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ORIGINAL ARTICLE

Nonlinear throughflow and internal heating effects on vibrating porous medium

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Abstract The effect of vertical throughflow and internal heating effects on fluid saturated porous medium under gravity modulation is investigated. The amplitude of modulation is considered to be very small and the disturbances are expanded in terms of power series of amplitude of convection. A weakly nonlinear stability analysis is proposed to study stationary convection. The Nusselt number is obtained numerically to present the results of heat transfer while using Ginzburg–Landau equation. The vertical throughflow has dual effect either to destabilize or to stabilize the system for downward or upward directions. The effect of internal heat source ($R_i > 0$) enhances or sink ($R_i < 0$) diminishes heat transfer in the system. The amplitude and frequency of modulation have the effects of increasing or diminishing heat transport. For linear model Venezian approach suggested that throughflow and internal heating have both destabilizing and stabilizing effects for suitable ranges of Ω. Further, the study establishes that heat transport can be controlled effectively by a mechanism that is external to the system throughflow and gravity modulation.

1. Introduction

Natural convection (buoyancy driven convection, in which gravitational force plays a main role) in fluid saturated porous medium is of interest due to its importance in various practical applications such as oil recovery process in petroleum industry, geothermal energy extraction, and insulation of reactor vessels. The above mentioned applications along with porous media occur in many natural situations. In these applications control of convective instability plays an important role. It is fact that, one of the effective mechanisms which control convective instability is to maintain a nonlinear temperature gradient. Such a gradient may be achieved by the following: time dependent heating or cooling at the boundaries, suitable thermal and rotation modulation, vibrating the porous medium periodically, volumetric distribution of internal heat sources and radiative heat transfer.

A modified complex body force (gravity modulation) is important when the system is under vertical vibrations. In this case the density gradient is subjected to vibrations, and the resulting buoyancy forces which are produced by the interaction of the density gradient with gravitational field have a complex spatiotemporal structures. The time dependent gravity field is of interest in space laboratory experiments, in areas of crystal growth and large-scale convection of atmosphere other applications. Many theoretical and experimental studies dealing with materials processing or physics of fluids under the microgravity conditions aboard an orbiting spacecraft have

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Nomenclature

Latin Symbols

$\mathbb{A}$	amplitude of convection
δ	amplitude of gravity modulation
d	depth of the fluid layer
$\vec{g}$	acceleration due to gravity
k_c	critical wave number
K	permeability of porous medium
Nu	Nusselt number
Pe	Péclet number $Pe = \frac{w_0 d}{\kappa_T}$
p	reduced pressure
Ra	thermal Rayleigh number, $Ra = \frac{\beta_T g \Delta T d K}{\nu \kappa_T}$
R_i	internal Rayleigh number, $R_i = \frac{Q d^2}{\kappa_T}$
R_0	critical Rayleigh number
T	temperature
Pr_D	Prandtl Darcy number $Pr_D = \frac{\phi \nu d^2}{K \kappa_T}$
ΔT	temperature difference across the porous layer
t	time
(x, z)	horizontal and vertical co-ordinates

Greek symbols

β_T	coefficient of thermal expansion
δ^2	square of horizontal wave number $\delta^2 = k_c^2 + \pi^2$
ϵ	perturbation parameter
κ_T	effective thermal diffusivity
γ	heat capacity ratio $\gamma = \frac{(\rho c)_m}{(\rho c)_f}$
Ω	frequency of modulation
μ	dynamic viscosity of the fluid
ϕ	porosity
ν	kinematic viscosity, $\left(\frac{\mu}{\rho_0}\right)$
ρ	fluid density
ψ	stream function
τ	slow time $\tau = \epsilon^2 t$
θ	phase angle
T'	perturbed temperature

Other symbols

∇^2	$\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$

Subscripts

b	basic state
c	critical
0	reference value

Superscripts

$'$	perturbed quantity
$*$	dimensionless quantity

been carried out by Nelson [1]. According to Wadih et al. [2,3], the vibrations can either substantially enhance or retard heat transfer and thus drastically affect the convection. The effect of modulated gravity on a convectively stable configuration can significantly influence the stability of a system by enhancing or decreasing its susceptibility to convection. Gershuni et al. [4] and Gresho and Sani [5] were the first to study the gravity modulation on the stability of a heated fluid layer. Their results show that the stability of the layer being heated from below is enhanced by g-jitter and being heated from below is enhanced by g-jitter. The instability of a viscoelastic fluid layer heated from below in a modulated gravitational field is studied numerically by Yang [6]. It is found that, modulation has a destabilization effect at low frequencies and a slight stabilization effect at high frequencies, which increases with increasing the amplitude of modulation. It is also pointed that, for viscoelastic fluid acted on by a modulated gravity, modulation has the same effects at both very low and very high frequencies, as those of Newtonian fluids. Using Venezian model the onset of convection in both fluid and porous layers is investigated by Malashetty and Padmavathi [7]. It is found that the low frequency g-jitter can have a significant effect on the stability of the problem. The Darcy limit and viscous flow limit are obtained as degenerate cases of the Brinkman model. The boundary-layer flow induced by a constant temperature vertical surface embedded in a vibrating porous medium is studied by Rees and Pop [8]. The amplitude of g-jitter is assumed to be small compared with the mean acceleration. It is found that, the effect of g-jitter is eventually confined to a thin layer embedded within the main boundary layer, but it becomes weak at increasing distances from the leading edge. A weakly nonlinear analysis in a porous medium under gravity modulation is investigated by Govender [9]. It is found that, the vibration frequency causes the convection amplitude to approach zero which means increasing the vibration frequency stabilizes the system. Kuznetsov [10] investigated bioconvection in a shallow horizontal fluid-saturated porous layer that contains a suspension of oxytactic bacteria, such as Bacillus subtilis. It is found that, linear stability analysis indicates g-jitter has a stabilizing effect on the suspension. Some of the relevant and documented works on gravity modulation are [11–15].

Several geophysical and technological applications involve non-isothermal flow of fluids through porous media, called throughflow where the basic flows not quiescently. In situ processing of energy resources such as coal, geothermal energy, oil shale and many practical problems often involves the throughflow in the porous medium. The importance of buoyancy-driven convection in such problem may become significant when precise processing is required. Moreover, the throughflow effect in such circumstances may be of interest because of the possibility of controlling the convective instability by adjusting the throughflow in addition to the gravitational force due to gravity. Throughflow alters the basic state temperature from linear to nonlinear with layer height, which in turn affects the stability of the system significantly. It is found that the throughflow is stabilizing if the bounding surfaces of the porous layer are of the same type but destabilizing in one particular direction if the boundaries are not of the same type [16–19]. However, it has been shown that the throughflow is destabilizing even if the boundaries are of the same type if the porous layer is heated internally [20] and also in the presence of an additional diffusing component. The effect of throughflow on the onset of convection in a horizontal porous layer for a Newtonian fluid has been studied by Nield [21]. The effect of throughflow and variable gravity field on thermal convection