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Heatlines and thermal management analysis for natural convection within inclined porous square cavities

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ABSTRACT

Heatline concept has been used in order to estimate thermal performance of various energy related systems. Heatlines and streamlines are found to be adequate to visualize and understand heat distribution and thermal mixing occurring inside a inclined porous square cavity. At high Darcy number, Da_m ($Da_m = 10^{-2}$), heatlines take the shapes of streamlines at the central core of the cavity resulting in enhanced thermal mixing as seen from closed convective heatline cells with high magnitudes. Heat transfer rates are discussed based on local and average Nusselt numbers and further, these are adequately explained based on heatlines. The inclined cavity with higher inclination angle ($\varphi = 75^\circ$) provides the higher $\overline{Nu}_{BC}$ whereas higher $\overline{Nu}_{DA}$ is observed for the small inclination angles ($\varphi = 15^\circ$) at $Da_m = 10^{-2}$. Note that, BC and DA denote the right and left walls, respectively. The larger inclination angle may be optimal for the energy efficient processes involving inclined enclosures due to larger heat flow circulations with enhanced thermal mixing.

1. Introduction

Natural convection within fluid saturated porous enclosures have received considerable attention due to important applications including fluidized bed [1], chemical and material processing [2–10] and various convective systems [11–21]. Studies of natural convection flow pattern within fluid saturated porous enclosures were carried out by Ingham and Pop [22] and Nield and Bejan [23]. Experimental as well as numerical investigations are the basis of earlier studies and numerical studies have received significant attention to understand various physical processes with optimal situations which are further essential for efficient industrial or experimental processing.

A number of numerical investigations [8,11,12,14,15,17,19–21,24–31] have been carried out on natural convection heat transfer for various precessing applications within fluid saturated porous enclosures. Piller and Stalio [8] presented numerical results for laminar fully developed natural convection in an inclined composite channel. They assumed the Forchheimer correction and thermal dispersion effects involving local thermal equilibrium between the porous matrix and the fluid. Aly and Ahmed [11] analyzed natural/mixed convection based on the non-Darcy model in a cavity saturated with anisotropic porous media using an incompressible smoothed particle hydrodynamics (ISPH) method. The ISPH algorithm was developed based on a semi-implicit velocity correction procedure while the pressure is obtained by solving pressure Poisson equation. Pandit and Chattopadhyay [12] proposed an extension of the fourth order compact scheme on nonuniform grids for solving two dimensional (2D) unsteady natural convection flows in a rectangular cavity filled with a fluid saturated porous medium. The cavity walls are maintained at various temperature boundary conditions with the uniformly or non-uniformly heated bottom wall, isothermally cold side walls and the adiabatic top wall. Sheremet and Trifonova [14] carried out numerical investigation on transient natural convection in a vertical cylinder involving both fluid and fluid saturated porous media. Their investigation is based on the Beavers–Joseph empirical boundary condition at the fluid-porous interface with the Darcy model for the porous layer and the Boussinesq approximation for the pure fluid. Studies of natural convection within porous annulus involving internal heat source and discrete heating were carried out by Sankar et al. [17]. Bagchi and Kulacki [19] studied natural convection in fluid superposed porous layers with local heating from bottom. Aleshkova and Sheremet [20] studied transient natural convection within porous square enclosure. Avila-Acevedo and Tsotsas [21] carried out experimental and numerical studies on

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Nomenclature

D_a	Darcy number
Da_m	modified Darcy number
g	acceleration due to gravity, m s^{-2}
K	permeability of the porous medium, m^2
L	side of the tilted square cavity, m
n	normal vector in outward direction
N	total number of nodes
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
p	pressure, Pa
P	dimensionless pressure
P_r	Prandtl number
Pr_m	modified Prandtl number
R	Residual of weak form
Ra	Rayleigh number
Ra_m	modified Rayleigh number
T	temperature, K
T_h	temperature of hot right wall, K
T_c	temperature of cold left wall, K
u	x component of velocity
U	x component of dimensionless velocity
v	y component of velocity
V	y component of dimensionless velocity
x	distance along x coordinate, m
X	dimensionless distance along x coordinate
y	distance along y coordinate, m
Y	dimensionless distance along y coordinate

Greek symbols

α	thermal diffusivity, m^2 s^{-1}
β	volume expansion coefficient, K^{-1}
ϵ	porosity of the medium
γ	penalty parameter
θ	dimensionless temperature
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
φ	inclination angle with the positive direction of X axis
Φ	basis functions
Π	dimensionless heatfunction
ψ	dimensionless streamfunction

Subscripts

eff	effective
f	fluid
i	residual wall
k	node number
m	modified
s	surface/wall

Superscripts

e	element

transient heat transfer within a cylinder filled with a porous medium involving variation of wall temperature. Meybodi and Hassanzadeh [24] proposed a theoretical model for mixing induced by buoyancy-driven flows in porous media to characterize the mixing process. Manole and Lage [25] numerically studied natural convection within fluid-saturated porous square cavity via solving the general momentum equation using the convective and Forchheimer terms. Kacur and Keer [26] developed an approximation scheme for solving a coupled system of flow and contaminant transport with adsorption in unsaturated–saturated porous media. Basak et al. [27] numerically investigated the natural convection flow within square cavities filled with porous matrix involving various types of the thermal boundary conditions. Nouri-Borujerdi et al. [28] analyzed the effect of Darcy numbers on the natural convection flow in a horizontal and fluid saturated porous layer with uniform internal heating. Numerical investigations on the natural convection within the porous media have also been carried out with nanofluids [15,29,30]. Natural convective flow and heat transfer inside a differentially heated enclosure filled with fluid-saturated porous medium was also presented by Khanafer [31].

Natural convection phenomena in inclined cavities have been studied by few investigators in recent years. Moya et al. [32] carried out the numerical investigation of two-dimensional natural convective flows in a tilted rectangular enclosure with porous media. Hsiao et al. [33] investigated the steady natural convection within an inclined porous cavity with a discrete heat source on a wall. Baytas and Pop [34] carried out numerical analysis for the steady-state free convection within an inclined cavity filled with a fluid-saturated porous medium. Oztop [35] analyzed the inclination effect on natural convection flow within partially cooled and inclined rectangular enclosures filled with saturated porous medium. Varol et al. [36] studied natural convective flow and heat transfer within inclined trapezoidal enclosures with fluid saturated porous medium. A few other studies on natural convection within inclined porous enclosures are also found in recent works [37,38]. Most of the earlier works on natural convection in porous media are mainly focused on flow and temperature characteristics which are studied via streamlines and isotherms. However, in order to investigate thermal management, it is necessary to analyze the distribution of heat which may be assessed by the method of heatlines.

The heatline approach has been found to be useful to visualize heat flow based on direction and intensity of heat transfer in two dimensional convective transport processes. Kimura and Bejan [39] and Bejan [40] introduced the concept of heatline approach to visualize the heat distribution for convective heat transfer processes. Recently, Bejan [41] explained the fundamental principles based on physics for heat flow visualization via heatlines to establish the novelty of the heatlines for the visualization of heat flow during convection. Although the concept ‘synergy’ [42] was claimed to be a tool to visualize the heat flow, the recent work [41] has established that synergy is a remake of heatlines, and that synergy has no physical connection with heat transfer enhancement. Basak and Roy [43] analyzed energy flows via heatlines during natural convection within square enclosures with hot bottom wall and cold side walls in presence of the top adiabatic wall. They also presented the derivation of generic boundary conditions on heatfunctions based on overall heat balance and average Nusselt numbers for hot and cold walls. Varol et al. [44] studied heatlines for natural convection heat transfer in porous triangular enclosures where bottom wall is non-isothermally heated. Dalal and Das [45] applied the method of numerical visualization of heat transport for convective heat transfer by heatlines to study natural convection inside a two-dimensional cavity with a wavy right vertical wall. Kaluri and Basak [46,47] analyzed thermal mixing during laminar natural convection in four different discretely heated porous square cavities and they focused on enhanced thermal processing of materials via distributed heating. Anandalakshmi et al. [48] studied heat distribution and thermal mixing during steady laminar natural convective flow inside a right-angled triangular enclosure filled with porous media