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Role of the importance of 'Forchheimer term' for visualization of natural convection in porous enclosures of various shapes

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ABSTRACT

The present study deals with the importance of the quadratic (Forchheimer) drag force for the flow through porous media during natural convection within various geometrical shapes (square, rhombus, concave and convex). The enclosures consist of the uniformly heated bottom wall, cold side walls and adiabatic top wall. The numerical simulations are performed via the Galerkin finite element method for various Darcy numbers ($10^{-5} \leqslant Da_m \leqslant 1$), Prandtl numbers ($Pr_m = 0.015, 0.7$ and 1000) at a high Rayleigh number ($Ra_m = 10^6$). Two different flow models are considered based on the inclusion of the quadratic drag term (the Forchheimer term); Case 1: the Darcy–Brinkman model and Case 2: the Darcy–Brinkma n–Forchheimer model. At the low and moderate Pr_m ($Pr_m = 0.015$ and 0.7), the effect of the Forchheimer term on the distributions of streamlines (ψ), heatlines (Π) and isotherms (θ) is significantly large for all Da_m at $Ra_m = 10^6$ in all the cavities. At the high Pr_m ($Pr_m = 1000$), both the magnitudes and qualitative trends of the heat and flow fields are unaffected by the Forchheimer term for all Da_m in all the cavities. The significance of the quadratic drag term on the heat flow visualization is addressed in detail via the heatline approach. The variation of the local Nusselt number (Nu_b) with the distance is also illustrated in detail for the Cases 1 and 2 for all the cavities. The overall heat transfer rate ($\overline{Nu_b}$) and percentage error ($\widehat{E}$) in $\overline{Nu_b}$ for the Cases 1 and 2 are also analyzed. At $Pr_m = 0.015$, $\widehat{E}$ is largest, that decreases with Pr_m for all the cavities and $\widehat{E}$ tends to 0% at $Pr_m = 1000$. The effect of the Forchheimer term for various shapes are also illustrated via $\widehat{E}$ vs Da_m. It is found that, $\widehat{E}$ is largest for the rhombic cavity at $Pr_m = 0.015$ and that is largest for the square and convex cavities at $Pr_m = 0.7$ with $Da_m > 10^{-4}$.

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1. Introduction

Convective heat transfer in the porous media has been the subject of extensive research over the past few years due to its importance in various industrial and technological applications such as microwave heating [1], geothermal systems [2], energy storage [3], gas transport [4], drying and crystallization [5] etc. The investigation of natural convection heat transfer in porous cavities with various geometrical shapes are carried out by previous researchers. Earlier studies on porous media considered various geometrical shapes such as the square or rectangular [6–11], triangular [12–14], trapezoidal [15,16], rhombic or parallelogramic [17,18] and complicated cavities [19,20] based on industrial applications. Due to the complexity of the flow in the porous matrix, the physical basis of governing equations for the flow in the porous matrix is not straight forward compared to that in the fluid media. Hence, a number of articles and books are devoted about the various mathematical models on the flow through the porous media [21–23].

The mathematical model for the flow through the porous media was first developed by Darcy [24] and the proposed model governs the linear relationship of the fluid velocity with the pressure gradient. Note that, the Darcy law is valid for a porous matrix with the less pore diameter and porosity [23,24]. Baytas and Pop [25] numerically studied the steady state natural convection heat transfer within an oblique enclosure using the Darcy model. In another study, numerical simulations for the two-dimensional steady state natural convection in the differentially heated porous square cavity were also carried out by Baytas and Pop [26]. Varol et al. [27] investigated natural convection flow in a porous right-angle trapezoidal cavity based on the Darcy law. They considered a hot left wall along with the adiabatic horizontal walls and a partially cooled right wall with the remaining portion of the right wall being maintained as adiabatic. They observed that the local and average heat

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Nomenclature

Da	Darcy number
Da_m	modified Darcy number
DB	Darcy–Brinkman
DBF	Darcy–Brinkman–Forchheimer
g	acceleration due to gravity, m s^{-2}
L	Height of the enclosure, m
k	thermal conductivity
K	permeability of the medium
$\mathbf{n}$	distance along the normal direction of a plane
N	total number of nodes
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
p	pressure, Pa
P	dimensionless pressure
Pr	Prandtl number
Pr_m	modified Prandtl number
Ra	Rayleigh number
Ra_m	modified Rayleigh number
S	Arc length of the walls
T	temperature, K
T_h	temperature of hot wall, K
T_c	temperature of cold wall, K
$\hat{u}$	x component of Darcy velocity, m s^{-1}
u	x component of intrinsic velocity, m s^{-1}
U	x component of dimensionless intrinsic velocity
$\hat{v}$	y component of Darcy velocity, m s^{-1}
v	y component of intrinsic velocity, m s^{-1}
V	y component of dimensionless intrinsic 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}
γ	penalty parameter
θ	dimensionless temperature
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
φ	angle with positive X-axis
ψ	dimensionless streamfunction
Π	dimensionless heatfunction
ϵ	porosity of the medium
Ω	two dimensional domain

Subscripts

av	average
b	bottom wall
Br	Brinkman model
Dr	Darcy model
eff	effective
f	fluid
Fr	Forchheimer model
i	global node number
k	local node number
l	left wall
r	right wall
t	top wall

Superscript

e	element

transfer rates are minimum when the position of the cooler is adjacent to the top wall. In addition, they found that, the cavity aspect ratio has small effect on the heat transfer rate. Varol [28] also analyzed natural convection based on the Darcy law in two entrapped porous trapezoidal cavities with the cold inclined walls and hot horizontal walls. Studies on natural convection in porous triangular enclosures based on the Darcy model have also been carried out for various geometrical and thermal parameters by Varol [14] and Oztop et al. [13].

As reported by various researchers, the Darcy law appropriately describes the fluid flow through the porous media for the low fluid velocity [23]. However, as the fluid velocity increases, the inertial forces gradually take the command over the viscous force. Note that, in this regime, the Darcy linear law may not be valid [23]. As the inertial forces gradually dominate, the Darcy–Forchheimer model which governs a non-linear relationship between the fluid velocity and pressure gradient may be appropriate [23,29]. In the Darcy–Forchheimer model, the nonlinear relationship between the fluid velocity and pressure gradient was developed by adding the higher-order velocity terms or the quadratic drag to the Darcy equation [23,29]. Note that, the nonlinear drag force which arises due to the friction between the solid and fluid matrix, is significant for the high fluid velocity (high Reynolds number). Further, Brinkman [30] modified the Darcy law based on the flow through the porous media for the highly viscous fluid. The Darcy–Brinkman model includes the viscous stresses offered by the solid boundary and that is important for the fluid flow in the porous matrix with very high porosity [23]. Note that, the extension of the Darcy law lead to develop the non-Darcy model and mainly two non-Darcy models such as the Darcy–Brinkman model and Forchheimer–Brinkman extended Darcy model are employed by researchers to study the flow through the porous media. A few earlier works on the flow through the porous media based on the Brinkman extended Darcy and Brinkman–Forchheimer extended Darcy model are outlined below.

Sivasankaran et al. [31] studied the effect of the discrete heating on the free convection heat transfer in a rectangular porous enclosure containing a heat-generating substance using the extended Darcy–Brinkman model. In addition, the Brinkman-extended Darcy model has been used to investigate the convective flow in a porous rectangular enclosure by Khandelwal et al. [32]. Moukalled and Darwish [33] employed the Darcy–Brinkman model to study the laminar natural convection in a fluid saturated porous enclosure between the two isothermal concentric cylinders of rhombic cross-sections. Further, Basak et al. [34] studied the effect of the uniform and non-uniform heating of the bottom wall of a porous trapezoidal enclosure, where the flow model is assumed to follow the Darcy–Brinkman model. The visualization of the convective heat transfer is studied for porous trapezoidal enclosures by Ramakrishna et al. [35] based on the Darcy–Brinkman model. The Darcy–Brinkman model is further employed for natural convection in porous triangular enclosures where the visualization of the heat transport is carried out via the heatline approach by Basak et al. [36]. Han and Hyun [17] numerically studied the effect of the Darcy–Brinkman model on the buoyant convection in a porous parallelogramic enclosure with the hot bottom wall, cold top wall and insulated inclined walls.

The inclusion of the quadratic drag term in the Brinkman modified Darcy equation results in the Darcy–Brinkman–Forchheimer model which can be used for the flow modeling in the porous

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