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A numerical study on natural convection and entropy generation in a porous enclosure with heat sources

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ABSTRACT

In this paper, fluid flow and thermal characteristics associated with natural convection heat transfer in a porous enclosure containing high temperature heat sources placed on top and bottom walls are studied. For this purpose, two-dimensional, time-dependent Navier–Stokes equations with Darcy–Brinkman–Forchheimer terms are solved in a Cartesian framework by using Streamline Upwind Petrov–Galerkin (SUPG) based finite element method. The effect of heat sources on flow pattern, entropy generation and temperature distribution are studied for different Darcy numbers, porosities and Rayleigh numbers. The results show that maximum entropy generation due to heat transfer irreversibility is observed in the vicinity of heat sources due to the presence of high thermal gradient. The global entropy generation due to fluid friction is found to increase in convection dominated regime. It is also observed that with increasing Darcy number, porosity and Rayleigh number the surface averaged Nusselt number for both top and bottom heat sources is increased.

1. Introduction

The natural convective heat transfer in a fluid-saturated porous media has received considerable attention due to their applications in thermal insulation systems, geothermal engineering, porous heat exchangers, food storage, underground disposal of nuclear waste materials, oil separation from sand by steam, electronic device cooling etc. A representative review of these applications and other heat transfer applications in porous media may be found in the recent books of Vafai [1], Ingham and Pop [2] and Nield and Bejan [3]. The phenomenon of fluid flow in porous medium is modeled by Darcy [4]. According to Darcy, for low velocity flows the pressure drop across a saturated porous medium was directly proportional to flow rate. The Darcy model applied to natural convection in finite enclosures filled with fluid-saturated porous medium has received considerable attention over the last several years [5–8]. Recently, Varol [9] analyzed fluid flow patterns and temperature distributions within a pair of entrapped porous trapezoidal cavities involving cold inclined walls and hot horizontal walls. The maximum surface averaged Nusselt number is obtained for highest Darcy-modified Rayleigh number ($Ra^* = Ra \times Da$) and lowest aspect ratio. Chamkha and Ismael [10] studied conjugate heat transfer in a porous enclosure filled with various nanofluids and heated by a thick triangular wall. It was found that, copper nanoparticles give better heat transfer rates than the other two nanoparticles types, aluminum oxide and titanium oxide. This may be due to relatively higher thermal conductivity of copper. All the above mentioned studies which are based on Darcy law are restricted to low Darcy and particle Reynolds numbers where the viscous drag and inertia terms in the governing equations can be neglected.

In situations where non-Darcian effects such as solid boundary and viscous effect are important, further extensions are required to Darcy law. Two distinguished modifications to Darcy law are the Brinkmans and Forchheimers modifications which treat the viscous stresses at the bounding walls and the non-linear drag effect due to the solid matrix respectively. Forchheimer [11] proposed an extension to Darcy law by adding a non-linear term in order to account for drag due to the solid matrix for moderate and high particle Reynolds number flows. The natural convection in a porous enclosure considering the Forchheimers non-linear drag effect was studied by Plumb and Huenefeld [12] and Lauriat and Prasad [13].

In order to handle situations of porous enclosures with high viscous and porosity effects Brinkmans [14] extension to Darcy law is suitable. Many studies have been performed to investigate convection heat transfer in porous medium with extended Brinkmans term to Darcy law [15–17]. Anandalakshmi and Basak [18] have studied the effect of various heating patterns (differential heating and Rayleigh–Benard convection) on entropy generation in a porous rhombic enclosure for different Da, Pr and inclination

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Nomenclature

AR	aspect ratio (H/L)
Be	local Bejan number
Da	Darcy number
g	acceleration due to gravity, m s^{-2}
H	width of the heat source, m
k	thermal conductivity, W m^{-1} K^{-1}
L	length of the square cavity, m
Nu	local Nusselt number
Nu_{avg}	surface averaged Nusselt number
n	directional normal
p	dimensional pressure, N m^{-2}
p	dimensionless pressure
Pr	Prandtl number
Ra	Rayleigh number
Ra^*	modified Rayleigh number ($Ra \times Da$)
S_θ	local entropy generation due to heat transfer
S_ψ	local entropy generation due to fluid friction
S_{tot}	local total entropy generation
T_c	temperature of cold vertical walls, K
T_h	temperature of both the heat sources, K
T_0	bulk temperature, K
t	dimensional time, s
u, v	dimensional velocity components in x and y directions, m s^{-1}
U^h	discontinuous upwind perturbation
u, v	dimensionless velocity components in x and y directions
W^h	continuous weighting function
x, y	dimensional Cartesian coordinates, m
X_P	dimensional distance along the periphery of heat source, m
x, y	dimensionless Cartesian coordinates

Greek letters

κ	permeability, m^2
ϵ	porosity
ρ	density of fluid, kg m^{-3}
σ	ratio of heat capacities $((\epsilon(\rho c_p)_f + (1-\epsilon)(\rho c_p)_s)/(\rho c_p)_f)$
α	thermal diffusivity, m^2 s^{-1}
β	volume expansion coefficient, K^{-1}
θ	dimensionless temperature
ν	kinematic viscosity, m^2 s^{-1}
τ	dimensionless time
Ω	area of the computational domain

Subscripts

avg	average
f	fluid
max	maximum
s	solid
tot	total

Superscripts

n	present time step
$n+1$	next time step

angles. Anandalakshmi and Basak [19] have performed similar analysis for studying an optimization strategy for energy efficient thermal convection within a rhombic enclosure filled with porous medium for various boundary conditions such as isothermal and sinusoidal heating of bottom wall. Al-Salem et al. [20] performed simulations on linearly heated enclosure to study the effect of magnetic field under mixed convection regime for different Hartmann numbers, Reynolds numbers and Grashof numbers. The results show that, heat transfer decreases with increase in magnetic field for all the parameters of the study.

Nithiarasu et al. [21] have derived the generalized Darcy–Brinkman–Forchheimer (DBF) model for fluid saturated porous medium. The differences between Darcian and non-Darcian flow regimes for different Darcy, Rayleigh and Biot numbers and aspect ratio is also examined in this study. Several studies have been performed on natural convection in finite enclosures filled with fluid-saturated porous medium using the generalized Darcy–Brinkman–Forchheimer (DBF) model [22–24]. Khanafer and Chamkha [25] categorized the flow regimes according to the number of eddies, established on the Ra–Re plane for various Rayleigh numbers in a heat generating porous annulus. Khanafer et al. [26] illustrated the effect of amplitude of waviness and number of undulations on natural convection in a fluid saturated porous enclosure containing a vertical wavy wall. Khanafer [27] extended the same problem with flexible wavy wall to investigate fluid–structure interaction for various parameters such as Rayleigh number, elasticity of the flexible wall, effective thermal conductivity of porous medium, and porosity. The results show that Rayleigh number and elasticity of the flexible wall have a profound impact on shape and penetration of the flexible wall and consequently on heat transfer enhancement.

Natural convection along a single heat source has been considered in above-mentioned studies. In practice, quite often the natural convection from one heat source affects another one, which may be placed in the wake of another. These kinds of convection from multiple heat source placed on vertical wall in series arrangement have been addressed by Saeid [28] and Varol et al. [29]. Their results indicate that the heat transfer from lower element can be enhanced by increasing Rayleigh number and temperature of the upper element. Kaluri and Basak [30] investigated optimal configuration for natural convection in a porous square enclosure with discrete flush mounted heat sources arranged in different configurations using entropy generation minimization (EGM) approach. The distributed heating methodology with multiple heaters is found to be an efficient strategy for thermal mixing, temperature uniformity and minimum entropy generation. Soleimani et al. [31] studied the location of wall mounted heat source and sink arranged in parallel manner and found optimized configuration as a function of Ra and size of source and sink. To the best of authors' knowledge, the studies on entropy generation during natural convection in a porous enclosure containing twin protruding heat sources arranged in parallel (in-line and staggered) manner has not been reported and that forms the motivation to the present study.

The objective of the present study is to analyze fluid flow, heat transfer and entropy generation in a porous enclosure containing an isothermal heat sources ($AR = 0.2$) arranged in-line and staggered manner on the horizontal adiabatic walls. The effect of orientation (in-line and staggered) of heat sources for maximum heat transfer rate and minimum entropy generation were analyzed to achieve the efficient strategy for optimal orientation of heat sources. This analysis has significance in industrial applications such as cooling of electronic components with the aid of porous metal foams [32], ignition of solid fuels [33], infiltration of liquid metals in porous media [34], materials processing [35,36], drying and transport of gases in porous media [37], combustion in heavy oils in porous reservoirs [38]. In the current study, a SUPG based finite element method has been employed to solve Navier–Stokes equations with Darcy–Brinkman–Forchheimer terms for fluid saturated porous medium for different parameters Darcy number