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Mixed convection of nanofluid filled cavity with oscillating lid under the influence of an inclined magnetic field

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In this study, mixed convection of an oscillating lid-driven cavity filled with nanofluid under the influence of an inclined uniform magnetic field was numerically investigated. The cavity is heated from below and cooled from above while side walls are assumed to be adiabatic. The top wall velocity varies sinusoidally while no-slip boundary conditions are imposed on the other walls of the cavity. The governing equations was solved by Galerkin weighted residual finite element formulation. The numerical investigation was performed for a range of parameters: Richardson number ($10^{-1} \leq \mathrm{Ri} \leq 10^{2}$), Hartmann number ($0 \leq \mathrm{Ha} \leq 60$), inclination angle of the magnetic field ($0 \leq \gamma \leq 90^{\circ}$), non-dimensional frequency of the oscillating lid ($0.001 \leq \mathrm{St} \leq 1$) and solid volume fraction of the nanoparticle ($0 \leq \phi \leq 0.04$). It is observed that the flow and thermal patterns within the cavity are affected by the variation of these parameters. The heat transfer process becomes inefficient for high Strouhal number, high Hartmann number and high Richardson number. Maximum enhancement of averaged heat transfer and the damping of the convection within the cavity due to the Lorentz forces caused by magnetic field are attained for magnetic inclination angles of $\gamma = 90^{\circ}$ and $\gamma = 60^{\circ}$. As the solid volume fraction of nanoparticles increases averaged heat transfer enhancement of 28.96% is obtained for volume fraction of $\phi = 0.04$ compared to base fluid.

1. Introduction

The interaction between the shear driven flow and natural convection in cavities is quite complex and due to its importance in many engineering fields such as cooling of electronic devices, coating, solidification, food processing, float glass production and microelectronic devices. A vast amount of literature is dedicated to the studies related to forced or mixed convection in various systems which are simplified models of some of the important engineering applications [1–5]. Lid velocity was assumed to be constant in most of the studies related to the mixed convection in lid driven cavity problems. Many researchers studied the oscillating lid parameters and found that on the flow field and heat transfer characteristics in cavities are affected by the variation of the oscillating lid parameters [6–10]. In some applications such as food processing, heat transfer and mass transport phenomena are effected by time dependent lid velocities. The interaction between the oscillating lid frequency and natural frequency of the cavity was investigated. Mixed convection in a square cavity with double-sided oscillating lids was numerically investigated by Noor et al. [6]. They identified various flow patterns and observed that the oscillating frequency has negligible influence on the flow patterns at very low Reynolds number. Khanafer et al. [9] studied the transient mixed convection in a sinusoidally sliding lid driven cavity using finite element method for various Reynolds numbers, Grashof numbers and lid oscillation frequencies. They observed enhancement or deterioration of heat transfer with Reynolds and Grashof number depending on the conduct of the velocity cycle. Chen and Cheng [8] numerically studied the mixed convection in a rectangular cavity with an oscillating lid.

Magnetic field effect of electrically conducting fluid on the heat transfer and fluid flow (magnetohydrodynamics-MHD) can be encountered in many engineering applications such as purification of molten metals, microelectro-mechanical systems, coolers of nuclear reactors and many systems [11]. Convection heat transfer can be controlled by using an external magnetic field as studied by many researchers [12–24]. Oztop et al. [25] studied the mixed convection with a magnetic field in a top sided lid-driven cavity heated by a corner heater. They showed that heat transfer decreases with increasing the Hartmann number and magnetic field plays an important role to control heat transfer and fluid flow.

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Nomenclature

B_0	magnetic field strength
Gr	Grashof number, $\frac{g\beta_f(T_h-T_c)H^3}{\nu_f^2}$
h	local heat transfer coefficient, (W/m^2K)
Ha	Hartmann number, $B_0H\sqrt{\frac{\sigma_{nf}}{\rho_{nf}\nu_f}}$
k	thermal conductivity, (W/m.K)
H	height of the enclosure, (m)
n	unit normal vector
Nu_x	local Nusselt number
Nu_m	averaged Nusselt number
p	pressure, (Pa)
Pr	Prandtl number, $\frac{\nu_f}{\alpha_f}$
Re	Reynolds number, $\frac{u_0H}{\nu_f}$
T	temperature, (K)
u, v	x-y velocity components, (m/s)
x, y	Cartesian coordinates, (m)

Greek Characters

α	thermal diffusivity, (m^2/s)
β	expansion coefficient, (1/K)
ϕ	solid volume fraction
ν	kinematic viscosity, (m^2/s)
θ	non-dimensional temperature, $\frac{T-T_c}{T_h-T_c}$
ρ	density of the fluid, (kg/m^3)
σ	electrical conductivity, (S/m)
Ψ	dimensionless stream function

Subscripts

c	cold
h	hot
m	average
nf	nanofluid
p	solid particle
st	static

Pirmohammadi and Ghassemi [26] studied the steady, laminar natural convection in the presence of a magnetic field in a tilted enclosure heated from below. Their results showed that for a given inclination angle, as the value of Hartmann number increases, the convection heat transfer reduces. Sheikholeslami and Ganji [27] numerically studied the effects of an external magnetic field on ferrofluid flow and heat transfer in a semi-annulus enclosure with sinusoidal hot wall by using Control Volume based Finite Element Method. They showed that for low Rayleigh number, as the Hartmann number increases and Magnetic number decreases, heat transfer enhances while opposite trend was observed for high Rayleigh number. In heat transfer applications, nano-sized particles are added in the base fluid such as water or ethylene glycol to improve the thermal conductivity of the base fluid [28–34]. Nanofluids improve the heat transfer characteristics with little pressure drop as compared to base fluids [28,35,36]. Hajmohammadi et al. [37] numerically studied the nanofluid flow over a permeable plate for convective boundary conditions by using Cu-water and Ag-water nanofluids. They observed that for injection and impermeable surface case, the inclusion of nanoparticles enhances convective heat transfer.

MHD with nanofluids offers a good possibility to control the convection as it has been studied by many researchers [38–56]. Sheikholeslami et al. [45] studied the magnetic field effect on natural convection heat transfer in cavity filled with CuO-water nanofluid using Lattice Boltzmann method. The effect of Brownian motion on the effective thermal conductivity was considered.

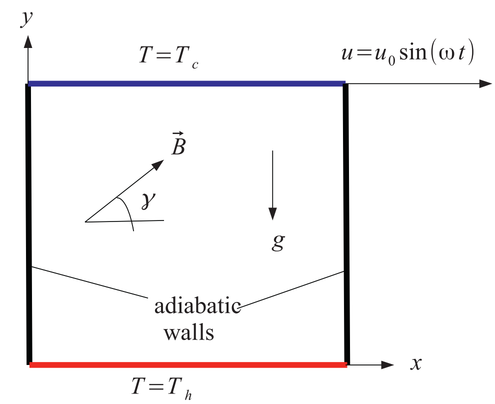

Fig. 1. Schematic diagram of the (a) – physical model with boundary conditions.

Hatami et al. [46] analytically investigated the MHD) Jeffery–Hamel nanofluid flow in non-parallel walls by using different base fluids and nanoparticles. They found that the skin friction coefficient is an increasing function of nanoparticle volume fraction but a decreasing function of Hartmann number. Mahmoudi et al. [38] numerically simulated the MHD natural convection in a triangular enclosure filled with nanofluid. The impact of the Rayleigh number, Hartmann number and nanoparticle volume fraction on the heat transfer and fluid flow are numerically investigated. Ghasemi et al. [39] studied the MHD natural convection in an enclosure filled with water – Al_2O_3 nanofluid. Their results showed that an enhancement or deterioration of the heat transfer may be obtained with an increase of the nanoparticle volume fraction depending on the value of Hartmann and Rayleigh numbers.

To the best of authors knowledge, mixed convection in an oscillating lid-driven cavity filled with nanofluid under the influence of an oriented magnetic field has never been reported in the literature even its importance in many engineering applications is apparent as outlined above. The studied problem may be encountered in some engineering applications or MHD with nanofluid may be utilized to control the convection in an oscillating lid driven cavity configuration. This study aims at investigating the effects of Richardson number, Hartmann number, orientation angle of the magnetic field, nanoparticle volume fraction and frequency of the oscillating lid on the fluid flow and heat transfer characteristics in a square cavity.

2. Mathematical formulation

The physical domain of square cavity with oscillating lid is shown in Fig. 1 along with boundary conditions. The temperature of bottom wall is higher than that of top one while vertical walls are adiabatic. The gravity acts in -y direction. A uniform magnetic field of $\vec{B}=B_x\vec{i}+B_y\vec{j}$ is applied and it makes angle of γ with the horizontal axis. The magnitude of the magnetic field is $B_0=\sqrt{B_x^2+B_y^2}$ and $\gamma=\tan^{-1}\left(\frac{B_y}{B_x}\right)$.The cavity is filled with Cu-water nanofluid (different solid volume fraction of ϕ) under the influence of the inclined magnetic field. Thermal equilibrium between the fluid phase and nanoparticles and no slip between them are assumed. Thermo-physical properties of water and copper at the reference temperature are presented in Table 1 [38]. The effects of joule heating, displacement currents and induced magnetic field are assumed to be negligible. The buoyancy force in the momentum equation is approximated by using the Boussinesq approximation.

Conservation equation of mass, momentum and energy in a two dimensional Cartesian coordinate system can be written in