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Full length article

Mixed convection of ferrofluids in a lid driven cavity with two rotating cylinders

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ABSTRACT

Mixed convection of ferrofluid filled lid driven cavity in the presence of two rotating cylinders were numerically investigated by using the finite element method. The cavity is heated from below, cooled from driven wall and rotating cylinder surfaces and side vertical walls of the cavity are assumed to be adiabatic. A magnetic dipole source is placed below the bottom wall of the cavity. The study is performed for various values of Reynolds numbers ($100 \leq Re \leq 1000$), angular rotational speed of the cylinders ($-400 \leq \Omega \leq 400$), magnetic dipole strengths ($0 \leq \gamma \leq 500$), angular velocity ratios of the cylinders ($0.25 \leq \Omega_i/\Omega_j \leq 4$) and diameter ratios of the cylinders ($0.5 \leq D_i/D_j \leq 2$). It is observed that flow patterns and thermal transport within the cavity are affected by variation in Reynolds number and magnetic dipole strength. The results of this investigation revealed that cylinder angular velocities, ratio of the angular velocities and diameter ratios have profound effect on heat transfer enhancement within the cavity. Averaged heat transfer enhancements of 181.5 % is achieved for clockwise rotation of the cylinder at $\Omega = -400$ compared to motionless cylinder case. Increasing the angular velocity ratio from $\Omega_2/\Omega_1 = 0.25$ to $\Omega_2/\Omega_1 = 4$ brings about 91.7 % of heat transfer enhancement.

1. Introduction

The interaction between the shear driven flow and natural convection effect is quite complex and has many engineering applications such as solidification, food processing, MEMs, nuclear reactors, coating etc. Mixed convection in a lid driven cavity is a benchmark problem for the study of interaction between the shear driven flow and free convection. In order to control the heat transfer and fluid flow within the cavity, active and passive methods were used. Some attempts can be mentioned as a) using magnetic field or electrical field b) using an obstruction within the cavity [1–11] c) using surface corrugation and its geometrical parameters [12,13]. The methods can be combined to have a large number of control parameters [14,15].

Recently, due to its importance in many industrial applications such as MEMs, coolers of nuclear reactors, purification of molten metals magnetic filed interaction with fluid flow and heat transfer were extensively studied. An external magnetic field can be used to control the convection inside the cavity [16–18]. Stability of ferromagnetic fluid for a fluid layer heated from below and subjected to a uniform vertical magnetic field was studied by Finlayson [19]. Kefayati [20] numerically studied the ferrofluid natural convection flow in a cavity with linearly temperature distribution using Lattice Boltzmann method. He observed that heat transfer decreases as the nanoscale ferromagnetic particle volume fraction increases. Rahman et al. [4] numerically investigated the conjugate effect of Joule heating and magnetic force for an obstructed lid-driven cavity saturated with an electrically conducting fluid using finite element method. Sheikholeslami and Ganji [21] numerically investigated the influence of an external magnetic field on ferrofluid flow and heat transfer in a semi annulus enclosure with sinusoidal hot wall using Control Volume based Finite Element Method. They showed that for low Rayleigh number, heat transfer enhances as the Hartmann number increases and magnetic number decreases. Al-Salem et al. [22] studied the effects of moving lid direction on MHD mixed convection in a cavity with linearly heated bottom wall using finite volume method. They observed that direction of lid is more effective on heat transfer and fluid flow in the cavity and heat transfer is decreased with increasing of magnetic

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Nomenclature

a, b	location of the magnetic dipole
B	magnetic induction
h	local heat transfer coefficient, (W/m^2 K)
H	magnetic field
k	thermal conductivity, (W/m K)
L	length of the enclosure, (m)
Mn	Magnetic number, $\mu_0 H_r^2/\rho_0 \nu_r^2$
n	unit normal vector
Nu	local Nusselt number, hL/k
p	pressure, (Pa)
Pr	Prandtl number, ν/α
Re	Reynolds number, $u_0 L/\nu$
T	temperature, (K)
u, v	x-y velocity components, (m/s)
x, y	cartesian coordinates, (m)

Greek characters

α	thermal diffusivity, (m^2/s)
θ	non-dimensional temperature,$T - T_c/T_h - T$
ν	kinematic viscosity, (m^2/s)
ρ	density of the fluid, (kg/m^3)
χ	magnetic susceptibility
γ	strength of the dipole
Φ	viscous dissipation
Ω	nondimensional rotation velocity of cylinder, $\omega L/2u_0$

Subscripts

c	cold wall
max	maximum
mean	average
h	hot wall

field parameter. Oztop et al. [23] studied the mixed convection with a magnetic field in a lid-driven cavity heated by a corner heater. They showed that heat transfer deteriorates as the Hartmann number increases and magnetic field can be used to control heat transfer and fluid flow.

An obstruction can be used to control the heat transfer and fluid flow within a cavity. Khanafer and Aithal [2] numerically studied the mixed convection in a lid-driven cavity with a circular object inside by using finite element method. Their results showed that the Richardson number, cylinder diameter and the location of the cylinder have impact on the transport phenomena within the cavity. Islam et al. [7] have inserted an isothermally heated square blockage inside a square cavity and the effects of various different blockage sizes, concentric and eccentric placement of the blockage inside the cavity have been numerically investigated using finite volume method. The investigation of mixed or natural convection in enclosures with rotating cylinders was conducted by several researchers [24–28]. Hussain and Hussein [28] numerically analyzed the mixed convection in a cavity having a rotating cylinder with finite volume method. Their results showed that cylinder locations have important effects on convection within the cavity. Costa and Raimundo [29] numerically studied the mixed convection in a differentially heated square enclosure with an active rotating circular cylinder. The effects of the radius, rotation velocity and thermal conductivity and thermal capacity of the cylinder on the mixed convection was studied. Recently, Selimefendigil and Oztop [15] studied the convection in a vented cavity with a rotating cylinder. They observed that the length and size of the recirculation zones can be controlled with magnetic dipole strength and angular rotational speed of the cylinder.

In the present study, a lid driven square cavity heated from below with two rotating cylinders under the influence of a magnetic source were numerically simulated. The present study aims at investigating the effects of Reynolds number, angular speed of the cylinders, the ratio of the angular velocities, the ratio of the cylinder diameters and the strength of the magnetic dipole source on the fluid flow and heat transfer characteristics of the lid driven cavity heated from below. Using the ratio of the angular velocities and the ratio of the cylinder diameters as additional control parameters for mixed convection along with magnetic dipole source is the

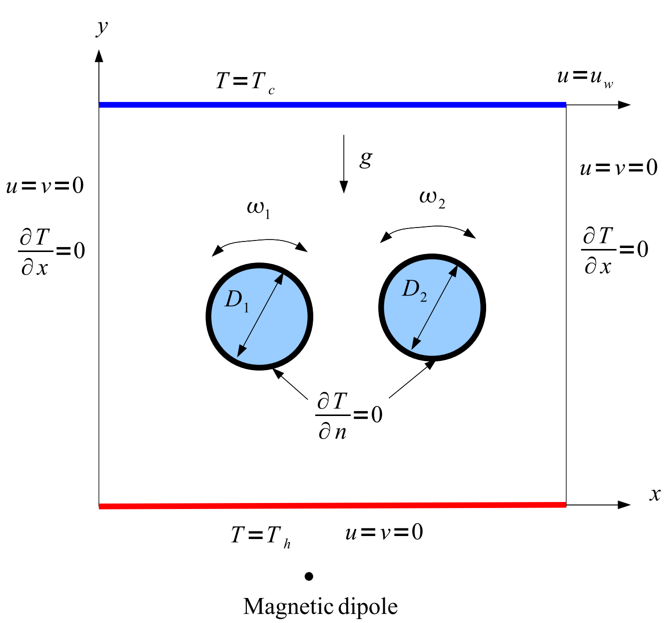

Fig. 1. Schematic description of lid-driven cavity with rotating cylinders and boundary conditions.

Table 1
Comparison results of averaged Nusselt number at the top wall of the lid driven cavity.

Re = 400	Iwatsu et al. [30]	Present
Gr = 100	3.84	3.81
Gr = 10^4	3.62	3.63
Gr = 10^6	1.22	1.26

Table 2
Grid independence test, ($\gamma = 500, \mathrm{Ri} = 1.14, D_1 = D_2, \Omega_1 = \Omega_2 = 400$).

Grid name	Grid size	Averaged Nusselt number
G1	1338	3.458
G2	3546	3.048
G3	15559	3.045
G4	33796	3.035
G5	73630	3.034