International Journal of Mechanical Sciences 118 (2016) 101–112

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Forced convection heat transfer in a channel under the influence of various non-uniform transverse magnetic field arrangements

M.M. Larimi, A. Ghanaat*, A. Ramiar, A.A. Ranjbar

Faculty of Mechanical Engineering, Babol, Noshirvani University of Technology, Iran

ARTICLE INFO

Keywords:
Ferro-fluid
Non-uniform magnetic field
Heat transfer
Surface friction

ABSTRACT

Magnetic nanofluids (MNFs) are suspensions, comprising a non-magnetic base fluid and magnetic nanoparticles. In modern set of suspensions called smart or functional fluids, fluid flow, particle movement, and heat transfer process can be controlled by magnetic fields. The present study investigated hydro-thermal characteristics of ferrofluid (water and Fe_3O_4) in a rib-channel exposed to several non-uniform transverse magnetic fields generated by an electric current going through several wires located perpendicularly in the flow between ribs. Two-phase mixture model and control volume technique were used to carry out the study. The effect of transverse magnetic field on heat transfer, consequent pressure loss, and wall shear stress resulting from this kind of magnetic field along the channel was investigated as well as the effect of various magnetic field arrangements. The results showed that magnetic field would have an unexpected influence on increasing Nusselt number in the channel, and raising the strength of magnetic field would cause an increase in minimum and maximum local Nusselt numbers, especially in rib regions. Furthermore, applying external magnetic field could noticeably affect fluid cooling at low Reynolds numbers. The influence of magnetic field on pressure drop and skin friction also are investigated in this study and it is illustrated that applying magnetic field increased skin friction especially in the case which whole magnetic wire located in one side on channel.

1. Introduction

Recent technological advances in electronics and thermal systems have led to an ever-increasing demand for heat transfer systems with higher efficiency. Of the many technological applications of magnetic fluids, four main categories can be singled out: (a) dynamic sealing; (b) heat dissipation; (c) damping; and (d) doping technological materials. One way to extract heat from a piece of equipment which heats up by functioning, keeping it not too hot, is using a good heat conductor capable of connecting the equipment to some mass with higher heat capacity, and perhaps, much bigger open surface to dissipate heat. In some cases, a good heat conductor need not be a solid since it would block the equipment operation (for example, if it has to vibrate). An alternative to achieve the desired goal could be using ferrofluid as heat conductor. A non-magnetic liquid would flow away from the place where supposed to operate. A good example is a loudspeaker whose coil heats up by functioning in which ferrofluid can be kept together with magnetic field of a magnet fixed on the loudspeaker horn. Nowadays, most of the high power loudspeakers are equipped with ferrofluid, which is a magnetic colloidal suspension of single domain magnetic nanoparticles. It can be utilized in heat transfer applications since the flow field established by ferrofluid can be suitably changed by applying external magnetic fields. Many investigations were carried out numerically and experimentally in the field of thermomagnetic convection of ferrofluid at different geometries in the presence of an external magnetic field [1–10].

Bhatti et al. [11,12] conducted research into entropy generation on MHD nanofluid towards a stagnation point flow over a stretching surface as well as MHD eyring–powell nanofluid through a permeable stretching surface. They observed that entropy generation number would increase due to an increment in Brinkman number and Reynolds number. Bhatti et al. [13] studied entropy generation with radiation on non-Newtonian Carreau nanofluid towards a shrinking sheet. They found that the influence of magnetic field and fluid parameters would oppose to the flow. They also found that thermal radiation effects and Prandtl number would show opposite behavior in temperature profile. A novel numerical method was used by Bhatti et al. [14] to simulate MHD stagnation-point flow over a permeable stretching/shrinking sheet in porous media in the presence of heat transfer. Qing et al. [15] studied entropy generation on MHD Casson nanofluid flow over a porous stretching/shrinking surface.

Zeeshan and Majeed [16] investigated non darcy mixed convection

* Corresponding author.
E-mail address: arash.ghanaat@gmail.com (A. Ghanaat).

http://dx.doi.org/10.1016/j.ijmecsci.2016.09.023
Received 7 June 2016; Received in revised form 18 September 2016; Accepted 20 September 2016
Available online 21 September 2016

Nomenclature

B	Magnetic Magnitude (T)
C_D	Drag Coefficient
Cc	Cunningham Correction Factor
D	Channel Diameter (m)
H	Magnetic Field Intensity (N/m A)
Ha	Hartmann Number
J	Current Density (A/m^2)
K_{nf}	Thermal diffusivity (W/m K)
M	Material Magnetization (N/m A)
Mn_f	Magnetic Numbers
Nu	Nusselt Number
F_L	Lorentz Force (N)
P	Pressure (Pa)
Re	Reynolds Number
T	Fluid Temperature (K)
T_c	Curie Temperature (K)
u,v,w	Velocity Components in x,y,z direction (m/s)

Greek symbols

μ_0	Magnetic Permeability Of Vacuum (N/A^2)
χ	Magnetic Susceptibility (m^3/Kg)
ρ	Density (Kg/m^3)
μ	Fluid Dynamic Viscosity (Pa s)
λ	Fluid Kinematic Viscosity (m^2/s)
γ	Magnetic Field Strength (N/m A)
σ	Electrical conductivity (S/m)
φ	Volume Fraction Of Nanoparticles
α_{nf}	Thermal Diffusivity of the Nanofluid
μ_{nf}	The Dynamic Viscosity Of the Nanofluid
μ_0	Magnetic Permeability Of Vacuum (N/A^2)

Indexes

s	Solid phase
f	Fluid phase
nf	Nano-fluid phase

flow of magnetic fluid over a permeable stretching sheet with ohmic dissipation. The results showed that skin friction coefficient would increase with rises in ferromagnetic interaction parameter, whereas Nusselt number would decrease. Shehzad et al. [17] analyzed convective heat transfer of nanofluid in a wavy channel. Ellahi et al. [18] studied shape effects of nanosize particles in Cu–H_2O nanofluid on entropy generation. They found a correlation between Nusselt number and skin friction corresponding to some active parameters. Zeeshan et al. [19,20] examined magnetohydrodynamic flow of water/ethylene glycol based nanofluids with natural convection through a porous medium and the effect of magnetic dipole on viscous ferrofluid passing a stretching surface with thermal radiation.

Makinde [21,22] researched the thermal boundary layer of nanofluids over an unsteady stretching sheet with a convective surface boundary condition. He also examined the effects of viscous dissipation and Newtonian heating on boundary-layer flow over a flat plate in three types of water-based nanofluids containing metallic or nonmetallic nanoparticles at a range of nanoparticle volume fractions. Khan et al. [23] studied non-aligned MHD stagnation point flow of variable viscosity nanofluids passing a stretching sheet with radiative heat. They found that non-alignment of re-attachment point on sheet surface would decrease with an increase in magnetic field intensity. Makinde et al. [24,25] analyzed heat transfer characteristics of Berman flow of water based nanofluids containing copper (Cu) and alumina (Al_2O_3) as nanoparticles in a porous channel with Navier slip, viscous dissipation, and convective cooling. They also studied MHD flow of a variable viscosity nanofluid over a radially stretching convective surface with radiative heat.

Strek and Jopek [26] simulated heat transfer with ferrofluid under the influence of magnetic dipole. Tzirtzilakis et al. [27] investigated biomagnetic fluid flow in a 3D rib-channel. They reported that the flow would noticeably influence the presence of magnetic field. Tzirtzilakis [28] studied electrical conductive blood flow under the influence of localized magnetic field in a channel with stenosis. Strek and Jopek [29] analyzed laminar heat transfer of ferrofluid flowing through a channel between two parallel plates under the influence of a magnetic dipole located below the channel. The upper and lower plates were kept at constant but different temperatures.

Li and Xuan [30] studied convective heat transfer of Fe_3O_4-water nanofluid flow over a fine wire under the influence of uniform and non-uniform magnetic fields. They found that in the absence of magnetic field, MNF would present higher heat transfer compared to water. Lajvardi et al. [31] conducted research into convective heat transfer of water-Fe_3O_4 ferrofluid flowing through a tube in laminar regime in the

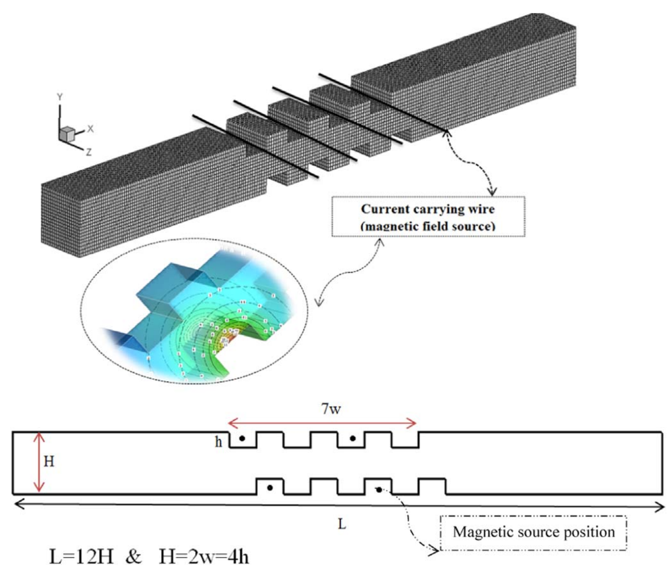

Fig. 1. Geometry.

presence of magnetic field perpendicular to flow direction. They evaluated the effect of ferrofluid concentration and magnet position in their experiments. Shima and Philip [32] studied the effect of magnetic field on thermal and rheological properties of MNFs and found that these properties could be tuned from low to very high values by varying magnetic field strength and its orientation. Gavili et al. [33] surveyed thermal conductivity of ferrofluid containing Fe_3O_4 nanoparticles suspended in de-ionized water. The results showed that in the absence of magnetic field, enhancing thermal conductivity would not be noticeable, while applying a magnetic field would increase thermal conductivity. The study reported more than 200% enhancement at maximum value under the effect of magnetic field. SyamSundar et al. [34] determined convective heat transfer coefficient and friction factor of Fe_3O_4 MNF flowing in a circular tube at $3000 < Re < 22{,}000$. The amount of heat transfer when using nanofluid was higher compared to water and increased with volume concentration. They developed a correlation between the experimental data to estimate Nusselt number and friction.

In a study conducted by Engler et al. [35], a commercial ferrofluid consisting of magnetite nanoparticles (6.3 vol%) and a synthetic ester as the base fluid called APG 513A (Ferrotec) were applied having pyromagnetic coefficient of 35.3 A/mK at magnetic field strength of