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Entropy generation due to three-dimensional double-diffusive convection of power-law fluids in heterogeneous porous media

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ABSTRACT

The article reports a numerical study of entropy generation due to the double-diffusive natural convection in a 3D heterogeneous porous cubic saturated with power-law fluids and submitted to horizontal thermal and concentration gradients. The governing equations based on a generalized non-Darcy model are solved by using the compact high order finite volume method. This approach is devised to detect the effects of the heterogeneity level, the buoyancy ratio and the porous thermal Rayleigh number on the fluid flow and its associated irreversibility characteristics. The results show that the mean Nusselt and Sherwood number reduce, while the total entropy generation increases, as the level of heterogeneity increases by the exponential distribution of the permeability; the mean Nusselt, Sherwood number and total entropy generation increases as the porous thermal Rayleigh number increases or the buoyancy ratio increases (decreases) for the thermal dominated flow (solutal dominated flow) by the heat and mass transfer performance. Apart from that, our numerical tests of the approach on the shear-thinning, the Newtonian and shear-thickening fluids show that the impacts of different power-law indexes on the entropy generation due to fluid friction, heat and mass transfer are mainly manifested in rheological properties, which elucidate that the shear-thinning fluids is more effective than shear-thickening fluids. The studies may help us establish a physically reasonable methodology to systemically assess fluid flow and energy consumption in heterogeneous porous media in the real world.

1. Introduction

The thermosolutal, i.e. double-diffusive convection, in a 2D/3D fluid-saturated porous medium, has received considerable attention over the last decades due to their applications in contaminant transport in saturated soils, the underground disposal of nuclear waste, petroleum drilling, chemical and food processing, etc. Extensive studies on this subject were carried out by researchers [1–8], which are based on the first law of thermodynamics. Current works also focus on the process efficiency based on the second law of thermodynamics. In any physical process, there is a loss in the amount of available energy. The loss of energy or the process efficiency, which may be due to heat transfer, mass transfer, fluid friction and Darcy dissipation irreversibilities, can be quantified in terms of entropy generation. Therefore by analyzing the entropy generation due to irreversibilities, the strategies to optimize the process may be achieved to increase the overall efficiency of the system.

A representative review of entropy generation in thermal system may be found in the recent publication of Torabi et al. [9]. Mchirgui et al. [10] investigated the entropy generation in double-diffusive convection through a square porous cavity saturated with a binary perfect gas mixture using Brinkman-extended Darcy formulation. Fersadou et al. [11] presented a numerical study of MHD mixed convection and entropy generation of a nanofluid in a vertical porous channel. Roy et al. [12] analyzed entropy generation during the mixed convection in square enclosures for various horizontal or vertical moving walls. Ghachem et al. [13] numerically studied the 3D double-diffusive convection flow and entropy generation in a solar distiller. Elazhary et al. [14] considered the effects of electric double layer (EDL) on the entropy generation during fully-developed forced convection in parallel-plate micro-channels at high zeta-potentials.

Recently, many studies have been reported on the entropy generation analysis for enclosures with various shapes [15,16] due to its importance in improving of heat transfer performance. What is more, heat transfer and fluid flow within an enclosure or channel

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Nomenclature

Be	Bejan number
Be_{avg}	average Bejan number
C	concentration
c_p	heat capacity of porous medium
c_f	heat capacity of fluid
Da	Darcy number
$D(x,y,z)$	effective mass diffusivity
D_0	mean value of mass diffusivity
g	gravitational acceleration
$K(x,y,z)$	permeability
K_0	mean value of permeability
$k(x,y,z)$	effective thermal diffusivity
k_0	mean value of thermal diffusivity
Le	Lewis number
n	power-law index
Nu	Nusselt number
N	buoyancy ratio
p, P	pressure
Pr	Prandtl number
$\bar{Q}$	vertical unit vector
Ra	porous Rayleigh number
Ra_T	thermal Reyleigh number
Ra_S	solutal Reyleigh number
Sh	Sherwood number
$\overline{S_T}, S_T$	heat transfer irreversibility
$\overline{S_C}, S_C$	mass transfer irreversibility
$\overline{S_F}, S_F$	fluid friction and Darcy dissipation irreversibility
$\overline{S_s}, S_s$	local entropy generation
T	temperature
t	time
u	velocity vector
u, U	velocity in x direction
v, V	velocity in y direction
w, W	velocity in z direction
x, X	x-coordinate
y, Y	y-coordinate
z, Z	z-coordinate

Greek symbols

γ	heat capacity ratio
ρ	density
Θ	dimensionless temperature
Φ	dimensionless concentration
ϕ	porosity of the porous media
α	thermal diffusion coefficient
β_T	thermal expansion coefficient
β_C	concentration expansion coefficient
μ, $\bar{\mu}$	dynamic viscosity
ζ	rate of change of $\ln(K)$ in the x direction
σ	rate of change of $\ln(K)$ in the y direction
δ	rate of change of $\ln(K)$ in the z direction
τ_{ij}	shear stree tensor
τ	dimensionless time
$\boldsymbol{\tau}$	shear stress tensor

can also be affected by using an obstruction [17–19]. Selimefendigil et al. [17] studied the natural convection and entropy generation in a nanofluid filled cavity having different shaped obstacles installed under the influence of magnetic field and internal heat generation. Datta et al. [18] carried out numerical investigations of heat transfer and entropy generation in a porous square enclosure in presence of an adiabatic block. Kolsi et al. [19] performed a study on a 3D natural convection and entropy generation in nanofluid filled enclosures with triangular solid insert at the corners.

However, most of the previous studies were concerned with a variety of the homogenous porous media subject to fluxes of heat and mass applied in the same direction. In fact, the heterogeneous distribution of permeability is encountered commonly in many porous environments in practical applications, e.g. reservoir rocks. Over the years, the effects of heterogeneity in porous media have attracted the attention of many researchers. Simmons et al. [20] investigated the critical role that heterogeneity played in the onset as well as the growth or decay of free convection motion for variable-density groundwater flow. A discussion on the effect of thermal nonequilibrium and non-uniform temperature gradients on the onset of convection in a heterogeneous porous medium had been made by Shivakumara et al. [21]. Fahs et al. [22] used the Fourier-Galerkin (FG) method to produce a reference benchmark solution for free convection in a square cavity filled with a heterogeneous porous medium. Musuuza et al. [23] concluded the investigations into the stability of density-driven flows in saturated heterogeneous porous media. Chaudhuri et al. [24] modeled a general form of solute transport in a mild heterogeneous porous medium with the consideration of random source conditions using stochastic finite element method. The problem of upscaling of effective hydraulic conductivity distributions in 3D heterogeneous media was numerically addressed by Boschan et al. [25].

Above investigations discussed so far refer to Newtonian fluid flow. In industrial practices such as oil recovery and materials processing, however, it is of great importance to study natural convection and entropy generation in porous media for non-Newtonian fluids. The entropy generation in double diffusive natural convection of power-law fluids in a 2D enclosure with Soret and Dufour effects was analyzed by Kefayati [26] using Finite Difference Lattice Boltzmann Method (FDLBM) and extended in Kefayati [27] to include an inclined porous cavity. Selimefendigil et al. [28] studied the MHD mixed convection and entropy generation of non-Newtonian power-law fluid inside a partially heated cavity with an adiabatic rotating cylinder under the influence of an inclined magnetic field. Fadili et al. [29] derived a 3D filtration law for power-law fluids flowing in heterogeneous porous media. Lack of discussion on the entropy generation during double-diffusive convection of power-law fluids in three-dimension may sometimes decrease the evaluation of the subject in this regard.

Presently, however, the entropy generation due to 3D double-diffusive convection of non-Newtonian power-law fluids in the heterogeneous porous media has not been reported enough even though its importance in many engineering fields is apparent as mentioned above. Recently, Zhu et al. [30] numerically studied the 3D double-diffusive convection of power-law fluids in the anisotropic porous media. In this paper, we attempt to propose an extended numerical study the entropy generation due to the 3D convection of non-Newtonian fluids in the heterogeneous porous media. Hence, the effects of heterogeneity level, the porous thermal Rayleigh numbers and buoyancy ratio on the 3D aspects and entropy generation of power-law fluids are exactly the focus of the present work.