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Effect of an alternating nonuniform magnetic field on ferrofluid flow and heat transfer in a channel

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Forced convective heat transfer of water based Fe_3O_4 nanofluid (ferrofluid) in the presence of an alternating non-uniform magnetic field is investigated numerically. The geometry is a two-dimensional channel which is subjected to a uniform heat flux at the top and bottom surfaces. Nonuniform magnetic field produced by eight line source dipoles is imposed on several parts of the channel. Also, a rectangular wave function is applied to the dipoles in order to turn them on and off alternatingly. The effects of the alternating magnetic field strength and frequency on the convective heat transfer are investigated for four different Reynolds numbers (Re=100, 600, 1200 and 2000) in the laminar flow regime. Comparing the results with zero magnetic field case, show that the heat transfer enhancement increases with the Reynolds number and reaches a maximum of 13.9% at Re=2000 and f=20 Hz. Moreover, at a constant Reynolds number, it increases with the magnetic field intensity while an optimum value exists for the frequency. Also, the optimum frequency increases with the Reynolds number. On the other hand, the heat transfer enhancement due to the magnetic field is always accompanied by a pressure drop penalty. A maximum pressure drop increase of 6% is observed at Re=2000 and f=5 Hz which shows that the pressure drop increase is not as significant as the heat transfer enhancement.

1. Introduction

The demand for more efficient cooling methods is increasing steadily due to the importance of energy saving and also due to development of modern industrial and scientific applications. Among several methods which have been proposed for cooling and heat transfer enhancement, using of nanofluids has achieved growing interest by many researchers recently. Adding nanoparticles to the carrier fluid improves the transport properties of the fluid such as thermal conductivty and leads to heat transfer enhancement.

An innovative enhancement method is the use of magnetic nanofluid called ferrofluid which is a synthesized colloidal mixture of nonmagnetic carrier liquid, typically water or oil, containing single domain permanently magnetized nano particles, typically magnetite [1].

Ferrofluid has the merits of nanoparticles in improving the thermal properties of the fluid. Moreover, the flow field and temperature distribution can be altered by applying an external magnetic field. Thus, there is additional potential for heat transfer enhancement by flow mixing and disturbing thermal boundary layer specifically in the laminar regime. Ferrofluid can be utilized in mechanical and thermal engineering, low Reynolds flows and micro scale heat exchangers in MEMS devices, aerospace, spacecraft cooling system in microgravity conditions and bioengineering [2–7].

A comprehensive literature review reveals that the majority of numerical works on heat transfer of ferrofluid is devoted to thermomagnetic convection in which ferrofluid is confined in an enclosure and is subjected to a magnetic field [8–21]. Geometries such as cubic enclosure [8,9], rectangular cell with different aspect ratios [10–18], cylindrical [19], annular [20] and triangular [21] enclosures have been considered in numerical and experimental studies with a variety of thermal boundary conditions.

By contrast, only a few works have concentrated on the forced convection heat transfer problem [22–32].

Neuringer [22] studied the effect of magnetic field on two cases numerically, the two-dimensional stagnation point flow of a heated ferrofluid against a cold wall and the two-dimensional parallel flow of a heated ferrofluid along a wall with linearly decreasing surface temperature. Wall shear stress, heat transfer, velocity and temperature boundary layer profiles were obtained for both cases and compared to the case with no magnetic field.

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Nomenclature

B	magnetic flux density (T)
C_p	specific heat (J/kgK)
$\vec{F}_K$	magnetic body force (N)
H	magnetic field(A/m)
i, j	unit vectors (horizontal, vertical)
m	strength of the magnetic field, (Am)
M	magnetization (A/m)
Nu	Nusselt number
P	Pressure (Pa)
Pr	Prantdl number ($\mathrm{Pr}=\nu/\alpha$)
r	radial direction (m)
T	Temperature(K)
t	time(s)
V_m	scalar magnetic potential
u, v	fluid velocities (horizontal, vertical, m/s)
X, Y	locations of a single line dipole, m
x, y	Cartesian coordinates (horizontal, vertical, m)

Greek symbols

α	thermal diffusivity(m^2/s)
β	volumetric thermal expansion coefficient (1/ K)
Θ	viscous dissipation
μ	dynamic viscosity(kg/m s)
μ_0	magnetic permeability in vacuum ($4\pi\times10^{-7}$ N/A^2)
ρ	density(kg/m^3)
ϕ	polar angle (rad)
χ_m	magnetic susceptibility

Subscripts

ref	reference condition
0	at reference temperature (300 K)
f	fluid
m	mean value
nf	nanofluid
p	particle

Ganguly et al. [3] numerically studied the two-dimensional forced convection heat transfer of a hot ferrofluid flowing through a channel with a cold wall under the influence of a line-source dipole. It was shown that the local vortex resulted from the magnetic field alters the advection energy transport and enhances the heat transfer.

Strek and Jopek [23] studied the two-dimensional and time dependent heat transfer of a ferrofluid in a channel with isothermal walls under the influence of the magnetic dipole located below the channel. They showed that an imposed thermal gradient produces a spatial variation in the magnetization through the temperature dependent magnetic susceptibility for ferrofluids and therefore renders the Kelvin body force nonuniform spatially. Furthermore, Strek [24] considered the ferrofluid flow in a channel with porous walls and studied the effect of Darcy number on the heat transfer and fluid flow.

Xuan et al. [25] calculated the flow and temperature distribution of a ferrofluid in a micro channel with adiabatic and isothermal walls using the lattice-Boltzmann method. In their work the magnetic force was considered a constant and it was shown that heat transfer augmentation depends on the magnitude and direction of the the magnetic force.

Aminfar et al. [26] numerically studied the mixed convection of a ferrofluid in a vertical tube in the presence of nonuniform magnetic field using a two phase mixture model and control volume technique. They considered the positive and negative magnetic field gradients and showed that that the magnetic field with negative gradient acts similar to the buoyancy force and enhances the Nusselt number, while the magnetic field with positive gradient decreases it. More recently, Aminfar et al. [27] studied the forced convection of ferrofluid in a duct under the influence of a transverse nonuniform magnetic field which was generated by an electric current going through a wire parallel with the duct. They reported a considerable enhancement of the average heat transfer coefficient for their studied case.

Additionally, several numerical works have been carried out on biomagnetic fluid dynamics (BFD) in which blood as a magnetic fluid is under the influence of an external magnetic field [28–32]. The governing equations for these problems are similar to those derived for ferrofluids. In these works magnetization of the fluid is assumed to vary linearly with temperature and magnetic field intensity, and the line dipole is used as the source of magnetic field. The temperature, as well as the skin friction and the rate of heat transfer were shown to be increasing near the magnetic source.

The present research addresses the laminar forced convective heat transfer of water based Fe_3O_4 ferrofluid in a two-dimensional channel under an alternating nonuniform magnetic field. A constant heat flux is applied at the top and bottom surfaces of the channel. The main objective is to characterize the heat transfer augmentation by periodical attraction of colder fluid to the surface by the magnetic field, transfer of surface heat to the fluid and release of the fluid into the bulk flow. The magnetic field is produced by placing the line dipoles on the top and bottom of the channel. A rectangular wave function is also applied to the dipoles in order to generate an alternating magnetic field. The effects of the magnetic field strength and frequency on the convective heat transfer is examined and the optimum frequency is obtained for different Reynolds numbers. Moreover, temporal variations of the velocity and the temperature profiles in the channel are calculated through a time dependent numerical simulation and then used to explain the heat transfer characteristics of the ferrofluids.

2. Problem description

The cold ferrofluid flows through a two-dimensional channel with the size of 0.004 m(H) × 0.5 m(L) which is heated by a uniform heat flux from top and bottom surfaces. The flow is considered homogenous and laminar. The thermal properties of the fluid are assumed to be constant and the buoyancy effects are negligible compared with the forced convection and hydromagnetic effects. The schematic of the problem is shown in Fig. 1.

A two-dimensional magnetic field used in the simulations is created by eight identical magnetic dipoles along the top and bottom surfaces. Four line dipoles are placed above the top surface and four line dipoles beneath the bottom surface. Magnetic field of a dipole can be an approximation of the field produced by an edge-dipole permanent magnet or an electromagnet composed of a rectangular current-carrying loop of very high aspect ratio. Other realistic magnetic fields can also be simulated by appropriate arrangment of a