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CFD modeling and sensitivity analysis of heat transfer enhancement of a ferrofluid flow in the presence of a magnetic field

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ABSTRACT

In this paper, a numerical method is developed to simulate the effect of an external magnetic field on convection heat transfer of a ferrofluid flow inside a rectangular duct. This model is two-dimensional, steady-state, laminar and incompressible. Simple finite volume method is used to couple and solve continuity, momentum and energy equations. In the first part of this paper, it is observed that ferrofluid particles movement along the magnetic field of a line dipole changes the streamline patterns and enhances heat transfer. In the second part of this paper, a sensitivity analysis is performed to investigate the effects of Reynolds number, magnetic field strength, location, and number of line dipoles on the convection heat transfer. It is observed that cooling rate is higher at larger Reynolds numbers while increasing magnetic field strength would not necessarily result in noticeable improvement in heat transfer. It is also noticed that magnetic field strength should be large enough to merge small vortexes and to create large circulation zones inside the duct. Our simulation also revealed that heat transfer could be augmented by adding line dipoles on high-temperature regions closer to the duct inlet.

1. Introduction

Efficient cooling has become very important in many applications including power semiconductor devices, microelectromechanical systems (MEMS), electronic chips and other power electronic devices [1–3]. Liquid cooling is a usual heat removal method in these applications [4]; however, this technique can become inefficient due to low specific heat capacity and thermal conductivity of the coolant liquids [5] particularly at low Reynolds numbers. This problem can be even more noticeable in high power devices that have high flux heat densities. Therefore, increasing liquid thermal conductivity and enhancing convection heat transfer are considered as solutions for overcoming the issue [6]. Magnetic nanofluid called ferrofluid as a coolant liquid has exhibited good potential for improving heat transfer [5,7–9]. Ferrofluids are colloidal suspensions of magnetite nanoparticles (cobalt, iron or magnetite) in a base liquid (usually water or oil) [10]. Although the liquid carrier possesses low electrical conductivity, magnetite nanoparticles can improve the thermal conductivity of the whole suspension. Furthermore, heat transfer can be enhanced through thermomagnetic heat transfer, wherein the ferrofluid flow pattern is altered by applying an external magnetic field [8]. This property of ferrofluids is vital in micro-scale devices where diffusion is limited due to low Reynolds number effects [11].

The nature of thermomagnetic heat transfer has not been well characterized yet. Most of the previous literature has focused on thermomagnetic free (natural) convection in different geometries [3,7,12–18]. Tangthieng et al. [7] solved two thermomagnetic heat transfer problems by using finite element analysis. In their first work, they studied thermomagnetic free convection in a ferrofluid flow between two vertical parallel plates with the same temperature while in the second problem they investigated heat transfer enhancement in a square box. They developed and extended Navier-stokes equations for each case and used a commercial code to solve these equations. Analyzing the results, they noticed slight and negligible heat transfer improvement in the first case. In contrary, the Nusselt number was increased noticeably in the second case (about 45%). Krakov et al. [14] studied the natural convection in the presence of a uniform magnetic field in a square cavity. Constant heat flux boundary condition was assumed at the bottom of the cavity while sidewalls were considered to be insulated. They performed several simulations for different orientations of a magnetic field and discovered that changing the angle between the magnetic field and temperature gradient would influence heat transfer intensity. Performing another similar study for a porous cavity, Krakov et al. [15] concluded that manipulating magnetic field could result in both amending and hindering the cooling rate

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Nomenclature

B	magnetic field (T)
C_p	specific heat (J/kg K)
F_k	magnetic body force (N)
H	magnetic field
h	convective heat transfer coefficient (W/m^2 K)
i	unit vector (horizontal)
j	unit vector (vertical)
k	thermal conductivity (w/m K)
m	strength of the magnetic field of a line dipole (A m)
M	magnetization (A/m)
Nu	Nusselt number
$\overline{Nu}$	average Nusselt number
P	pressure
Pr	Prandtl number
q_w	wall heat flux (w/m^2)
Re	Reynolds number
t	time (s)
T	temperature (K)
u	velocity in x direction (m/s)
v	velocity in y direction
U	velocity vector
V_m	scalar magnetic potential
X	horizontal locations of a single line dipole, m
Y	vertical locations of a single line dipole, m
x	axial distance (m)
y	vertical distance

Greek symbols

β	volumetric thermal expansion coefficient (1/K)
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
∅	Viscous dissipation
χ_m	magnetic susceptibility
θ	dimensionless temperature

Subscripts

0	reference temperature
of	Outlet flow

because of the competition between gravity convection and thermomagnetic convection mechanisms. Yamaguchi et al. [18] conducted both numerical and experimental tests to characterize the effect of a magnetic field caused by a ring magnet on a flow between two concentric cylinders. The also performed a similar study on a partitioned square cavity and inferred that convection heat transfer could be augmented by applying an external magnetic field at higher Rayleigh numbers. Odenbach et al. [3,16] studied zero gravity thermomagnetic convection in a cylindrical geometry and in a case of a radially imposed magnetic field. Although they managed to conduct a series of elegant experiments to investigate the effect of a realistic imposed magnetic field, they did not find a function for heat transfer enhancement based on magnetizing current.

Although imposing a magnetic field can improve the free convection heat transfer, it has a higher potential for increasing the forced convection heat transfer since it distorts the thermal boundary layer [11]. Strek and Jopek [19] developed a transient, two-dimensional numerical model to study the effect of a magnetic field on convection heat transfer of a laminar flow between two isothermal walls. The magnetic field was caused by a magnetic dipole which was placed under the channel. They showed that the temperature gradient between two surfaces caused non-uniform body forces and inferred that this could either improve or hinder heat transfer. Xuan et al. [1] used a thermal lattice-Boltzmann method to obtain temperature and flow distribution of a ferrofluid flow inside a micro channel in the presence of a constant magnetic field. They concluded that heat transfer improvement depends on the orientation and magnitude of the magnetic field. They also inferred that the highest heat transfer augmentation occurs when magnetic field lines are parallel with the flow streamlines. Ganguly et al. [8] studied the effect of several line dipoles on the ferrofluid flow heat transfer by calculating Kelvin body forces components in x and y directions. They used finite difference method to solve the governing equations and inferred that magnetic field caused by line dipoles could create several circulation zones and improve heat transfer. Although their work provided a very good understanding of heat transfer augmentation in the presence of one or several magnetic fields, they did not provide a good visualization of streamlines to provide more details of thermomagnetic heat transfer. They also did not investigate the effect of line dipoles locations on thermomagnetic heat transfer. Aminfar et al. [20] developed a two-phase numerical model to study the mix convection of a ferrofluid in a vertical duct in the presence of a magnetic field caused by a line dipole placed under the duct. They showed that imposing a magnetic field with a negative gradient in flow direction could enhance heat transfer by flattening the velocity profile while imposing a magnetic field with a positive gradient in flow direction lowered heat transfer rate. Performing several experimental tests and changing the magnetic flux density from 0 mT and 500 mT, Motozawa et al. [21] measured 20% improvement in heat transfer coefficient in the rectangular duct subjected to constant heat flux. Lajvardi et al. [9] conducted a similar experimental tests and noticed heat transfer improvement when they applied a perpendicular uniform magnetic field on a ferrofluid flow. They attributed this improvement to changes in the ferrofluid properties including aggregation and changes in solid volume fraction. Azizian et al. [22] used an experimental approach to study the effect of an external magnetic field on laminar convection heat transfer. A noticeable improvement in local heat transfer coefficient (up to 300%) was noticed in their experimental results. They validated their experimental results by performing numerical simulations using COMSOL Multiphysics. It was construed that the accumulation of Fe_3O_4 particles in the vicinity of the magnets is the main reason for heat transfer enhancement. Goharkhah et al. [11] studied the effect of a non-uniform magnetic field caused by eight line dipoles on a ferrofluid flow in a channel. Constant heat fluxes were assumed on top and bottom surfaces of the channel. They changed the magnetic field by feeding a rectangular wave function to the dipoles. They modified Navier-stokes equation by adding magnetic body forces and used SIMPLEC procedure for coupling and solving the equations. They also performed sensitivity analysis on the different Reynolds number and different magnetic field strengths and concluded that cooling rate is proportional to Reynolds number and magnetic field strength. Although their work provided a good insight into the concept of thermomagnetic convection, they did not investigate the effects of multiple dipoles and the special distribution of these dipoles on heat transfer. In one of the most recent studies, Szabo at al. [23] studied a transition from natural convection to thermomagnetic convection in presence of a non-uniform magnetic field. They inferred that there is a gradual transition between natural convention to