that the average heat transfer increase by 27.6 at a Reynolds number of 80 with a high frequency of connecting and disconnecting the magnetic field. Azizian et al. [14] investigated the effect of an external magnetic field on the convective heat transfer of Fe_3O_4 ferrofluids with 0.86% solid volume concentration under laminar flow regime conditions. Their results showed that large enhancement in the local heat transfer coefficient can be achieved by increasing the magnetic field strength and gradient. Goharkhah et al. [15] studied the effects of constant and alternating magnetic fields on the laminar forced convective heat transfer of water based Fe_3O_4 ferrofluid in a heated tube. They measured the local convective heat transfer coefficients at both thermally developing and fully developed regions for three different volume fractions of 1%, 1.5% and 2% and in the Reynolds number range of 400–1200. Their results revealed that the application of a Fe_3O_4 ferrofluid improves the average convective heat transfer up to 13.5% compared to the de-ionized (DI) water in the laminar flow regime in the absence of a magnetic field. Additionally, they found that this value grows up to 18.9% and 31.4% by application of constant and alternating magnetic fields, respectively.

In recent years, some studies have been carried out to investigate the effects of additives such as CNTs on the thermal conductivity and viscosity of ferrofluids. Hong et al. [16] reported for the first time that the thermal conductivity of the Fe_2O_3/CNT hybrid nanofluid containing 0.02 wt% Fe_2O_3 and 0.01 wt% CNTs could be enhanced by the external magnetic field. They suggested that the reasonable explanation for these interesting results is that the magnetic particles form aligned chains under applied magnetic field and help to connect the nanotubes, which results in improved thermal conductivity. Wensel et al. [17] observed an approximately 10% increase in the thermal conductivity of heat transfer nanofluids containing metal oxide nanoparticles and CNTs with very low percentage loading (around 0.02 wt%) of these two nanomaterials. Horton et al. [18] showed that the thermal conductivity of heat transfer nanofluids containing 0.05 wt% Ni coated CNT nanoparticles can be significantly enhanced (>60%) by applied magnetic field. Baby and Sundara [19] presented a novel magnetic nanofluid obtained by dispersing silicon dioxide coated on Fe_3O_4 particle decorated CNTs ($Fe_3O_4 + SiO_2$/CNT) in DI-water. Their results showed that dispersed water based nanofluids containing Fe_3O_4/CNTs and $Fe_3O_4 + SiO_2$/CNT show a thermal conductivity enhancement of 20% and 24.5%, respectively, for a volume concentration of 0.03% in the presence of a magnetic field. Sundar et al. [20] measured the thermal conductivity and the viscosity of the CNT + Fe_3O_4/water hybrid nanofluid. A thermal conductivity enhancement of 13.88–28.46% is observed at 0.3% volume concentration of hybrid nanofluid in the temperature range of 25–60 °C, compared to the base fluid. Furthermore, their results showed that the enhancement in viscosity for 0.3% nanofluid was 0.27% and 50% compared to base fluid in the temperatures ranging from 20 °C to 60 °C.

To the best knowledge of the authors, there are not any archival publications considering the detailed behavior of the laminar forced convective heat transfer of a ferrofluid loaded with CNTs in the presence or absence of a magnetic field. The objective of present investigation is to determine experimentally the effects of constant and alternating magnetic fields on the laminar forced convective heat transfer of a homogeneous mixture of magnetic nanoparticles coated with TMAH and GA coated CNTs in a long heated tube. For this purpose, the convective heat transfer has been analyzed at different Reynolds number, Fe_3O_4 and CNT concentrations, and magnetic field strengths and frequencies. The results will be compared with those of no magnetic field.

2. Experimental setup

2.1. Apparatus

In order to inspect the laminar forced convective heat transfer behavior of the Fe_3O_4/CNT hybrid nanofluid in a tube under the influence of constant and alternating magnetic fields, an experimental setup was used. The schematic of this experimental setup is shown in Fig. 1. A 24 V DC pump with a head of 3 m and adjustable pumping speed is used to establish the flow of the nanofluid contained in a tank. A rotameter is used after the pump to measure the flow rate. The main part of the test section is fabricated from copper tube with an inner diameter of 4.8 mm, an outer diameter of 6 mm, and a length of 1.25 m. Eight K-type thermocouples attached to the outer tube wall are used to record the local temperature of the tube wall. Two K-type thermocouples are also used to measure the bulk temperature of the inlet and outlet fluids. In case of laminar flow, the hydrodynamic entry length (L_h) is defined as $L_h = 0.05Red_{in}$ [21], where Re is the Reynolds number and d_{in} is the inner diameter of the pipe. For our experiments, the longest entrance length was found to be 52 cm. Hence, to ensure that the flow becomes hydrodynamically fully-developed before temperature measurements, the first thermocouple is placed at a 50 cm distance from the tube inlet, and the remaining thermocouples are places at a 10 cm distance from each other. A 12-channel data logger is used to record temperature values measured by the thermocouples. A nickel–chromium heating element with a DC power supply and a maximum output of 300 W and thermal insulation is used to apply a uniform heat flux on the outer wall of the tube. This type of heating element covers the entire surface of the tube without having any magnetic field attenuator particle. To achieve a steady-state system, the exit heated nanofluid from the tube is cooled due to the heat transfer to the cold water from an 1800 W thermal bath via a shell and tube heat exchanger. Therefore, nanofluid inlet temperature to the tube can be controlled by the thermal bath reservoir temperature. Trial and error method is used to find the required thermal bath temperature to achieve a constant flow inlet temperature. As previously mentioned, a K-type thermocouple is used to measure the bulk temperature of the inlet fluid to the tube. When the measured temperature of this thermocouple remains constant, it is concluded that the thermal bath temperature is suitable. The magnetic generation system is composed of six electromagnets, a high voltage DC power supply, a signal generator and an oscilloscope. Each electromagnet consists of a U-shaped zinc ferrite core and two copper windings placed in both legs of the core. These U-shaped cores are made of low hysteresis and a high saturation flux density, which are essential for generating an alternating magnetic field. The windings have 2000 turns of 0.25 mm diameter copper wire. The length of each electromagnet is 80 mm and the distance between successive electromagnets is 20 mm. As can be seen from Fig. 1, three pairs of electromagnets with opposite poles facing each other, are placed on both sides of the tube. Fig. 2 shows the arrangement of these electromagnets.

An eight-channel variable voltage DC power supply is designed to control the current density in all the windings of the electromagnets and hence the magnetic field strength produces by elec-