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Analysis of entropy generation in combined buoyancy-Marangoni convection of power-law nanofluids in 3D heterogeneous porous media

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ABSTRACT

In this paper, entropy generation due to the combined buoyancy-Marangoni convection of non-Newtonian power-law nanofluids in a 3D heterogeneous porous cubic cavity is investigated in detail with the compact high order finite volume method. The fluid in the cavity is a CMC-based nanofluids containing CuO nanoparticles, and the numerical study is conducted for a wide range of heterogeneity level ranging from 0 to 1.5, Marangoni number from 0 to 1000, thermal Rayleigh number from 10^4 to 10^6, buoyancy ratio from −2.0 to −0.1, nanoparticle volume fraction from 0 to 0.1 and power-law index from 0.76 to 1.0 to identify the irreversibility characteristics. The results show that the total entropy generation is considerably affected by the heterogeneity in permeability; it increases when the level of heterogeneity increases. Marangoni number becomes a more effective parameter on total entropy generation for lower values of thermal Rayleigh numbers. For thermal dominated flow, the increase in the buoyancy ratio provokes various irreversibilities to enhance; on the other hand, for solutal dominated flow, the rise of the buoyancy ratio declines the entropy generation. Moreover, it is also shown that the enhancement of the nanoparticle volume fraction reduces the total entropy generation. Apart from that, our numerical tests show the flow field and entropy generation are influenced appreciably by the presence of the power-law index.

1. Introduction

The thermal-solutal capillary-buoyancy convection usually takes place in a mixture liquid layer with free surface under the combined effects of capillary and buoyancy forces, which are induced by the temperature and concentration gradients. Substantial theoretical, experimental and numerical work [1–8], which is based on the first law of thermodynamics, thus far has appeared on this subject due to engineering applications such as crystal growth, solar energy, cooling of electronical devices, glass manufacturing, some chemical processing and building heating and ventilation. However, convectional heat transfer fluids used in these applications such as water, mineral oils and ethylene glycol mixture have restricted designers, because of their low thermal conductivity. Thus, nanofluids are developed to improve the heat exchange performances, which refers to a liquid containing a dispersion of submicronic solid particles (nanoparticles).

Moreover, the optimal design of heat and mass transfer in different cited applications is obtained with precision calculation of entropy generation since it clarifies energy losses in a system evidently. Hence, entropy generation is investigated into natural convection of pure fluids [9,10] and nanofluids extensively based on the second law of thermodynamics. Ashorynejad et al. [11] investigated different nanofluids effect on entropy generation on natural convection in a porous cavity and found that the entropy generation is a decreasing function of volume fractions of nanofluid. Selimefendigil et al. [12] examined natural convection and entropy generation in a nano-fluid filled cavity having different shaped obstacles installed under the influence of a uniform magnetic field and uniform heat generation. Mehrali et al. [13] reported an investigation on heat transfer and entropy generation for laminar forced convection flow of graphene nanoplatelets nanofluids in a horizontal tube. Selimefendigil et al. [14] performed the entropy generation analysis of mixed convection of CuO–water nanofluid filled lid driven cavity having its upper and lower triangular domains under the influence of inclined magnetic fields. Bouchoucha et al. [15] considered the effects of non-isothermal heating on natural convection and entropy generation in a nanofluid (water-Al_2O_3) filled cavity with thick bottom wall. Malik et al. [16] presented a numerical study of MHD convection and entropy generation of nanofluid in a porous enclosure with sinusoidal heating. Al-Zamily [17] employed finite element method to analyze natural

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Nomenclature

Be	Bejan number
C	concentration
C_p	heat capacity of porous medium
C_{nf}	heat capacity of nanofluids
Da	Darcy number
$D_{eff}(x, y, z)$	effective mass diffusivity
D	mass diffusivity
g	gravitational acceleration
$K(x, y, z)$	permeability
K	permeability
$k_{eff}(x, y, z)$	effective thermal diffusivity
k	thermal diffusivity
Le	Lewis number
M	Marangoni numbers
N	buoyancy ratio
N_M	surface tension ratio
n	power-law index
p, P	pressure
Pr	Prandtl number
$\bar{Q}$	vertical unit vector
Ra	porous Rayleigh number
$\bar{S}, S$	irreversibility
$\bar{S}_s, S_s$	local entropy generation
T	temperature
t	time
$\mathbf{u}$	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
$\beta_{T_{nf}}$	thermal expansion coefficient
$\beta_{C_{nf}}$	solutal expansion coefficient
β_T	thermal coefficients of surface tension
β_C	solutal coefficients of surface tension
μ_{eff}, $\bar{\mu}$	dynamic viscosity
$\zeta_1, \zeta_2, \zeta_3$	rate of change of $\ln(K)$ in the x,y,z direction
σ	surface tension
δ	solid volume fraction
τ_{ij}	shear stree tensor
τ	dimensionless time
$\boldsymbol{\tau}$	shear stress tensor

Subscripts

nf	nanofluids
f	base fluid of nanofluids
s	solid fraction of nanofluids
T	thermal/heat
C	solutal/mass
F	fluid friction
avg	average
tot	total
0	mean value

convection and entropy generation in a cavity filled with multi-layers of porous medium and nanofluid with a heat generation.

It must be pointed out that the previous researches are mostly analyzed in two-dimensional configurations but 3D effects are often predominant and give a better understanding the process efficiency. Younis et al. [18] investigated 3D double diffusion natural convection in open lid enclosure filled with binary fluids. Oztop et al. [19] performed three-dimensional computational analysis of entropy generation due to natural convection in partially open enclosure by using finite volume method. Kolsi et al. [20] carried out a numerical investigation of combined buoyancy-thermocapillary convection and entropy generation in 3D cavity filled with Al_2O_3 nanofluid. Kolsi et al. [21] studied the 3D buoyancy-induced flow and entropy generation of nanofluid-filled open cavities with an adiabatic diamond shaped obstacle. But till now, none conduct the study about entropy generation due to the thermal-solutal capillary-buoyancy convection of nanofluids in two/three dimensional configurations.

For the above investigations, the base fluid was assumed to be Newtonian, but it is demonstrated that many nanofluids exhibit non-Newtonian, mainly shear-thinning behavior [22]. Kefayati [23] carried out a numerical simulation of heat transfer and entropy generation of MHD natural convection of non-Newtonian power-law nanofluids in an enclosure. Also, Kefayati [24] analyzed heat transfer and entropy generation on laminar natural convection of non-Newtonian power-law nanofluids in a porous square cavity by finite difference lattice Boltzmann method. However, the number of studies on entropy generation due to thermal-solutal capillary-buoyancy convection of nanofluids, where Non-Newtonian power-law fluids is considered as the base fluid, is very small.

As is well known, the convection heat and mass transfer in porous media has become a very interesting topic in the past decades. However, most 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. Islam et al. [25] performed comprehensive investigation of non-modal growth of perturbations and heterogeneity effects on double diffusive natural convection of CO_2 in a brine saturated geothermal reservoir. Barros et al. [26] provided a theoretical framework to quantify dilution of a nonreactive solute within a steady state flow as affected by the spatial variability of the hydraulic conductivity. Borgne et al. [27] investigated the temporal scaling properties of mixing in heterogeneous permeability fields. Recently, Hayat et al. [28] presented analysis deals with the nanofluid flow through a porous space with convective conditions and heterogeneous–homogeneous reactions.

Presently, however, the entropy generation due to 3D thermal-solutal capillary-buoyancy convection of non-Newtonian power-law nanofluids in the heterogeneous porous media has not been reported enough even though its importance in many engineering fields is apparent as mentioned above. Recently, the 3D double-diffusive convection of power-law fluids in the anisotropic porous media was studied numerically by Zhu et al. [29] and extended in Zhu et al. [30] to include the heterogeneous porous media. In this