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Experimental investigation on laminar forced convection heat transfer of ferrofluids under an alternating magnetic field

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ABSTRACT

This research study presents an experimental investigation on forced convection heat transfer of an aqueous ferrofluid flow passing through a circular copper tube in the presence of an alternating magnetic field. The flow passes through the tube under a uniform heat flux and laminar flow conditions. The primary objective was to intensify the particle migration and disturbance of the boundary layer by utilizing the magnetic field effect on the nanoparticles for more heat transfer enhancement. Complicated convection regimes caused by interactions between magnetic nanoparticles under various conditions were studied. The process of heat transfer was examined with different volume concentrations and under different frequencies of the applied magnetic field in detail. The convective heat transfer coefficient for distilled water and ferrofluid was measured and compared under various conditions. The results showed that applying an alternating magnetic field can enhance the convective heat transfer rate. The effects of magnetic field, volume concentration and Reynolds number on the convective heat transfer coefficient were widely investigated, and the Optimum conditions were obtained. Increasing the alternating magnetic field frequency and the volume fraction led to better heat transfer enhancement. The effect of the magnetic field in low Reynolds numbers was higher, and a maximum of 27.6% enhancement in the convection heat transfer was observed.

1. Introduction

Since the last two decades, research studies have shown that nanoengineering and nanoscience have enormous potential to dynamically evolve the technology in the new century. Recent advances in micro and nano electromechanical systems (MEMS and NEMS), microfluids, nanofluids, and ferrofluids indicate the high importance of this new area of science, as evidenced by the proliferation of research, articles, books, etc. devoted to nanoscience and nanoengineering among other research.

There are many diverse complex factors hindering the process of heat transfer. Consequently, low heat transfer coefficient values have become a considerable concern in many fields of heat transfer such as miniaturized systems. Fortunately, the advent of nanofluids and ferrofluids in the heat transfer field could be a feasible solution to a considerable proportion of possible difficulties ahead [1,2].

Ferrofluids are liquids containing single-domain nanoparticles (magnetite, ferric oxide, iron nickel oxide, etc.) with a mean diameter of 15 nm or less. Ferrofluids satisfy ferrohydrodynamic equations under a magnetic field. The interactions between magnetic fields and fluids (magnetic forces and hydrodynamic equations) result in ferrohydrodynamics (FHDs) which has opened a new horizon in plenty of new fields of study such as medicine and mechanics with new applications. One of these applications could be the heat transfer enhancement.

Ferrofluids are colloidal mixture of magnetic particles synthesized in a career liquid (generally water or oil), comprise of 85% career liquid, 10% surfactant, and 5% magnetic particles. In the absence of a magnetic field, ferrofluids have some common interactions with nanofluids such as Brownian motion. Because of the Brownian motion effect, the particles suspended in the career liquid will not normally settle down. The particles are coated with surfactants such as oleic acid, tetra methyl ammonium hydroxide, citric acid, and soy lecithin to prevent from aggregation [3].

Generally, liquids have low thermal conductivity in comparison with metal suspensions. This is primarily because of the fact that thermal conductivity of solids is higher than liquids. Choi and Eastman [4] enhanced thermal conductivity of conventional fluids by suspending metallic nanopartcles in water. Using Al_2O_3 and Cuo Particles dispersed in water, Wang et al. [5] observed enhancement

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Nomenclature

C_p	specific heat (J/kg K)
D	diameter (m)
f	frequency (Hz)
$\bar{h}$	average convective heat transfer coefficient along the tube (W/m^2 K)
h	convective heat transfer coefficient (W/m^2 K)
I	current (A)
k	thermal conductivity (W/m K)
L	tube length (m)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
n	number of thermocouples
Nu	Nusselt number
Pr	Prandtl number
q''	heat flux (W/m^2)
q	heat flow (W)
T	temperature (°C)
V	voltage (V)
x	axial distance from the inlet of the tube (m)

Greek letters

μ	viscosity (Pa s)
τ	alternating magnetic field connection or disconnection time (s)
ϕ	volume fraction (%)
ρ	density (kg/m^3)
η	heat transfer enhancement percentage in comparison with distilled water (%)
δ	boundary layer thickness (m)

Subscripts

ff	ferrofluid
w	water
s	wall
p	particle

in thermal conductivity of nanofluids and discussed the mechanism of enhancement. Min-Sheng Liu et al. had research studies on CNT (carbon nanotube) with different base fluids showing noticeable enhancement in thermal conductivity [6]. Also, they observed 22.4% enhancement in thermal conductivity of ethylene glycol containing Cuo nanoparticles and showed that in low volume fractions, thermal conductivity of nanofluids is approximately linear with volume fraction [7]. There is plenty of research about enhancement of thermal conductivity of nanofluids and ferrofluids. Using the hot-wire technique, many researchers investigated various nanofluids with different particle types such as copper nanoparticles, gold nanoparticles, carbon nanotubes [8], multi-walled carbon nanotube, copper oxide, silicon dioxide and silver [9] with diverse procedures of synthesizing. Moreover, there are some investigations about thermal conductivity of magnetic fluids and ferrofluids. Li et al. [10] measured the viscosity and thermal conductivity of magnetic fluids under external magnetic fields and studied the effects of volume concentration and surfactants on thermal properties. They concluded that with increasing magnetic field strength, viscosity and thermal conductivity increase unless the magnetic particles are saturated. Gavili et al. [11] measured thermal conductivity and the saturation time of ferrofluids under various magnetic field strengths and reached about a maximum of 200% enhancement in thermal conductivity.

Additionally, there are numerous experimental and numerical investigations on the enhancement of laminar and turbulent forced convection heat transfer with various subjects such as the effect of particle type, particle concentration, etc., leading to remarkable results with the observance of considerable increase in heat transfer coefficient. Xuan and Li [12] had research studies on forced convection of nanofluids under turbulent flow conditions and discussed the effects of volume concentration and Reynolds number on convective heat transfer enhancement. Jung et al. [13] investigated about laminar forced convection heat transfer of Al_2O_3 nanofluids in a microcircular channel with a result of 32% convective heat transfer enhancement. Anoop et al. [14] had investigations about the effect of particle size on the process of forced convection heat transfer in the entrance region. They found out that diminishing the nanoparticle size leads to a higher convective heat transfer coefficient, and this enhancement is more effective in the entrance region in comparison with the fully developed region. Wen and Ding [15] carried out experiments about forced convection heat transfer with γ-Al_2O_3/water nanofluid and achieved noticeable enhancement in heat transfer, and also, some other researchers conducted similar investigations with diverse nanofluids under laminar flow conditions and observed heat transfer enhancement unanimously [16–21]. Sundar et al. [22] conducted experiments about forced convection of magnetic nanofluids under turbulent flow conditions with different volume concentrations and concluded that magnetic particles caused 31% enhancement in heat transfer.

Research studies about ferrofluids are numerous, but ferrofluid heat transfer has not been studied enough. Numerical investigations about ferrofluid heat transfer and Nusselt number in a two dimension cavity were conducted by Ashoury et al., and they introduced a general correlation for the overall Nusselt number [23]. A flow between two parallel planes and under the exposure of a line-source dipole magnetic field showed an increase in heat transfer [24]. Also, convection of ferrofluids in an alternating magnetic field was well characterized by Belayeav and Smorodin considering the frequency and strength of the external magnetic field, and also, the layer thickness and temperature [25]. Li and Xuan [26] had some research studies about the effect of uniform and non-uniform magnetic fields on ferrofluid convective heat transfer in low Reynolds numbers. They concluded that these magnetic fields can strongly affect the process of heat transfer.

Ferrofluid characteristics, such as viscosity and conductivity, can be subjected to change under an external magnetic field, and their rheological characteristics can be accurately controlled. Also, as mentioned, ferrofluids have the capability of heat transfer enhancement. Therefore, they have been an interesting issue for many, but not well characterized yet. Ferrofluid forced convection heat transfer under a constant magnetic field was studied by Lajvardy et al. [27] and this investigation resulted in a noticeable heat transfer enhancement, but the number of these studies is limited. Experimental studies on forced ferroconvection have not been conducted under an alternating magnetic field, and the effects of the magnetic field frequency and fluid concentration on laminar forced ferroconvection are still unspecified and in need of more study. The process of ferrofluid convection heat transfer under an alternating magnetic field is complicated, and an experimental investigation can help to study this phenomenon. The main objective of this investigation is to study the convective heat transfer of ferrofluids under alternating magnetic fields and to identify the effective factors on this complicated behavior for the first time.