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MHD mixed convection of viscoplastic fluids in different aspect ratios of a lid-driven cavity using LBM

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ABSTRACT

In this paper, a two-dimensional simulation of mixed convection in an enclosure with differentially heated sidewalls in the presence of a uniform magnetic field has been performed for different aspect ratios of the enclosure while the enclosure is filled with a viscoplastic fluid. The viscoplastic fluid has been simulated by the exact Bingham model without any regulations. Lattice Boltzmann Method (LBM) has been applied to solve the problem. Heat transfer, fluid flow, and yielded/unyielded zones are investigated for certain pertinent parameters of the Reynolds number ($Re = 100$, 500, and 1000), the Hartmann number ($Ha = 0$, 2, and 5), the Bingham number ($Bn = 1$, 5, and 10), the aspect ratio ($AR = 0.25$, 1, and 4), and Eckert number($Ec = 0$, 10^{-4}, 10^{-3}, and 10^{-2}) when the Grashof and prandtl numbers are fixed at $Gr = 10^4$ and $Pr = 1$; respectively. Results show that the increase in the Reynolds number augments the heat transfer and changes the extent of the unyielded section. Furthermore, for fixed studied parameters, an increase in the Bingham number decreases the heat transfer while enlarging the unyielded section. The rise of the aspect ratio alters the size and position of the unyielded/yielded zones. As Hartmann number rises, the heat transfer drops gradually and the unyielded parts increase significantly. The change of the magnetic field angle alters the heat transfer and the unyielded/yielded regions in the cavity. It was observed that the viscous dissipation and the joule heating parts in the energy equation based on the practical values of Eckret numbers have marginal effects on heat transfer and yielded/unyielded sections.

1. Introduction

1.1. Magnetohydrodynamics

Magnetic field is widely utilized on materials which show viscoplastic behavior in different industries such as cement and food industries [1,2]. Magnetohydrodynamics (MHD) is the study of the interaction between magnetic fields and moving, conducting fluids. Magnetic fields influence many natural and man-made flows. They are routinely used in industry to heat, pump, stir and levitate liquid metals. There are three types of magnetic fields; a terrestrial magnetic field which is maintained by fluid motion in the earth's core, a solar magnetic field, which generates sunspots and solar flares, and a galactic field which influences the formation of stars. When a constant current is injected into a fluid under the influence of a magnetic field, the resulting Lorentz force will, in general, produce motion. Electromagnetic pumps were one of the earliest applications of MHD, and were routinely used in various industries [3]. Fluid flow and heat transfer analysis in lid-driven cavities is one of the most widely studied problems in thermo-fluids area. 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 [4–15]. This is because the driven cavity configuration is encountered in many practical engineering and industrial applications, e.g., materials processing, flow and heat transfer in solar ponds, dynamics of lakes, reservoirs and cooling ponds, crystal growing, float glass production, metal casting, food processing, galvanizing, and metal coating, etc.

1.2. MHD on natural and mixed convection of Newtonian fluids

MHD natural and mixed convection of Newtonian fluids in a cavity with different boundary conditions have been studied widely by researchers. Sathiyamoorthy and Chamkha [16] have done a numerical study for natural convection flow of electrically conducting liquid gallium in a square cavity whereas the bottom wall is uniformly heated and the left and right vertical wall is lin-

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Nomenclature

A	the first Rivlin-Ericksen tensor
AR	aspect ratio of the cavity (AR = $\frac{H}{L}$)
Bn	Bingham number
c	lattice speed
c_p	specific heat capacity at constant pressure
E	electric field strength
Ec	Eckert number
F	external forces
f_α	density distribution functions for the specific node of α
f_α^{eq}	equilibrium density distribution functions for the specific node of α
g_α	internal energy distribution functions for the specific node of α
g_α^{eq}	equilibrium internal energy distribution functions for the specific node of α
g	gravity
Ha	Hartmann number
H	enclosure height
J	electric current density
k	thermal conductivity
L	enclosure width
N	body force
Nu	Nusselt number
p	pressure
Pr	Prandtl number
Re	Reynolds number
T	temperature
t	time
x, y	Cartesian coordinates
u	velocity in x direction
U_0	the speed of the upper wall
v	velocity in y direction

Greek letters

β_T	thermal expansion coefficient
ϕ	relaxation time
Φ	electrical potential
$\boldsymbol{\tau}$	stress tensor
τ_y	yield stress
ξ	discrete particle speeds
Δx	lattice spacing in x direction
Δy	lattice spacing in y direction
Δt	time increment
α	thermal diffusivity
ρ	density of fluid
σ	electrical conductivity of the fluid
$\boldsymbol{\Lambda}$	the viscoplasticity constraint
θ	the inclined angle of the magnetic field

Subscripts

avg	average
C	cold
d	dynamic
H	hot
x, y	Cartesian coordinates
α	specific node
s	static

early heated while the top wall kept thermally insulated. They exhibited that the magnetic field with inclined angle has effects on the flow and heat transfer rates in the cavity. Number of investigators which effects of MHD mixed convection in lid-driven cavities is very limited. Sivasankaran et al. [17] investigated mixed convection in a square cavity of sinusoidal boundary temperatures at the sidewalls in the presence of magnetic field numerically. Rahman et al. [18] studied the development of magnetic field effect on mixed convective flow in a horizontal channel with a bottom heated open enclosure. Their results indicate that various Hartmann, Rayleigh and Reynolds numbers strongly affect the flow phenomenon and temperature field inside the cavity whereas in the channel these effects are less significant. Oztop et al. [19] considered laminar mixed convection flow in the presence of magnetic field in a top sided lid-driven cavity heated by a corner heater. They exhibited heat transfer decreases with increasing of Hartmann number. Nasrin and Parvin [20] made a numerical work on Hydromagnetic effect on mixed convection in a lid-driven cavity with sinusoidal corrugated bottom surface. They indicated that the average Nusselt number at the heated surface increases with an increase of the number of waves as well as the Reynolds number, while decreases with increment of Hartmann number. Kefayati et al. [21] simulated mixed convection of MHD in a lid-driven cavity by a linearly heated wall, using LBM. They studied different parameters of Hartmann numbers, Richardson numbers, and the inclinations of the magnetic field. Effects of a magnetic field on mixed convection flow in a two–sided lid–driven cavity were analyzed, using Lattice Boltzmann method (LBM) by Sajjadi et al. [22]. Results demonstrated that the heat transfer augmented with an increment of the Richardson number for different Hartmann numbers. In addition, the heat transfer declined with the growth of the magnetic field for various Richardson numbers. Sajjadi et al. [23] used the lattice Boltzmann method to solve the turbulent and laminar MHD natural convection in a square cavity. In this paper a fluid with Pr = 6.2 and different Rayleigh numbers for laminar and turbulent flows in the presence of a magnetic field was investigated. Ashorynejad et al. [24] presented a numerical study about the effect of a uniform magnetic field on free convection in a horizontal cylindrical annulus using the lattice Boltzmann method. The inner and outer cylinders were maintained at uniform temperatures and it was assumed the walls were insulating with a magnetic field. Detailed numerical results of heat transfer rate, temperature, and velocity fields were presented for studied parameters. Ashorynejad et al. [25] investigated the effect of static radial magnetic field on natural convection heat transfer in a horizontal cylindrical annulus enclosure filled with nanofluid numerically using the Lattice Boltzmann method (LBM). The inner and outer cylinder surfaces were maintained at the different uniform temperatures. The surfaces were non-magnetic material. The investigation was carried out for different governing parameters namely, Hartmann number, nanoparticle volume fraction and Rayleigh number. Yousofvand et al. [26] analyzed MHD mixed convection inside an electromagnetic pump, with Cu-water nanofluid as the working fluid numerically. To find the best heat transfer and pumping performance, an in-house parallel lattice Boltzmann code was developed to solve the problem in a 3D domain. The study was conducted for the certain pertinent parameters of Rayleigh number, magnetic field strength, electric field strength and the nanoparticle volume fraction. Mehryan et al. [27] investigated numerically the problem of unsteady natural convection inside a square cavity partitioned by a flexible impermeable membrane. The finite element method with the arbitrary Lagrangian–Eulerian (ALE) technique was used to model the interaction of the fluid and the membrane. The horizontal walls of the cavity were kept adia-