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Free convection in a wavy cavity filled with a porous medium

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Abstract

The steady-state free convection inside a cavity made of two horizontal straight walls and two vertical bent-wavy walls and filled with a fluid-saturated porous medium is numerically investigated in the present paper. The wavy walls are assumed to follow a profile of cosine curve. The horizontal walls are kept adiabatic, while the bent-wavy walls are isothermal but kept at different temperatures. The Darcy and energy equations (in non-dimensional stream function and temperature formulation) are solved numerically using the Galerkin Finite Element Method (FEM). Flow and heat transfer characteristics (isothermal, streamlines and local and average Nusselt numbers) are investigated for some values of the Rayleigh number, cavity aspect ratio and surface waviness parameter. The present results are compared with those reported in the open literature for a square cavity with straight walls. It was found that these results are in excellent agreement.

Keywords: Porous media; Wavy cavity; Heat transfer; Computational

1. Introduction

Convective heat transfer in porous media has attracted the attention of engineers and scientists from many varying disciplines such as, chemical, civil, environmental, mechanical, aerospace, nuclear engineering, applied mathematicians, geothermal physics, food science, etc. To a large extent, this interest is stimulated by the fact that thermally driven flows in porous media are of considerable practical applications in the modern industry. It has given insight in the understanding dynamics of terrestrial heat flow through aquifer, hot fluid and ignition front displacements in reservoir engineering, heat exchange between soil and atmosphere, flow of moisture through porous industrial materials, heat exchangers with fluidized beds, fibre and granular insulation materials, packed-bed chemical reactors, oil recovery, ceramic processing and catalytic reactors, to name just a few applications. The fundamental importance of convective flow in porous media has been ascertained in the recent books by Ingham and Pop [1], Nield and Bejan [2], Vafai [3], Pop and Ingham [4], Bejan and Kraus [5], Ingham et al. [6] and Bejan et al. [7] appeared periodically in the literature.

The prediction of heat transfer from irregular surfaces is a topic of fundamental importance for some heat transfer devices, such as, flat plate solar collectors, flat plate condensers in refrigerators, double-wall thermal insulation, underground cable systems, electric machinery, cooling system of micro-electronic devices, natural

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Nomenclature

a	amplitude of the wave
A	aspect ratio
g	gravitational acceleration, $\mathrm{m\,s^{-2}}$
K	permeability of the porous medium, $\mathrm{m^2}$
k	thermal conductivity, $\mathrm{W\,m^{-1}\,K^{-1}}$
L	cavity height, m
Nu	local Nusselt number
Nu_a	average Nusselt number
Ra	Rayleigh number for porous medium
S	the length of the bent-wall, m
t	dimensionless time
$\bar{t}$	time, s
T	fluid temperature, K
T_c	temperature of the cold bent-wall (left), K
T_h	temperature of the hot bent-wall (right), K
T_0	characteristic temperature of the fluid-saturated porous medium, K
u, v	dimensionless velocity components along x- and y-axes, respectively
$\bar{u}, \bar{v}$	velocity components along x- and y-axes, respectively, $\mathrm{m\,s^{-1}}$
W	average width of the cavity, m
x, y	dimensionless Cartesian coordinates
$\bar{x}, \bar{y}$	Cartesian coordinates, m

Greek symbols

α_m	effective thermal diffusivity, $\mathrm{m^2\,s^{-1}}$
β	coefficient of thermal expansion, $\mathrm{K^{-1}}$
ε	the prescribed error
θ	dimensionless temperature
λ	surface waviness
ρ	fluid density, $\mathrm{kg\,m^{-3}}$
σ	ratio of composite material heat capacity to convective fluid heat capacity
ν	kinematic viscosity, $\mathrm{m^2\,s^{-1}}$
ψ	dimensionless stream function

circulation in the atmosphere, the molten core of the Earth, etc. In addition, roughened surfaces could be used in the cooling of electrical and nuclear components where the wall heat flux is known. Surfaces are sometimes intentionally roughened to enhance heat transfer. Extensive studies on heat transfer in regular cavities filled with porous media have been done in the past decades and various extensions of the problem have been reported in the literature (see Baytas and Pop [8,9], and Baytas et al. [10]). However, it is necessary to study the heat transfer for more complex geometries because the prediction of heat transfer for irregular surfaces is a topic of great importance and irregular surfaces often occur in many applications. Recently, several studies by Rathish Kumar et al. [11,12], Murthy et al. [13] and Kumar and Shalini [14] have been reported that were concerned with the steady natural convection heat transfer in wavy vertical porous enclosures. Attachment of baffles fins or other suitable protrusion to the hot surface of fluid saturated porous enclosure can affect considerably the convection process in the system (see Riley [15]). Recently, Mahmud et al. [16], and Das and Mahmud [17] have studied the steady free convection inside vertical opposite-phase wavy enclosures and horizontal inphase wavy cavity (Benard convection problem) filled with a clean (Newtonian) fluid. Also, Mahmud and Fraser [18] reported numerical results for flow and heat transfer characteristics of a viscous and incompressible fluid (clean fluid) inside a bent cavity made of two straight-horizontal adiabatic walls and two bent-vertical isothermal walls. Rate of heat transfer in terms of local and average Nusselt numbers were calculated for different Rayleigh numbers. The prediction of fluid flow and heat transfer from irregular surface is also an important topic of aerospace application. Kubota and Uchida [19] analysed the characteristics of a transpiration cooling system with use of porous media for hypersonic reentry vehicles.

The aim of this paper is to examine the steady free convection inside a bent cavity filled with a porous medium made of two horizontal straight adiabatic walls and two bent-vertical wavy walls, which are at constant but different temperatures. The model considered is the extension of Mahmud and Fraser [18] problem to the porous medium case. However, to our best knowledge, such an investigation for a porous cavity has not been reported to date. The numerical results have been obtained numerically by solving the governing evolutionary Darcy and energy equations using the Galerkin Finite Element Method (FEM) described in the book by Zienkiewicz and Taylor [20] for a range values of the parameters like the aspect ratio (A), surface waviness (λ) and the modified Rayleigh number for the porous medium (Ra). Results are presented in terms of local and average Nusselt numbers, isotherms and streamlines for different values of the governing parameters.

2. Governing equations

The geometry of this problem as schematically shown in Fig. 1 is a porous cavity with two bent-vertical wavy walls of height L, interval spacing W and amplitude of the wavy bent wall a. It is assumed that initially the