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Mixed convective heat transfer in an enclosure containing a heat-generating porous bed under the influence of bottom injection

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ABSTRACT

The present study numerically models the process of heat removal from a heat-generating porous bed with cold fluid injection from the bottom of the bed. This type of situation is encountered during post-accident situations in nuclear reactors and involves augmentation of heat removal capacity with forced coolant injection from the bottom. A steady-state analysis is carried out with the assumption of laminar flow regime and without accounting for phase change. Darcy-Brinkmann-Forchheimer approximation and local thermal equilibrium assumption are adopted for modelling the momentum and energy equations in porous media, respectively. It is observed that the fluid flow is determined based on the dominancy of the two co-existing flow mechanisms viz. inertial flow due to forced fluid injection and buoyancy-driven flow due to heat generation within the porous bed. In addition, permeability of the porous media significantly affects the flow mechanism, especially near the fluid inlet. Heat transfer characteristics closely follow the flow mechanism established within the enclosure.

1. Introduction

Mixed convective flow involving heat-generating porous media is a phenomena of considerable importance since it is encountered in several natural as well as industrial processes. Significant applications among these include extraction of geothermal energy, convection within the earth's mantle, electronic chip cooling, storage of spent fuel of nuclear power plants etc. The motivation for the present work is, however, derived from the application of mixed convection in cooling of decay heat-generating porous debris bed formed as a consequence of severe accident in a nuclear reactor. Ensuring proper cooling of such debris beds is essential since the resulting temperature excursion due to inadequate cooling may lead to re-melting of the material and cause further progression down the accident sequence, ultimately leading to radioactivity release to the environment [1]. Thus, the heat removal rate from the debris bed must be augmented in order to eliminate this possibility. One of the augmentation methods usually followed is to supplement the top flooding mechanism with cold fluid injection from the bottom of the heat-generating bed [2,3]. The present study attempts to numerically model the fluid flow and the consequent heat transfer mechanism for a similar configuration.

Extensive studies have been carried out over the years characterising mixed convection involving porous media for various geometries. Al-Amiri [4] adopted a non-Darcian porous medium and highlighted the impact of the quadratic drag term on fluid flow and heat transfer characteristics for the same configuration. A similar configuration was employed for analysing double diffusive mixed convection by Khanafer and Vafai [5]. Santosh Kumar et al. [6] utilised a double lid-driven cavity, with the vertical walls maintained at different temperatures and moving in opposite directions, to compare the numerical predictions using the Brinkmann-extended Darcy model and Brinkmann-Forchheimer-Darcy model. Basak et al. [7] assessed the impact of non-uniform heating over uniform heating in a lid-driven square cavity, filled with a Darcian porous medium, with differentially heated vertical walls and heated bottom wall. Heat-lines were utilised to analyse the effect of various thermal boundary conditions on mixed convection in a lid-driven porous square cavity by Basak et al. [8]. Mahmud and Pop [9] studied mixed convection in a vented enclosure filled with porous medium and concluded that dimension of the enclosure plays an important role in determining fluid flow patterns and thereby, heat transfer in the enclosure. The effect of the presence of porous blocks in a vented enclosure was studied

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Nomenclature

c_p	specific heat capacity (J/kg·K)
D_p	particle diameter (m)
Da	Darcy Number
D	channel diameter (m)
E	energy flux vector
F_c	forchheimer Co-efficient
g	acceleration due to gravity (m/s^2)
Gr	Grashof number
H	bed Height (m)
k	thermal conductivity (W/m.K)
K	permeability (m^2)
L	enclosure height (m)
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
q'''	volumetric heat generation rate (W/m^3)
R	bed radius (m)
Re	Reynolds' number
Ri	Richardson number
T	temperature (K)
U, V	velocity (m/s)
W	enclosure width (m)

Greek Letters

α	thermal diffusivity (m^2/s)
β	thermal expansion co-efficient (1/K)
ε	porosity
η	passability (m)
θ	dimensionless temperature
λ	thermal conductivity ratio
μ	dynamic viscosity (kg/m.s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
φ	sphericity or shape factor
ϕ	bed angle (°)
ψ	dimensionless absolute stream function
Π	dimensionless heat function

Subscripts

avg	average value
eff	effective value
f	fluid phase
in	inlet channel
max	maximum value
out	outlet channel
ref	Reference value
s	solid phase

Superscripts

′	dimensionless quantities

by Shuja et al. [10]. Krishna Murthy and Ratish Kumar [11] highlighted the impact of non-uniform heating in a vented square enclosure with a non-Darcian porous medium, while the effect of multiple suction/injection was reported by Ratish Kumar and Krishna Murthy [12]. Moraga et al. [13] considered two distinct porous layers in their study on mixed convection in a vented square enclosure. Mixed convection in porous channels has also been investigated by several other researchers [14–16].

Literature survey, however, reveals a dearth of significant studies on mixed convection involving heat-generating porous media although several important works can be found in the domain of either natural convection [17–20] or forced convection [21]. Khanafer and Chamkha [22] analysed laminar mixed convective flow in a lid-driven square cavity, with differentially heated horizontal walls and adiabatic vertical walls, filled with fluid-saturated Darcian porous medium and concluded that the flow mechanism as well as heat transfer characteristics are strongly dependent on the Richardson number (Ri) as well as the Darcy number (Da). In addition, internal heat generation was found to significantly affect the isotherm distribution in the enclosure, although the flow mechanism remained almost unaffected. The analysis of Kumari and Nath [23] using a similar geometry also highlighted Ri and Da as the pertinent parameters affecting mixed convection. A double lid-driven cavity filled with heat-generating porous media was considered by Muthtamilselvan et al. [24]. The horizontal walls were differentially heated and moving in opposite directions, while the vertical walls were assumed to be stationery and adiabatic. It was reported that the mode of heat transfer switches from conduction to convection for Darcy number (Da) > 10^{-3} and that heat transfer rate decreases at a fixed Da for internal $Ra > 10^2$. The above observations were found to be valid for both uniform and non-uniform heating of the hot wall. Mixed convection in a heat-generating porous annulus was reported by Khanafer and Chamkha [25]. Results indicate that in addition to Ri and Da, Reynolds number (Re) and the annulus dimensions also play a significant role in determining fluid flow as well as heat transfer within the annulus. Umavathi and Sultana [26] reported the effect of different dimensionless parameters viz. mixed convection parameter, porous parameter and heat source/sink parameter on mixed convective flow in a vertical porous channel with boundary conditions of the third kind. Jha et al. [27] carried out an analytical study of laminar mixed convective flow in a vertical tube filled with isotropic porous material and heat generation/absorption. The results were presented in terms of Pr, the ratio of Gr to Re, dimensionless frequency, Da and dimensionless heat-generating parameter.

It can be inferred from the above cited works that the problem of mixed convection in an enclosure with a heat-generating porous bed and cold fluid injection from the bottom of the bed has not been addressed yet. Thus, attention must be devoted to the modelling and analysis of the aforesaid problem especially due to the significance of the stated application. Additionally, the problem also involves a clear fluid – porous configuration which requires incorporation of the interface conditions between the porous and the fluid domain. The porous bed is modelled as a truncated conical structure in order to approximate the shape of a typical debris bed formed in an accident situation [28]. Similar configuration of the porous bed has already been used in natural convective situation by Chakravarty et al. [19,20]. The entire analysis is carried out using dimensionless form of the governing equations using the commercial computational fluid dynamics tool ANSYS FLUENT 14.5 and the results are presented in terms of dimensionless parameters viz. Ri, Re, Gr and Da. In addition to stream function and isotherms, the concept of energy flux vectors [29] has been utilised in the present study for the purpose of visualising the convective energy transport process. This has already been used for visualising energy transport in natural convection situations involving clear fluid [30] as well as porous media [31,32] and also in case of forced convection problems [33]. Chakravarty et al. [20]