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Double-diffusive natural convection and entropy generation of Bingham fluid in an inclined cavity

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ABSTRACT

In this paper, double-diffusive natural convection, studying Soret and Dufour effects and viscous dissipation in a square cavity filled with Bingham fluid has been simulated by Finite Difference Lattice Boltzmann Method (FDLBM). In addition, entropy generations through fluid friction, heat transfer, and mass transfer has been studied. The problem has been solved by applying the regularised Papanastasiou model. This study has been conducted for certain pertinent parameters of Rayleigh number ($Ra = 10^3, 10^4$ and 10^5), Bingham number (Bn), Lewis number (Le = 2.5, 5 and 10), Dufour parameter (D_f = 0, 1, and 5), Soret parameter (S_r = 0, 1, and 5), Eckert number (Ec = 0, 0.001, and 0.01), inclined angle (θ = 0, 40, 80, and 120) and the Buoyancy ratio ($N = -1$, 0.1, 1). Results indicate that the increase in Rayleigh number enhances heat and mass transfer for various Bingham numbers and inclined angles. The alteration of the inclined angle changes heat and mass transfer. In addition, the rise of the inclined angle alter the unyielded zones. The increase in the Lewis number augments mass transfer in different inclined angles while it causes heat transfer to drop marginally at θ = 0, 40, and 120. The heat transfer increases with the rise of the Dufour parameter and the mass transfer enhances as the Soret parameter increases for different Bingham numbers and Rayleigh numbers. In some cases, the augmentation of Soret and Dufour parameters alter the behavior of heat and mass transfer against the alteration of the inclined angle. The addition of Soret and Dufour parameters and Lewis numbers do not affect the unyielded zone considerably. The augmentation of the buoyancy ratio number enhances heat and mass transfer. The rise of buoyancy ratio number alters the unyielded section significantly. The increase in Eckert number declines heat transfer, but it has a marginal effect on mass transfer. The augmentation of Rayleigh number enhances different entropy generations and declines the average Bejan number. The increase in the Bingham number provokes various irreversibilities to drop significantly. The rise of Soret and Dufour parameters enhances the entropy generations due to heat transfer and fluid friction. The rise of Eckert number alters various entropy generations, but the alteration does not follow a specific manner in different studied parameters.

1. Introduction

Bingham fluid is a special sub-class of non-Newtonian fluids in which the flow field is divided into two regions: the first is an unyielded zone where the fluid is at rest or undergoes a rigid motion, and the second where the fluid flows like a viscous liquid. In the unyielded zone, the second invariant of the extra stress tensor is less than or equal to the yield stress and a constitutive relation does not exist. In the yielded region, this invariant exceeds the yield stress and a constitutive relation exists for the extra stress tensor. Thus, the location and shape of the yield surface(s), i.e. the interface between these two sets, is also a part of the solution of flow problems of such fluids [1]. Bingham fluids occur in various chemical, metal, and food industries, e.g., margarine, mayonnaise and ketchup. Analysis of natural convection in enclosures has been extensively conducted using different numerical techniques and experiments because of its wide applications and interest in engineering e.g. nuclear energy, double pane windows, heating and cooling of buildings, solar collectors, electronic cooling, etc. The wide range of studies into this topic has led to the natural convection in a cavity to become a common benchmark among researchers in the field of CFD (Computational Fluid Dynamics). It consists of a two-dimensional cavity and the temperature of the heated section on the left is maintained at a higher temperature and the right wall is held at a lower temperature. The horizontal walls are

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Nomenclature

$\mathbf{A_1}$	first Rivlin-Ericksen tensor
Be	Bejan number
C	concentration
c	lattice speed
c_p	specific heat at constant pressure
D	mass diffusivity
D_f	Dufour parameter
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
k	thermal conductivity
L	length of the cavity
Le	Lewis number
N	Buoyancy ratio
Nu	Nusselt number
p	pressure
Pr	Prandtl number
R	gas constant
Ra	Rayleigh number
S_D	entropy due to mass transfer
S_F	entropy due to fluid friction
S_T	entropy due to heat transfer
S_S	summation of entropy generations
Sh	Sherwood number
T	temperature
t	time
x, y	Cartesian coordinates
u	velocity in x direction
v	velocity in y direction

Greek letters

β	thermal expansion coefficient
ϕ	relaxation time
τ	shear stress
ξ	discrete particle speeds
Δx	lattice spacing
Δt	time increment
α	thermal diffusivity
ρ	density of fluid
η	dynamic viscosity
ψ	stream function value
II	second invariant
θ	inclined angle

Subscripts

avg	average
C	cold
H	hot
x, y	Cartesian coordinates
α	numbers of nodes
f	fluid
s	solid
T	thermal
tot	total
D	solutal

considered to be adiabatic and the density variation is approximated by the standard Boussinesq model. The natural convection flow of a Newtonian fluid has been studied numerically by de Vahl Davis [2], Quere and de Roquefort [3], Quere [4]. Natural convection of Bingham fluid in a cavity has been studied recently by researchers. Vola et al. [5] studied the natural convection in a cavity filled with a Bingham fluid using the Bingham model without any regularisation of the constitutive law. They applied a numerical method based on the combination of the characteristic/Galerkin method to cope with convection and of the FortinGlowinski decomposition/coordination method to deal with the non-differentiable and nonlinear terms that derive from the constitutive law. However, the streamlines and isotherms for various yield stress values were limited to one value of the Rayleigh number ($Ra = 10^4$). Turan et al. [6] conducted a study into the simulations of natural convection in square enclosures filled with an incompressible Bingham fluid. The considered flow was laminar and steady. The commercial package FLUENT was utilised to solve the problem. In this study, a second-order central differencing scheme was used for the diffusive terms and a second order up-wind scheme for the convective terms. Coupling of the pressure and velocity fields was achieved using the SIMPLE algorithm. It should be noted that the default Bingham model in FLUENT is a bi viscosity model [7]. The heat transfer and the flow velocities were investigated over a wide range of Rayleigh and Prandtl numbers. They found that the average Nusselt number augments with the rise of the Rayleigh number for both Newtonian and Bingham fluids, whereas the Nusselt numbers of Bingham fluids were smaller than those in Newtonian fluids for a fixed nominal Rayleigh number. They also mentioned that the mean Nusselt number of Bingham

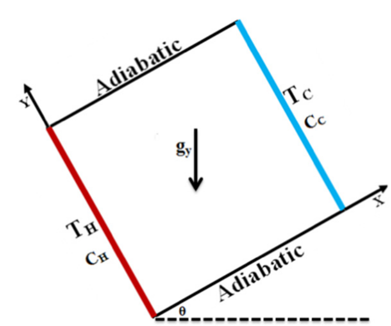

Fig. 1. Geometry of the present study.

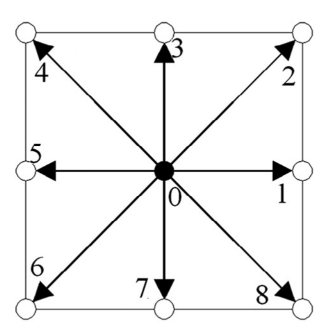

Fig. 2. Discrete velocity distribution in D2Q9.