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Mesoscopic simulation of magnetic field effect on natural convection of power-law fluids in a partially heated cavity

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ABSTRACT

In this paper, effect of a magnetic field on natural convection of non-Newtonian power-law fluids in a partially heated cavity, has been analyzed by using the Finite-Difference Lattice Boltzmann Method (FDLBM). This study has been conducted for certain pertinent parameters of Rayleigh number ($Ra = 10^4$ and 10^5), Hartmann number ($Ha = 0$–60), power-law index ($n = 0.5$–1.5), and length of heated section ($H/L = 0.25$, 0.5, and 0.75), as the magnetic field is applied horizontally. Results indicate that the augmentation of the power-law index in the absence of the magnetic field causes heat transfer to drop. Generally, the magnetic field decreases heat transfer in different power-law indexes. The increment of the magnetic field power declines the effect of the power-law index on heat transfer. The magnetic field for various Hartmann numbers at $Ra = 10^4$; has different effects on heat transfer with the enhancement of power-law index. At $Ra = 10^5$ and for $Ha = 0$ to 30, heat transfer falls with rise of the power-law index as the effect is weakened by increase in Hartmann number significantly. The influence of power-law index on heat transfer augments with increase in the size of the heated section.

Keywords: Non-Newtonian fluid; Power-law model; Natural convection; Magnetic field; FDLBM; Partially heated cavity

1. Introduction

An external magnetic field is widely utilized for the process of manufacturing polymers. In multifarious polymers classes (Thermoplasts and Thermosets), the convection process is the foremost section of heat transfer during engineering production (Gowariker et al., 2001; Harper, 1996; William, 2004). Molten polymers could be modeled by non-Newtonian power-law model (Middleman, 1977; Mackley et al., 1994). Flow in an enclosure driven by the buoyancy force is a fundamental problem in fluid mechanics. This type of flow can be used as validation in academic researches and various applications of engineering (Davis, 1983; Le Quéré, 1991; Bejan, 1995). The effect of a magnetic field on the convection process in cavities on different fluids and boundary conditions, has been widely studied by using various numerical methods (Sathiyamoorthy and Chamkha, 2010; Pirmohammadi and Ghassemi, 2009; Kefayati et al., 2012, 2013). In addition, several investigations on natural convection for non-Newtonian power-law fluids were conducted by researchers with different models and numerical methods (Ohta et al., 2002; Kim et al., 2003; Lamsaadi et al., 2006a,b; Lamsaadi et al., 2008; Matin et al., 2013). Turan et al. (2011) simulated two-dimensional steady-state of laminar natural convection in square enclosures filled with power-law fluids. They indicated that the Nusselt number decreases with increase in the power-law index, while average Nusselt number is marginally affected by the increase in the Prandtl number. Natural convection of Newtonian and non-Newtonian power-law type fluids in two-dimensional rectangular tilted enclosures was numerically investigated by Khezzar et al. (2012). They cited that the shear thinning and thickening manners result in significant increase and decrease, respectively, in heat transfer rate in comparison to the heat transfer rate of a Newtonian fluid.

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Nomenclature

B	magnetic field
c	lattice speed
c_p	specific heat at constant pressure
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
H	the length of the heated section
Ha	Hartmann number
K	the consistency coefficient
L	the length of the cavity
n	power-law index
Nu	Nusselt number
P	pressure
Pr	Prandtl number
Ra	Rayleigh 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
γ	the angle of the magnetic field

Subscripts

avg	average
C	Cold
H	Hot
x,y	Cartesian coordinates
α	The number of the node

The simulation of the problem requires a special innovative numerical method which has the capacity to solve it accurately and efficiently. The Lattice Boltzmann Method is a powerful mesoscopic method in different subjects such as nanofluid, ferrofluid, MHD flow, turbulent flow, and so on (Kefayati, 2013a,b,c,d,e, 2014a,b; Ashorynejad et al., 2013; Sajjadi et al., 2011, 2012). However, it is not as successful in non-Newtonian fluid, especially on energy equations. The Finite Difference Lattice Boltzmann Method (FDLBM) has been applied to solve the problem as it has the ability to derive shear stresses equations in the forms of the classical equations, in contrast with the Lattice Boltzmann Method (LBM). In contrast to independency of the method to relaxation time, common LBM causes the method to resolve different non-Newtonian fluid energy equations successfully, as the method protects the positive points of LBM simultaneously. In addition, the validation of the method and its mesh independency, demonstrates that it is more capable than conventional LBM. The method has been proposed and developed by Fu et al. (2009, 2010, 2011, 2012, 2013), Fu and So (2009) and Fu (2011), and they have solved multifarious problems with it. Recently, the effect of a magnetic field on non-Newtonian blood flow in lid-driven cavities with different boundary conditions (Kefayati, 2014c,d), natural convection of molten polymer (Kefayati, 2014e), the influence of a magnetic field on natural convection of power-law fluid in enclosures (Kefayati, 2014f,g), double diffusion mixed convection of shear thinning fluids in the presence and the absence of a magnetic field (Kefayati, 2014h, in press-a,b), and laminar mixed convection of non-Newtonian nanofluids in a square lid-driven cavity (Kefayati, 2014i) have been simulated by the FDLBM. The mentioned solved problems demonstrate the ability of the method for solution of various complicated non-Newtonian problems.

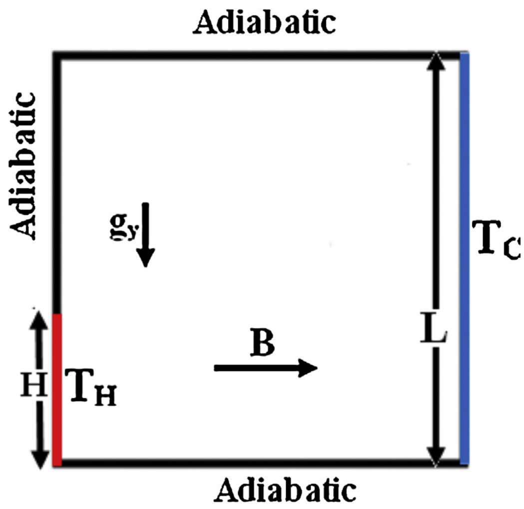

Fig. 1 – Geometry of the present study.

This paper deals with the numerical simulation of a magnetic field's effect on non-Newtonian power-law fluid in a partially heated cavity utilizing the FDLBM. The results of the FDLBM are validated with previous numerical investigations, and the effects of the main considered parameters (Rayleigh number, Hartmann number, power-law index, the size of the heated section) on flow and thermal fields are researched.

2. Problem statement

The geometry of the present problem is shown in Fig. 1. It consists of a two-dimensional cavity with the height of L. The temperature of the heated section is maintained at a high temperature of T_H, where the heated section length has been studied at ($H/L = 0.25$, 0.5 and 0.75). The right wall is fixed at a low temperature of T_C. The top and bottom horizontal walls have been considered to be adiabatic. The cavity is filled with non-Newtonian power-law fluids, while the Prandtl number is fixed at $Pr = 10$. The flow is incompressible, and laminar. The density variation is approximated by the standard Boussinesq model. The uniform magnetic field with a constant magnitude B is applied horizontally ($\gamma = 0°$). Viscous dissipation in energy equation has been neglected. The induced magnetic field assumed to be negligible in comparison with the external magnetic field, while the imposed and induced electrical fields are assumed to be insignificant.