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Lattice Boltzmann method for thermomagnetic convection and entropy generation of paramagnetic fluid in porous enclosure under magnetic quadrupole field

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In this study, thermomagnetic convection in a porous cavity filled with paramagnetic fluid under a magnetic quadrupole field is studied using lattice Boltzmann method (LBM), and the corresponding entropy generation is analyzed. The horizontal walls of the porous enclosure are adiabatic, and the temperatures of the vertical walls are different. The effects of Darcy number (*Da*), porosity (ε), and magnetic force number (γ) on the heat transfer, fluid flow, and entropy generation characteristics are investigated. The results show that, as the magnetic force number increases, the flow is strengthened. The local Nusselt numbers (Nu_{loc}) increase and the average Bejan number (Be_{ave}) decreases under the non-gravitational condition. Nu_{loc} change a little along the hot wall due to the lower value of Darcy number and higher values of Darcy number lead to higher buoyancy forces, Nu_{loc} change significantly under the gravitational or non-gravitational condition. Moreover, the average Nusselt number (Nu_{ave}) and total entropy generation (S_{total}) slightly decrease at first and thereafter increase when the magnetic force dominates the entire domain under the gravitational condition. It is also observed that, when $\varepsilon_0 = \varepsilon_1 = 0.5$, $\gamma > 10$, the average Nusselt number (Nu_{ave}) is significantly higher than in the other cases. Furthermore, the average Nusselt number (Nu_{ave}) reaches its minimum value when $\varepsilon_0 = \varepsilon_1 = 0.5$, $\gamma = 4$.

1. Introduction

The effect of a magnetic field on the flow and heat transfer of fluids is widely researched in many open literatures. It has immense significance in electronic packages, crystal growth, and blood flow control [1–3]. Saleh et al. [4] analyzed the effect of a uniform magnetic field on the convection in a trapezoidal enclosure filled with a fluid-saturated porous medium, and observed that the heat transfer performance decreases significantly upon decreasing the angle of sloping wall in the horizontal magnetic field. An experimental study of ferrofluid flow under a magnetic field was performed in porous media by Sints et al. [5] and Sadrhosseini et al. [6], both of whom reported that ferrofluid and magnetic field had a relative effect on the flow and heat transfer of fluid. It is observed that Sheikholeslami's group [7–14] analyzed the effect on flow and heat transfer with CuO-water nanofluid and Fe_3O_4-Ethylene glycol nanofluid in a porous model via control volume based finite element method (CVFEM), it was found that Convective heat transfer improves with augment of Darcy and Reynolds number but it reduced with rise of Hartmann number and porosity had opposite relationship with temperature gradient when CuO-water nanofluid was analyzed, it was investigated that maximum Nusselt number belongs to Platelet shape Fe_3O_4 nanoparticles and Nusselt number is an increasing function of Darcy number when Fe_3O_4-Ethylene glycol nanofluid was analyzed.

In recent years, the lattice Boltzmann method (LBM) has attracted immense attention owing to its simulation superiority for micro-scale flow and heat transfer, such as biological fluid, crystal growth, porous media and magnetic fluid. Many researchers have applied this method to investigate the fluid flow and heat transfer performances in porous media under a magnetic field. Farhadi et al. [15] studied the effect of Prandtl number on the flow structure and heat transfer rates in a magnetohydrodynamic flow in a lid-driven cavity filled with a porous medium [16]. Sheikholeslami's group [17–19] studied the influence of a magnetic field on Fe_3O_4-water and CuO-water nanofluid flow and heat transfer in a porous cavity via LBM, and the nanofluid volume fraction, *Ha*, *Ra*, and *Da* were considered. The aforementioned studies were mostly focused on the ferrofluid flow and heat transfer characteristics under a uniform magnetic field. A few researchers have paid attention to paramagnetic fluid under a magnetic field. Huang

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Nomenclature

$\mathbf{b}$	magnetic flux density (T)
b_0	reference magnetic flux density, $b_0 = Br$ (T)
$\mathbf{B}$	dimensionless magnetic flux
Br	magnetic flux density of permanent magnets (T)
c_p	fluid specific heat at constant pressure
Da	Darcy number
H	magnetic field intensity
Ha	Hartmann number
k_f	fluid thermal conductivity (W m^{-1} K^{-1})
k_s	solid thermal conductivity (W m^{-1} K^{-1})
D	length of the enclosure (m)
Nu	Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
p	pressure (Pa)
P	dimensionless pressure
T_0	reference temperature
T_c	cold-wall temperature (K)
T_f	fluid temperature (K)
T_h	hot-wall temperature (K)
u, v	velocity components
U, V	dimensionless velocity components
x, y	Cartesian coordinates
X, Y	dimensionless Cartesian coordinates
$\boldsymbol{U}$	dimensionless velocity vector
K	permeability of porous media
G	gravity (kg/m^2 s)
f_i	flow distribution functions
g_i	temperature distribution functions
f_i^{eq}	equilibrium flow distribution functions
g_i^{eq}	equilibrium temperature distribution functions
F_i	external force
c_i	discrete lattice velocity
δt	lattice time step
S_HTI	local heat transfer irreversibility
S_FFI	local fluid fraction irreversibility
Be	Bejan number

Greek symbols

ε	porosity
α_m	effective thermal diffusivity
ρ_f	density (kg/m^3)
μ	dynamic viscosity (kg/m s)
υ_f	fluid kinematic viscosity (m^2/s)
γ	dimensionless magnetic strength parameter
υ_e	effective fluid dynamic viscosity
θ	dimensionless fluid temperature
β	thermal expansion coefficient (K^{-1})
χ_0	reference mass magnetic susceptibility (m^3/kg)
μ_m	magnetic permeability (H m^{-1})
Φ	dimensionless thermal conductivity
φ_m	scalar magnetic potential
ω_i	weighting factors
τ_f	relaxation times of flow field
τ_g	relaxation times of temperature
ρ	lattice fluid density
φ	irreversibility distribution ratio

Subscripts

0	reference value
c	cold
f	fluid
h	hot
s	solid
t	total
i	discrete lattice direction
ave	average
m	effective value

and co-workers [20,21] presented a theory of magnetically controlled convection and studied the thermal convective instability of paramagnetic fluids in a non-uniform magnetic field. Devos et al. [22] proposed a novel technique for analyzing the magnetic properties of liquids by employing a magnetic force under the gradient of high magnetic fields; the experimental results and theoretical expectations accordingly determine the magnetic susceptibility of the solution. Bednarz et al. [23,24] carried out experiments and numerical calculation for natural convection in a cubic enclosure, and they reported that the magnetic field could enhance the heat transfer rate and drive the convective motion. Suvash et al. [25] numerically investigated the thermomagnetic convection of paramagnetic fluids confined to a uniform gradient magnetic field in an open square enclosure, and they observed that different combinations of gravitational and magnetic buoyancy forces could enhance or reverse the convection under a strong magnetic field. Kaneda et al. [26,27] investigated the effect of magnetic thermal force on the heat and fluid flow inside a pipe and observed that the magnetic strength of a permanent magnet could enhance the heat transfer in the gravity; however, the enhancement occurred very close to the magnet. Furthermore, Jiang's team [28–32] conducted a principally in-depth study of a paramagnetic fluid (air) under a magnetic quadrupole field in a cubic (porous) enclosure. First, they applied the finite-volume method to simulate the thermomagnetic convection of air in the porous square enclosure and observed that the magnetic force number, Da, Ra, and dimensionless solid-to-fluid heat transfer coefficient have a significant influence on the heat transfer and flow behaviors; subsequently, the thermomagnetic convection of air in the cavity was analyzed using the LBM method, and the effects of magnetic force number and Rayleigh number on the heat transfer and flow characteristics were investigated. Gravity has a positive effect on the heat transfer under a weak magnetic field. Finally, the entropy generation and heat transfer in a square enclosure in the absence of a gravity field were discussed. The total entropy generation increased with the increase in the magnetic force number.

Generally, experimental and numerical studies of paramagnetic fluid under a magnetic field are performed in porous media, and LBM is used to simulate the heat transfer performances in the cavity. However, LBM as a novel numerical method for thermomagnetic convection of paramagnetic fluid and entropy generation in porous media confined to a magnetic quadrupole field under gravity has yet to be elucidated. Therefore, the objective of the present study is to numerically simulate the natural convection heat transfer and entropy generation in porous media under a magnetic quadrupole field via LBM. The effects of Darcy number (Da), porosity (ε), and magnetic force number (γ) on the heat transfer, fluid flow, and entropy generation characteristics are analyzed and discussed.

2. Physical model

The physical model of the present work is illustrated in Fig. 1. As shown in Fig. 1, a porous enclosure filled with air is placed in a horizontal position and four permanent magnets are placed around the enclosure in order to generate an inhomogeneous magnetic