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Effect of MHD on heat transfer through ferrofluid inside a square cavity containing obstacle/heat source

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A R T I C L E I N F O

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A B S T R A C T

This article contains numerical simulations of the influence of external magnetic field on free convection heat transfer in ferrofluid flow through a square cavity filled with water based ferrofluid when a heated square blockage with different aspect ratios ($0.25 \le A/H \le 0.5$) is placed at the centre of enclosure. Vertical boundaries of enclosure are assumed insulated, top horizontal wall is taken as cold while bottom horizontal wall is heated uniformly. The square obstacle is present at the centre of cavity which also serves as heat source in fluid. The mathematical model is presented in the form of nonlinear PDE's, which are solved using Galerkin finite element method. Results are shown for wide ranges of physical parameters like Rayleigh, Prandtl and Hartmann numbers etc. The heat and flow structures are noticed to be significantly dependent on strength of magnetic field, Rayleigh number and concentration of ferroparticles present in the base fluid.

1. Introduction

Phenomena of natural convection in cavities of different geometrical orientations is the region of prime interest for young investigators due to its applications in technology and engineering including heat transfer in refrigerator, cooling and heating systems of buildings and solar systems, condensers etc. Investigations on convection heat transfer are presented in the books of Martynenko and Khramtsov [1] and Pop and Ingham [2].

In last few decades, many researchers investigated the heat transfer through natural convection in various geometries of cavities like Sathiyamoorthy and Chamkha [3] carried out simulations of electrically conducting free convective flow inside a linearly heated square enclosure. They assumed uniform heating along bottom wall where top wall of container is taken insulated whereas vertical boundaries are heated linearly and MHD is applied with inclination angles $\phi = 0$ and $\phi = \frac{\pi}{2}$. Revnic et al. [4] analysed effect of MHD on unsteady free convective heat transfer inside a square container considering a constant heat generation.

Javed et al. [5] investigated natural convective energy transfer through isosceles triangular cavity containing porous medium in the presence of uniform magnetic field when its side walls are either heated uniformly or non-uniformly. They used finite element method to calculate numerical solutions and shown results for various ranges of physical flow parameters including Hartmann, Prandtl and Rayleigh numbers. Mohammad and Viskanta [6] worked on numerical computation of lid driven mixed convective heat flow inside a container of rectangular shape containing liquid gallium. In their study, enclosure is provided heat from lower boundary while upper boundary is taken cold and is considered to be moving with constant velocity. They observed significant effects of moving lid on flow and thermal structure. Basak et al. [7] numerically examined heat transfer inside a trapezoidal shaped enclosure, considering uniform heating along bottom wall, linear heating along side walls. They computed results for various inclination angles of side walls and for wide range of physical parameters governing the flow. Hossain and Alim [8] investigated free convective heat flow through a trapezoidal container under the influence of MHD when bottom wall is subject to either uniform or nonuniform heating. They considered insulated upper wall and different angles of inclination for side walls of container and shown that the heat transfer and flow structures is significantly dependent upon physical parameters including Rayleigh number, Prandtl number and inclination angle.

Ferrofluid is a combination of nanoscale ferromagnetic particles with some base fluid in which these particles are mixed like water as in our case. Ferrofluids are known to become heavily magnetized when strong magnetic field is applied upon it and this property make the ferrofluids suitable for many scientific and engineering applications like rocket fuel in space, high speed computer disk drives, audio speakers and to form liquid seals around spinning drive shafts etc. Ferrofluids are also used in material sciences, medical applications, analytical instrumentations, optics, domain detection, switches, solenoids and heat transfer etc. [9]. Some interesting research work has been done on

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Nomenclature

Ar	Aspect ratio (Ar = A/H), m
A	Height of the heated square blockage, m
B_0	Magnetic induction, Tesla N/Am^2
c_p	Specific Heat, J/kg K
g	Gravitational acceleration, m/s^2
H	Square cavity size, m
Ha	Hartmann Number($Ha^2 = \sigma_f B_0^2 H^2/\mu_f$)
K	Thermal Conductivity, W/m K
L	Cavity Length, m
Nu	Nusselt number
$\overline{Nu}$	Average Nusselt number
P	Pressure, N/m^2
P	Dimensionless pressure, $P = pH^2/\rho_{ff}\,\alpha_f^2$
Pr	Prandtl Number
Ra	Rayleigh Number ($Ra = g\beta_f H^3(T_h - T_c)Pr/\nu_f^2$)
T	Temperature, K
T_c	Low Temperature, K
T_h	High Temperature, K
(u,v)	Dimensional velocity components
(U,V)	Non-dimensional velocity components
x, y	Dimensional coordinates
X, Y	Dimensionless coordinates

Greek symbols

α	Thermal diffusivity, m^2/s
β	Coefficient of thermal expansion, K^{-1}
γ	Penalty parameter
ΔT	Temperature difference, T_h-T_c, K
θ	Non-dimensionless temperature
ϕ	Solid Volume Friction
μ	Dynamic viscosity, Kg/m s
ρ	Local density, Kg/m^3
ν	Kinematic viscosity, m^2/s
σ	Electrical conductivity, Am/V
ψ	Dimensionless Stream function

Subscript

b	Bottom wall
c	Cold
h	Heat source
f	Base fluid
ff	Ferrofluid
s	ferroparticle
t	Top wall

ferrofluids in recent years including Mustafa et al. [10] who analysed heat flow in ferrofluid over a stretchable rotating disk under the influence of MHD. Satyajit et al. [11] investigated free convective heat flow in cobalt-kerosene ferrofluid filled in a C-shapped cavity in the presence of MHD. They computed numerical results for wide range of physical parameters Ra ($10^3 \le Ra \le 10^7$), Ha ($0 \le Ha \le 100$) and solid volume fraction ($0 \le \phi \le 0.15$) and found that heat flow rate increases up to 52.65% due to augmentation in Ra while considering solid volume fraction 15%. They furthermore demonstrated that escalation in Ha decreases heat flow rate. Sheikholeslami and Ganji [12] examined the influence of magnetic field on convective heat flow through ferrofluid flowing in a semi annular container considering sinusoidal hot wall and shown numerical results for wide range of various physical parameters arising due to ferrohydrodynamic (FHD). Heat dissipation effects convective heat flow inside a partially heated square container filled with kerosene cobalt ferrofluid considering MHD effects incorporating Lattice Boltzmann Method (LBM) is examined by Keyfayati [13]. He found heat transfer is decreasing function of solid volume fraction. Heat flow through free convection in a square enclosure filled with ferrofluid considering MHD effects is analysed by Selimefendigil et al. [14]. They computed numerical results to show the effects of pertinent flow parameters on heat and fluid flow patterns when a heater is placed on left boundary and right vertical boundary is supplied uniform heat considering all other boundaries to be adiabatic. Using numerical and statistical techniques, Rahman et al. [15] computed results for natural convection in ferrofluid filled inside the semi-circular cavity influenced by MHD effects and noticed that Ra, Ha and ϕ have significant effects on temperature gradient and flow structures. Kefayati [16] used Lattice Boltzmann Method to examine free convective heat flow in a linearly heated container of square shape under MHD effects when ferrofuid is flowing through the cavity and noticed that Nusselt number decreases when ferromagnetic particle volume fraction increases for any Ra. Selimefendigil and Oztop [17] examined heat flow by forced convection through ferrofluid under MHD effects with an adiabatic rotating cylinder present in the square cavity and shown results for different ranges of flow parameters. Taking into account various heater configurations, Rabbi et al. [18] computationally examined MHD effects upon mixed convective heat flow through triangular and semi-circular notched enclosure containing Fe_3O_4-water ferrofluid. They presented results against different values of pertinent flow parameters.

Above literature survey reveals that study of heat transfer in ferrofluid through cavities of different geometrical shapes is a popular field of research. Despite of invention of ferrofluid in 1963 there is still a lot to explore in this area. It is therefore the purpose of present investigation is to investigate the effects of different flow parameters on nature of heat and fluid flow in water based ferrofluid filled inside an enclosure influenced by magnetic effects when cavity is heated from lower horizontal wall where vertical walls are insulated and top horizontal wall is kept as cold with hot square block is placed at centre of the cavity with different aspect ratios. The present study may be experienced in several engineering applications that are electromechanical systems (MEMS), solar collectors, microelectronic devices, heating and cooling of buildings, solidification, coating, float glass production, double pane windows, micro nuclear energy and many more [19–23]. Convective heat transfer control in the presence of a uniform magnetic field in a cavity can be utilized to affect the heat transfer characteristics. Results obtained by present numerical investigation can be employed to get the optimal flow and geometrical parameters to attain effective heat transfer development in above mentioned systems.

2. Mathematical model

A geometrical representation of the square cavity which is considered in this investigation is presented in Fig. 1. The height and width of the enclosure is represented by *H* and length of cavity is supposed to be long enough so the investigation can be considered as 2D in Cartesian co-ordinate system. The bottom horizontal boundary of enclosure is taken at a constant hot temperature T_h while top horizontal boundary is considered at cold temperature $T_{c,}$ whereas side walls of a cavity are maintained as adiabatic. A heated square block with different aspect ratios ($0.25 \le A/H \le 0.5$) is placed at the centre of the square enclosure as shown in Fig. 1.

The gravitational acceleration acts along negative y axis. All thermo-physical characteristics of fluid are considered constant except density and Boussinesq approximation [24] is applied for the density deviation due to temperature dependence of ferrofluid in the buoyancy