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Double-diffusive laminar natural convection and entropy generation of Carreau fluid in a heated enclosure with an inner circular cold cylinder (Part II: Entropy generation)

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ABSTRACT

In this paper, entropy generation of double-diffusive natural convection, studying Soret and Dufour effects and viscous dissipation in a heated enclosure with an inner cold cylinder filled with non-Newtonian Carreau fluid has been simulated by Finite Difference Lattice Boltzmann Method (FDLBM). This study has been conducted for certain pertinent parameters of Rayleigh number ($Ra = 10^4$ and 10^5), Carreau number ($Cu = 1$, 10, and 20), 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 ($Ec = 0$, 1, and 10), the Buoyancy ratio (N = −1, 0.1, 1), the radius of the inner cylinder ($R_d = 0.1$ L, 0.2 L, 0.3 L, and 0.4 L), the horizontal distance of the circular cylinder from the center of the enclosure ($\Omega = -0.2$ L, 0 and 0.2 L), the vertical distance of the circular cylinder from the center of the enclosure ($\delta = -0.2$ L, 0 and 0.2 L). Results indicate that the augmentation of Rayleigh number enhances different entropy generations and declines the average Bejan number. The increase in the power-law index provokes various irreversibilities to drop significantly. The rise of Soret and Dufour parameters enhance the entropy generations due to heat transfer and fluid friction. The rise of Eckert number enhances the summation entropy generations. The increase in Lewis number augments the total summation entropy generations gradually. The enhancement of the buoyancy ratio causes the summation entropy generations to increase considerably. The rise of Carreau number declines the total entropy generation gradually. The least value of the total entropy generation in the vertical position of the cylinder occurs at $\delta = -0.2$ L. The increase in the size of the cylinder augments the total entropy generation substantially. The minimum values of the total entropy generations are observed in the center position ($\delta = 0$) in different horizontal positions.

1. Introduction

Natural convection flow of a Newtonian fluid has been studied immensely by researchers [1–3] due to its wide applications e.g. nuclear energy, double pane windows, heating and cooling of buildings, solar collectors, electronic cooling, etc. Many studies have conducted the effect of the presence of a hot or cold body inside the enclosure on the natural convection phenomena and focused on the diverse body shapes such as circular, square and triangular cylinders [4–9]. Natural convection of non-Newtonian power-law fluids and Bingham fluids recently have been studied by some researchers [10–17]. However, natural convection of Carreau fluids in an enclosure have not been considered thus far. Carreau fluid is a special sub-class of non-Newtonian fluids in which follows the Carreau model [18]. This model was introduced in 1972 and is used extensively up to date. Carreau models have been employed to simulate various chemical, metal, molten plastics, slurries, paints, blood, etc. Some isothermal and non-isotermal problems have been studied [19–22]. The optimal design of the cited industries is obtained with precision calculation of entropy generation since it clarifies energy losses in a system evidently. Entropy generation on natural convection has been scrutinized in some researches. Ilis et al. [23] investigated entropy generation in rectangular cavities with different aspect ratios numerically. It was demonstrated that heat transfer and fluid friction irreversibility in a cavity vary considerably with the studied aspect ratios. In addition, the total entropy generation in a cavity increases with Rayleigh number, however, the rate of increase depends on the aspect ratio. El-Maghlany et al. [24] analyzed entropy generation associated with laminar natural convection in

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Nomenclature

b	body force
C	concentration
c	lattice speed
c_p	specific heat capacity at constant pressure
Cu	Carreau number
D	mass diffusivity
D_f	Dufour parameter
E	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
h_α	internal concentration distribution functions for the specific node of α
h_α^{eq}	equilibrium internal concentration distribution functions for the specific node of α
k	thermal conductivity
K_{TC}	thermodiffusion coefficient
K_{CT}	diffusionthermo coefficient
L	length of the cavity
Le	Lewis number
n	power-law index
N	Buoyancy ratio
Nu	Nusselt number
p	pressure
Pr	Prandtl number
R	gas constant
Ra	Rayleigh number
R_d	radius of the inner circular cylinder
S	rate of strain tensor
Sh	Sherwood number
S_r	Soret parameter
T	temperature
t	time
x, y	Cartesian coordinates
x_c, y_c	the horizontal and vertical positions of the cylinder center
u	velocity in x direction
v	velocity in y direction

Greek letters

β_T	thermal expansion coefficient
β_C	solutal expansion coefficient
ϕ	relaxation time
τ	shear stress
ξ	discrete particle speeds
Δx	lattice spacing
Δt	time increment
δ	the vertical distance from the center
Ω	the horizontal distance from the center
α	thermal diffusivity
ρ	density of fluid
η	dynamic viscosity
η_0	zero shear viscosity
η_∞	infinite shear viscosity
ψ	stream function value
λ	time constant

Subscripts

avg	average
B	bottom
C	cold
c	center
d	dynamic
H	hot
L	left
x, y	Cartesian coordinates
α	specific node
R	right
s	static
T	thermal, top
tot	total
D	solutal

an infinite square cavity, subjected to an isotropic heat field with various intensities for different Rayleigh numbers. Mun et al.[25] studied entropy generation of natural convection in square enclosure with an inner cylinder. They scrutinized the simulations for different Rayleigh numbers, inclined angles, and Prandtl numbers. Doo et al.[26] analyzed entropy generation of natural convection in square enclosure with inner cylinder. They scrutinized the simulations for different Rayleigh numbers, the vertical position of inner cylinder, and Prandtl numbers.

Lattice Boltzmann method (LBM) has been demonstrated to be a very effective mesoscopic numerical method to model a broad variety of complex fluid flow phenomena [27–42]. This is because the main equation of the LBM is hyperbolic and can be solved locally, explicitly, and efficiently on parallel computers. However, the specific relation between the relaxation time and the viscosity has caused LBM not to have the considerable success in non-Newtonian fluid especially on energy equations. In this connection, Fu et al. [43,44] proposed a new equation for the equilibrium distribution function, modifying the LB model. Here, this equilibrium distribution function is altered in different directions and nodes while the relaxation time is fixed. Independency of the method to the relaxation time in contrast with common LBM provokes the method to solve 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 is more capable than conventional LBM. Huilgol and Kefayati [45] derived the three dimensional equations of continuum mechanics for this method and demonstrated that the theoretical development can be applied to all fluids, whether they be Newtonian, or power law fluids, or viscoelastic and viscoplastic fluids. Following the study, Huilgol and Kefayati [46] developed this method for the cartesian, cylindrical and spherical coordinates. Kefayati [47] simulated double-diffusive natural convection with Soret and Dufour effects in a square cavity filled with non-Newtonian power-law fluid by FDLBM while entropy generations through fluid friction, heat transfer, and mass transfer were analysed. Kefayati [48,49] analysed double diffusive natural convection and entropy generation of non-Newtonian power-law fluids in an inclined porous cavity in the presence of Soret and Dufour parameters by FDLBM. Kefayati and Huilgol [50] conducted a two-dimensional simulation of steady mixed convection in a square enclosure with differentially heated sidewalls when the enclosure is filled with a Bingham fluid, using FDLBM. The problem was solved by the Bingham model