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A thermal non-equilibrium model for 3D double diffusive convection of power-law fluids with chemical reaction in the porous medium

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ABSTRACT

The article reports a numerical study of the double-diffusive natural convection of power-law fluids in a porous cubic cavity with chemical reaction under the local thermal non-equilibrium (LTNE) state and submitted to horizontal temperature and concentration gradients. The complete governing equations, in which the generalized non-Darcy model is employed as momentum equation and a two-temperature model that represents temperature fields of the fluid and solid phases separately is used for energy equation, are solved by the compact high order finite volume method. Special attentions are given to detecting the effects of the porosity modified conductivity ratio (γ), the inter-phase heat transfer coefficient (H), the chemical reaction parameter (λ), the Dufour parameter (Du), the Soret parameter (Sr) and the Lewis number (Le) on the fluid flow as well as on rates of heat and mass transfer. Our simulations show that the heat transfer rate of solid increases, while the heat transfer rate of fluid and mass transfer rate keep constants, as the LTNE parameters (i.e., γ and H) increase. For any relatively large value of γ and H, the almost thermal equilibrium state is achieved due to the similar thermal distribution of fluid and solid phases. On the contrary, the chemical reaction parameter has significant influence on mass transfer than on heat transfer under the LTNE conditions. In addition, the heat and mass transfer enhance with the increment of the Soret and Dufour parameters. Augmentation of Lewis number enhances mass transfer but reduces heat transfer. Apart from that, our numerical tests show the flow field is influenced appreciably by the presence of the power-law index (n), Darcy number (Da) and porous thermal Rayleigh number (Ra).

1. Introduction

Double-diffusive convective flow with heat and mass transfer embedded in a fluid-saturated porous medium has been studied widely over the last decades due to their applications in the spreading of chemical pollutants in saturated soil, petroleum drilling, chemical and food processing, etc. Extensive studies on this subject were carried out by researchers [1–8]. Albeit the fact that none of these processes is deprived from existence of chemical reactions of some sort or another, relatively limited number of research works have been conducted which consider the inclusion of such chemical reactions into these processes. It is believed that coupled heat and mass transfer problems in presence of chemical reaction are of importance in many applications especially those encountered in chemical reactors of porous structure, geothermal reservoir, fire and combustion modeling, nuclear reactor cores, etc. Chemical reactions can be modeled as either heterogeneous or homogeneous processes. It depends on whether they occur at an interface or as a single phase volume reaction. In most cases of chemical reactions, the reaction rate depends on the concentration of the species itself. One of the simplest chemical reactions is the first-order reaction in which the rate of reaction is directly proportional to the species concentration.

Patil et al. [9] investigated analytically the effects of chemical reaction on free convective flow of a polar fluid through a porous medium in the presence of internal heat generation. Eid [10] studied the effects of chemical reaction and heat generation or absorption on MHD mixed convective boundary layer flow of a nanofluid through a porous medium due to an exponentially stretching sheet. Ghesmat et al. [11] examined the impact of geochemistry on convective mixing in a gravitationally unstable diffusive boundary layer in porous media with consideration of a second-order type reaction. Mohamed et al. [12] carried out a finite element analysis to study hydromagnetic flow and heat transfer of a heat generation fluid over a surface embedded in a non-Darcy porous

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Nomenclature

C	concentration [kg m^{-3}]
C_p	heat capacity [J kg^{-1} K^{-1}]
Da	Darcy number
D	mass diffusivity [m^2 s^{-1}]
Du	Dufour parameter
$\mathbf{g}$	gravitational acceleration vector [m s^{-2}]
h	inter-phase heat transfer coefficient [W m^{-3} K^{-1}]
Ha	dimensionless internal heat source
K	permeability [m^2]
k_c	chemical reaction parameter
k_{TC}	Dufour coefficient
k_{CT}	Soret coefficient
k	thermal conductivity [W m^{-1} K^{-1}]
Le	Lewis number
m	consistency index [N s^n m^{-2}]
n	power-law index
Nu	Nusselt number
N	buoyancy ratio
p	pressure [kg m^{-1} s^{-2}]
P	dimensionless pressure
Pr	Prandtl number
q	internal heat production per unit volume [W m^{-3}]
Ra	porous thermal Rayleigh number
Sr	Soret parameter
Sh	Sherwood number
T	temperature [K]
t	time [s]
$\mathbf{u}$	velocity vector (u, v, w) [m s^{-1}]
$\mathbf{U}$	dimensionless velocity vector (U, V, W)
x, y, z	Cartesian coordinates [m]
X, Y, Z	dimensionless Cartesian coordinates

Greek symbols

γ	porosity modified conductivity ratio
ρ	density [kg m^{-3}]
Θ	dimensionless temperature
Φ	dimensionless concentration
ϕ	porosity of the porous media
ξ	diffusivity ratio
β	thermal/compositional expansion coefficient [K^{-1}]/[m^3 kg^{-1}]
μ	dynamic viscosity [m^2 s^{-1}]
λ	dimensionless chemical reaction parameter
$\tau_{ij}, \boldsymbol{\tau}$	shear stress tensor
τ	dimensionless time

Subscripts

f	fluid
s	porous medium
T	thermal/heat
C	solutal/mass

medium in the presence of chemical reaction. Ravindran et al. [13] reported the unsteady mixed convection MHD flow over a vertical cone with non-uniform slot mass transfer in the presence of transverse magnetic field, heat generation/absorption and a first order chemical reaction. A numerical study has been conducted by Pal et al. [14] to examine the influence of thermal radiation on mixed convection heat and mass transfer stagnation-point flow in nanofluids over stretching/shrinking sheet in a porous medium with chemical reaction. Recently, Hussain et al. [15] discussed free convective heat transfer with Hall effects, heat absorption and chemical reaction over an accelerated moving plate in a rotating system. Eid [16] studied the effects of effectiveness chemical reaction on viscous flow of a non-Darcy nanofluid over a non-linearly stretching sheet in a porous medium in the presence of thermal radiation and Soret effect. In addition, the heat and mass transfer simultaneously affect each other that will cause the cross-diffusion effect. Mansour et al. [17] presented an analysis to investigate the effects of chemical reaction, thermal stratification, Soret number and Dufour number on MHD free convective heat and mass transfer over a vertical stretching surface embedded in a saturated porous medium. Kandasamy et al. [18] applied the group theoretic method to solve the problem of Soret and Dufour effects on free convective heat and mass transfer over a porous stretching surface in the presence of thermophoresis and chemical reaction with variable stream conditions.

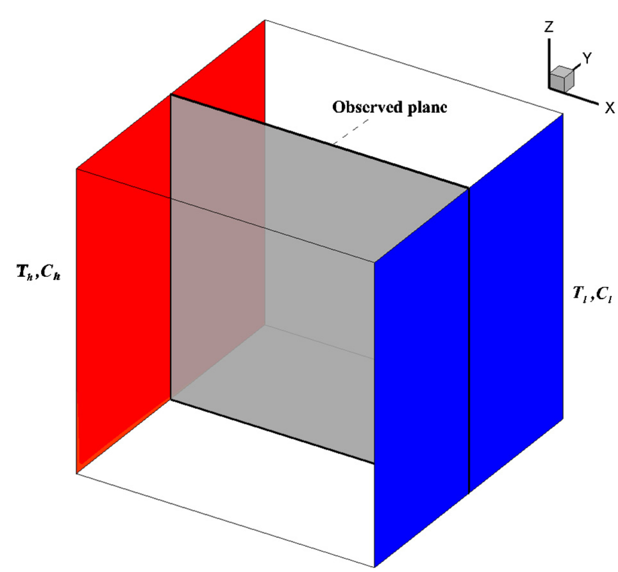

Fig. 1. Schematic of the physical model and the coordinate system.

However, most of the previous studies dealing with heat and mass transfer in porous media have assumed local thermal equilibrium (LTE) between the fluid and solid phases. In fact, this assumption does not hold well in many practical applications (e.g. nuclear reactor cores), as the fluid and the solid matrix have different temperature, which leads to local thermally non-equilibrium (LTNE) condition. The LTNE situation can be handled by considering separate energy equations for fluid and solid phases with a coupling in between them to represent the energy exchange. Baytas [19] proposed a thermal non-equilibrium model to study the steady state natural convection in a square enclosure filled with a heat-generating solid phase, non-Darcy porous medium. The investigation on finger type double diffusive convective instability in a fluid-saturated porous medium in the presence of coupled heat-solute diffusion was undertaken by Saravanan et al. [20] on the basis of a local thermal nonequilibrium (LTNE) condition. Also, Saravanan et al. [21] paid attention to the onset of thermovibrational convection in a vertically vibrating porous layer exhibiting thermal nonequilibrium. Gao et al. [22] developed a thermal lattice Boltzmann model for natural convection in porous media under local