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Two-phase simulation of non-Newtonian nanofluid natural convection in a circular annulus partially or completely filled with porous media

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A R T I C L E I N F O

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A B S T R A C T

In this study, natural convection heat transfer and entropy generation of the non-Newtonian power-law nanofluid including Al_2O_3 nanoparticles, inside a cylindrical annular cavity with a concentric circular heat source covered with a conductive porous layer are investigated numerically. The nanofluid is modeled using two-phase mixture model and the mixture viscosity and thermal conductivity are computed by Corcione's correlations. The effect of partial or complete filling of the enclosure with porous media for various Rayleigh ($Ra = 10^4$–10^6), Darcy ($Da = 10^{-4}$–10^{-1}), power-law index ($n = 0.6$–1.4), effective to base fluid thermal conductivity ratio ($k_{eff}/k_f = 16, 4$) and the porous layer thickness (R_d) are studied on heat transfer, entropy generation and the overall performance. Results are presented and compared in terms of the average Nu, non-dimensional entropy generation, Bejan number, streamline and isotherm contours and performance coefficient (PE). Outcomes indicate that for $k_{eff}/k_f = 16$ the fully porous cavity is recommended, while for $k_{eff}/k_f = 4$, depending on the value of Ra, Da and n parameters a proper porous layer thickness should be selected. Also, shear-thinning nanofluids show higher Nu with respect to the other studied cases. Fully porous cavities have the lowest entropy generation with the highest PE value, and for shear-thinning nanofluids the highest PE corresponds to $Ra = 10^4$.

1. Introduction

Convective heat transfer in enclosures has various applications in engineering equipment and problems including but not restricted to air conditioning systems, solar collectors and solar stills [1], electromagnetic pumps [2], fuel cells, thermal insulation systems, geothermal engineering, heat exchangers [3], electronic device cooling, refrigerators, and more [4].

In the past decades, many scientists and engineers attempted to increase the efficiency and the rate of heat transfer in cavities, and various methods have been employed to meet this need. One of these methods for enhancing the heat transfer rate is to increase conducting properties of the fluid. This improvement can be obtained by using nanofluids i.e. a combination of a base fluid (usually water, oil or ethylene glycol) and high thermal conductive metallic nanoparticles such as Cu, Al_2O_3, SiO_2 and so on. Kakaç et al. [5] showed that even a small concentration of nanoparticles (1–5%) can cause a significant increase in the heat transfer coefficients.

Various methods for modeling nanofluids have been developed; they are generally classified under two main models: single-phase and two-phase models [5]. In single-phase models it is assumed that nanoparticles and the base fluid create a homogeneous single-phase mixture with effective properties. Continuity, momentum and energy equations for the mixture are solved using the effective nanofluid properties. Different two-phase models are commonly used in fluid dynamics such as: 1. volume of fluid (VOF) [6]; 2- two-phase mixture model [7]; 3- Eulerian-Eulerian model [8]; 4- Eulerian-Lagrangian model [9] and; 5- double-diffusive model [10]. Two-phase models can provide more accurate results in expense of higher computational costs relative to single-phase models. However, among these two-phase models for numerical simulation of low concentration nanofluid flows, two-phase mixture model can provide accurately enough outcomes with lowest computational costs [11].

Using porous media made of high thermal conductive materials (such as metal foams) can also improve the heat transfer. The erratic motion of fluid between pore spaces of porous materials can substantially increase the fluid-solid contact with subsequent heat transfer enhancement.

In the recent years, simultaneous use of nanofluids and porous materials in enhanced heat transfer problems has also found a great deal of attentions. In many studies the natural convection of a nanofluid in porous square cavities has been investigated. Bourantas et al. [12] simulated

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Nomenclature

Be	Bejan number
C	consistency index ($\mathrm{Ns^n m^{-2}}$)
C_d	inertia coefficient of porous media
C_p	specific heat ($\mathrm{J\ kg^{-1}K^{-1}}$)
d_f	diameter of the base fluid molecule (m)
D_p	mean particle diameter (m)
d_p	diameter of the nanoparticle (m)
Da	Darcy number
D_{ij}	rate of deformation tensor
f_{drag}	drag friction
g	gravitational acceleration ($\mathrm{ms^{-2}}$)
Gr	Grashof number
K	permeability of porous medium ($\mathrm{m^2}$)
k	thermal conductivity ($\mathrm{W\ m^{-1}K^{-1}}$)
k_b	Boltzmann constant ($\mathrm{J\ K^{-1}}$)
n	power-law index
N_s	dimensionless entropy generation
Nu	Nusselt number
P	pressure (Pa)
PE	performance number
Pr	Prandtl number
R_d	porous to entire zone ratio
R_{in}	inner radius (m)
R_{out}	outer radius (m)
R_p	porous zone radius (m)
Ra	Rayleigh number
Re	Reynolds number
Ri	Richardson number
S_{gen}	entropy generation rate ($\mathrm{W\ m^{-3}K^{-1}}$)
$S_{gen,f}$	friction entropy generation ($\mathrm{W\ m^{-3}K^{-1}}$)
$S_{gen,T}$	thermal entropy generation ($\mathrm{W\ m^{-3}K^{-1}}$)
T	temperature (K)
T_0	bulk temperature (K)
$\mathrm{T_{fr}}$	Base fluid freezing point (K)
V	velocity ($\mathrm{ms^{-1}}$)

Subscripts

avg	average
c	cold
dr	drift
eff	effective
f	base fluid
h	hot
m	mixture(nanofluid)
p	nanoparticle
r,θ	polar coordinates (m,-)
s	solid medium
tot	total

Greek letters

α	thermal diffusivity ($\mathrm{m^2s^{-1}}$)
β	thermal expansion coefficient ($\mathrm{K^{-1}}$)
ε	porosity
φ	nanoparticle volume fraction
μ	dynamic viscosity ($\mathrm{kg\ m^{-1}s^{-1}}$)
ρ	density ($\mathrm{kg\ m^{-3}}$)
τ	shear stress (Pa)
ψ	stream function

free convection of nanofluid in a square porous cavity using extended Darcy–Brinkman model. It was found that increasing the nanoparticle volume fraction causes a considerable decline in the maximum temperature of the heat source as a result of amplified natural convection. Sheremet et al. [13] studied the impact of variable thermal boundary condition on free convection of nanofluid in a square porous cavity using Tiwari and Das' nanofluid model. They found that an increase in the volume fraction of nanofluid in the aluminum porous zone leads to a decrease in the average Nusselt number, while opposite fact observed in the porous zone with glass balls. MHD nanofluid free convection in a porous enclosure with different porous-fluid thermal conductivity ratios (K^*) has been investigated by Ghasemi and Siavashi [14]. They showed that depending on K^*, Ra and Ha values, use of nanofluid with porous media can be either beneficial or detrimental for heat transfer enhancement. Bouchoucha et al. [15] investigated the thermal performance of sinusoidal boundary condition in a square porous cavity saturated with nanofluid. It was found that Bejan number increases with increasing volume fraction or the wall thickness of the cavity. Begum et al. [16] examined the effect of magnetic field orientation on MHD mixed convection of Cu-water nanofluid in a porous cavity under sinusoidal boundary condition. Results indicated the orientation of magnetic field and Hartmann number have negative effect on convection and the influence of Hartmann number controlled the overall heat transfer. Ghasemi and Siavashi [17] studied nanofluid natural convection inside a porous enclosure with different linear temperature distribution on its side walls using LBM. They found an optimal Rayleigh number to maximize heat transfer for each Darcy number. Kolsi et al. [18] investigated the magneto-hydrodynamic free convection of a cubical enclosure filled with nanofluid and controlled the heat transfer using an inclined plate.

Some researchers investigated the impacts of internal heat sources and their location inside the cavity. Lam et al. [19] investigated the effect of internal heat sources attached to the upper and lower walls on entropy generation and temperature distribution in porous medium for different thermal parameters and heat source location. Siavashi et al. [10] developed a numerical code and studied different source shapes and configurations in a porous cavity for double-diffusive flow. They suggested that cavities with two internal heat sources have better heat and mass transfer performance compared with the single source enclosures. Also, for the mentioned cavities, cases with two rectangular sources show higher Nusselt and Sherwood numbers. Garoosi et al. [20] analyzed the mixed convection in a square cavity saturated by nanofluid in presence of wall heat sources and internal heaters using two-phase mixture model. They have found that increasing the number of heat sources has a direct relation with increase in the heat transfer rate. Sheikholeslami et al. [21] investigated the effects of complex heat source in a cylindrical cavity and found that number of undulations directly affects the temperature gradient.

The effects of enclosure shape are studied in a number of researches. Mahian et al. [22] inquired the free convection in square and triangular porous cavities filled with nanofluids. Sheremet et al. [23] studied the MHD free convection of a wavy enclosure filled with nanofluid and showed that an increase in Ha displaced the major convection cell core. Also, variation of the cavity inclination angle changes the convection heat transfer. Qi et al. [24] investigated the natural convection of nanofluid in cavities with different aspect ratios using lattice Boltzmann method and concluded that the average Nu increases with increasing aspect ratio of the enclosure. Selimefendigil and Oztop [25] investigated the mixed convection of nanofluid in a cavity with an elastic wall. They reported that the average heat transfer enhances at $\mathrm{Ri}=1$, 100 and declines at $\mathrm{Ri}=0.01$ for Young's modulus of the elastic wall 500 with respect to 10^6. Also, a number of researches have been conducted in trapezoid [26], square annulus [27] and circular annulus [28].

A few research works have also investigated convection in enclosures or tubes partially filled with porous media. Siavashi et al. [29] found an optimal porous layer thickness for laminar forced convection inside an annulus to maximize heat transfer with minimum pressure drop. In another study [30] they found an optimal porous rib arrangement with the same purpose. Alsabery et al. [31] studied the natural convection in a trapezoidal partially filled enclosure with a nanofluid porous layer and a non-Newtonian layer. Selimefendigil et al. [32] studied mixed convec-