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Two- and three-dimensional multiple steady states in a porous cavity heated and salted from below

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ABSTRACT

Two- and three-dimensional numerical studies of double-diffusive natural convection in homogeneous and isotropic porous media, saturated with a binary fluid are analyzed. Top and bottom faces of the enclosures are subject respectively to different but uniform temperatures and concentrations, while its vertical boundaries are considered adiabatic and impermeable to mass transfer. The flow through the medium is governed by the Darcy model. The existence of multiple steady-state solutions is proved for both 2D and 3D models and all the solutions obtained are presented and described. Conjugate effects of the thermal Rayleigh number and the buoyancy ratio on heat transfer, mass transfer and existence range of each flow structure are discussed. Important differences in terms of heat and mass transfer are observed between different solutions. Depending on the governing parameters and the type of solution, the flow structure could be 2D or 3D. It is also found that all the 2D solutions are obtained with the 3D model but the latter has more degrees of freedom allowing a reorganization of the flow not possible in the case of 2D model. For $\mathrm{Ra} = 200$ and opposing thermal and species buoyancy forces, there exists a critical value of N ($N = -0.6$) below which the concentration stabilizes the flow by settling a bulk stratification. In such a case, the corresponding heat and mass transfer processes are ruled by pure diffusion solely ($\mathrm{Nu} = \mathrm{Sh} = 1$).

1. Introduction

Double-diffusive natural convection in porous media saturated with binary fluids has received growing attention owing to the practical importance of the phenomenon in various natural and industrial applications. In such problems, convection (also referred as thermosolutal convection) is driven by simultaneous temperature and concentration gradients. Moisture migration in fibrous insulation, drying processes, transport of contaminants in saturated soil, grains storage installation, food processing, electrochemical processes, etc. are some examples implying thermosolutal convection. A comprehensive review of the literature concerning experimental and theoretical studies of double-diffusive natural convection in saturated porous media is documented in the recent books by Vadasz (ed.) [1], Nield and Bejan [2], Ingham and Pop (eds.) [3] and Vafai (ed.) [4].

In the literature, numerous papers of early published works on double-diffusive convection have dealt with the two-dimensional approach and are concerned with vertical [5–9] or horizontal [10–14] cavities submitted to various thermal and solutal boundary conditions. Comparatively, the three-dimensional model has been considered in few studies where the limitations of the 2D model have been outlined. Earlier, Kimura et al. [15] have extended their previous 2D transient convection [16] conducted in a square cross-section of fluid-saturated porous material heated from below to three-dimensional convection in a fluid-saturated cube of porous material using the same numerical approach (a pseudo-spectral numerical scheme). Both similarities and differences between two-dimensional and fully three-dimensional modes were observed and discussed. It is found that the occurrence of a transition from more complex to less complex flows is common features of two- and three-dimensional convection. We learn also in this study that there are quantitative differences between two- and three-dimensional convection and a number of characteristics is observed only in the three-dimensional convective mode. From their side, Sezai and Mohamad [17] used a three-dimensional mathematical model based on the Brinkman extended Darcy equation to study double-diffusive natural convection in a fluid-saturated porous cubic enclosure subject to opposing and horizontal gradients of temperature and concentration. The flow is driven by conditions of

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