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ORIGINAL ARTICLE

Numerical investigation of pure mixed convection in a ferrofluid-filled lid-driven cavity for different heater configurations

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Abstract Mixed convection has been a center point of attraction to the heat transfer engineers for many years. Here, pure mixed convection analysis in cavity is carried out for two different geometric heater configurations under externally applied magnetic field. Ferrofluid (Fe_3O_4–water) is considered as working fluid and modeled as single phase fluid. The heaters at the bottom wall are kept at constant high temperature while vertical side walls are adiabatic. The top wall is moving at a constant velocity in both geometric configurations and is kept at constant low temperature. Galerkin weighted residuals method of finite element analysis is implemented to solve the governing equations. The analysis has been carried out for a wide range of Richardson number (Ri = 0.1–10), Reynolds number (Re = 100–500), Hartmann number (Ha = 0–100) and solid volume fraction (φ = 0–0.15) of ferrofluid. The overall heat transfer performance for both the configurations is quantitatively investigated by average Nusselt number at the heated boundary wall. It is observed that higher Ri enhances the heat transfer rate, although higher Ha decreases heat transfer rate. Moreover, at higher Ri and lower Ha, semi-circular notched cavity shows significantly better (more than 30%) heat transfer rate.

1. Introduction

Magneto-hydrodynamic (MHD) convection is the heat transfer mechanism in fluid under external magnetic field. This topic has turned out to be a focal point of enormous amount of

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Nomenclature

a	notch spacing length (m)
g	acceleration due to gravity (m s^{-2})
k	thermal conductivity of fluid (W m^{-1} K^{-1})
L	length of the square cavity (m)
Nu	average Nusselt number on heater surface
p	pressure (Pa)
P	dimensionless pressure
Pr	Prandtl number
Ha	Hartmann number
Re	Reynolds number
Gr	Grashof number
Ri	Richardson number
s	heater wall perimeter
T	temperature (K)
u	velocity at x-direction (m s^{-1})
U	dimensionless velocity at x-direction
v	velocity at y-direction (m s^{-1})
V	dimensionless velocity at y-direction
X	dimensionless distance along x-coordinate
Y	dimensionless distance along y-coordinate

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
β	volume expansion coefficient (K^{-1})
φ	solid volume fraction of ferrofluid
μ	dynamic viscosity (Ns m^{-2})
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
σ	electrical conductivity ((Ω m)$^{-1}$)
ψ	stream function
Θ	dimensionless temperature

Subscripts

h	hot
c	cold
f	base fluid (water)
ff	ferrofluid
p	ferrous particle

researches from the last three decades because of its wide range of application in petroleum industries, plasma physics, geophysics, MHD pump, MHD flow meter, cooling of nuclear reactors and various thermal systems [1–3].

Previously, several investigations on natural, forced and mixed convection have been performed under external magnetic field. It was reported by many researchers that natural convection can be affected by external magnetic field [4–7]. Rudraiah et al. [8] investigated the effect of magnetic field on natural convection in a rectangular enclosure numerically and presented a correlation formula of Nusselt number. They found that the effect of the magnetic field decreased the rate of heat transfer at any Grashof number. Similar studies have been performed for different geometries such as square enclosure [9,10], semi-annulus enclosure [11,12], and trapezoidal enclosure [13]. It is also noticeable that many researchers investigated MHD natural convection using nanoparticles improvised in a base fluid [14–20]. Mahmoudia et al. [21] investigated MHD natural convection and entropy generation in a trapezoidal enclosure using Cu–water nanofluid. They found that enhancement of Nusselt number occurred with increasing Hartmann number at $Ra = 10^4$ and 10^5, but at even higher Rayleigh number, opposite occurred. Moreover, ferrofluid also has become very popular while achieving higher heat transfer rate [22,23]. Recently, few researchers investigated natural convection in different geometric configurations using ferrofluids [24–26]. Gavili et al. [27] investigated thermo-magnetic convection process in two-dimensional enclosure filled with ferrofluid. It was concluded that average Nusselt number increased when magnetic field and temperature gradient had same direction. Lajvardi et al. [28] carried out experimental study on natural convection using ferrofluid under external magnetic field. It was reported that significant enhancement of heat transfer was present at lower strength of magnetic field. Bondareva et al. [29] investigated the effect of uniform magnetic field on laminar flow regimes of natural convection in an enclosure. It was observed that Rayleigh number, Hartmann number and orientation of magnetic field had impact on velocity distribution, temperature field and average Nusselt number.

Many researchers tried to figure out how external magnetic field affected heat transfer rate while analyzing mixed convection [30–32]. Oztop et al. [33] studied MHD mixed convection in an open channel with a fully or partially heated cavity. It was evident that higher value of Ha did not lead to any change in flow field for any length of heater. It was also reported that at any values of Richardson number, higher amount of nanoparticles increased heat transfer rate. Some related investigations for different cavities and boundary conditions can be found in [34–36]. Many researchers reported that nanofluids and ferrofluids had significant influence on mixed convection [37,38]. Ahmed et al. [39] investigated MHD mixed convection of a lid-driven cavity filled with nanofluid. It was investigated that the existence of an inclined magnetic field decreased the fluid movement and hence decreased the heat transfer rate. Sheremet et al. [40] studied mixed convection in a lid-driven square cavity with nanofluid inside. It was evident that Prandtl, Reynolds number, Grashof number, Lewis number, buoyancy-ratio, the Brownian motion, and the thermophoresis had effect on flow and heat transfer. Aminfar et al. [41] investigated numerically the hydro-thermal characteristics of a ferrofluid in a vertical rectangular duct which was exposed to a non-uniform transverse magnetic field.

The present study is concerned with the comparison of heat transfer performance between semi-circular and triangular notches in lid-driven cavities. The purpose of this investigation is to study heater geometry effect on pure mixed convection heat transfer. Ferrofluid has been considered as the working fluid. The flow and thermal field have been studied and discussed by streamline and isothermal contours respectively.