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Magnetic field effect on heat and mass transfer of mixed convection of shear-thinning fluids in a lid-driven enclosure with non-uniform boundary conditions

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ABSTRACT

In this paper, the effect of a magnetic field on mixed convection of shear-thinning fluids in a square lid-driven cavity with sinusoidal boundary conditions under the combined buoyancy effects of thermal and mass diffusion has been analyzed by finite difference lattice Boltzmann method (FDLBM). This study has been conducted for the certain pertinent parameters of Richardson number ($Ri = 0.00062$–1), Hartmann number ($Ha = 0$–100), Lewis number ($Le = 5$ and 50), power-law index ($n = 0.2$–1) as the buoyancy ratio is studied from $N = -10$ to 10. Results indicate that the augmentation of Richardson number causes heat and mass transfer to drop. The enhancement of Hartmann number declines heat and mass transfer for multifarious buoyancy ratios and power-law indexes steadily at $Ri = 0.00062$ and 0.01. The fall of the power law index declines heat and mass transfer at $Ri = 0.00062$ and 0.01 for various Hartmann numbers and buoyancy ratios. The increase in power-law index and Hartmann number influence heat and mass transfer differently at $Ri = 1$ for various buoyancy ratios and Lewis numbers. The growth of Lewis number enhances mass transfer for the studied Hartmann numbers and buoyancy ratios.

1. Introduction

Flow and heat transfer analysis in lid-driven cavities is one of the most widely studied problems in thermo-fluids areas. Numerous investigations have been conducted in the past on lid-driven cavity flow and heat transfer considering various combinations of the imposed temperature gradients and cavity configurations [1–7]. In fact, the driven cavity configuration is encountered in many practical engineering and industrial applications as the mentioned applications usually combine with mass transfer. Considerable researches into the mixed convection due to combined thermal and mass (concentration) buoyancy forces have been conducted. Al-Amiri et al. [8] investigated steady mixed convection in a square lid-driven cavity under the combined buoyancy effects of thermal and mass diffusion. The transport equations were solved numerically using the Galerkin weighted residual method. The heat and mass transfer rates were examined using several operational dimensionless parameters, such as the Richardson number, Lewis number and buoyancy ratio parameter. The average Nusselt and Sherwood numbers were obtained at the bottom hot wall for some values of the parameters considered in the investigation. Teamah and El-Maghlany [9] studied the mixed convection in a rectangular lid-driven cavity under the combined buoyancy effects of thermal and mass diffusion. They reported that heat and mass transfer increases as the Richardson number decreases. Moreover, the increase in Lewis number causes the mass transfer to enhance while no significant effect on the heat transfer. In addition, they stated that as the absolute value of buoyancy ratio increases, the heat and mass transfer augments.

The flow of an electrically conducting fluid in a magnetic field is influenced by magnetohydrodynamic (MHD) forces resulting from the interaction of induced electric currents with the applied magnetic field. An externally imposed magnetic field is a widely used tool for the process of manufacturing metals. The molten flows in this process behave usually like shear-thinning fluids; therefore, it is not possible practically to be studied as a Newtonian fluid. For example, a magnetic field is applied on the melt during solidification process in injection molding in magnesium injection molding. Moreover, as we know the dominant heat transfer process in injection molding is convection while the melt behaves like shear-thinning fluids [10]. In addition, mass transport inside microstructures plays a significant role in fabrication of microsystems. The familiar example of the phenomenon is convective-diffusive mass transfer in fabrication of microelectromechanical systems (MEMS). Wang et al. [11] demonstrated the importance of mass transfer which is accompanied with convective heat transfer in micro molds. The effect of magnetic field

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Nomenclature

B	magnetic field
C	concentration
c	lattice speed
c_p	specific heat at constant pressure
D	mass diffusivity
F	external forces
f	density distribution functions
f^{eq}	equilibrium density distribution functions
g	internal energy distribution functions
g^{eq}	equilibrium internal energy distribution functions
g_y	gravity
Gr	Grashof number
Ha	Hartmann number
K	the consistency coefficient
L	the length of the cavity
Le	Lewis number
n	power-law index
N	buoyancy ratio
Nu	Nusselt number
P	pressure
Pr	Prandtl number
Re	Reynolds number
Ri	Richardson number
Sc	Schmidt number
Sh	Sherwood number
T	temperature
t	time
x, y	Cartesian coordinates
u	velocity in x direction
v	velocity in y direction

Greek letters

σ	the electrical conductivity
ϕ	relaxation time
τ	shear stress
ζ	discrete particle speeds
Δx	lattice spacing
Δt	time increment
α	thermal diffusivity
ρ	density
μ	dynamic viscosity
ψ	stream function value
β	thermal expansion coefficient

Subscripts

avg	average
C	cold
H	hot
x, y	Cartesian coordinates
α	the number of the node
S	solutal
T	thermal

on the convection process in cavities with different boundary conditions has been studied by various numerical methods widely as the base fluid in the simulations is a Newtonian fluid. Rahman et al. [12] studied numerically the problem of conjugate effect of joule heating and magnatohydrodynamics mixed convection in an obstructed lid driven square cavity. They used Galerkin finite element formulation and observed that heat transfer decreases with decreasing of Hartmann number. Chamkha [13] made a numerical work on hydromagnetic combined convection flow in a lid-driven cavity with internal heat generation using finite volume approach. The presence of the internal heat generation effects was found to decrease the average Nusselt number significantly for aiding flow and to increase it for opposing flow. Sivasankaran et al. [14] numerically studied the mixed convection in a square cavity of sinusoidal boundary temperatures at the sidewalls in the presence of a magnetic field. In their case, the horizontal walls of the cavity were adiabatic. They indicated that the flow behavior and heat transfer rate inside the cavity are strongly affected by the presence of the magnetic field. Oztop et al. [15] considered laminar mixed convection flow in the presence of a magnetic field in a top sided lid-driven cavity heated by a corner heater. They showed that heat transfer decreases with increasing of Hartmann number. Moreover, the rate of reduction is higher for high values of the Grashof numbers. Kefayati et al. [16] simulated MHD mixed convection in a lid-driven square cavity with a linearly heated wall. They exhibited the augmentation of Richardson number causes heat transfer to increase, as the heat transfer decreases with the increment of Hartmann number for various Richardson numbers and the directions of the magnetic field.

Natural convection of power-law fluid has been studied widely with different numerical methods recently as some of them have been explained in detail here. Kim et al. [17] studied the transient natural convection of non-Newtonian power-law fluids in a square enclosure with differentially heated vertical side walls subjected to constant wall temperatures. They studied a range of nominal Rayleigh numbers from $Ra = 10^5$ to 10^7 and Prandtl numbers from $Pr = 10^2$ to 10^4 and demonstrated that the mean Nusselt number increases with decreasing power-law index. Natural convection of Newtonian and non-Newtonian power-law type fluids in two-dimensional rectangular tilted enclosures was investigated numerically by Khezzar et al. [18]. They indicated that shear thinning and thickening result in significant increase and decrease, respectively, in the heat transfer rate in comparison to the heat transfer rate of a Newtonian fluid. The increase and decrease in the average Nusselt number for shear-thinning and shear-thickening fluids is Rayleigh number, Prandtl number, aspect ratio and power law index dependent. Matin et al. [19] studied two-dimensional steady-state natural convection of non-Newtonian power-law fluid between two eccentric horizontal square ducts with constant temperature. They found that there is a minimum situation for the Nusselt number *versus* the eccentricity dependent on the other parameters. Moreover, it was obtained that varying the Prandtl number almost does not affect heat transfer characteristics except for some cases.

Furthermore, simulation of the problem with the complexity requires a special numerical method with the capacity to afford it properly. Lattice Boltzmann method is a powerful mesoscopic method for different shapes in multifarious subjects such as nanofluid, ferrofluid, MHD flow, porous medium, turbulent flow, melting and so on [20–38]. Nevertheless, it does not have the considerable success in non-Newtonian fluid. Finite difference lattice Boltzmann method (FDLBM) has solved the problem as it has the ability to derive the shear stresses equations in the form of the classical equations in contrast with lattice Boltzmann method (LBM) [39–40]. Independency of the method to the relaxation time in contrast with common LBM causes the method to solve different non-Newtonian fluid successfully [41–50] while the method protects the positive points of LBM simultaneously.

The main aim of this study is to scrutinize the effect of a vertical magnetic field on heat and mass transfer of mixed convection of non-Newtonian shear-thinning flow in a lid-driven cavity with sinusoidal boundary conditions. Furthermore, this investigation is worthwhile methodologically as it has been studied by FDLBM. Moreover, it is endeavored to express the effect of different parameters on the flow and thermal fields. The results of FDLBM are validated with previous numerical investigations and the effects of the main parameters (power-law index, Richardson number, Hartmann number, Lewis number and buoyancy