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Natural convection heat transfer in a partially opened cavity filled with porous media

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ABSTRACT

This paper examines the steady natural convection in a partially opened enclosure filled with porous media using the Brinkman–Forchheimer model. Whilst the part of the left vertical wall of the cavity is heated, the other walls are adiabatic or thermally insulated Based upon numerical predictions, the effects of pertinent parameters such as Grashof number, Darcy number, porosity, length of the heated wall and the location center of the opened cavity are examined. It is found that as the Grashof number increases, due to strengthening buoyancy driven flows, the local Nusselt number from partially heated vertical wall, at a given position on this wall increases. This, in turn, increases the temperature of the heated wall. The results of this study can be used in the design of an effective cooling system for electronic components to help ensure effective and safe operational conditions.

1. Introduction

Convective flows in enclosures filled with porous media are good examples for geological area, mechanical and chemical engineering, civil engineering, petroleum and environment engineering as reviewed by Nield and Bejan [1], Ingham and Pop [2], Pop and Ingham [3], Bejan et al. [4], Vafai [5,6], and Vadasz [7]. However, most of existing studies in literature refer on heat and fluid flow in closed porous rectangular and divided or undivided enclosures, as can be seen in the papers by Varol et al. [8,9], Oztop [10], Oztop et al. [11], Basak et al. [12], etc.

However, partially or fully opened cavities filled with viscous fluid were studied in earlier works. In this context, Abib and Jaluria [13] made a numerical analysis of the buoyancy-induced flow in a partially open enclosure with a single opening. They employed a stream-function vorticity formulation within the framework of the Boussinesq approximation. They found that the Rayleigh number is increased, the recirculation region decreases in size and moves toward the vertical wall. Polat and Bilgen [14] numerically studied the laminar steady state natural convection in inclined shallow cavities. They observed that heat transfer approaches asymptotic values at Rayleigh numbers independent of the aspect ratio and asymptotic values are close to that for a flat plate with constant heat flux. Bilgen and Oztop [15] studied naturally the convection heat transfer in partially open inclined square cavities. Penot [16] analyzed the two-dimensional natural convection problem in isothermal open cavities. Mohamad [17] worked on isothermal open cavities with aspect ratio for different aspect ratio. He showed that the inclination angle did not have any significant effect on the heat transfer rate from the isothermal plate, but substantial one on the local Nusselt number.

Studies on partially opened cavities filled with porous media are quite limited. Hagshenas et al. [18] made a numerical analysis using Lattice-Boltzmann technique on natural convection in an open-ended square cavity packed with porous medium. The effect of a porous medium is taken into account by introducing the porosity into the equilibrium distribution function and adding a force term to the evolution equation. Moraga et al. [19] studied the mixed convection heat transfer in a ventilated rectangular cavity with a horizontal strip occupied by two media of different permeability. They observed that the as the Darcy number increases, the velocity gradients increase near the walls, causing an increase of the friction coefficient. Finally, we mention that Ettefagh and Vafai [20] solved the problem of natural convection in open-ended cavities with a porous obstructing medium. Pakdee and Rattanadecho [21] worked on natural convection with partially heated porous cavity by considering convection effects. Other related studies were performed by Vafai and Ettefagh [22,23], Ettefagh et al. [24], Khanafer and Vafai [25,26].

The main aim of the present study is to understand the effects of partial openings and partial heater effects in porous media filled enclosures. The present paper is, therefore, a complex work on

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Nomenclature

C_F	Forchheimer constant
Da	Darcy number
g	gravitational acceleration
Gr	Grashof number
h	length of the heated wall
H	length of the square cavity
K	permeability of the porous medium
n	normal to the wall
Nu_x	local Nusselt number
Nu_m	is the mean Nusselt number
p	dimensional pressure
P	dimensionless pressure
Pr	Prandtl number
T	fluid temperature
u, v	dimensional velocity components along x- and y-axes
U, V	dimensionless velocity components along X- and Y-axes
x, y	dimensional Cartesian coordinates
X, Y	dimensionless coordinates
Greek letters	
α	thermal diffusivity
β	thermal expansion coefficient
ε	porosity
Θ	dimensionless temperature
ν	kinematic viscosity
Subscripts	
c	cold
h	hot
int	interior
out	outlet

partially heated and opened cavity filled with a porous medium using the Brinkman–Forchheimer model very well described in the book by Nakayama [27].

2. Considered model

The model is a partially heated and partially opened square cavity of length H filled with a fluid saturated porous medium, as shown in Fig. 1. In this model, the heated wall is under constant temperature boundary conditions (isothermal wall) and remaining impermeable walls are adiabatic. The changes location center (OC) of the opened cavity depends on the cases considered.

3. Basic equations

We assume that the convective incompressible and viscous fluid flow is described by Brinkman–Forchheimer model and that the Boussinesq approximation is valid. It is also assumed that the gravity acts in downwards vertical direction and that the fluid properties are constant. Under these assumptions, the continuity, momentum and energy equations can be written in dimensionless form as follows:

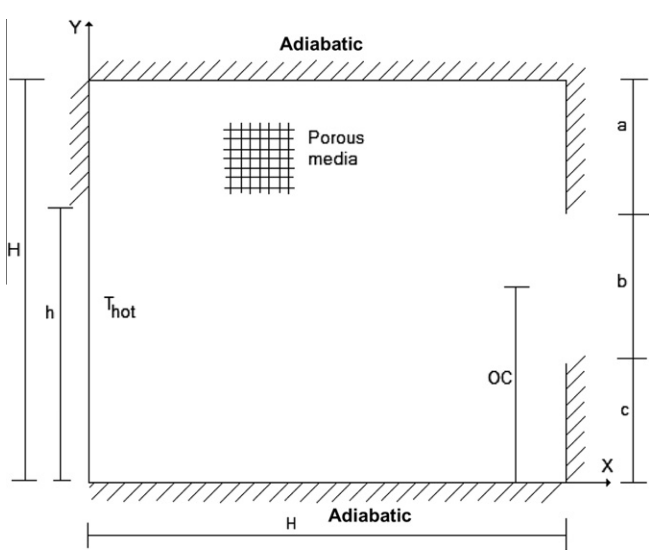

Fig. 1. Definition of physical model with coordinates.

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0, \tag{1}$$

$$\frac{U}{\varepsilon^2}\frac{\partial U}{\partial X}+\frac{V}{\varepsilon^2}\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{Pr}{Da}U+C_F\frac{(U^2+V^2)^{1/2}}{\sqrt{Da}}\frac{U}{\varepsilon^{3/2}}+\frac{Pr}{\varepsilon}\left(\frac{\partial^2 U}{\partial Y^2}+\frac{\partial^2 U}{\partial Y^2}\right), \tag{2}$$

$$\frac{U}{\varepsilon^2}\frac{\partial V}{\partial X}+\frac{V}{\varepsilon^2}\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\frac{Pr}{Da}V+C_F\frac{(U^2+V^2)^{1/2}}{\sqrt{Da}}\frac{V}{\varepsilon^{3/2}}+\frac{Pr}{\varepsilon}\left(\frac{\partial^2 V}{\partial Y^2}+\frac{\partial^2 V}{\partial Y^2}\right)+Gr\,Pr^2\Theta \tag{3}$$

$$U\frac{\partial \Theta}{\partial X}+V\frac{\partial \Theta}{\partial Y}=\frac{\partial^2 \Theta}{\partial X^2}+\frac{\partial^2 \Theta}{\partial Y^2}, \tag{4}$$

where the following dimensionless variables have been used

$$X=\frac{x}{H}\quad Y=\frac{y}{H}\quad U=\frac{u}{\alpha/H},\quad V=\frac{v}{\alpha/H},\quad P=\frac{p}{\rho\alpha/H^2},\quad \Theta=\frac{T-T_c}{T_h-T_c}. \tag{5}$$

Here U and V are the dimensionless velocity components along X- and Y-axes, T is the temperature of the fluid-saturated porous medium, Θ is the dimensionless temperature, porosity ε and the mining of the other quantities is explained in the Nomenclature. We assume that the boundary conditions of Eqs. (1)–(4) are

On all solid boundaries

$$U=V=0,\quad \frac{\partial P}{\partial n}=0 \tag{6a}$$

on the opening wall

$$\frac{\partial U}{\partial X}=\frac{\partial V}{\partial X}=\frac{\partial \Theta}{\partial X}=0, \tag{6b}$$

on the adiabatic boundaries

$$\frac{\partial \Theta}{\partial n}=0, \tag{6c}$$

on the partial heater

$$\Theta=1. \tag{6d}$$

Eqs. (1)–(4) contain the Darcy number Da, the Grashof number Gr and the Prandtl number Pr, which are defined as