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Analysis of combined thermal and magnetic convection ferrofluid flow in a cavity ☆

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Abstract

A numerical analysis of the magnetic gradient and thermal buoyancy induced cavity ferrofluid flow is conducted by a semi-implicit finite element method. The physical model for a square cavity containing two different temperature side walls and a magnet near bottom wall is described by mass, momentum and energy equations. Conditions for the fixed Prandtl number, Rayleigh number and different ferro-hydrodynamic interaction parameter are studied for $5\times10^{8}\leq\beta\leq1.6\times10^{10}$. Results show the flow strength increases with the strengthening magnetic field. However, the side-wall heat transfer rate presents a decrease trend with the increase in magnetic field strength, for the magnet located near the bottom central area evokes the circulation to move toward the central portion. In summary, a proper choice of magnet strength and location can adjust the flow field and local heat transfer rate to fit the practical application.

Keywords: Ferrofluid; Magnetic field strength; Ferro-hydrodynamic interaction

1. Introduction

The thermally driven cavity flow has served as a benchmark configuration for numerical model validation [1]. A great deal of research on this topic has been accumulated in the review papers [2,3]. In addition, the electromagnetic field is the other source to excite a fluid flow for some fluids such as ferrofluid. A ferrofluid consists of a suspension of monodomain ferromagnetic particles such as magnetite in a nonmagnetic carrier fluid [4,5]. Besides the applications in lubrication, sealing of bearing, and directing injected chemical agents toward particular contaminated zones etc., the oil-based ferrofluids are used to change heat transfer in electromagnetic equipment [6]. The study of a convection flow driven by thermal buoyancy and magnetic force is useful in understanding the above heat transfer phenomena. The relating literature about thermal convection of ferrofluids, Finlayson [7] applied linear theory to investigate the flow instability for the fluid heated from below in presence of a vertical uniform magnetic field. Vaidyanathan et al. [8] investigated thermoconvective instability of a ferromagnetic fluid in a saturated porous medium with Brinkman model by linearized stability analysis. Oldenburg et al. [9] presented the equations and methods to simulate the ferrofluid flow raised by external magnetic force in porous media and compared with laboratory measurements. Borglin et al. [10]

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Nomenclature

a	half of height of permanent magnet
b	half of width of permanent magnet
Br	residual magnetization
c	specific heat
g	gravitational acceleration
$\boldsymbol{g}$	gravitational direction unit vector
H	magnetic field strength
k	thermal conductivity
K	pyromagnetic coefficient
L	length of permanent magnet
M	magnetization
Nu	Nusselt number
n	normal direction
p	non-dimensional pressure
Pr	Prandtl number $= \nu/\alpha$
Ra	Rayleigh number $= g\beta_T(T_C - T_1)W^3/\nu\alpha$
t	time
T	temperature
$\boldsymbol{V}$	non-dimensional velocity vector
W	width of cavity
x,y	dimensional Cartesian coordinates

Greek symbols

α	effective thermal diffusivity $= k/(\rho c)$
β	ferro-hydrodynamic interaction parameter $= K(T_C - T_1)\mathrm{Br}W^2/(4\pi\rho\alpha^2)$
β_T	thermal expansion coefficient
ε	ratio of Curie temperature to temperature difference $(T_C - T_1)$
θ	non-dimensional temperature $= (T_C - T)/(T_C - T_1)$
λ	thermal dissipation parameter $= \alpha^2/[c(T_C - T_1)W^2]$
μ_0	magnetic permeability
μ	dynamic viscosity
ν	kinematic viscosity
ρ	fluid density
τ	non-dimensional time $= t/(W^2/\alpha)$

Subscripts

C	Curie temperature
1	cold wall

constructed a measuring system to experimentally investigate ferrofluid flow in porous media, and demonstrated the magnetically controlled flow field.

Referring to the above literature, they are mainly focused on ferrofluid flow instability analysis between two infinite plates or only magnetic effect existing conditions. The flow in a confined space driven by thermal buoyancy and magnetic force is not explored much. Therefore, in this paper ferrofluid flows subjected to a magnetic field and side-wall heating in a cavity are analyzed to probe the interaction between these two factors in a confined domain. The numerical results may provide useful information about ferrofluid flow and heat transfer phenomena in a cavity for real application.