International Communications in Heat and Mass Transfer 75 (2016) 100–114

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Buoyancy induced convection in a porous cavity with sinusoidally and partially thermally active sidewalls under local thermal non-equilibrium condition

Feng Wu [a,*], Gang Wang [b], Wenjing Zhou [c]

[a] School of Chemical Engineering, Northwest University, Taibai North Road 229, Xi'an 710069, China
[b] School of Civil Engineering, Lanzhou University of Technology, Lanzhou, Gansu 730050, China
[c] School of Chemical Engineering and Technology, Xi'an Jiaotong University, Xi'an 710049, China

ARTICLE INFO

Available online 11 April 2016

Keywords:
Natural convection
Local thermal non-equilibrium model
Sinusoidal heating and cooling
Partially active walls
Porous medium

ABSTRACT

Steady non-Darcy natural convection in a porous cavity with non-uniform thermal boundary condition is studied numerically by adopting the local thermal non-equilibrium (LTNE) model in this paper. The top and bottom walls of the cavity are adiabatic. The left vertical wall is partially heated and cooled by sinusoidal temperature profile and the right side wall of the cavity is partially cooled by uniform thermal boundary condition. The results show that, the oscillation amplitude of the local Nusselt number profiles (Nu_{fy}, Nu_{sy}) along the Y coordinate decreases with the increase of H. The difference of the local Nusselt numbers between different cases of partial cooling (case A–case D) can be reduced by increasing of N. The difference of solid-to-fluid temperature differences between different cases of partial cooling can be reduced by increasing of H and γ. Positive values of the average Nusselt number appear at the left side wall of the porous cavity, which indicates that there exists heat transfer along the positive direction of the X axis in the porous cavity. Compared with the left wall of the cavity, it is faster for the right wall to reach the thermal equilibrium state, which approaches a constant value for low values of H ($H = 3000$).

1. Introduction

Buoyancy driven convection in fluid-saturated, heat-generating porous enclosures has been gaining interest in recent years because of their wide variety of application in engineering areas [1–3], such as design and operation of nuclear reactor cores, radioactive waste management, storage of grain, cooling of electronic devices, and design of chemical catalytic reactors. Some studies on natural convection in heat-generating porous media have been reported [4–10]. However, most of the early theoretical studies adopted the assumption of the local thermal equilibrium between solid and fluid phases. Based on this model, the temperatures of the solid and fluid phases are considered to be the same within the representative elementary volume. Actually, the solid porous matrix may have a different temperature from that of the saturating fluid and the thermal equilibrium model may be questionable.

The investigation of porous media as a thermal non-equilibrium system has received more and more attention. There are a number of studies on the thermal non-equilibrium model used in convection heat transfer problems [1–3,8–26]. Al-Amiri [1] numerically simulated natural convection in a differentially heated square cavity filled with porous media using the two-energy equation model. He found that the increase in the Grashof number and/or the Darcy number can boot the contribution of the convection heat transfer to the overall energy transport. Baytas and Pop [2] studied free convection in a differentially heated square cavity filled with porous media using the local thermal non-equilibrium model. It was found that such a model modifies substantially the behavior of the flow characteristics, particularly those of the local heat transfer coefficients. Baytas [3] performed a numerical investigation on natural convection of a heat-generating porous cavity with isothermally cooled walls using the local thermal non-equilibrium model. Khashan et al. [11] numerically simulated natural convection in a porous cavity heated from below using the local thermal non-equilibrium model. Saeid and Mohamad [12] investigated periodic free convection from a vertical plate in a saturated porous medium with the local thermal non-equilibrium model. Badruddin et al. [13] numerically studied heat transfer by convection, conduction and radiation in a saturated porous medium enclosed in a square cavity using the local thermal non-equilibrium model. Pippal and Bera [16] numerically investigated influence of the 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), the maximum heat transfer used to take place at a minimum value of aspect ratio. In LTE state aspect ratio is almost independent of LTE parameter and lies in between 1 and 1.5. Recently, heat transfer in a channel

* Corresponding author. Tel.: +86 15309202861.
E-mail address: wufeng@nwu.edu.cn (F. Wu).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.03.026
0735-1933/© 2016 Elsevier Ltd. All rights reserved.

Nomenclature

c_p	[J/(kg K)]	specific heat at constant pressure
C_F	[–]	Forchheimer coefficient
Da	[–]	Darcy number
G	[m/s^2]	gravitational acceleration
H	[W/(m^3 K)]	volumetric heat transfer coefficient between the solid and fluid phases
H	[–]	inter-phase heat transfer coefficient
K	[W/(m K)]	thermal conductivity
K	[m^2]	permeability of the porous medium
L	[m]	side length of the cavity
Nu	[–]	average Nusselt number
Nu_y	[–]	local Nusselt number
P	[Pa]	Pressure
P	[–]	dimensionless pressure
Pr	[–]	Prandtl number
Q	[–]	dimensionless total heat transfer rate
q_s'''	[W/m^3]	rate of volumetric heat generation in solid phase
Ra	[–]	Rayleigh number
T	[K]	temperature
u, *v*	[m/s]	velocity components along the *x* and *y* axes
U, *V*	[–]	non-dimensional velocity components
x, *y*	[m]	Cartesian coordinates
X, *Y*	[–]	non-dimensional Cartesian coordinates
Greek symbols		
A	[m^2/s]	thermal diffusivity
B	[K^{-1}]	coefficient of volume expansion
γ	[–]	thermal conductivity ratio
ε	[–]	porosity
θ	[–]	non-dimensional temperature
ν_f	[m^2/s]	fluid kinematic viscosity
ρ	[kg/m^3]	density
ψ	[–]	dimensionless stream function
Subscripts		
F	[–]	fluid
S	[–]	solid

partially filled with a porous medium under local thermal non-equilibrium condition was analytically studied by Mahmoudi et al. [19]. They found that Nusselt numbers can be strongly dependent upon the applied interface model. Using the local thermal non-equilibrium model, Gao et al. [20] proposed a thermal lattice Boltzmann model for natural convection in a porous media through an appropriate selection of equilibrium distribution functions and discrete source term. Mahmoudi [21,22] numerically studied the effect of thermal radiation from the solid phase on the fluid and solid temperature fields inside a porous medium by studying forced convection heat transfer process within a pipe filled with a porous material. Ting et al. [23] analytically investigated thermal performance and entropy generation of water–alumina nanofluid flows in porous media embedded in a microchannel under local thermal non-equilibrium condition. Barletta and Rees [24] analytically studied the onset of secondary convective flow in a fluid-saturated porous layer inclined horizontally and heated from below. They found that the neutral stability condition for the longitudinal modes corresponds to that of the horizontal layer, by scaling the Darcy–Rayleigh number with cosine of the inclination angle to the horizontal. Dehghan et al. [26] analytically investigated the thermally developing forced convective heat transfer inside a channel filled with a porous medium whose walls are imposed to a constant heat flux. They found that the LTNE intensity decreases by increasing the conductivity ratio (*k*) and the Biot number (*Bi*).

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 many studies the wall of the cavities is considered at a constant temperature or constant heat flux while in actual cases these thermal boundary conditions seldom exist. Non-uniform temperature profile in enclosures is useful for some engineering applications. Cases such as solar energy collection and cooling of electronic components the thermally active walls may be subject to non-uniform distribution of temperature due to shading or other effects in the fields. Hence, the study on natural convection fluid flow and heat transfer in the enclosures with non-uniform temperature profile on the walls is important in such situations. But most of the research works are concerned with natural convection in rectangular geometries with isothermal or isoflux thermal boundary conditions on the side walls, and very few investigators have studied the natural convection with non-uniform thermal boundary conditions [27–39]. Non-uniform temperature profile in enclosures is useful for some engineering applications. By using non-uniform sinusoidal temperature variation at the bottom wall, Saeid [27] studied natural convection in a porous cavity with sinusoidal bottom wall temperature and cooled top wall. It was found that the average Nusselt number increases when the amplitude of the temperature variation increases. Dalal and Das [28] studied natural convection in an inclined two-dimensional enclosure with sinusoidal temperature profile on one wall. They found that inclination of the cavity affects the fluid flow and heat transfer. Basak et al. [29] reported the comparison study on natural convection using uniform and sinusoidal thermal boundary conditions. The results revealed that the overall heat transfer rate for sinusoidal heating case is lower than the uniform one. Zahmatkesh [30] 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, Varol et al. [31] numerically studied steady natural convection flow through a fluid-saturated porous medium in a rectangular enclosure with a sinusoidal varying temperature profile on the bottom wall. They found that the heat transfer increases with an increase of the amplitude of sinusoidal function and decreases with an increase of the aspect ratio of the enclosure. Khandelwal et al. [32] numerically investigated the influence of periodicity of sinusoidal bottom boundary condition on natural convection in porous enclosure, and they found that as the periodicity is decreased by increasing periodicity parameter (*N*), the absolute value of the local Nusselt number at the bottom left corner point increases in both situations.

Sathiyamoorthy et al. [37] 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. Sankar et al. [38] reported a numerical investigation of the natural convective 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 zone has different effects on velocity and heat transfer, and the heat transfer rate approaches a constant value for very low values of the Darcy number. Other studies of the natural convection in porous enclosure with partially active thermal boundary conditions can be found in [39].

The present review of literature shows that there are no open literatures in which the heat transfer characteristic of a heat-generating porous enclosure with sinusoidally and partially thermally active sidewalls under local thermal non-equilibrium condition has been reported. The main objective of the present paper is to study the non-Darcian natural convective heat transfer in a heat-generating porous enclosure