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Throughflow and non-uniform heating effects on double diffusive oscillatory convection in a porous medium

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Abstract A weak nonlinear oscillatory mode of thermal instability is investigated while deriving a non autonomous complex Ginzburg–Landau equation. Darcy porous medium is considered in the presence of vertical throughflow and time periodic thermal boundaries. Only infinitesimal disturbances are considered. The disturbances in velocity, temperature and solutal fields are treated by a perturbation expansion in powers of amplitude of applied temperature field. The effect of throughflow has either to stabilize or to destabilize the system for stress free and isothermal boundary conditions. Nusselt and Sherwood numbers are obtained numerically and presented the results on heat and mass transfer. It is found that, throughflow and thermal modulation can be used alternatively to control the heat and mass transfer. Further, it is also found that oscillatory flow enhances the heat and mass transfer than stationary flow. Effect of modulation frequency and phase angle on mean Nusselt number is also discussed.

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1. Introduction

The problem of thermal instability in a porous medium is well documented by Vafai [1–6]. The study of thermal instability in porous media is an important concept in thermal and engineering sciences, geothermal energy utilization, oil reservoir modeling, building of thermal insulations, and nuclear waste disposals to mention a few. There is a growing interest in externally modulated hydrodynamic systems, both theoretically and experimentally. These systems show a novel behavior in response to parametric forcing near a point of instability. Depending on the relative strength and rate of forcing, predictions exist for a variety of responses to the modulation. Davis [7] pointed that, the dynamic of stabilization and destabilization may lead to dramatic changes of behavior depending on the proper tuning of the amplitude and frequency of the modulation. If an imposed modulation can destabilize an otherwise stable state, then there is a major enhancement of heat/mass/momentum transport. If an imposed modulation can stabilize or otherwise in unstable state, then higher efficiencies can be attained in various processing techniques. The convective

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phenomenon can be controlled by applying a time periodic modulation to the driving force provided by some mechanical source, rotation, magnetic field, buoyancy, temperature-gradient. One of the effective mechanisms that considered in this paper is a time periodic heating of wall temperature at the boundaries, where in many practical applications the steady state temperature field is a function of both space and time. This nonuniform temperature gradient can be used as a mechanism to stabilize or destabilize the convective flow. The related problems are investigated by [8–18] for various physical models and boundary conditions.

Convection concerns the process of combined heat and mass transfer which are driven by buoyancy forces are usually referred as double diffusive convection. In this case the mass friction gradient and the temperature gradient are independent. In some practical problems, such as seawater flow, mantle flow in the earth's crust, in devicing an effective method [19] of disposing waste material and extraction of energy and engineering applications the double diffusive convection plays an important role. The linear and nonlinear stability of double diffusive convection in porous media has been studied extensively in the presence of uniform temperature and concentration gradients [6], and [20]. Siddheshwar et al. [21] investigated temperature and gravity modulation effects on double diffusive convection in porous medium. They found that, both modulations can be used simultaneously to enhance or diminish heat and mass transfer in the system while considering a weakly non-linear theory for stationary mode. Bhadauria [22] also analyzed the additional effects of internal heating and anisotropy. He found that, internal heat and anisotropy also can be used to enhance or diminish heat and mass transfer in the system. Malashetty et al. [23] studied the effect of rotation on double diffusive convection while considering linear theory for onset of convection and nonlinear theory for finite amplitude convection. Kiran and Bhadauria [24] investigated double diffusive magnetoconvection under the effects of gravity modulation and chaotic, oscillatory mode of convection. They found that, gravity modulation can be used to control thermal instability and dynamic of the problem with suitable ranges of modulation parameters.

Throughflow effect on double-diffusive convection in a porous medium is important concept due to its applications in engineering, geophysics and seabed hydrodynamics. Throughflow plays an important role in the directional solidification of concentrated alloys, in which mushy zone exists and it is regarded as a porous layer with double diffusive origin. The basic state temperature profile of throughflow changes from linear to nonlinear with layer height, which in turn affects the stability of the system significantly. The effect of throughflow on the onset of convection in a horizontal porous medium has also been given in [25–28]. Nield [29] and Shivakumara [30] have shown that a small amount of throughflow can have a destabilizing effect if the boundaries are of different types and a physical explanation for the same has been given. They also found that, the effect of throughflow is not invariably stabilizing and depends on the nature of the boundaries. Khalili and Shivakumara [31] have investigated the effect of throughflow and internal heat generation on the onset of convection in a porous medium. They have shown that throughflow destabilizes the system, even if the boundaries are of the same type, a result which is not true in the absence of an internal heat source. The non-Darcian effects on convective instability in a porous medium with throughflow have been investigated in order to account for inertia and boundary effects by Shivakumara [32]. The effect of throughflow on the stability of double diffusive convection in a porous layer is investigated by Shivakumara and Khalili [33] for different types of hydrodynamic boundary conditions. They found that throughflow is destabilizing even if the lower and upper boundaries are of the same type and stabilizing as well as destabilizing, irrespective of its direction, when the boundaries are of different types. Khalili and Shivakumara [34] investigated throughflow in the porous layer is governed by Darcy–Forchheimer equation and the Beavers–Joseph condition is applied at the interface of fluid and the porous layer. They found that destabilization arises due to throughflow, and the ratio of fluid layer thickness to porous layer thickness, plays an important role in deciding the stability of the system depending on the Prandtl number. Hill [35] investigated linear and nonlinear thermal instability of vertical throughflow in a fluid-saturated porous layer, while Hill et al. [36] have extended the problem for penetrative convection by considering density is quadratic in temperature. Brevdo and Ruderman [37,38] have analyzed convective instability in a porous medium with inclined temperature gradient and vertical throughflow. Later on many researchers have investigated throughflow effects considering different physical models, some of them are given in [39–46].

From the literature no study has been found which considers modulation along with vertical throughflow for nonlinear mode of thermal instability. Throughflow has been investigated for various boundary conditions with linear stability analysis. It is to be noted that, for understanding heat and mass transfer in the system one must study the interaction of streamline flow with temperature, and solutal concentrations through nonlinear analysis. The objective of the present article was, therefore, to investigate weakly nonlinear stability characteristics of a porous layer with simultaneous temperature and solute concentration gradients for constant vertical throughflow. Analytic expressions for both Nusselt and Sherwood numbers were derived from the complex non-autonomous Ginzburg–Landau equation [15,16,47–49] to calculate finite amplitude.

2. Mathematical formulation

An infinitely extended horizontal binary fluid saturated porous medium of depth d has been considered. The porous layer is homogeneous and isotropic and it is heated and salted from below. The physical configuration of the problem is given in Fig. 1. Using the modified Darcy's law and employing the Boussinesq approximation for density variations, the governing equations of the present problem are given by Bhadauria [22] for isotropic porous medium:

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0, \tag{1}$$

$$\frac{\rho_0}{\varepsilon}\frac{\partial \vec{q}}{\partial t}=-\nabla p+\rho\vec{g}-\frac{\mu}{K}\vec{q}, \tag{2}$$

$$\gamma\frac{\partial T}{\partial t}+(\vec{q}\cdot\nabla)T=\kappa_T\nabla^2 T, \tag{3}$$

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