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Vibration effect on the onset of thermal convection in an inhomogeneous porous layer underlying a fluid layer

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ABSTRACT

The linear stability problem for a two-layer system consisting of a horizontal pure fluid layer and an inhomogeneous porous layer saturated with the same fluid and heated from below in the presence of vertical high-frequency and small-amplitude vibrations in a gravitational field is studied in the framework of the averaging method. The problem is solved numerically with a shooting method. Bimodal neutral curves of the stability of mechanical equilibrium characterized by the absence of an averaged fluid flow in layers are obtained for the linear profile of porosity within a porous layer and permeability versus porosity through the Carman–Kozeny relation. We consider a competition between perturbations of shorter wavelength (short-wave perturbations) localized mainly in the fluid layer and those of longer wavelength (long-wave perturbations) spanning both layers near the stability threshold in the case when the intensity of vibrations and porosity gradient change. It is shown that when porosity increases with depth, instability is associated with the development of large-scale and long-wave perturbations. The stability threshold of these perturbations weakly depends on the vibration intensity in the range of the parameters considered. Perturbations penetrate into the porous medium poorly when porosity decreases with depth. Vibrations in such a situation stabilize the short-wave instability mode noticeably and lead to an increase in the wavelength of the most dangerous perturbations of equilibrium due to different contributions of inertial effects to fluid and porous layers. It has been found that when the vibration intensity and porosity gradient increase, a hard abrupt transition from short-wave to long-wave perturbations is replaced by a smooth change in the wavelength of critical perturbations related to the loss of stability of equilibrium in the examined two-layer system.

1. Introduction

Convective heat and mass transfer in both pure fluids and porous media saturated with fluid is caused by the heterogeneity of fluid density, when the fluid is heated from below in a gravitational field. Convective flow enhances heat transfer in layers in contrast to the motionless state, when heat is transferred only by means of heat conduction [1,2]. For the non-isothermal fluid involved together with the cavity into translational high-frequency vibrations, the thermovibrational mechanism of mean flow generation arises in addition to the thermogravitational mechanism of convection described previously [3–5]. It is associated with the vibration effect on the heterogeneity of density in the fluid undergoing forced oscillations in the presence of a vertical temperature gradient. The thermovibrational convection mechanism is not related to the gravity effect and can occur when the fluid is heated from either below or above. In [4,5], the stability of oscillating gar flow in a plane horizontal channel in the presence of a transverse temperature gradient and a pressure gradient that changes harmonically along the channel in a gravitational field was investigated theoretically and experimentally. The results obtained indicate that the convection of gas can be excited in a threshold manner even if the fluid is heated from above. This convection is known as thermo-oscillatory convection.

The interaction between thermogravitational and thermovibrational mechanisms of convection in single-component fluids [3,6,7] and homogeneous fluid-saturated porous media [8–14] depending on the orientation of an axis of vibrations with respect to temperature gradient and acceleration of gravity can lead to either increase or decrease in the stability threshold of a

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quasi-equilibrium state characterized by the absence of an averaged fluid flow. In the case of vertical high-frequency vibrations, when the axis of vibrations coincides with the direction of temperature gradient and acceleration of gravity, there is stabilization of the quasi-equilibrium state.

The effect of high-frequency and small-amplitude vibrations on the excitation of convection in fluids and fluid-saturated porous media is due to the synchronous response of the systems to external periodic actions [3,8–11]. In this case, instead of the analysis of periodic solutions of the Mathieu equation obtained by the direct method, it is possible to apply the averaging method, in which all of the velocity, temperature and pressure fields are represented as sums of their mean components averaged over the period of vibrations and pulsation (oscillating) components and to determine the conditions for occurrence of an averaged fluid motion. A review of the main results confirming the stabilizing effect of vertical high-frequency vibrations on the threshold of convection excitation in a porous layer obtained in the framework of the averaging method is given in [15,16]. The solution of the linear stability problem within two approaches mentioned above and physical assumptions concerning the applicability of the averaging method to the porous layer are presented in [17,18].

The direct method for the linear stability analysis is used in the case of finite amplitude and frequency of vibrations. With this method, one can obtain not only the synchronous periodic solution with a period equal to the period of vibrations, but also the subharmonic solution with a period twice as large as the period of external vibrational action. The direct method was used to describe the excitation of convective motion in a gravity modulated porous layer saturated with fluid and heated from below or above [19–21]. It is shown that high-frequency vibrations have the greatest effect on convection when the layer is heated from below [19]. They stabilize the stability threshold with respect to synchronous perturbations. Thermal vibrational convection is slowly destabilized by vibrations in the region of subharmonic solutions. The frequency value corresponding to the transition from synchronous to subharmonic solutions was determined [21]. The weakly nonlinear analysis was carried out in [22], where the convection amplitude was found to approach zero with increasing vibration frequency. The case of low frequency vibrations was considered in [23]. The influence of vertical vibrations on convection in a cylindrical porous layer heated from below was studied in [24]. Only synchronous perturbations took place in this case, and no transition to subharmonic solutions was observed as was in a horizontal porous layer [21]. An analogy between the gravity modulated porous layer heated from below and the inverted pendulum with an oscillating pivot point was established in [25]. A review of the most important results obtained in this field of research is given in [26].

The onset of double-diffusive convection in a horizontal layer heated from below or a rectangular cavity of homogeneous porous medium saturated with a binary fluid under high-frequency vibrations in a gravitational field was studied in [27,28] for vertical and other orientations of the vibration axis. It was established that vertical vibrations can both stabilize and destabilize the stability threshold of a quasi-equilibrium in the layer depending on the buoyancy ratio characterizing density heterogeneities caused by thermal and compositional gradients. The influence of high-frequency vibrations on the threshold of convection excitation in a rectangular cavity filled with a saturated porous medium in the presence of the Soret effect was studied in [29,30]. The results show that the destabilizing effect occurs in the presence of longitudinal horizontal vibration. Transverse vertical vibrations lead to the stabilization of a quasi-equilibrium state as in the case of a pure single-component fluid.

For a horizontal layer of a binary fluid with the Soret effect, the stabilizing effect of vertical high-frequency vibrations was detected for all parameters of the fluid studied [31]. Vertical vibrations can destabilize the motionless state in the binary fluid layer with the thermal diffusion effect, when they have a finite frequency [32]. At finite frequencies of vibrations, in addition to the main region of equilibrium instability with respect to perturbations synchronous with the external periodic action, there are areas of parametric instability related to synchronous and subharmonic perturbations of equilibrium, as well as to quasi-periodic perturbations.

The peculiarity of convection excitation in the layered systems consisting of a pure fluid and a homogeneous porous medium saturated with fluid in the presence of a vertical temperature gradient in a static gravitational field is the bimodal nature of neutral instability curves [33–40]. For thick fluid layers the lowest instability level is associated with the development of perturbations with shorter wavelength (short-wave perturbations) located mainly in the fluid layer. When a relative thickness of the fluid layer decreases, perturbations with longer wavelength (long-wave perturbations) penetrating both layers become the most dangerous. For intermediate values of the ratio of thicknesses of the fluid and porous layers there is a competition between these two types of critical perturbations. Changes in porosity and permeability with depth within a porous layer for the system of a fluid layer and an inhomogeneous porous layer saturated with the fluid can affect the competition between short-wave and long-wave perturbations of equilibrium in layers [41,42]. Since the fluid, when it moves through a porous medium, experiences the resistance of a porous matrix, large-scale long-wave perturbations become more sensitive to changes in pore permeability and porosity in comparison with those of shorter wavelength penetrating the porous layer poorly. The stability threshold with respect to short-wave perturbations varies slightly as permeability and porosity of the medium change.

The effect of vertical high-frequency vibrations on the competition between long-wave and short-wave perturbations of mechanical equilibrium in a two-layer system of a pure fluid layer and a homogeneous porous layer saturated with the fluid and heated from below in a gravitational field has been studied in [43–46]. It was shown that vibrations enhance the stability threshold and lead to an increase in the wavelength of the most dangerous perturbations of equilibrium. Due to the different contributions of inertial effects to layers of the pure fluid and fluid-saturated porous medium, short-wave perturbations are stabilized by vibrations more considerably in comparison with long-wave perturbations. In the porous layer these effects are less pronounced, so it is required a larger amplitude and frequency of vibrations to stabilize long-wave instability modes than in the case of short-wave modes. The authors of work [45] constructed a stability map for various fixed values of porous-medium permeability and the ratios of layer thicknesses in the absence and presence of vibrations. Porosity did not vary. It was revealed that in the presence of vibrations the long-wave instability in the two-layer system was observed at lower permeabilities of the porous layer and larger relative thicknesses of the fluid layer than in a static gravitational field.

In this paper we investigate the excitation of thermal convection in a two-layer system of a horizontal pure fluid layer and an inhomogeneous porous layer saturated with the same fluid under vertical high-frequency vibrations in a gravitational field. There are two ways to control the stability threshold of mechanical equilibrium in the layered system: a) variation of porosity with depth accompanied by the corresponding change in permeability, and b) variation of the vibration intensity. It is expected that the use of these methods will affect significantly the interaction of short-wave and long-wave perturbations of an equilibrium state.

We consider a linear profile of porosity varying with depth. Permeability is estimated by the Carman–Kozeny relation for a porous