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Magnetic field effect on natural convection and entropy generation in a half-moon shaped cavity with semi-circular bottom heater having different ferrofluid inside

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ABSTRACT

In this study magneto-hydrodynamic convection in a half-moon shaped cavity filled with ferrofluid has been analyzed numerically. The cavity has two semi-circular bottom heaters and effect of the distance between these two heaters ($\lambda = 0.1, 0.4$) has been thoroughly investigated. Numerical simulation has been carried out for a wide range of Rayleigh number ($Ra = 10^3 \sim 10^7$), Hartmann number ($Ha = 0 \sim 100$) and inclination angle of magnetic field ($\gamma = 0° \sim 90°$) to understand the flow field, thermal field and entropy generation respectively. Cobalt-kerosene and Fe_3O_4 -water ferrofluids are used for the present investigation and considered as a single phase fluid. Galerkin weighted residual method of finite element analysis has been used for numerical solution. The code validation and grid independency test have been carried out to justify the numerical accuracy. It has been observed that increment of magnetic field reduces the heat transfer rate, whereas increment of heater distance augments the heat transfer rate significantly. Results are discussed on the basis of Nusselt number (Nu), Bejan number (Be) and shown by contours and 3D plots. It has also been found that $\lambda = 0.4$ always shows better heat transfer rate and entropy optimization.

1. Introduction

Magneto-hydrodynamic convection (MHD) has received considerable attention due to its scientific, technological and industrial applications in MHD pump, MHD flow meter, metal hardening, crystal growth in liquids, electronic package and cooling of nuclear reactors, etc. [1–5]. When free convection occurs under the presence of external magnetic field, there are two body forces, a buoyancy force and a Lorentz force. As they interact with each other, it causes a characteristic phenomenon which influences the flow and heat transfer.

Considerable number of research works have been conducted in this area. Most of these studies involve different cavity sizes under various convection heat transfer phenomena [6,7]. The effect of external magnetic field on convective heat transfer has also gained popularity by this time . A few researchers have shown that external magnetic field has some adverse effect on heat transfer [8–11]. Rudraiah et al. [12] investigated that average Nusselt number decreased with the increment of the Hartmann number.

Recently, nanofluids have been introduced to increase the heat transfer rate in a significant manner. Numerical study of natural convection cooling have been investigated under external magnetic field for different enclosures filled with nanofluids [13,14]. Saleh et al. [15] concluded that enhancement of heat transfer could be performed by *Cu* nanoparticles with higher concentrations. Higher Hartmann number affecting the heat transfer rate was also a finding by these investigations. Other comprehensive review of the previous studies on magneto-hydrodynamic convection can be found in [16–19].

A few researchers also analyzed entropy generation through numerical analysis during natural convection [20,21]. They found that entropy generation was increased when nanoparticles were present. The effect of inclination angle was also studied by some researchers [22,23]. They studied that negative inclined angles decreased the heat transfer towards the inclination angle 0°. They also studied that minimum entropy generation occurred at inclination angle greater than 45°.

Besides other nanofluids, ferrofluids also exhibited some interesting phenomena under the presence of external magnetic field [24,25]. Kefayati [26] studied the natural convection of ferrofluid filled cavity with linearly temperature distribution. It was concluded that heat transfer decreased with increment of

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Nomenclature

a	dimensional distance between semi-circular heaters (m)
A	area of the enclosure (m^2)
b	radius of the semi-circular cavity (m)
B_0	magnetic induction
Be	Bejan number
g	gravitational acceleration (m/s^2)
Ha	Hartmann number
k	thermal conductivity of fluid (W/mk)
L	diameter of the cavity (m)
Nu	average Nusselt number
p	dimensional pressure (N/m^2)
P	dimensionless pressure
Pr	Prandtl number
Ra	Rayleigh number
r	dimensionless radius of the cavity
s	circumference (m)
S_ψ	entropy generation due to fluid friction
S_θ	entropy generation due to heat transfer
T	temperature (K)
u, v	dimensional velocity components (m/s)
U, V	dimensionless velocity components
x, y	dimensional coordinates (–)
X, Y	dimensionless coordinates (–)

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (1/K)
γ	inclination angle of magnetic field (°)
ϕ	solid volume fraction of ferrofluid
λ	dimensionless distance between semi-circular heaters
μ	dynamic viscosity (Ns/m^2)
ν	kinematic viscosity (m^2/s)
ψ	stream function
ρ	density (kg/m^3)
σ	electrical conductivity ($1/(\Omega\, m)$)
Θ	dimensionless temperature

Subscripts

c	cold
f	fluid (water)
ff	ferrofluid
h	hot
m	mean

nanoscale ferromagnetic particle volume fraction for different Rayleigh numbers. It was also reported that average Nusselt number increased when the temperature gradient and magnetic field had same directions [27]. Ashouri et al. [28] analyzed the correlation for Nusselt number in magnetic convection heat transfer in a square cavity filled with ferrofluid. Correlation of overall Nusselt number for a wide range of parameters was introduced in the study. Sheikholeslami et al. [29] investigated ferrofluid flow and heat transfer analysis in a semi-annulus enclosure with magnetic heat source. It was found that Nusselt number shows increasing behavior with Rayleigh number, solid volume fraction and a decreasing relationship with Hartmann number and radiation parameter.It was also revealed that the augmentation of heat transfer has been ensured using ferrofluids both numerically and experimentally [30,31].

Most recently Rahman et al. [32] analyzed the numerical simulation of half-moon shaped enclosure with variable thermal boundary conditions for different nanofluids. It was revealed that heat transfer of the cavity can be augmented upto 30% with the presence of nanoparticles. Again, Rahman et al. [33] studied unsteady magnetohydro-dynamic natural convection in a half-moon shaped cavity using ferrofluid as working fluid. It was concluded that there was a strong interaction between magnetic particle (cobalt) and base fluid (kerosene) under external magnetic field which could be tuned properly for better heat transfer rate.

The main objective of this study is to analyze the geometric effect on magneto-hydrodynamic convection in a half-moon shaped cavity filled with ferrofluid having two semi-circular bottom heaters. The effect of distance between this two heaters has been studied for two different cases ($\lambda = 0.1, 0.4$). Effect of Hartmann number (Ha), Rayleigh number (Ra) and inclination angle of the magnetic field (γ) on thermal and flow field has been investigated. Combined effect of Ha, Ra and γ on Nusselt number (Nu) and Bejan number (Be) shows better insight of heat transfer and entropy optimization.

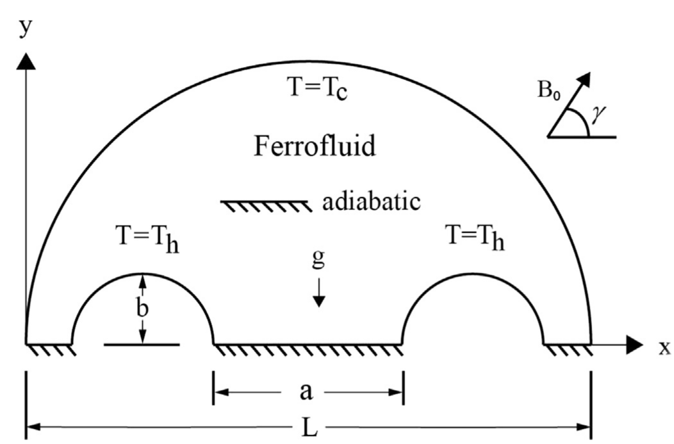

Fig. 1. Schematic diagram of the half-moon shaped cavity with semi-circular bottom heaters.

2. Mathematical formulation

2.1. Physical modeling

The physical model under this study is shown in Fig. 1 with necessary boundary conditions. A half-moon shaped cavity of diameter L having two semi-circles of radii b at the distance of a is considered for this investigation. The two dimensional co-ordinate system is defined and the gravity is acting along the negative y-axis. The round upper wall is kept at low temperature ($T = T_c$). The horizontal wall of the cavity is insulated whereas the two semi-circles situated at the bottom horizontal line are heated ($T = T_h$). Magnetic field of strength B_o is applied along different inclination angles (γ) with respect to x-axis. All solid boundaries are assumed to be no-slip walls. Radiation mode of heat transfer and viscous dissipation are considered to be negligible.