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Investigations on the effect of non-uniform temperature on fluid flow and heat transfer in a trapezoidal cavity filled with porous media

K. Aparna [a,*], K.N. Seetharamu [b]

[a] Jain University, Bangalore 560 004, India
[b] PESIT, Bangalore 560 085, India

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ABSTRACT

Simulations were carried out for natural convection in a trapezoidal cavity filled with porous media to investigate the effect of uniformly and non-uniformly heated bottom wall using finite element computational procedure. The enclosure used for flow and heat transfer analysis has hot bottom wall, constant temperature cold top wall and adiabatic side walls. The bottom wall is subjected to uniform/linear/sinusoidally varying temperatures. Results are presented in the form of stream lines, isotherms, heatline plots, local and average Nusselt numbers. Heatline visualization technique is a useful method that gives information on heat transport from the heated to cold region inside the porous trapezoidal enclosure with varying temperature boundary conditions. Nusselt numbers are computed for Darcy-modified Rayleigh numbers or Rayleigh number (Ra) ranging from 100 to 2000 for an aspect ratio (H/L) of 0.5. It is observed from this study that the uniform temperature at the bottom wall of the enclosure gives higher Nusselt number as compared to the linear and sinusoidally varying temperature cases. The average Nusselt numbers increases monotonically with Rayleigh number for bottom wall and top walls. The power law correlations between average Nusselt number and Rayleigh numbers are presented for convection dominated regions.

1. Introduction

Flow in the porous enclosure has considerable importance in various practical situations such as in buildings in which heat is transferred across an insulation filled enclosure. Examples of engineering applications include the design of granular and fibrous insulations, packed bed solar energy storage, and dendritic solidification of binary alloys in castings. The monograph on convection in porous media by Nield and Bejan [1] provides elaborate exposition of research in natural convection configuration for several decades. Geometry of the enclosure and the orientation of enclosure are varied for natural convection phenomenon studies. The enclosure phenomena can be organized into two classes: 1) Enclosures heated from the side and 2) Enclosures heated from bottom. The fundamental difference between enclosures heated from the side and enclosures heated from bottom is that in enclosures heated from the side, a buoyancy-driven flow is present as a result of small temperature difference that is imposed between the two sidewalls. In enclosures heated from bottom, the imposed temperature difference must exceed a finite critical value before the first signs of fluid motion and convective heat transfer are detected.

In this study, heat transfer by natural convection across porous media-filled enclosure is considered. Literature survey concerned with this is given by Kaviany [2], Ingham and Pop [3], Vafai [4], Pop and Ingham [5], Bejan and Kraus [6], Lewis, Nithiarsu and Seetharamu [7–8]. Natural convection through a vertical cylindrical annular porous medium has received much attention [9,10]. Ching-Yang cheng [11] studied Soret and Dufour effects on free convection over a vertical cylinder. Mahdy [12] studied the effect of chemical reaction and heat generation on convection from a vertical truncated cone with variable viscosity.

Tanmay Basak [13] studied numerically the effect of various thermal boundary conditions in a square cavity filled with porous medium using penalty finite element method. In this study, numerical results are presented in terms of stream functions, temperature profiles and Nusselt numbers. Non-uniform heating of the bottom wall produces greater heat transfer rate at the centre of bottom wall than uniform heating case for all Rayleigh numbers, but average Nusselt number shows overall lower heat transfer rate for non-uniform heating case. Yasin Varol et al. [14] investigated steady state free convection heat transfer in a right-angle

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* Corresponding author.

E-mail addresses: aparnab.vit@gmail.com (K. Aparna), knseethramu@yahoo.com (K.N. Seetharamu).

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Nomenclature

AR	dimensionless aspect ratio (AR = H/L)
H	height of the enclosure, m
L	length of the enclosure, m
Nu	Nusselt number
Ra	Rayleigh number
K	permeability, m^2
x, y	dimensional coordinates along horizontal and vertical walls of the enclosures, m
X	dimensionless distance along x coordinate
Y	dimensionless distance along y coordinate
u, v	velocity components along x and y axes, ms^{-1}
U	dimensionless velocity along X axis
V	dimensionless velocity along Y axis
Nu	local Nusselt number
Nu_{avg}	average Nusselt number
Da	Darcy number
T_h	hot wall temperature,^{0}c
T_c	cold wall temperature,^{0}c

Greek symbols

α	thermal diffusivity, $m^2\ s^{-1}$
β	thermal expansion coefficient, K^{-1}
γ	inclination angle
μ	dynamic viscosity, Pa.sec
ν	kinematic viscosity, $m^2\ s^{-1}$
Ψ	stream function
ψ	dimensionless stream function
Θ	dimensionless temperature $\frac{T-T_c}{T_h-T_c}$
Θ_h	dimensionless hot wall temperature
Θ_c	dimensionless cold wall temperature

Subscripts

c	cold
h	hot

triangular enclosure, whose vertical wall is insulated and inclined and bottom walls are differentially heated. The effect of aspect ratio ranging from 0.25 to 1.0 and Rayleigh number ranging from 50 to 1000 is investigated, as governing parameters on heat transfer and flow field. Aleshkova et al. [15] simulated mathematically unsteady natural convection in a square cavity filled with porous medium having finite thickness heat conducting walls with local heat source. Special attention was given to analysis of Rayleigh number effect ($Ra = 10^5, 10^6$) of Darcy number effect ($Da = 10^{-5}, 10^{-4}, 10^{-3}, \infty$) of transient factor $0 < \tau < 1000$ and of the heat conductivity ratio on velocity and temperature fields.

A two-dimensional heat function formulation to study the net energy distribution pattern in the field of laminar natural convection within a square cavity differentially heated in the vertical direction is presented [16]. Numerical computations indicate that as the Rayleigh number increases in the order stated above, the heatline patterns exhibit apparent centrosymmetric characteristics about the vertical mid section of the enclosure for supercritical Rayleigh numbers. Heat transport due to natural convection in porous triangular cavities using heatline method is visualized [17–18]. Ram Satish Kaluri et al. [19] analyzed numerically heat distribution and thermal mixing during steady laminar natural convective flow within fluid-saturated porous square cavities and trapezoidal cavity for uniform and non-uniform heating of the bottom wall [20]. Bejan's heatline of heat flow due to natural convection of water near 4 °C in thick walled rectangular porous cavity with finite difference method is visualized [21]. Prathibha Biswal et al. [22] studied the sensitivity of heatfunction boundary conditions on invariance of Bejan's heatlines for natural convection in enclosures with various wall heatings. The enclosures with various shapes (square, curved, trapezoidal, tilted square and parallelogrammic) are considered. Elsa Báez et al. [23] studied numerically 2-D natural convection flows for porous media and for homogeneous fluids inside a rectangular activity with inclination. They have concluded that in rectangular porous cavities with Rayleigh's number $\geqslant 100$, multiple cells appear for some angles whereas in homogeneous fluids, for Rayleigh's number of the order of 10^5–10^6, secondary cells appear for some angles and flow becomes oscillatory. Revnic et al. [24] studied the steady free convection flow in a square enclosure filled with a bidisperse porous medium (BDPM).

A few investigations on natural convection within porous trapezoidal enclosures have been carried out by earlier researchers [25–27] with various inclination angles and effect of uniform and non-uniform heating of the bottom wall. Yasin Varol et al. [28–30] analyzed numerically natural convection in inclined, divided and maximum density effects in a porous trapezoidal cavity. The main attribute for choosing the trapezoidal shape cavity is to enhance the heat transfer rate due to its extended hot bottom surface. The flow inside these cavities is much more complicated to investigate, as the boundary zone and the middle core zone never have the same effect for a certain boundary condition considered. These types of cavities are used to store heat using porous material underground, heat transfer in a solar trapezoidal cavity absorber for solar collectors. The main application of this type of trapezoidal cavity is in Compact Linear Fresnel Reflectors. The basic design of the absorber for the CLFR system is an inverted trapezoidal air cavity. This design has been demonstrated to be simple and cost effective with good optical and thermal performance. Linear Fresnel reflectors use long, thin segments of mirrors to focus sunlight onto a fixed absorber located at a common focal point of the reflectors. CLFR utilizes multiple absorbers within the vicinity of the mirrors. The reflectors are located at the base of the system and converge the sun's rays into the absorber. Actual or real cavities occurring in practice generally have shapes different from square or rectangular shape. Thus, various channels of constructions, panels of electronic equipment and solar energy collectors are considered as non-rectangular cavities. The present work is based on Basak et al. [25] and Varol [28]. Basak et al. [25] have studied the effect of natural convection in a porous trapezoidal cavity with uniform and sinusoidal temperature at bottom wall with various inclination angles and cavity that is shorter at bottom and long at the top. Yasin Varol [28] studied divided trapezoidal cavity filled with fluid saturated porous media. The cavity considered has a wide application in the studies of Linear Fresnel Reflector Solar concentrator system [31–32]. However, in the present investigation, natural convection studies are extended for uniform, linear and sinusoidal heating of the bottom wall and their comparison for different Rayleigh numbers in terms of streamlines, isotherms and heatlines.

Sheikholeslami et al. investigated computationally the hydrothermal characteristics of nano fluid flow and heat transfer in a square enclosure with a rectangular heated body. The Lattice Boltzmann Method (LBM) has been adopted to solve the problem. The effects of various governing parameters are studied and the effective thermal conductivity and viscosity of nano fluid are calculated