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Long-Wave Instability in the Raylegh-Benard Problem with High Frequency Vibrations

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Abstract: The influence of vertical oscillations of inertia field on a convective instability and flow patterns in a horizontal fluid layer heated from below is studied experimentally. The flow is investigated for fluids with the Prandtl number ranging from 7 (n-heptane) to 16 (ethanol), which ensure the effect for high frequency vibrations with small amplitude. The flow evolution is determined on the base of the visual observations with use of stroboscopic lighting and powdered aluminum, the measurements of heat transport across the layer. It is realized the dynamical stabilization of the convective modes which are usually unstable in the static gravitational field. It is found that in a certain range of parameters the long-wave mode of instability can occur. The earlier unknown instability regions and flow patterns have been discovered. The results indicate that with the use of an oscillating inertia field it is possible to control the convection stability, intensity of the heat transfer and the structure of convection motions. These effects can be used in various technological devices having applications in fluid mechanics, chemical and bioengineering techniques.

Key words: Gravitational thermal convection • Oscillating inertia field • Pattern formation • Heat transfer • Long-wave instability

INTRODUCTION

The effect of high-frequency vibrations of different orientations on the stability of the mechanical quasiequilibrium in a heated horizontal layer has been the subject of several theoretical and experimental investigations of different authors. The book by Gershuni and Lyubimov [1] provides a comprehensive discussion of the effects of time-dependent modulation, including the method of averaging for analysis of the high-frequency limit and stability analysis. Several important problems of the buoyancy driven convection in modulated power fields was considered theoretically in [2].

Generally, the problem of convection in the variable inertial fields has received an intensive development last decades, when it was established that the fluctuations of micro accelerations on board of the space vehicles play a significant role in the processes of crystal growth and in other technological experiments performed under weightlessness conditions; among the numerous publications dealing with this question we shall point out, for instance [3-5].

Most part of the published experimental works, directed at the studies of convection in the fluid subjected simultaneously by gravity and vibration, also consider the horizontal layers. These experiments are focused on two typical situations when the direction of vibrations is parallel or perpendicular to the plane of the layer. Experiments [6, 7] have realized the stabilizing effect of the transversal high-frequency vibrations and destabilizing impact of the longitudinal ones, predicted by the theories [1, 2].

The subject of this paper is buoyancy driven thermal convection and heat transfer in the case when static gravity field is modulated by vertical, spatially uniform and oscillating in time inertial accelerations.

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Such situation takes place when the vessel, filled with a liquid, makes rectilinear periodic displacements as a whole in relation to laboratory reference frame. Here we report a new mode of instability found experimentally in the Rayleigh-Bénard problem with high-frequency vibrations.

Experimental Apparatus and Procedure: The experimental facility for investigation of the effects of vibrations in non-isothermal liquids should satisfy the rigid requirements, which follow from the analysis of governing similarity criteria of the problem. The stability of mechanical equilibrium as well as the intensity and structure of convection movement in a static gravity field is determined by Rayleigh number [1, 2]:

$$Ra = \frac{g\beta\Delta Th^3}{v\chi}.$$
 (1)

Here β , χ and v stand for coefficients of thermal expansion, thermal diffusivity and kinematic viscosity of a liquid respectively; ΔT is the temperature difference between solid walls of the layer; h – the thickness of the layer, g - gravity acceleration. The influence of linear inertial accelerations upon the convection is characterized by dimensionless vibration velocity [1].

$$\alpha = \frac{b\omega\sqrt{v\chi}}{gh^2}.$$
 (2)

Here *b* and ω stand respectively for the amplitude and circular frequency of the translational displacement of a fluid-filled cavity as a whole. From the definition of the governing parameters [1, 2] one can conclude that in order to strengthen the role of vibration mechanism it is necessary to increase the vibration velocity $b\omega$ and to use the layers of smaller thickness *h*, larger temperature difference ΔT . In addition one should use liquids with as high values of thermal expansion coefficient β (or parameter complex $\beta/v\chi$) as possible.

Therefore, n-heptane C₇ H₁₆ was used mainly in experiments, having one of the largest value of $\beta/\nu\chi = 2.32.10^{1} \text{ s}^{2}.\text{K}^{-1}.\text{cm}^{-4}$ and, simultaneously, one of the smallest values of Prandtl number Pr = 6.9 among the available liquids. It is important to notice, that for high values of the Prandtl number defined as $Pr = \nu/\chi$, fluid inertia becomes insignificant and only thermal inertia plays a role. It means that the heat is rather convected than diffuses. Thus, in the case under consideration if one intends to study the effect of vibrations of fluid flows, one should look at moderate or even low Prandtl

number fluids. Notice that n-heptane has one of the smallest values of Prandtl number (Pr = 6.9) among the available liquids which satisfies the criteria set out above. In addition, in experiments we have used ethanol ($\beta / v\chi = 82.1 \text{ s}^2.\text{K}^{-1}.\text{cm}^{-4}$, Pr = 16). All values are specified for the temperature 20°C.

As for the thickness h of a liquid layer, it is known that the optimal value for observation of convection instability of a mechanical equilibrium in most of the liquids is about few millimeters [1, 2].

The convection cell, where flows were established, was a cylindrical cavity with the diameter 75 ± 0.5 mm and the depth $h = 2.00 \pm 0.02$ mm. The cavity was confined by two heat-exchangers, one of which consisted of aluminum plates and another was prepared from Plexiglas. The bottom surface of the layer was an aluminum exchanger with the channels for constant temperature circulating water. A top transparent heat exchanger was composed of two Plexiglas parallel plates, which separated a gap for pumping thermostat water. The circular sidewall of the layer was also made of Plexiglas. It makes possible to perform the visual observations of flow patterns in different planes.

The structures of liquid motions were observed by sight and registered at photo and video camera in stroboscopic illumination. The particles of aluminum powder were added in a testing liquid. To visualize the flow, aluminum powder was suspended in the fluid. The aluminum particles are disk-shaped and tend to lie with the plane of the disk on the stream surface. This was a very helpful point because the broad features of flows were immediately apparent. Usage of aluminum powder allowed both to observe the average properties of the flow and to trace the passage of a single particle. It is known that addition of small solid particles to flow may change the stability properties [5, 8]. However, our test experiments have shown that an addition of particles to the flow varies the critical value for onset of primary instability within 3%.

The temperature difference ΔT between horizontal borders of a cavity was measured with copper-constantan differential thermocouples connected to a digital potentiometer with fluctuation within 0.03 C. The electrodes and junctions of each thermocouple were settled down in the heat exchangers.

The convective cell was mounted on a vibro-table based on a crank mechanism setting in a movement by the collector high-power electric motor through the belt transmission. The vibration platform can impart to the cell translational linearly polarized vertical vibrations with a frequency of from 0.5 to 25 Hz and amplitudes of 0.5–8.0 cm. The developed acceleration amplitude $\omega^2 b$ amounted up to 103 g.

RESULTS AND DISCUSSION

As it is known [1], high-frequency vertical vibrations of a liquid-filled chamber heated from below, result in the suppression of the Rayleigh convection. In our experiments the effect of dynamic stabilization also predominated. When describing these effects, it is convenient to use a non-dimension vibration velocity α (2). The map of convection regimes in the parameter plane (α , Ra) obtained in the experiments with ethanol is represented in Figure 1. In the investigated range of control parameters, this map may be divided into two domains with drastically different fluid behavior.

In the domain "a" of the figure the non-isothermal fluid is in the mechanical equilibrium, including the case when it becomes unstable in the static inertia field: $Ra > Ra_{cr}$. The curve of neutral stability shown in Fig.1 has vertical asymptote $\alpha^* = (4.2 \pm 0.2).10^{-2}$. The asymptotic vibration frequency is equal to 11.2 Hz in the case of ethanol and 20.5 Hz for n-heptane. For higher values of frequency the fluid layer is absolutely stable for any values of the Rayleigh number.

In the area of map bounded by the axis of ordinates and neutral curve indicated as the region "b" in Fig.1, the structure of fluid flow observed during experiments was qualitatively similar to the Rayleigh-Bénard convection realizing in the static gravity field. But when varying the vibration velocity α , the wavelength of the convective structure changes dramatically. Figure 2 illustrates this change. All photos have been made at fixed value of the Rayleigh number $Ra = 10^4$. Note that the effect described below can be only observed for parameter values from low part of the domain of instability shown in Fig.1 ($Ra < 1.2.10^4$).



Fig. 1: A map of convection regimes in a horizontal layer, heated from below and subjected to vertical vibrations. Ethanol, b = 4.1 cm

It is known that when a realistic system is used the shape of the boundaries will mandate the final pattern. Though more often convective Rayleigh-Bénard pattern tends to be a system of regular right hexagonal cells filling the layer, it may appear as rolls or a superposition of them. The technology of obtaining of convective rolls consisted of the following steps. In the beginning of series of observations, immediately before the vibrations starting, the convective layer with fluid, which was previously stratified according to temperature distribution, was inclined with respect to horizon for a few minutes. It helped to create a system of approximately parallel space periodic rolls. After that, the layer was returned in original condition and has been exposed to high frequency vibrations.

The first photo shown in Figure 2 presents the convection arising in the static gravity field ($\alpha = 0, f = 0$). Looking at the photo, it is necessary to take into account the following: in the gap between two neighboring dark lines there are a couple of contrary rotating convective rolls (Fig.2a). Their horizontal cross size in the absence of vibrations is defined approximately be the thickness of the layer (see the flow pattern schematically shown on the left in Fig.1).



Fig. 2: Evolution of convection structures in a horizontal layer heated from below and subjected to transversal vibrations. n-Heptane, $Ra = 1.0.10^4$, b = 4.1 cm. a) – d): f = 0, 10.0, 17.0 and 20.5 Hz respectively.



Fig. 3: The dependence of a flow pattern wave number k on the non-dimensional vibration velocity along the horizontal section $Ra = 1.0.10^4$ of region "b" in Fig. 1. n-Heptane, b = 4.1 cm

We have found that the modulation of a gravity field of increasing intensity results in an increase of wavelength of the roll pattern (Fig.2, photos b and c). By increasing the vibration velocity speed α and approaching to the neutral stability curve, one can obtain flow pattern consisting just two rolls. The wavelength of these rolls was about 35 mm. Thus, their spatial period has increased by more than one order of magnitude in comparison with that in the static case. This process can be described as the formation of the long-wave instability mode in the Rayleigh-Bénard convection. Figure 3 illustrate the change of wave number of the Rayleigh-Bénard rolls when the parameter α is increased.

Finally, the photo shown in Fig. 2d represents the mechanical equilibrium of fluid in the area "a" of a map (Fig.1). This situation has been discussed above.

CONCLUSION

The stability properties and pattern formation of the thermal convection in a horizontal layer differently heated from below and subjected to high frequency transversal vibrations were studied experimentally. The several liquids with the Prandtl number ranging from 7 (n-heptane) to 16 (ethanol) were used as a working fluid in order to ensure the effect. We found that by increasing the parameter of vibration velocity the wavelength of Rayleigh-Bénard rolls sharply increases tending to infinity before final stabilization due to vibrations. Thus, the special choice of a working fluid and the taking into account several factors has made it possible for the first time to obtain long wave instability mode in the Rayleigh-Bénard classical problem.

The obtained results indicate that with the use of a variable inertia field it is possible to control the convection stability, intensity of the heat transfer and the structure of convection motions. These effects certainly can be used in various technological devices where during the work cycle one needs to set different flow patterns, using only the external means of control. For example, this might be necessary in micro-fluidic devices [9], chemical reactor of the continuous cycle [10], some bioengineering techniques [11] an so on.

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