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Natural convection of alumina-water nanofluid in an open cavity having multiple porous layers

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ABSTRACT

Control of heat transfer performance is a main challenge in different engineering applications. The present paper deals with numerical simulation of porous layers effect on natural convection in an open cavity with a hot vertical wall and cold alumina/water nanofluid penetrated into the cavity from open boundary. Mathematical description of the considered problem is based on Navier–Stokes equations with a single-phase nanofluid approach and the Brinkman-extended Darcy model for porous layers under the local thermal equilibrium approximation. The control parameters are the Rayleigh number ($Ra = 10^4$–10^5), distance between the left wall and the first vertical porous layer ($\delta = 0.1$–0.4), porous layers thicknesses ($\gamma_1 = 0.1$–0.3 and $\gamma_2 = 0.1$–0.3) and nanoparticles volume fraction ($\phi = 0$–0.04). It has been found the heat transfer enhancement with nanoparticles concentration for small distance between the hot wall and the first porous layer ($\delta = 0.1$). In the case of $\gamma_1 \leq 0.2$ a growth of the distance between the left wall and the first porous layer ($\delta \geq 0.2$) leads to the heat transfer rate augmentation.

1. Introduction

Porous layers can be considered as a good control parameter for heat transfer performance due to huge heat transfer surface and effective interaction between heat conduction in a solid matrix and convective heat transfer inside pores [1–3]. Therefore, analysis of heat transfer in complex domains including clear fluid layers and porous layers is very important and useful for an optimization of various engineering devices.

Many different papers on numerical and experimental analysis of fluid flow and heat transfer in porous media have been published. Alloi et al. [4] numerically studied the natural convection in an inclined closed space filled with a fluid saturated porous medium. They showed that both the inclination angle of the porous layer and the form of drag parameter, have a strong effect on the strength heat transfer in the closed space. Dixon and Kulacki [5] worked on combined convection in fluid superposed porous layers. The system is heated partially from the bottom. A numerical analysis is performed for laminar flow in the fluid sublayer and Darcy-Brinkman-Forchheimer flow in the porous sublayer. After that they did work experimentally for almost same conditions [6]. Siavashi and Rostami [7] performed a work on non-Newtonian nanofluid buoyancy induced convection and entropy generation in a circular annulus partially or completely filled with porous media. They found that fully porous cavities have the lowest entropy generation owing to the low temperature gradients of fluid in the porous zone. Gibanov et al. [8] have studied an influence of inclined magnetic field on mixed convection in a lid-driven ferrofluid cavity with a porous layer. It has been revealed that magnetic field inclination angle and porous layer height can be very good control parameters for heat transfer enhancement and fluid flow intensification. Martinez et al. [9] solved the 3D problem on free convection in a layered porous enclosure heated from below and cooled from the top. The system is defined as a cubic porous enclosure comprising three layers, of which the external ones share constant physical properties and the internal layer is allowed to vary in both permeability and thermal conductivity. The model is based on Darcy's law and the Boussinesq approximation. A parametric study to evaluate the sensitivity of the Nusselt number to a decrease in the permeability of the internal layer shows that strong permeability contrasts are required to observe an appreciable drop in the Nusselt number. If additionally the thickness of the internal layer is increased, a further decrease in the Nusselt number is observed as long as the convective modes remain the same, if the convective

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Nomenclature

Roman letters

A	aspect ratio
c	specific heat
Da	Darcy number
$\mathbf{g}$	gravitational acceleration vector
H	height of the cavity
H_1, H_2, H_3, H_4, H_5, H_6	special functions
h_1	thickness of porous layer I
h_2	thickness of porous layer II
K	permeability of the porous layer
L	length of the cavity
l	distance between the left wall and porous layer I
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
T	dimensional temperature
t	dimensional time
T_c	cold wall temperature
T_h	hot wall temperature
u, v	dimensionless velocity components
$\bar{u}$, $\bar{v}$	dimensional velocity components
x, y	dimensionless Cartesian coordinates
$\bar{x}$, $\bar{y}$	dimensional Cartesian coordinates

Greek symbols

β	thermal expansion coefficient
γ_1	dimensionless thickness of the porous layer I
γ_2	dimensionless thickness of the porous layer II
δ	dimensionless distance between the left wall and porous layer I
ε_1	porosity of the porous layer I
ε_2	porosity of the porous layer II
θ	dimensionless temperature
λ	thermal conductivity
μ	dynamic viscosity
ρ	density
ρc	heat capacitance
$\rho\beta$	buoyancy coefficient
τ	dimensionless time
ϕ	nanoparticles volume fraction
ψ	dimensionless stream function
ω	dimensionless vorticity

Subscripts

c	cold
f	fluid
h	hot
max	maximum value
mnf	porous layer saturated with nanofluid
nf	nanofluid
p	(nano) particle
s	solid matrix of porous layer

modes change the Nusselt number may increase. Decreasing the thermal conductivity of the middle layer causes first an increment in the Nusselt number and then a drop. On the other hand, the Nusselt number decreases in an approximately linear trend when the thermal conductivity of the layer is increased.

Hu et al. [10] performed a serial of numerical simulations for natural convection in a square closed space with a cylinder covered by a porous layer. They adopted the Darcy–Brinkman–Forchheimer equation to describe the flow. It has been found that the addition of a porous layer can change the flow pattern and enhance the heat transfer. Mehryan et al. [11] analyzed the conjugate natural convection in a porous medium filled enclosure. The enclosure is occupied with micropolar nanofluid. They observed that the Nusselt numbers for both phases significantly decrease as the thickness of the solid wall increases. Astanina et al. [12] solved the combined convection problem of nanofluid in a lid-driven enclosure which has two porous layers. Bagchi and Kulacki [13] worked on combined (superposed) fluid-porous layer in a heated enclosure from the bottom side. They showed that the Nusselt numbers increase with a reduction of the geometrical parameters and increase with the Darcy number. Wang et al. [14] studied the effect of surface thermal radiation on natural convection in a closed space with a horizontal porous layer. Hadidi et al. [15] made a computational solution on thermosolutal natural convective heat and mass transfer in the presence of bi-layered porous media. They used control volume approach to solve the governing equations and found that the permeability of the two porous layers has significant effect on the flow and diffusive. Selimefendigil et al. [16] studied two-dimensional combined convection in superposed nanofluid and porous layers in a square closed space in the presence of rotating cylinder. Shivakumara and Dhananjaya [17] worked on penetrative Brinkman convection in an anisotropic porous layer which is saturated by nanofluid. Other interesting results on convective heat transfer in porous cavities have been published in [18,19]. In the case of nanofluid flow in cavities, some interesting results can be found in [20–22].

The objective of the present investigation is to numerically study the natural convection in an open cavity having two porous layers saturated with an alumina-water nanofluid. Based on above literature survey and author's knowledge the considered in this paper heat transfer process is discussed for the first time. There is no work on conjugate solution for natural convection in the presence of composite porous material and open cavity. The problem can be applied for building such as insulation applications for higher velocities.

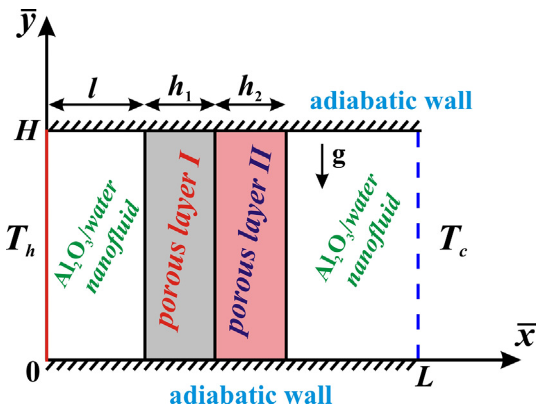

Fig. 1. Physical model and coordinate system.