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Experimental study of internal forced convection of ferrofluid flow in non-magnetizable/magnetizable porous media

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ABSTRACT

In this work, the thermal and hydrodynamic performance of ferromagnetic fluid, which flows through a copper tube in thermal entrance region, has been studied. The flow in the tube is laminar and subjected to constant heat flux. A part of the tube contains a porous medium with paramagnetic properties and porosity of 0.46. Ferrofluid is composed of Fe_3o_4 and water with $(CH_3)_4NOH$ as a surfactant that is prepared in three different volume fractions. The effects of constant and oscillating magnetic fields on convective heat transfer coefficient were examined for various Reynolds numbers, frequencies and volume fractions. The results show that the maximum enhancements of average heat transfer coefficient of Ferrofluid in a magnetizable porous medium under constant and oscillating magnetic fields are 9% and 38.66%, respectively in comparison with that of water in no magnetic field condition. This enhancement is reduced to 6.39% and 36.13% for a non magnetizable porous medium. The results indicate that variable magnetic field enhances convective heat transfer coefficient and this enhancement is greater in the magnetizable porous medium.

1. Introduction

Heat transfer is important in many industries to control temperature and there are several methods to improve its rate. Nanofluids possess immense potential to enhance the heat transfer character of the original fluid due to improved thermal transport properties. Ferrofluids are colloidal suspension which consist of magnetic particles in a base fluid. To prevent the particles from agglomerating under van der Waals attraction forces, a surfactant is used. Ferrofluid as a nanofluid with particles consisting magnetization properties has a higher thermal conductivity than other conventional fluids such as water and ethylene glycol. Furthermore, it has the potential to change the thickness of its boundary layer under the magnetic field and improve the heat transfer rate.

This ability to control the flow from outside of the pipe (non-intrusively) and no need to move the parts are important for space applications [1].

Some studies have focused on the conductive heat transfer of nanofluids. These studies have demonstrated that the application of nanoparticles in a fluid improves the conductive heat transfer.

Liu et al. conducted research into the carbon nanotube with different base fluids and observed a considerable increase in the conductive heat transfer [2]. They also observed a 22.4% enhancement in thermal conductivity of ethylene glycol containing CuO nanoparticles [3]. Conductive heat transfer of ferrofluids has been studied as well. Li et al. [4] investigated the viscosity and thermal conductivity of the magnetic fluids under the effect of an external magnetic field and they identified the effects of volume concentration and surfactants on these properties. They concluded that unless the magnetic particles are saturated, viscosity and thermal conductivity increase with increasing magnetic field strength. In a study by Gavili et al. [5], they reached an approximately 200% enhancement in thermal conductivity and obtained the time necessary for the fluids to reach the saturation state. Many studies have been carried out concerning convective heat transfer of nanofluids. Sheremet et al. [6] studied MHD free convection in a wavy open porous tall cavity filled with nanofluids under an effect of corner heater. Their results show that heat transfer enhancement with Rayleigh number and heat transfer reduction with Hartmann number, while magnetic field inclination angle leads to non-monotonic changes of the heat transfer rate.

Sheikholeslami et al. [7] simulated the nanofluid heat transfer in presence of magnetic field. Their results prove that temperature gradient augments with augment of solid particle concentration and buoyancy forces, while it decreases with augment of magnetic field.

Theoretical investigation of MHD forced convection of nanofluids and the effects of nanoparticle migrations was studied by Malvandi et al. [8–11]. They concluded that the exerted magnetic field manipulates the suspended particles and rearranges their consideration in the

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Nomenclature

D	diameter (m)
L	tube length (m)
U	fluid average speed (m/s)
$\dot{m}$	flow rate (m^3/s)
V	voltage (V)
I	current (I)
q	heat flow (W)
q''	heat flux (W/m^2)
m	mass (kg)
T	temperature (°C)
x	axial distance from the inlet of the tube (m)
C_P	specific heat (J/kg K)
K	thermal conductivity (W/m K)
h	convective heat transfer coefficient (W/m^2 K)
f	frequency (Hz)
Re	Reynolds number
Pr	Prandtl number

Greek letters

ν	kinematic viscosity (m^2/s)
τ	oscillating magnetic field period (s)
ρ	density (kg/m^3)
φ	volume fraction
η	heat transfer enhancement percentage

Subscripts

s	wall
m	bulk
in	inlet
out	outlet
w	water
p	particle

fluid which strongly changes heat transfer characteristics of the flow. Also, it was shown that increase in volume fraction of nanoparticles enhances both heat transfer rate and pressure drop.

Gibanov et al. [12] investigated the convective heat transfer of ferrofluid in a lid-driven cavity with a heat-conducting solid backward step under the effect of a variable magnetic field. They performed the analysis for a wide range of Hartmann number, nanoparticles volume fraction, and magnetic number. They found that the growth of the magnetic number leads to the heat transfer enhancement.

Lajvardi et al. [13] studied the effect of magnetic nanoparticles concentrations and magnet position on convective heat transfer of ferrofluid. They infer that the main reason for the enhancement of heat transfer coefficient could be due to remarkable changes in thermophysical properties of ferrofluid under the influence of applied magnetic field.

Yarahmadi et al. [14] investigated the effects of ferrofluids on the forced convective heat transfer in a tube with a round cross-section. The maximum enhancement of 19.8% was obtained in the local convective heat transfer by using the oscillating magnetic field in comparison with the case in which no magnetic field was applied.

Goharkhah et al. [15] studied 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 experimentally. In the absence of a magnetic field, the 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 an intensity of B = 500G, respectively. According to their studies, The heat transfer increases as the Reynolds number, ferrofluid concentration, and the intensity of the magnetic field increase.

Strek [16] investigated the heat transfer of ferrofluid in a channel with porous wall numerically. He obtained the velocity field vectors and temperature contour of ferrofluid flow under magnetic field.

Some studies have focused on the convective heat transfer coefficient of ferrofluid in the porous media.

Gibanov et al. [17] studied the MHD natural convection and entropy generation in an open cavity having different horizontal porous blocks saturated with a ferrofluid. Their results show that an addition of spherical ferric oxide nanoparticles can order the flow structures inside the cavity.

Makinde et al. [18] analyzed the MHD nanofluid flow over a convectively heated permeable vertical plate embedded in a porous medium. They investigated the dependency of the Nusselt number on magnetic parameter M, nanofluid buoyancy ratio Nr, Eckert number Ec, Lewis number Le, Brownian motion number Nb, thermophoresis number Nt and suction/injection parameter fw. Also they provided a correlation based estimation.

Khamis et al. [19] investigated the unsteady flow of variable viscosity Cu-water and Al2O3-water nanofluids in a porous pipe with buoyancy force. Their results showed that with suction, Cu-water produces higher skin friction and heat transfer rate than Al2O3-water. Both nanofluids velocity and temperature increase with a decrease in viscosity and an increase in buoyancy force intensity.

Khamis et al. [20] studied the buoyancy - driven heat transfer of water based nanofluid in a permeable cylindrical pipe with Naiver slip through a saturated porous medium numerically. Their results reveal that both nanofluid temperature and velocity are enhanced with increasing nanoparticle volume fraction and Grashof number and reduced with the increasing viscosity; Navier slip parameter; porous media resistance parameter and porous media shape factor parameter.

Sheikhnejad et al. [21] studied the heat transfer of laminar ferrofluid flow in horizontal tube partially filled with porous media under fixed parallel magnet bars. Their experimental results show promising notable enhancement in heat transfer coefficient as a consequence of partially filled porous media and use of a magnetic field. Also, it is shown that the use of both porous media and a constant magnetic field highly improves heat transfer up to 2.4-fold.

Sheikholeslami et al. [22] simulated the convective flow of water based nanofluid inside a porous enclosure via non-equilibrium model. The Roles of solid-nanofluid interface heat transfer parameter (Nhs), Rayleigh number (Ra), porosity (ε), and Hartmann number (Ha) were examined. They demonstrated that $|\psi|_{max}$ enhance with rise of Nhs but it augments with rise of Ra. Porosity has opposite relationship with temperature gradient.

Sheikholeslami et al. [23] simulated the nanofluid flow and natural convection in a porous media under the influence of electric field using CVFEM. Their Results show that maximum Nusselt number belongs to Platelet shape Fe_3O_4 nanoparticles. Nusselt number is an increasing function of Darcy number, supplied voltage and Rayleigh number.

Salehpour et al. [24] investigated the thermal and hydrodynamic performances of MHD ferrofluid flow inside a porous channel. Their results show that employing alternating magnetic field increases the heat transfer rate due to more intensified disturbance of the thermal boundary layer and improvement of the nanoparticles migrations. Also, the alternating magnetic field reduces pressure drop because of the periodic magnetic forces, leading to enhanced overall heat transfer performance of the channel.

Sehat et al. [25] studied the convective heat transfer of ferrofluid in a tube filled with permeable material. They examined the effect of

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