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Effects of thermal nonequilibrium and non-uniform temperature gradients on the onset of convection in a heterogeneous porous medium☆

I.S. Shivakumara [a,1], Jinho Lee [a,*], K. Vajravelu [a,2], A.L. Mamatha [a,b]

[a] School of Mechanical Engineering, Yonsei University, Seoul 120–749, South Korea
[b] Smt. Rukmini Shedthi Memorial National Government First Grade College, Department of Mathematics, Barkur, 576 210, Udupi District, India

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ABSTRACT

The simultaneous effect of local thermal nonequilibrium (LTNE), vertical heterogeneity of permeability, and non-uniform basic temperature gradient on the criterion for the onset of Darcy–Benard convection is studied. The eigenvalue problem is solved numerically using the Galerkin method. The interaction of various types of permeability heterogeneity and non-uniform basic temperature gradient functions on the stability characteristics of the system is analyzed. It is observed that the linear variation (about the mean) of the permeability and the basic temperature gradient with depth has no added effect on the criterion for the onset of convection. However, the concurrent variation in heterogeneous permeability and non-uniform basic temperature gradient functions has more stabilizing effect on the system, while opposite is the trend when the effect of non-uniform basic temperature gradient alone is present.

1. Introduction

Buoyancy-driven convection in a layer of fluid (in a saturated porous medium) heated uniformly from below has been studied extensively by several researchers over the years because of its natural occurrence and also its relevance in various applications such as biomedical engineering, drying processes, thermal insulation, radioactive waste management, transpiration cooling, geophysical systems, and contaminant transport in groundwater, ceramic processing, solid-matrix compact heat exchangers and many others. Copious literature is available on this as well as related topics and it is well documented in the literature (Ingham and Pop [1], Vafai [2], Nield and Bejan [3], Vadasz [4]).

The effect of heterogeneity in either permeability or thermal conductivity or both on thermal convective instability in a layer of fluid in a porous medium is of importance since there can be dramatic effects in the case of heterogeneity (Braester and Vadasz [5], Simmons et al. [6] and Prasad and Simmons [7]). The effects of hydrodynamic and thermal heterogeneity, for the case of variation in both the horizontal and vertical directions, on the onset of convection in a horizontal layer of saturated porous medium uniformly heated from below, are studied analytically for the case of weak heterogeneity by Nield and Kuznetsov [8]. A discussion on the effect of heterogeneity on the onset of convection induced by a vertical density gradient in a saturated porous medium has been made by Nield and Simmons [9]. Whereas, the combined effects of vertical and horizontal heterogeneity on the onset of transient convection in a porous medium are investigated by Nield and Kuznetsov [10]. Recently, Nield and Kuznetsov [11] have studied the effect of vertical heterogeneity on the onset of convection in a horizontal layer of fluid in a saturated porous medium, uniformly heated from below but with a non-uniform basic temperature gradient resulting from transient heating or otherwise. All the above studies are based on local thermal equilibrium (LTE) model.

However, in many practical applications involving hyper-porous materials and also media in which there is a large temperature difference between the fluid and the solid phases, it has been realized that the assumption of LTE model is inadequate for proper understanding of the heat transfer problems. In such circumstances, the local thermal non-equilibrium (LTNE) effects are to be taken into consideration. Therefore, the recent trend in the study of thermal convective instability problems in porous media is to account for LTNE effects by considering a two-field model for energy equation each representing the fluid and solid phases separately. Under certain circumstances, investigations have been carried out in the recent past to know LTNE effects on forced and free convection in fluid saturated porous media.

The LTNE effects on forced convection flows in a porous medium have been covered exhaustively in the excellent reviews by Vafai and Amiri [12] and Kuznetsov [13]. Banu and Rees [14] have studied the criterion for the onset of convection in a Darcy porous medium using LTNE model. The effect of LTNE on the onset of convection in a porous

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* Corresponding author.
E-mail addresses: shivakumarais@gmail.com (I.S. Shivakumara), jinholee@yonsei.ac.kr (J. Lee), vajravel@mail.ucf.edu (K. Vajravelu).
[1] Permanent address: UGC-CAS in Fluid Mechanics, Department of Mathematics, Bangalore University, Bangalore-560 001, India.
[2] Permanent address: Department of Mathematics, University of Central Florida, Orlando, FL 32816, USA.

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