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Natural convection in a porous rectangular enclosure with sinusoidal temperature distributions on both side walls using a thermal non-equilibrium model

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ABSTRACT

This study reports a numerical investigation of the natural convective flow and heat transfer in a rectangular cavity filled with a heat-generating porous medium by adopting the local thermal non-equilibrium model. The top and bottom walls of the enclosure are adiabatic and the left and right walls are partially heated and partially cooled by sinusoidal temperature profile. The results show that periodic variations with positive and negative values appear in the isotherms for fluid phase and solid phase, and the periodicity increases with the increase of N. The phase deviation has significant influence on fluid flow and heat transfer in the porous cavity. When N is large enough ($N = 32$), patterns of streamlines, isotherms for fluid phase and solid phase display like that of uniform thermal boundary condition case, and the total heat transfer rate through the whole cavity is close to that resulted by uniform thermal boundary condition. The heat transfer of porous cavity can be enhanced by sinusoidal thermal boundary condition and the phase deviation has tiny effect on the heat transfer of cavity when N is large enough ($N = 32$). The increase of inter-phase heat transfer coefficient leads to faster reduction of Q with the increase of periodicity parameter.

1. Introduction

Heat transfer and natural convection in fluid-saturated, heat-generating porous enclosures is of practical interest in the last few decades owing to its wide geophysical and engineering applications [1–3]. Examples include storage of design and operation of nuclear reactor cores, radioactive waste management, storage of agricultural and food products, design of chemical catalytic reactors, cooling of electronic devices, etc. Some studies on natural convection in heat-generating porous media have been reported [4–9]. However, most of these studies dealing with heat transfer in porous media have been dealt by considering that the fluid phase and solid phase of porous media are in thermal equilibrium state. With this assumption, the temperature of solid and fluid are considered to be the same within the representative elementary volume. Actually, in many applications this assumption of thermal equilibrium does not hold well, as the fluid and solid matrix have different temperatures, which leads to thermally non-equilibrium condition. For examples, the thermal non-equilibrium model is important for post-accident heat removal from pebble-bed nuclear reactors, solar energy collection and cooling of electronic components. As aforesaid, the assumption of local thermal equilibrium between the solid and fluid phases is inadequate for a number of problems.

In recent years, a good number of published articles [1–3,8–18] focus on natural convection due to heating and cooling of side walls, where local thermal non-equilibrium model are adopted. These research works presented detailed analyses for the effects of thermal non-equilibrium on fluid flow through a porous packed bed. Al-Amiri [1] conducted a numerical simulation by using the two-energy equation model to study natural convection in a differentially heated square cavity filled with porous media. Baytas and Pop [2] investigated free convection in a differentially heated square cavity filled with porous media by adopting the thermal non-equilibrium model. It is found that such a model modifies substantially the flow characteristics, particularly the local heat transfer coefficients. Baytas [3] performed a numerical study on natural convection of a heat-generating porous cavity with isothermally cooled walls using the thermal non-equilibrium model, and the heat generation in the porous cavity takes place within the solid phase. Khashan et al. [10] carried out a numerical simulation of

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Nomenclature

c_p	specific heat at constant pressure, J/(kg K)
C_F	Forchheimer coefficient
Da	Darcy number
g	gravitational acceleration, m/s^2
h	volumetric heat transfer coefficient between the solid and fluid phases, W/(m^3 K)
H	inter-phase heat transfer coefficient $=hL^2/\varepsilon k_f$
k	thermal conductivity, W/(m K)
K	permeability of the porous medium, m^2
L	enclosure width, m
M	enclosure height, m
N	periodicity parameter
Nu	average Nusselt number
Nu_{fy}	local Nusselt number of fluid phase
Nu_{sy}	local Nusselt number of solid phase
p	pressure, Pa
P	dimensionless pressure
Q	dimensionless total heat transfer rate
Pr	Prandtl number
q_s'''	rate of volumetric heat generation in solid phase, W/m^3
Ra	Rayleigh number
T	temperature, K
u, v	velocity components along x and y axes, m/s
U, V	non-dimensional velocity components
x, y	Cartesian coordinates, m
X, Y	non-dimensional Cartesian coordinates
Greek symbols	
α	thermal diffusivity, m^2/s
β	coefficient of volume expansion, K^{-1}
γ	thermal conductivity ratio $=\varepsilon k_f/(1-\varepsilon)k_s$
ε	porosity
θ	non-dimensional temperature
ν_f	fluid kinematic viscosity, m^2/s
ρ	density, kg/m^3
ϕ	phase deviation
ψ	dimensionless stream function
subscripts	
f	fluid
s	solid

natural convection and heat transfer in a porous cavity heated below by using a thermal non-equilibrium model. Saeid et al. [11] studied periodic free convection from a vertical plate in a saturated porous medium with the thermal non-equilibrium model. Badruddin et al. [12] numerically investigated heat transfer by convection, conduction and radiation in a saturated porous medium enclosed in a square cavity by using a thermal non-equilibrium model. Pippal and Bera [15] numerically investigated the influence of local thermal non-equilibrium state between solid porous matrix and saturated fluid on natural convection in a slender enclosure. They found that, in both (LTE as well as LTNE states), maximum heat transfer takes place at a minimum value of aspect ratio. Recently, Gao et al. [18] proposed a thermal lattice Boltzmann model for natural convection in a porous media under local thermal non-equilibrium conditions through an appropriate selection of equilibrium distribution functions and discrete source term, it was verified that the model can be served as a feasible and efficient tool for non-equilibrium natural convection problems in porous media. Mahmoudi et al. [19] analytically investigated the heat transfer in a channel partially filled with a porous medium under local thermal non-equilibrium condition. They found that Nusselt numbers can be strongly dependent upon the applied interface model.

How to increase heat transfer rate in enclosures so as to design compact natural convection has become a main concern in recent years, much focus has also been directed to the fluid flow and heat transfer characteristics under different boundary conditions. In addition to natural convection in porous enclosures with uniform thermal boundaries, recent attention has been intensively paid on the cases with non-uniform temperature distributions on the walls. By using sinusoidal temperature profile at the bottom wall, Saeid [20] found that the average Nusselt number increases when the amplitude of the temperature variation increases. Basak et al. [21] reported the comparison study on natural convection using uniform and non-uniform boundary conditions. It was found that the overall heat transfer rate for non-uniform heating case is lower than that of the uniform one. Sathiyamoorthy et al. [22] studied the influence of linearly heated vertical wall(s) and uniformly heated bottom wall on flow and heat transfer characteristics due to natural convection within a square cavity filled with porous medium. They found that, in the case of linearly heated side walls, the presence of strong symmetric secondary circulations enhances the local mixing process in the lower half of the cavity for low Prandtl number fluid, and secondary circulations become weaker for higher Prandtl number fluid. Deng et al. [23] numerically investigated natural convection in a rectangular enclosure with sinusoidal temperature distributions on both sidewalls, the results show that the natural convection heat transfer in enclosures with two sinusoidal temperature distributions on the side walls is superior to that of a single sinusoidal temperature profile on one side wall. Zahmatkesh [24] investigated the importance of thermal boundary conditions of the heated/cooled walls for heat transfer and entropy generation characteristics. It is reported that the optimum case with respect to heat transfer as well as entropy generation could be achieved by non-uniform heating. In the same year, a theoretical study of buoyancy-driven flow and heat transfer in an inclined trapezoidal enclosure filled with a fluid-saturated porous medium heated and cooled by inclined walls has been performed by Varol et al. [25], and it was found that the heat transfer rate increases with the increase of the amplitude of sinusoidal function and decreases with the increase of the aspect ratio of the enclosure. Sankar et al. [26] reported a numerical investigation of the convective flow and heat transfer in a square porous cavity with partially active thermal walls. Their results revealed that the location of heating and cooling zones has a significant influence on the flow pattern and the corresponding heat transfer in the enclosure. The location of partial heating has different effects on fluid velocity and heat transfer, and the heat transfer rate approaches a constant value for very low values of Darcy number. Recently, by using heatline concept, Saleh and Hashim [27] numerically simulated the convection in an inclined square porous enclosure with sinusoidally varying wall temperature. It was found that decreasing the inclination angle was found to increase the number of cells in the enclosure and decrease the heat transfer rate. Mejri et al. [28] numerically investigated magnetic field effect on the laminar natural convection and entropy generation in a nanofluid-filled enclosure with sinusoidal heating on both side walls. They found that, for all phase deviation, the heat transfer and fluid flow