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Research Article

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Thermal vibrational convection in a rotating plane layer

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Abstract. The influence of rotation on the thermal vibrational convection of liquid in a horizontal plane layer is studied experimentally. The convection in the layer is excited by the vibrations of circular polarization in the horizontal plane. The research is carried out in a liquid layer heated from above, under conditions of a strong stabilizing effect of gravity. In this case, the vibrational convection is excited at a relatively high intensity of vibrations and manifests itself in the development of short-wavelength convective structures in the form of beads. It is found that the rotation has a stabilizing effect and increase the vibrational convection excitation threshold. A map of convective stability is plotted on the plane of dimensionless parameters: vibrational parameter, and dimensionless velocity of rotation, for different values of the gravitational Rayleigh number. The results are compared with the classic case of gravitational convection in a rotating layer. It is shown that, similarly to the case of gravitational convection, rotation has a stabilizing effect on vibroconvective stability; the threshold value of the vibration parameter increases with the dimensionless velocity. It is found that at large negative values of the gravitational Rayleigh number, when cellular convective structures of vibroconvective nature are characterized by large wave numbers, in the studied area of the dimensionless frequency, rotation has little effect on the wave number of spatial convective structures, but changes their shape.

Keywords: thermal vibrational convection, rotation, stability, heat transfer

Introduction

The problem of thermal convection in rotating systems occupies an important place in the section of convection and heat transfer (Chandrasekhar 1961, Rossby 1969, Boubnov and Golitsyn 2012). Along with the problem of convection in stars, atmospheres and planetary cores, this problem is widespread in practical human activities (Lappa 2009, Lappa 2012). One of the fundamental and thoroughly studied problems is gravitational convection in a horizontal plane layer of liquid rotating around a vertical axis and heated from below (Chandrasekhar 1961). The dimensionless control parameters for problems of this type are the classical Rayleigh number $Ra = g\beta\Theta h^3/\nu\chi$, dimensionless velocity of rotation $\omega_{\rm rot} = \Omega_{\rm rot} h^2/\nu$, characterizing the ratio of the Coriolis force to the viscosity force, the centrifugal Rayleigh number $Ra_{\rm c} = \Omega_{\rm rot}^2 R\beta\Theta h^3/\nu\chi$ and the Prandtl number $Pr = \nu/\chi$. Here g – gravity acceleration, $\Omega_{\rm rot} = 2\pi f_{\rm rot}$ – cavity angular velocity, Θ, h and R – characteristic temperature difference, cavity size (e.g. layer thickness) and distance to the axis of rotation, β, χ and ν – coefficients of volume expansion, thermal diffusivity and kinematic viscosity of the liquid. At present, the conditions for the occurrence of gravitational convection and the structure of supercritical flows depending on the controlling dimensionless parameters have been experimentally and theoretically studied in detail. It is shown that with an increase in the dimensionless velocity of rotation (analogous to the Taylor number), the threshold value of the Rayleigh number increases, the wave number of convective cells also grows.

Another mechanism of thermal convection excitation is a vibrational one (Gershuni and Lyubimov 1998). It is fundamentally different from the gravitational mechanism and based on the average mass forces generated in a non-isothermal fluid as a result of its oscillations (Zen'kovskaya and Simonenko 1966). The oscillating force fields, in turn, can be imposed by the vibrations of the cavity. The thermovibrational mechanism can be effectively used to control over convection and heat transfer in non-isothermal systems under microgravity conditions (Gershuni and Zhukhovitsky 1979, Mialdun et al. 2008, Shevtsova et al. 2010). The results of a simulation of fluid motion under the action of an oscillating external force in ground-based laboratories can be applied to the development of the researches under the conditions of orbital flight, such as the growth of semiconductor and biological crystals, and the production of highly pure and composite materials.

Thermal vibrational convection is determined by the interaction of oscillating fields of temperature and velocity. In the limiting case of high-frequency translational vibrations of the cavity, when the oscillations of the liquid are inviscid, the average effect of vibrations is described by the vibrational parameter $R_{\mathrm{v}} = \left(b\Omega_{\mathrm{vib}}\beta\Theta h\right)^2 / 2\nu\chi$ (Gershuni and Lyubimov 1998). Here b is the amplitude and Ω_{vib} is the cyclic frequency of translational oscillations of the cavity (frequency of the force field oscillations in the cavity reference frame). Thermal vibrational convection under the action of circularly polarized translational vibrations was theoretically considered in (Kozlov 1991, Pesch et al. 2008), in this case, the uniform inertial force field rotates in the reference frame of the cavity. An experimental study of thermovibrational convection in a plane horizontal liquid layer heated from above was carried out in (Kozlov et al. 2019, Kozlov et al. 2021). Under conditions of large negative values of the gravitational Rayleigh number, it was found that vibrational convection develops in the form of spatial structures, where the elongated convective rolls are broken along the length into relatively short segments forming a beads-like pattern. Convection in this formulation is determined by the vibrational parameter R_{v}, the threshold value of which increases with increasing the modulus of Ra. On the plane of dimensionless control parameters Ra, R_{v} the results of the studies are in good agreement with the results of theoretical calculations of the threshold stability curve in the area of large negative values of the Rayleigh number in a layer that performs high-frequency linear translational vibrations (Ivanova and Kozlov 2003). It should be noted that in accordance with (Kozlov 1991) in the problem of the linear theory of a plane layer stability, the action of linear translational vibrations coincides with the action of circular vibrations.

The study of vibrational convection under the action of various complicating factors has been widely developed in recent years (Smorodin et al. 2018, Vorobev and Lyubimova 2019). It was found, in particular, that in case of non-translational vibrations of the cavity, the thermal vibrational mechanism changes qualitatively, along with quadratic terms, the terms linear in density inhomogeneity appear in the average force (Ivanova and Kozlov 2003). An additional factor, that qualitatively changes the vibroconvective mechanism, is rotation, the effect of which on thermovibrational convection was described theoretically in (Kozlov 2004). An interesting example of thermal convection, which can be referred to as "vibrational" is the averaged convection in a cavity rotating around a horizontal axis (Ivanova et al. 2003). The oscillations of a non-isothermal fluid relative to the cavity in this case occur in the absence of vibrations; they are caused by the gravity field rotating in the cavity reference frame. As it is shown in (Kozlov 2004, Ivanova et al. 2003) the averaged convection in this case is determined by the "vibrational" parameter $R_{\mathrm{v}} = \left(g\beta\Theta h\right)^2 / 2\nu\chi\Omega_{\mathrm{rot}}^2$. Note that with a horizontal orientation of the rotation axis, the static component of the gravity field is absent in the cavity reference frame, and, neglecting the centrifugal force field, the averaged convection is determined only by the “vibrational” mechanism. The peculiarity of this statement is that the frequency of the force field oscillations in the cavity reference frame Ω_{osc} coincides with the rotational velocity Ω_{rot}. In a plane layer, the convection develops in the form of the cells that are immobile relative to the cavity and arranged in an order similar to hexagonal one (Ivanova et al. 2003). The threshold of cellular structures excitation (critical value of R_{v}) and the wavenumber of the convective structures increase with an increase in the dimensionless rotation velocity ω_{rot}.

The study of the influence of rotation on thermal convection and heat transfer under conditions of simultaneous action of gravitational and vibrational mechanisms is of particular interest. In (Vjatkin et al. 2017) the thermal convection in a rotating plane layer was studied for its various orientations in space. It was shown that the deviation of the axis of rotation from the vertical leads to the appearance of the gravity field component, which is tangential to the plane of the layer. This component rotates (oscillates) in the cavity reference frame and leads to the generation of an averaged thermovibrational convection. Simultaneously, that gravity field component, which is normal to the plane of the layer, remains static in the reference frame of the cavity and is responsible for the classical gravitational convection. In this case, convection and heat transfer are determined by two independent convective mechanisms, gravitational and "thermovibrational", which manifest themselves simultaneously in the threshold excitation of cellular convective structures of different sizes. In the area below the excitation threshold of vibrational convection, the existence of toroidal rolls generated in the layer by inertial waves was found (Kozlov et al. 2015). The static (in the laboratory reference frame) component of gravity plays the role of the oscillating (in the cavity reference frame) force, and the change in the force field in the cavity reference frame occurs with a rotation frequency. Note that the problem of vibrational thermal convection caused by rotating force field at an independently specified rate of the cavity rotation remains unexplored.

The purpose of this work is an experimental study of the effect of rotation on vibrational thermal convection in the case when the oscillation frequency of the inertial force field significantly exceeds the rotation frequency. The object of study is a convection in a horizontal plane layer with isothermal boundaries of different temperatures, which performs high-frequency circular translational oscillations in its own plane. The main attention is paid to the case of negative values of the gravitational Rayleigh number (heating of the layer from above), when vibrational convection is excited under conditions of a strong stabilizing effect of the gravity field. The results of the experiments in this formulation are important for understanding the specifics of the manifestation of the thermal vibrational mechanism of convection in a rotating system (Kozlov 2004).

The paper is organized as follows. In Section "Experimental technique and procedure" we present a description of the experimental technique and experimental setup, which provides the harmonic vibrations of circular polarization with variable amplitude and frequency and independent rotation of cavity with definite frequency, and describe the thermochromics' technique of convective cells visualization. To validate the experimental setup and thermochromics' technique, the classical case – thermal gravitational convection in rotating horizontal plane layer – is investigated. In Section "Experimental results" we study: a) thermal vibrational convection of stably stratified liquid layer depending on the governing dimensionless parameters, Rayleigh number, vibrational parameter and dimensionless vibration frequency; b) effect of rotation on thermal vibrational convection in plane layer at presence of gravity field. The next Section "Analyzes", where the results of experimental study of vibrational convection in rotating plane layer are compared with the experimental and theoretical studies in other cases, is followed by "Conclusion".

Experimental technique and procedure

Problem formulation

The convection in a horizontal plane layer with the boundaries of different temperatures T_1 and T_2 is considered (Fig.1). The layer performs translational vibrations along a circular path with a cyclic vibration frequency Ω_{vib} and an amplitude b in the laboratory reference frame $x'y'z'$. Radius vector $\mathbf{r}$, directed to the origin of the moving system xyz rotates in the laboratory reference frame around the axis z' according to the law $\mathbf{r} = b\left(\cos\left(\Omega_{vib}t\right)\mathbf{i}' + \sin\left(\Omega_{vib}t\right)\mathbf{j}'\right)$. At this, in a moving reference frame xyz, associated with the cavity, an inertial force field uniform in space is excited. The force field rotation frequency in the oscillating reference frame equals Ω_{vib}. At the same time, the layer could perform a relatively slow rotation around the vertical axis with an angular velocity Ω_{rot} ($\Omega_{\text{rot}} << \Omega_{\text{vib}}$).

The layer has the boundaries of different temperatures. In the case where the lower boundary has a higher temperature, $\left(T_1 < T_2\right)$, the gravitational convection is possible in the layer. When the temperature of the upper boundary is higher than the temperature of the lower one, $\left(T_1 > T_2\right)$, the gravity field plays a stabilizing role. In this formulation, the vibrational convection in the layer is studied.

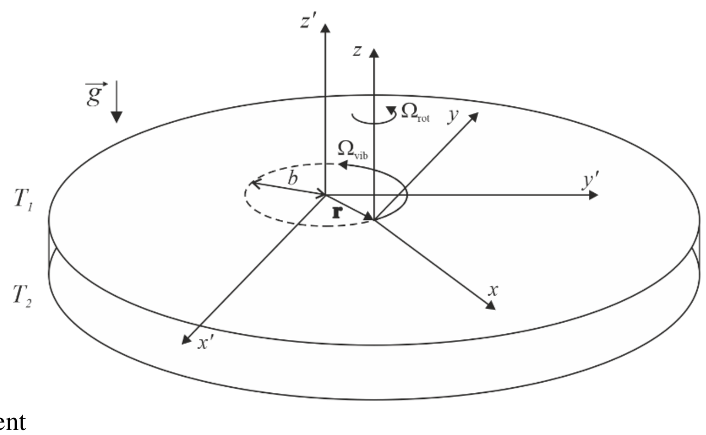


Fig.1 Problem statement

As it follows from (Kozlov 2004) the vibrational thermal convection under conditions of high-frequency circular oscillations is determined by the following dimensionless parameters: Rayleigh number $Ra = g\beta\Theta h^3/\nu\chi$, Prandtl number $Pr = \nu/\chi$, vibrational parameter $R_v = (b\Omega_{vib}\beta\Theta h)^2/2\nu\chi$, dimensionless velocity of rotation $\omega_{rot} = \Omega_{rot}h^2/\nu$, centrifugal Rayleigh number $Ra_c = \Omega_{rot}^2 R\beta\Theta h^3/\nu\chi$.

Experimental setup and methodic

The working layer is formed by two flat heat exchangers *I* and *II* (Fig.2). Between the heat exchangers, the spacer *III* with a cylindrical side border is installed. The diameter of the side border is $d = 13.8$ cm. The spacer thickness sets the layer thickness, which varies in experiments in the interval $h = 0.20 - 1.50$ cm. To ensure the uniformity of the layer thickness, there is a system of holes and bolts located along the perimeter of the spacer.

The upper heat exchanger *I* is transparent and is formed by a Plexiglas side frame *1* and two silicate glasses *2* and *3*, with thickness 0.5cm. Water is supplied inside the heat exchanger from a jet thermostat (LOIP LT-316A) through the side hole *4* in the Plexiglas frame. Water is drained through a hole in the center of the top glass *2,* in the figure, the channel *5* connected to the hole is shown. This design provides optimal water circulation in the heat exchanger and high-quality observation over the convective structures in the layer. The lower glass *3* of the upper heat exchanger on the side of the working layer is supplied with a temperature sensor T_1. The sensor is a resistance thermometer, which is made of thin copper wire with a diameter of 0.02mm and placed on the adhesive layer of a thin transparent PVC film with a thickness of 0.1 mm. The sensor is glued along the layer diameter and has the form of a strip with a width of 2cm.

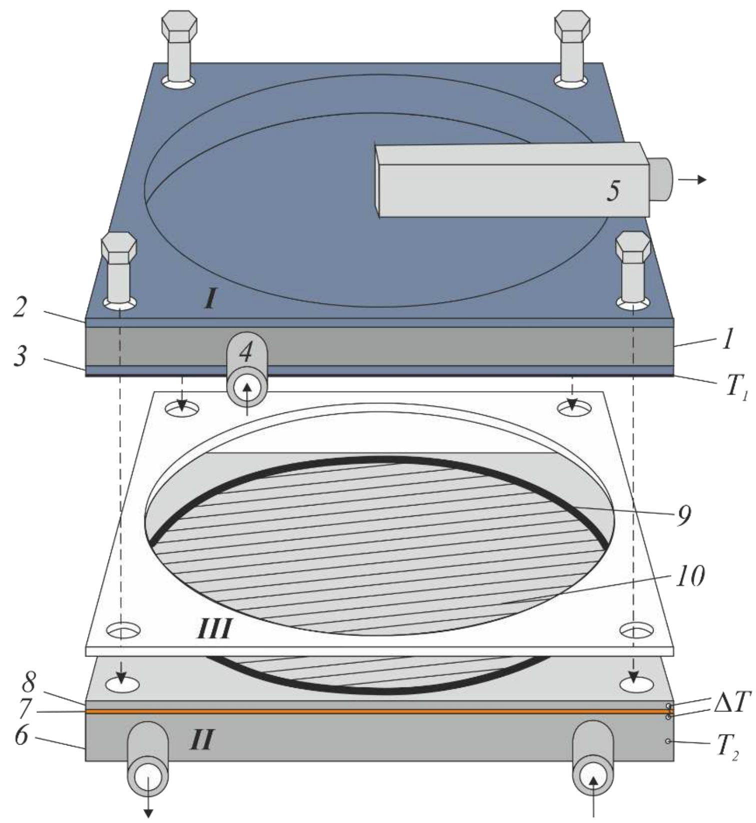


Fig.2 Scheme of the experimental cuvette

The lower heat exchanger *II* is made of an aluminum block *6* with a thickness of 1.6cm. On the surface of the heat exchanger, there is a thermal pad *7* with a thickness of 0.1cm made of a material with a low thermal conductivity, and above the thermal pad there is an aluminum plate *8* with a thickness of 0.3cm, designed to equalize the temperature at the boundary of the working layer. Along the perimeter of the working layer in the plate *8* there is a sealing ring *9* with a width of 0.2 cm, filled with silicone. The use of a transparent upper heat exchanger makes it possible to observe and register the convective structures that appear in the layer. For this purpose, a sheet of thermochromic film *10* is glued on the lower boundary of the cavity over the plate *8*. The sheet with a thickness of 0.15 mm is an indicator component (microencapsulated liquid crystal ink) protected on both sides by a transparent mylar (polymer) base, one of which is also supplied with an adhesive layer. The ink is able to change its color when exposed to temperature in a narrow range and return to its original color after returning to its original state. In this experiment, the activation temperature range is from 30ºC to 35ºC. At temperatures below 30ºC or higher than 35ºC, the temperature indicator is practically black. When heated to 30ºC it turns yellow-green and over 33ºC becomes blue with a further transition to dark blue. With fast response times, these temperature sensitive sheets provide a quick visual indication of temperature field. To protect against chemical interaction with the working fluid, a transparent PVC film with a thickness of 0.10 mm is glued on top of the thermochromic sheet.

Measurement of the heat flux through the layer is carried out by the temperature drop ΔT on the heat flow sensor using a thermocouple, the junctions of which are located at the boundary of the working layer and in the lower heat exchanger. The temperature of the heat exchanger itself is measured using a resistance thermometer T_2. The temperature difference between the layer boundaries is determined as $\Theta = T_1 - \Delta T - T_2$. In experiments, the temperature difference at the layer boundaries varies from $\Theta = 0$ ºC to $\Theta = 35$ ºC and is set by the temperature of the fluid pumped through the heat exchangers. In the series of experiments the heat exchangers temperatures are set and maintained constant with precision 0.1ºC with help of water from jet thermostats (LOIP LT-316A) circulating in the heat exchangers. High fluid flow through the exchangers ensures the temperature uniformity at the boundaries of the working layer. In different series of experiments, the constant temperatures of the layer boundaries may be set in a range $T_{1,2} = 22 - 70$ ºC. A registration of the temperature data and its transfer to a computer is carried out using a Termodat device.

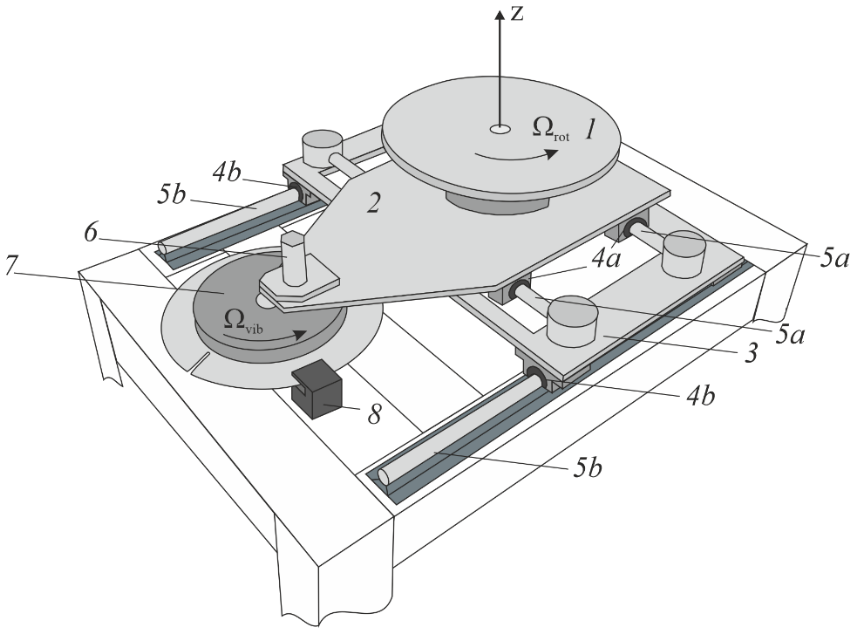


Fig.3 Scheme of a vibration stand that set the circular translational vibrations in a horizontal plane

The experiments are carried out using a mechanical vibration stand (Fig.3), which sets the circular vibrations of the cuvette. The vibration stand consists of a table *1*, which can rotate around a vertical axis with an angular velocity Ω_{rot}. The table is intended for installation of the experimental cuvettes. The rotating inertial field in the reference frame associated with the platform *2*, is created by the circular oscillations of the table axis in the horizontal plane. For this purpose, the mobile platforms *2* and *3* are equipped with linear ball bearings *4a* and *4b*, which allow the platform *2* to move in mutually perpendicular directions on linear guides *5a* and *5b*. The mobile platform *2* is connected to a pivot *6*, eccentrically located on a rotating disk *7*. The disc is driven by a servomotor of a type EMG-15ASA22 with high accuracy of maintaining the angular velocity of rotation Ω_{vib}. The rotation of the disk leads to a circular movement of the pivot and the generation of circular translational vibrations of the platform *2* with a rotating table *1* mounted on it. The oscillation frequency is measured by a digital tachometer *8*, with the help of an additional pad with a slot fixed on a rotating disk *7*. The amplitude and the frequency of vibrations change in the range $b = 0 - 5.0$ cm, $f_{\text{vib}} \equiv \Omega_{\text{vib}}/2\pi = 0 - 9$ Hz. The relative error in measuring the amplitude and frequency of vibrations does not exceed 1% and 0.1%, respectively. Coordination of the work of all elements of linear movements and their precise installation on the vibration stand ensures the uniformity of the disk *7* rotation and the absence of parasitic vibrations.

The uniqueness of the vibration stand is in the simultaneous rotation of the cuvette *1* (Fig.4) and the translational circular motion of the rotation axis. The rotation of the cuvette is set by a stepper motor *2* of a type FL86STH156-6204A by means of a light cardan shaft *3*. The shaft on one side is fixed on the axis of the hydraulic collector *4*, on the other side – on the axis of the rotating table. The rotation velocity varies in the range $f_{\text{rot}} = 0 - 5.0$ rps and is maintained with a precision 0.01%. The experiment provides the in-phase rotation of the cuvette and the temperature meter Termodat *5*, for this, a bevel gear *6* is used. The temperature data from the measuring module is received through a copper ring collector *7* and converter *8* to a computer in real time. The observations and photographic recording are carried out through the upper transparent heat exchanger using a camera *9*.

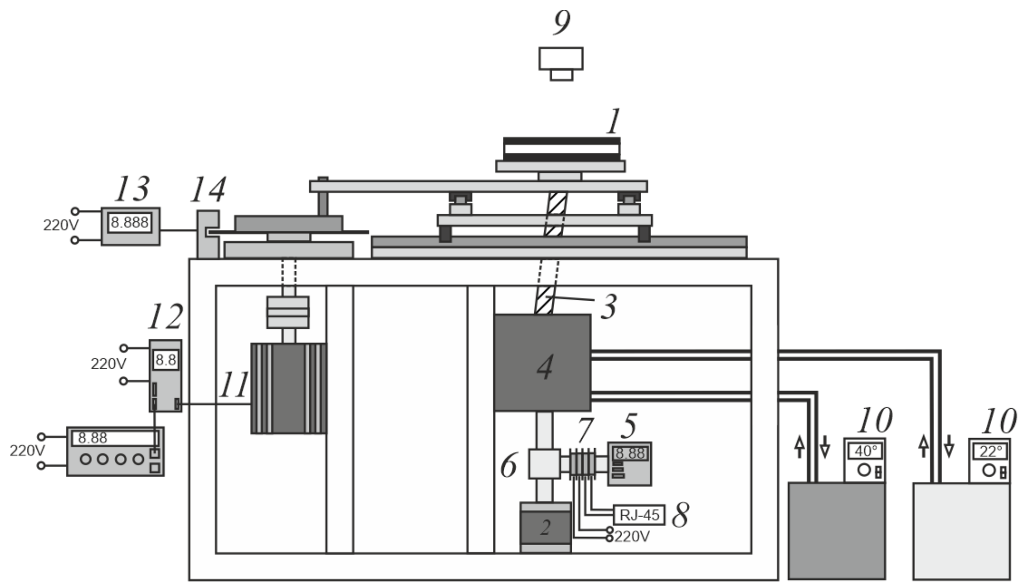


Fig.4 Vibration stand scheme, side view.

The constant temperature of the layer boundaries is maintained by the water pumped from jet thermostats *10*. A hydraulic collector *4* is used to connect the thermostats to the rotating cuvette. The outer immovable body of the collector is made of caprolon. Inside the body there is a rotating hydraulic distributor – a shaft equipped with a system of holes to distinguish between incoming and outgoing flows of hot and cold water. The system of control over the circular vibration consists of a servomotor *11,* which sets the circular translational motion of the cavity, the feedback sensor *12*, used to control the position of the motor shaft. A tachometer *13* and a photosensor *14* are used as a measure of the frequency of the cavity circular movements.

The analysis of the results of verification of the shaker using high-speed video recording shows that the trajectories of movement of the points of the platform corresponds to a circle in the horizontal plane. The movement occurs according to the harmonic law; the deviation from the circular trajectory does not exceed 0.05 mm.

Validation of the experimental technique. Gravitational convection in rotating plane layer

The experimental setup is calibrated in the classical case, when studying the threshold of gravitational convection excitation in a horizontal plane liquid layer rotating around a vertical axis. To determine the thresholds of the gravitational convection excitation in the case $T_1 < T_2$, at the given temperatures of the heat exchangers, the layer rotation velocity decreases step by step, and the heat transfer through the layer is recorded using temperature sensors. A characteristic of heat transfer is the Nusselt number, $Nu = \left(\Delta T/\Delta T_0\right)\big|_\Theta$, defined as the ratio of the heat flux through the layer to the heat flux in the absence of convection, for a given Θ. In the absence of convection the value of ΔT is close to ΔT_0 (the temperature drop ΔT_0 is determined when the layer is horizontal, and the hot heat exchanger is on top). At high rotation velocity (when $\omega_{\rm rot} > 150$) the number Nu is close to unity, i.e. there is no convection in a layer. With decrease in $f_{\rm rot}$, at some critical dimensionless velocity of rotation, the value of Nu increases (Fig. 5). A sharp increase in Nu indicates a change in the heat transfer regime and the occurrence of convection in the layer. The graph shows the experimental data for two different values of Θ. One can see that with an increase in the temperature difference between the layer boundaries, the critical value of the dimensionless rotation velocity increases.

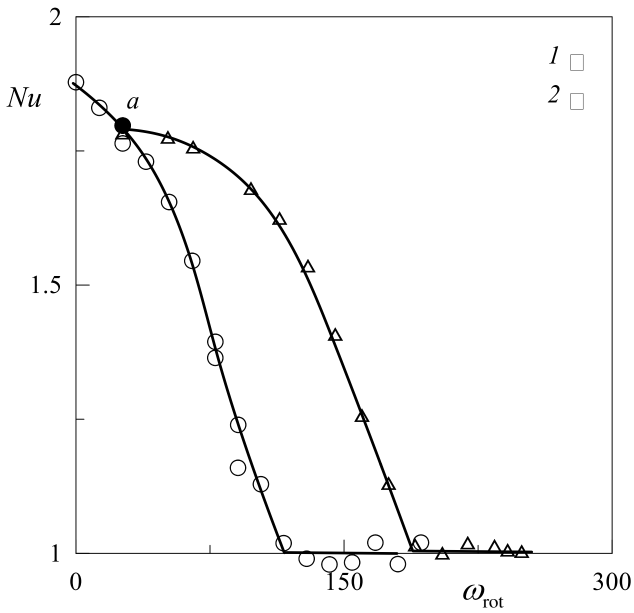


Fig.5 A dependence of Nu on the dimensionless velocity of rotation in the alcohol layer *h*=0.32cm at temperature differences of the layer boundaries *1* – $\Theta = 3.6\,°\mathrm{C}$, *2* – $\Theta = 12.3\,°\mathrm{C}$

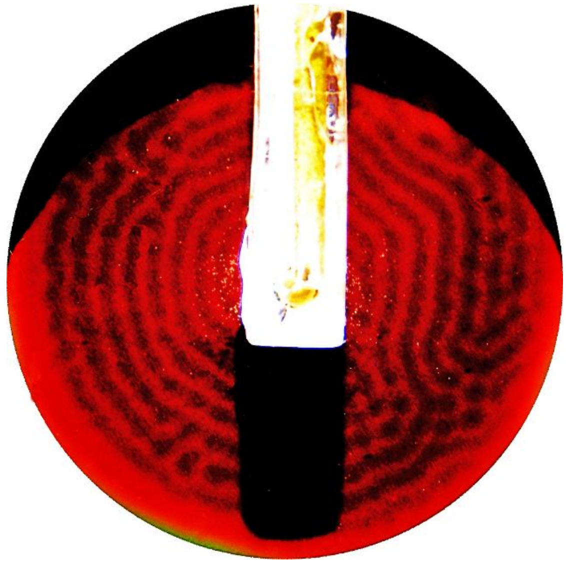


Fig.6 Convective structures at $f_{\rm rot} = 0.5$ rps, (point *a* in fig.5 and fig.7), $Ra = 1.0 \cdot 10^4$, $\omega_{\rm rot} = 26$

Upon reaching the stability threshold, the convective structures develop in the layer (Fig.6). The use of a finely dispersed visualizer in thermal experiments, when the upper boundary has a higher temperature, is problematic, since the visualizer particles settle on the lower boundary. An alternative visualizer is the thermochromic film capable of visualizing temperature changes near its surface. The film is located on the lower boundary of the layer (upper side of the lower aluminum heat exchanger). To visualize the temperature of the liquid near the surface of the heat exchanger between the thermochromic film and the isothermal boundary of the aluminum block, there is a thermal resistance in the form of a lavsan film with a thickness 0.1 mm. The hotter areas are bright in color and correspond to the rising heat fluxes. The dark areas refer to the less heated flows descending from the upper boundary of the layer. The photographic registration of the structures is carried out in the light of a flash lamp; in the photograph, a shadow from the upper insert, which serves to drain water from the heat exchanger, is visible in the center of the cuvette. In experiments, a thermochromic film with an operating range $T_{\rm oper} = 33 \pm 3\,°\mathrm{C}$ is used. Upon reaching the stability threshold, the convective structures in a form of the regular convective cells (Fig.6) develop in the layer.

The boundary of instability depending on the dimensionless velocity is shown in Fig.7, the solid line corresponds to the theory (Chandrasekhar 1961). The gravitational Rayleigh number is represented as $Ra = g\beta\Theta h^3 / \nu\chi$, and in the area of high frequencies varies according to the law $Ra = 18.8\,\omega_{\rm rot}^{4/3}$ (Boubnov and Golitsyn 2012). The excitation thresholds of the convection in a layer of alcohol found according to Fig.5, are shown on the plane $\omega_{\rm rot}, Ra$ by the filled points. The empty symbols in the form of a square correspond to the results obtained in the experiments with water. The dashed curve shows the change in parameters during a single experiment. The symbols located along the dashed curve show the change in parameters with a step-by-step decrease in the rotation velocity in the experiment

(Fig.5). The dimensionless velocity of rotation ω_{rot} is decreased in the experiment; at some critical value of ω_{rot} the convection occurs. This happens when the dashed curve crosses the threshold curve shown by the solid line. In the supercritical area, as the rotation velocity decreases, the number Ra decreases a little. This is due to the fact that the temperature difference at the layer boundaries decreases as a result of an increase in the temperature drop on the thermal resistance sensor. The excitation threshold of the convection in the considered case is in good agreement with the theoretical value.

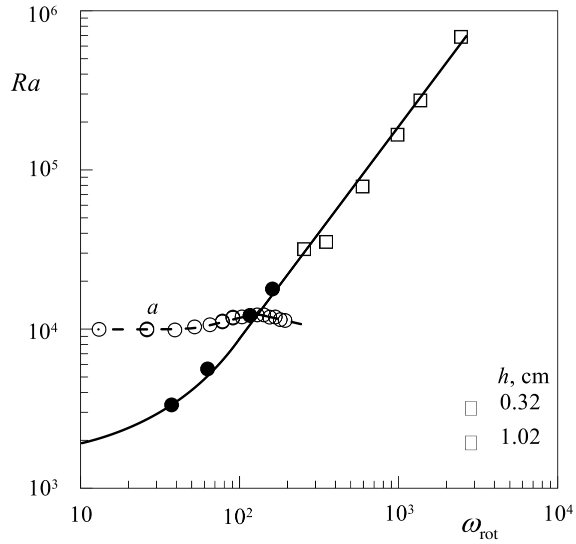


Fig.7 Threshold curve of instability of the rotating liquid layer. Dotes present experiments with alcohol, squares – with water. Empty circles present the change in Ra with decrease of rotation velocity in one experiment

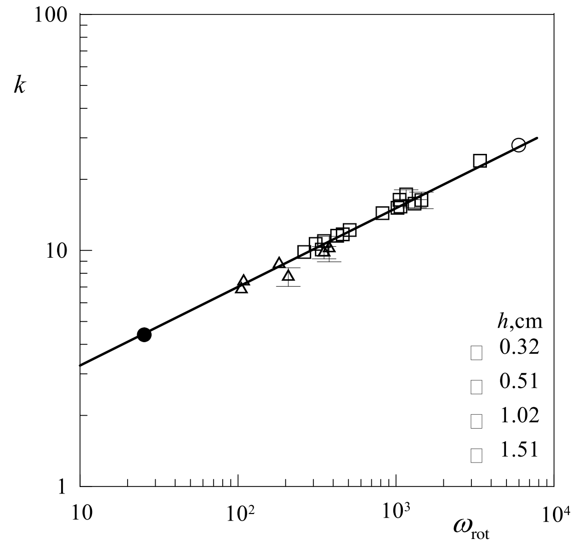


Fig.8 Dimensionless wave number of the convective structures in a rotating horizontal liquid layer depending on the dimensionless velocity of rotation

The dimensionless wavenumber of the structures near the threshold for the layer of alcohol (symbol a, Fig.5 and 7) is marked on the plane ω_{rot}, k by filled symbol (Fig.8). The wave number is calculated by the formula $k = \sqrt{k_1^2 + k_2^2}$, and for the given case (Fig.7) takes a value $k = 4.4 \pm 0.4$, here $k_{1,2} = 2\pi h / \lambda_{1,2}$ are the wave numbers of the structures in mutually perpendicular directions. At high ω_{rot} the convective cells distribution has a hexagonal order and the wavenumber is calculated according the formula $k = 4\pi h / \sqrt{3}\lambda$, where λ characterizes the distance between the centers of neighbor cells. The experiments carried out in a layer of water with a thickness $h = 0.51$, 1.02, 1.51 cm, demonstrate the agreement of the wave numbers in the threshold (empty symbols in Fig.8). The theoretical dependence of the wave number on the dimensionless velocity of rotation in the area of high rotation velocities has the form $k = 1.51 \cdot \omega_{\text{rot}}^{1/3}$ (Boubnov and Golitsyn 2012). As it can be seen from the graph, the results of the experiments performed with the layers of different thicknesses and with different liquids are in good agreement with the theoretical curve represented by a solid line.

Good agreement between the experimental results and the theoretical predictions in the classical problem attests the high quality of the developed setup and the high accuracy of both the temperature measurement technique and the convective flow visualization technique.

Experimental results

Thermal vibrational convection without rotation $(\omega_{\text{rot}} = 0,\ Ra < 0)$

Begin the study of vibrational thermal convection generated by a rotating force field in a cavity that performs independent rotation with the limiting case of no rotation. The researches of the problem in this statement was started in (Kozlov et al 2021). The visualization technique with using thermochromic film described above makes it possible to display weak changes in liquid temperature near the lower "cold" boundary of the cavity. The light areas correspond to an increased temperature near the lower boundary, which is associated with the descent of hot "tongues" from the hot upper boundary of the layer. Fig.9 shows that the convective flows have the form of two-dimensional rolls with a wavelength λ_1, close to twice the layer thickness. The rolls are divided along the length into segments with a wavelength $\lambda_2 < \lambda_1$, where λ_2 is the distance between the centers of adjacent segments. Note that it is not possible to visualize this small-scale periodicity by another method, for example, using a calliroscope. In Fig.10*a* there is a fragment of the central part of the cavity, taken from the photo in Fig.9. In this fragment the characteristic wavelengths λ_1 and λ_2 are shown. As it can be seen from Fig.10*b*, in the supercritical area with an increase in the frequency of vibrations, the wavelength λ_1 and λ_2 do not change within the confidence interval.

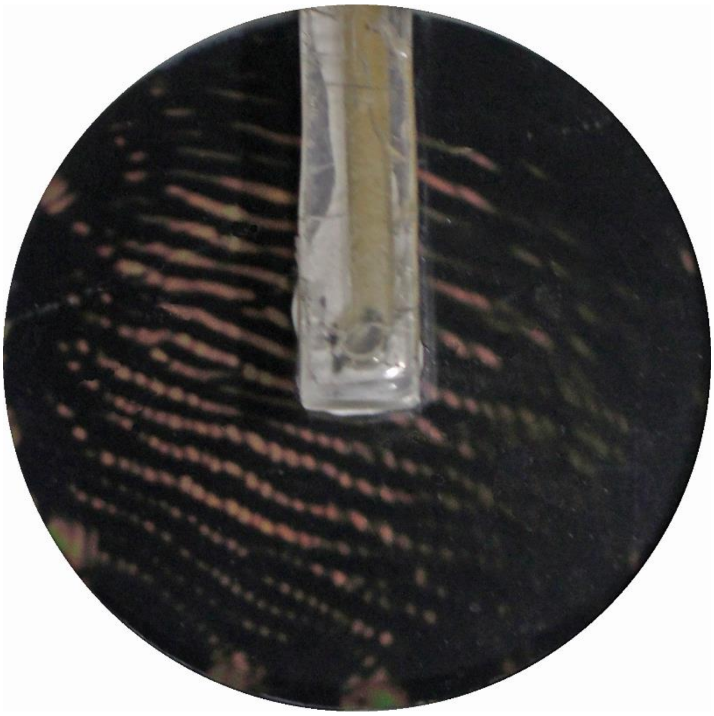
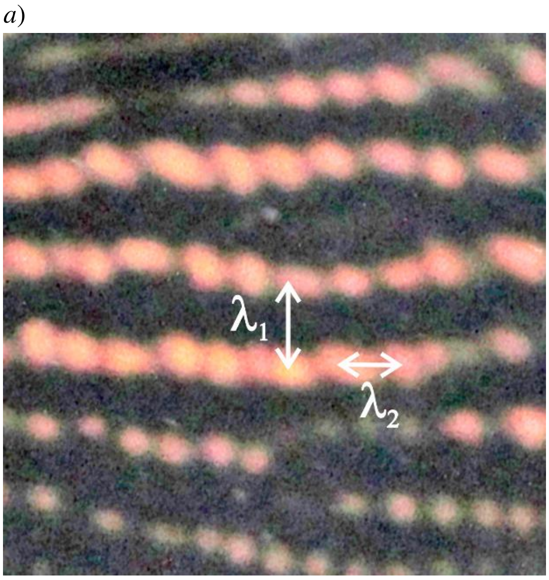


Fig.9 Photograph of vibroconvective structures visualized with thermochromic film in a layer of thickness $h = 0.32$ cm, at $\Theta = 24.5$ °C, $b = 4.1$ cm, $f_{vib} = 7.2$ Hz. $\left(Ra = -1.06 \cdot 10^5, R_v = 2.05 \cdot 10^5\right)$

a)



b)

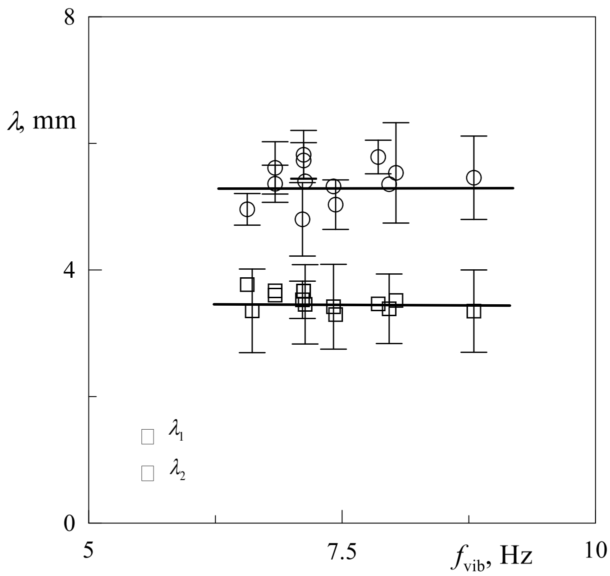


Fig.10 *a*) Fragment of the structures. *b*) Wavelengths depending on the vibration frequency, $h = 0.32$ cm, at $\Theta = 24.5$ °C, $b = 4.1$ cm

The dimensionless wave numbers given for the rolls and the periodic structures (Fig.11), are calculated as $k_{1,2} = 2\pi h / \lambda_{1,2}$. The dimensionless wave number of convective rolls $k_1 \approx 3.5$ (which corresponds to the diameter of an individual roll close to the layer thickness) does not change with increasing supercriticality. The total wave number of the convective structures k , calculated as $k = \sqrt{k_1^2 + k_2^2}$, has an average value $k = 6.5 \pm 0.5$, which is in a satisfactory agreement with the theoretically predicted threshold value for the limiting case of high dimensionless cavity vibration frequencies (Ivanova and Kozlov 2003) at the value of $Ra = -1.3 \cdot 10^5$ corresponding to the experiment. It should be noted that the linear analysis of stability provides information only on the magnitude of the wave number, while in the form of the spatial cells degeneracy is observed. An unusual mode of the instability discovered in experiments (Kozlov et al. 2021) is called "beads". The convective cellular structures excited in the threshold in the form of the rolls (the size of which is consistent with the layer thickness) are divided along their length into short segments.

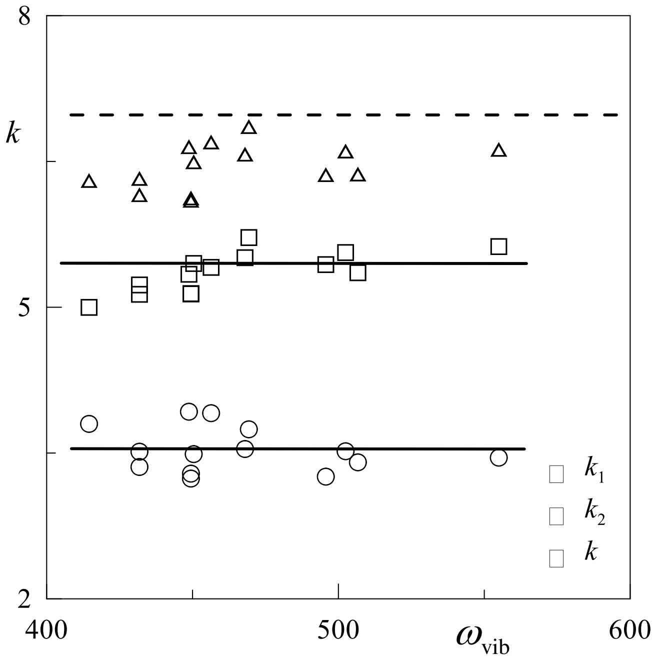


Fig.11 Wave numbers depending on the dimensionless frequency of vibration. The dashed line corresponds to the theoretical value of the total wavenumber of the most dangerous perturbation at $Ra = -1.3 \cdot 10^5$

A minimally invasive thermochromic technique made it possible to determine the fine structure of the periodic convective cells and to abandon the visualization technique using light-reflecting particles, which, as experiments shows, in the case of vibration exposure, can change the structure of the convective cells.

Effect of rotation on vibrational convection in stably stratifies liquid layer

The procedure for conducting the experiment and determining the threshold is similar to that described in the previous section. At a given vibration amplitude, the temperature measurements (heat flux and temperature difference at the layer boundaries) and the observations over the temperature distribution at the bottom of the cavity (thermochromic technique) are curried out with a stepwise increase (decrease) in the frequency of vibrations. The difference is that the layer simultaneously rotates with a given frequency. In this case, in the structure of the averaged convection excited by the circular translational vibrations (a rotating force field) the Coriolis force plays an important role.

Consider the excitation of vibrational convection in a rotating layer heated from above. For a given temperature difference and vibration amplitude in the layer of alcohol $h = 0.32$ cm, at low vibration frequencies, the temperature difference between the layer boundaries does not change, the liquid is in a quasi-equilibrium state. In this case, the heat flow, which is characterized by a temperature drop ΔT across the thermal resistance, remains unchanged

(Fig.12). Upon reaching a certain critical value of the vibration frequency, a threshold increase in the temperature drop ΔT across the thermal resistance is observed (increase in the heat flux through the layer, Fig.12 lower curves), which is accompanied by a temperature drop at the layer boundary Θ (Fig.12 upper curves). The synchronous change in ΔT and Θ is determined by the experimental procedure, while the value of ΔT increase, does not fully match with the decrease in the value of Θ. This is explained by the fact that the total temperature difference in the experiment $T_1 - T_2$, consists of several terms $T_1 - T_2 = \Theta + \Delta T + \Delta T_{gl}$. Here ΔT_{gl} is the temperature drop on the lower glass of the hot (upper) heat exchanger.

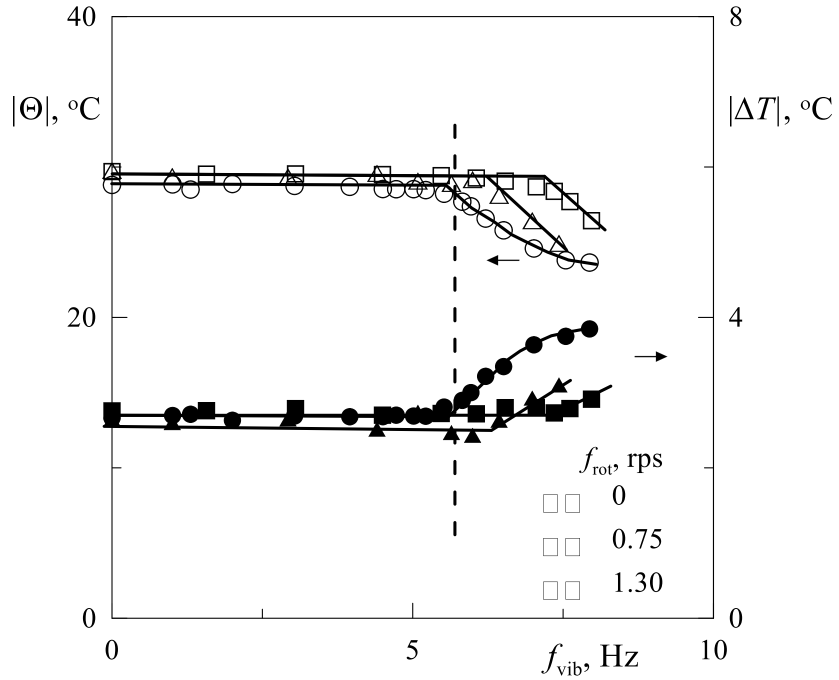


Fig.12 Changing of the temperature difference between the layer boundaries and the temperature difference on the heat flow sensor with the vibration frequency. The vibration amplitude $b = 4.1$ cm

With an increase in the layer rotation velocity, the excitation threshold of the convection at a given amplitude and temperature difference of the layer boundaries occurs at a higher vibration frequency f_{vib}. The threshold curves, presented above, correspond to the case of coincidence of the direction of rotation and circular vibrations of the cavity. Note that in the considered case, when the vibration frequency significantly exceeds the rotation frequency, $f_{\text{vib}} >> f_{\text{rot}}$, a change in the direction of the cavity rotation to one opposite of circular vibrations does not affect the excitation threshold of vibrational convection.

Fig.13. shows the structures observed in the supercritical region in a rotating layer at a relatively low rotation velocity $f_{\text{rot}} < 1$ rps. A comparison with the case of no layer rotation (Fig.13*a*) shows that the arrangement of the cells has a similar character. At the same time, the periodic structures against the background of the rolls become more distinguishable, while separate cells acquire individuality, however, their mutual arrangement and the existence of different spatial periods (wavelengths) in perpendicular directions is preserved. With an increase in rotation velocity up to $f_{\text{rot}} = 1.3$ rps the influence of the centrifugal mechanism increases, the structure of vibrational convection in the layer becomes more complicated: simultaneously with the transformation of the convective cells, an increase in the width of the dark area near the side boundary of the cavity is observed. The increase in the dark area is explained by a decrease in the temperature near the side boundary under the action of convective flows caused by the centrifugal force of inertia. The liquid temperature near the side boundary becomes outside the working range of the thermochromic film.

In the photographs, the white rectangles mark the areas in which the wavelengths of the convective structures were measured. The wavelengths depending on the vibration frequency at different rotation velocities are represented by different symbols in Fig.14. It can be seen that with a change in the vibration frequency of the cavity, the wavelengths do not change. The wavelength λ_1, characterizing the distance between the parallel rolls, practically does not change (Fig.14) with increasing the rotation velocity, and the wavelength consistent with the case of no rotation (Fig.10). Thus, the measurements show that the rotation in the investigated range of parameters has practically no effect on the geometric dimensions of the convective cells. It should be noted that in Fig.13*a*, obtained in the absence of rotation, in some areas only parallel rolls without visible division into "beads" are observed. This can be explained by the limited temperature resolution of the thermochromic film, when the periodic temperature change near the surface of the cold heat exchanger, caused by the division of the rolls into "beads", is beyond the film sensitivity. At rotation, this phenomenon is not observed; the entire field of the working layer is relatively uniformly filled with solitary cells. (Fig.13, *b,c,d*). This fact indicates that the rotation individualizes the cells, although their sizes remain practically unchanged.

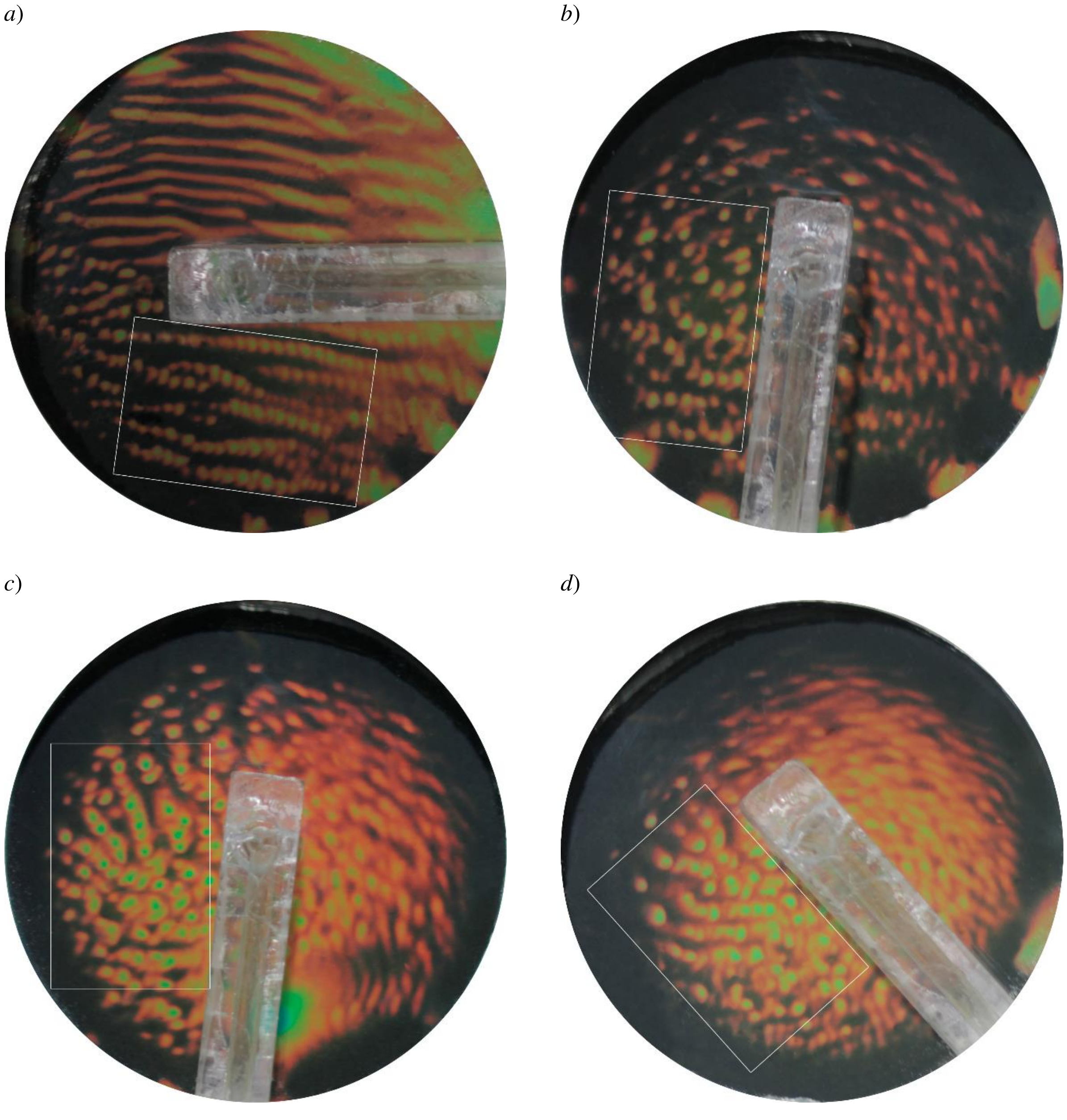


Fig.13 Photos of the convective structures in the supercritical area at $b = 4.1$ cm, close vibration frequencies and different rotation velocities: *a*) $f_{\text{rot}} = 0,\ f_{\text{vib}} = 7.05\,\text{Hz}$, $Ra = -1.08\cdot 10^5, R_v = 1.96\cdot 10^5$; *b*) $f_{\text{rot}} = 0.25\,\text{rps},\ f_{\text{vib}} = 7.12\,\text{Hz}$, $Ra = -1.12\cdot 10^5, R_v = 2.05\cdot 10^5$; *c*) $f_{\text{rot}} = 0.50\,\text{rps},\ f_{\text{vib}} = 7.11\,\text{Hz}$, $Ra = -1.14\cdot 10^5, R_v = 2.18\cdot 10^5$; *d*) $f_{\text{rot}} = 0.68\,\text{rps},\ f_{\text{vib}} = 7.35\,\text{Hz}$, $Ra = -1.17\cdot 10^5, R_v = 2.59\cdot 10^5$

In Fig.15 the values of the wave numbers for the corresponding wavelengths (see Fig.14) are given. The wave numbers are calculated as in the absence of rotation. The total wavenumbers are presented by the solid symbols.

As follows from the experiments, the convective structures and the wave numbers practically do not change with the rotation frequency in the studied interval of f_{rot} and do not change in the range of dimensionless frequency of vibration $\omega_{\text{vib}} = 400 - 520$. Note that the direction of the cavity rotation with respect to the direction of the inertial force field rotation in the considered case, when $f_{\text{vib}} >> f_{\text{rot}}$, also does not affect the structure of the convective cells (see Fig.15, points for $f_{\text{rot}} = \pm 0.25$ rps).

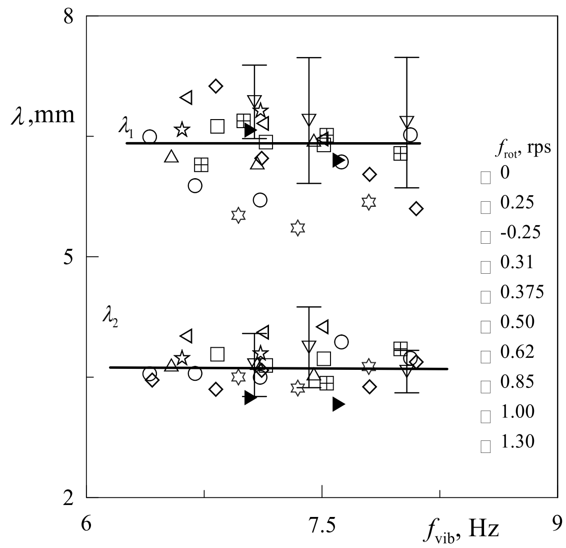


Fig.14 Wavelengths depending on the vibration frequency at $Ra = -1.3 \cdot 10^5$

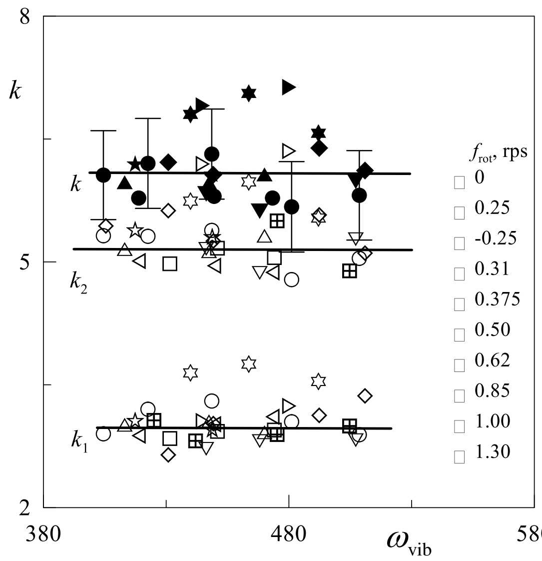


Fig.15 Wave numbers of the convective structures in the supercritical region as a function of the dimensionless vibration frequency at different cavity rotation rates. $Ra = -1.3 \cdot 10^5$

Analysis

In the problem of the excitation of averaged thermal convection in a uniformly rotating horizontal plane layer, two mechanisms simultaneously participate: gravitational and vibrational ones, determined by the gravitational Rayleigh number $Ra = g\beta\Theta h^3 / \nu\chi$ and the vibration parameter $R_{\text{v}} = (b\Omega_{\text{vib}}\beta\Theta h)^2 / 2\nu\chi$.

The heat transfer in the layer is considered on the plane R_{v}, Nu (Fig.16). The heat-conducting regime in the absence of convective flows corresponds to the value $Nu = 1$. The threshold excitation of the convection is accompanied by a sharp increase in the heat transfer. With an increase in the layer rotation velocity, the vibrational convection excitation threshold shifts to the area of large values of the parameter R_{v}. The experiments are carried out at close values of the Rayleigh number.

The thresholds found according to the heat transfer crisis are shown on the plane of dimensionless parameters $R_{\text{v}}, \omega_{\text{rot}}$ (Fig.17). The investigated thresholds are obtained for two different values of Ra, (the information on the value of the gravitational Rayleigh number is given in Fig.17*c*) and are shown by two types of empty symbols. The filled symbols correspond to the excitation thresholds of vibrational convection in the absence of rotation. With an increase in the dimensionless velocity of rotation, the threshold value of R_{v} increases.

The additional information in Fig.17*b* is the values of the centrifugal number Ra_{c}, which increases monotonically with an increase in the dimensionless rotation velocity. Note that in the interval $\omega_{\text{rot}} = 0 - 60$, at $Ra_c < 3 \cdot 10^4$, the centrifugal convection does not affect the structure of the vibroconvective flows in the layer. With a further increase in Ra_c (with an increase in ω_{rot}) the area in which the cells are observed shrinks along the radius. The rapid rotation results in a flow induced by a centrifugal force, which forms a dark (cold) region near the lateral cylindrical boundary of the cavity (Fig. 13).

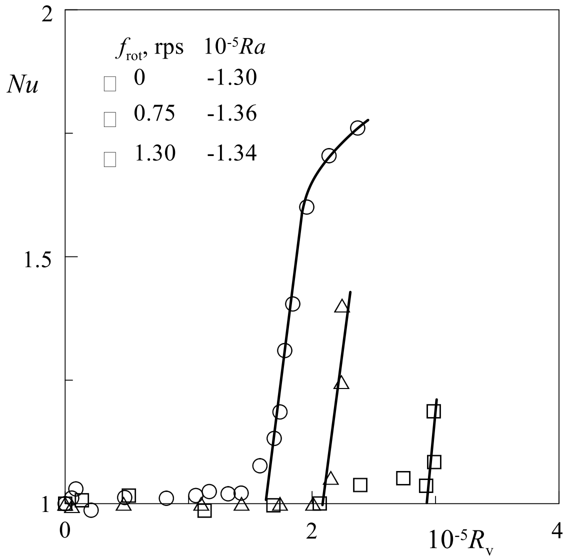


Fig.16 Heat transfer depending on the vibration parameter R_v.

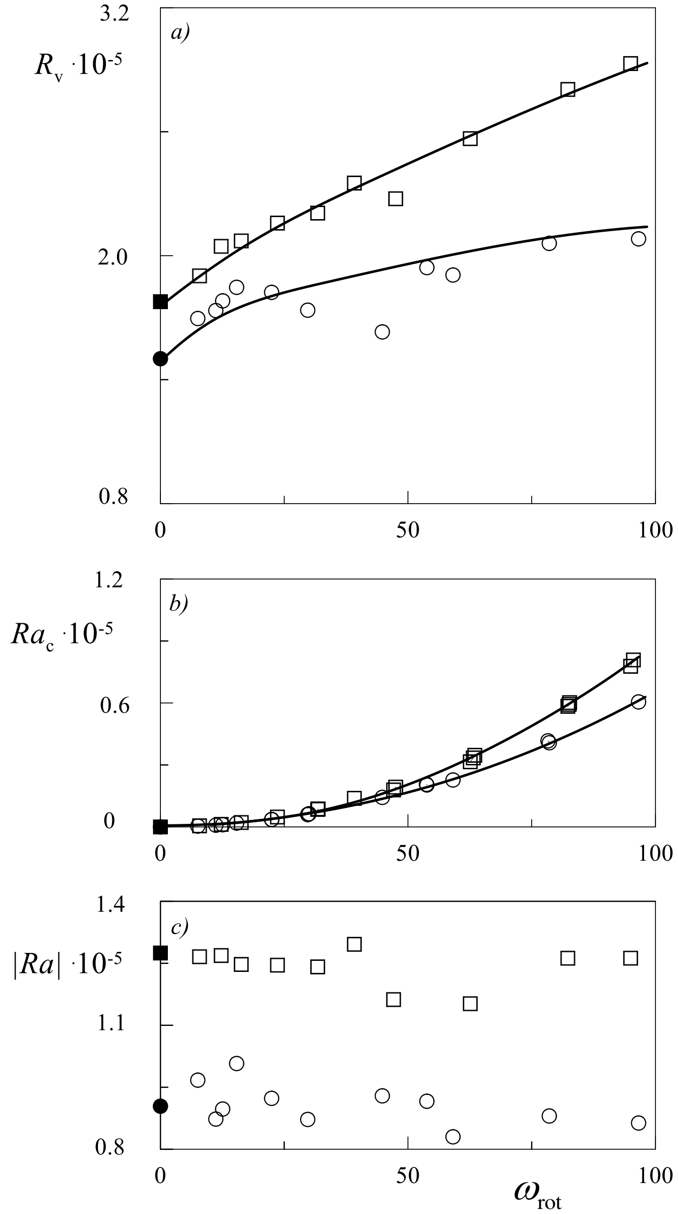


Fig.17 The values of the parameters R_v, Ra_c, Ra in the excitation threshold of thermovibrational convection depending on the dimensionless velocity of rotation

The insignificant change of Θ in experiments causes the change in the values of Ra from one experiment to another. In Fig.17*c* for each value of ω_{vib} the corresponding values of Ra are given. The efforts are made to ensure that the deviation of Ra from some average value in each experimental series is insignificant.

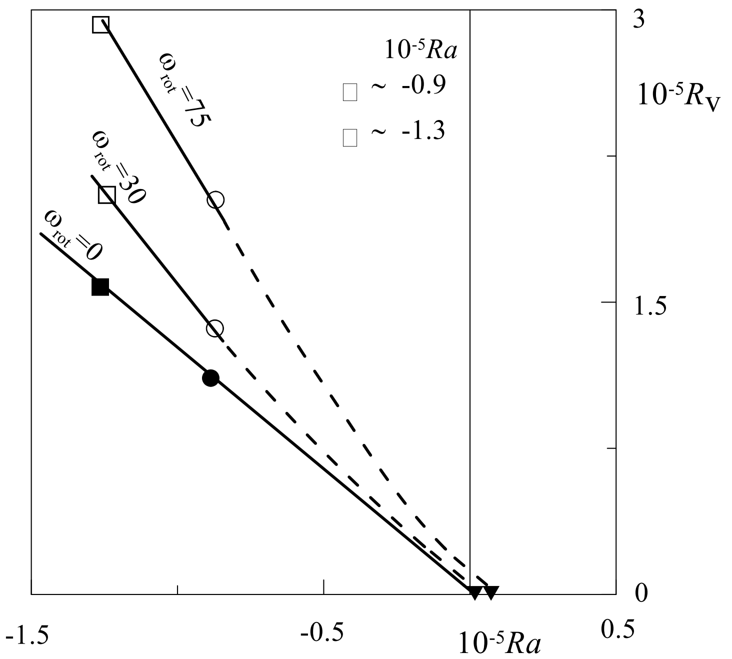


Fig.18 Excitation thresholds of vibrational convection on the plane Ra, R_{v}

Let us compare the thresholds curves obtained at rotation with the thresholds in the absence of rotation on the plane of control parameters Ra, R_{v}. In Fig.18 the solid line shows the theoretical threshold curve for the stability of quasi-equilibrium (Ivanova and Kozlov 2003) in the absence of rotation, $\omega_{\text{rot}}=0$. In the area of moderate values of the Rayleigh number $|Ra|<10^4$ this threshold is described by the expression $R_{\text{v}}=1.247\cdot(1708-Ra)$ (Gershuni and Lyubimov 1998). The boundary passes through two reference points; in each of them one of the convection mechanisms is absent. In the case of only the vibrational mechanism of convection, when $Ra=0$, the threshold value of the vibration parameter is equal to $R_{\text{v}}=2129$. In the absence of vibrations $(R_{\text{v}}=0)$, the theoretical limit rests on the classical threshold value of the Rayleigh number $Ra=1708$. As it has been mentioned, the experimental studies of the excitation threshold of vibrational thermal convection in the absence of rotation (Kozlov et al. 2021) in the area of negative values of Ra agrees with this theoretical curve.

On this plane the threshold points are presented for the values of the dimensionless velocity of rotation, $\omega_{\text{rot}}=30$ and $\omega_{\text{rot}}=75$. As it can be seen, with an increase in the dimensionless velocity of rotation at the given values of Ra ($Ra\approx-0.9\cdot10^5$ and $Ra\approx-1.3\cdot10^5$) the critical values of the vibration parameter R_{v} increase. This happens similarly to the well-known phenomenon of increasing the stability of gravitational convection with increasing the rotation velocity. At the axis Ra ($R_{\text{v}}=0$) there are thresholds for $\omega_{\text{rot}}=30$ ($Ra^*=3.34\cdot10^3$) and $\omega_{\text{rot}}=75$ ($Ra^*=5.97\cdot10^3$) which are consistent with the experimental results (Fig.6). In the figure the dashed lines show the hypothetical threshold curves for these values of the dimensionless velocity of rotation, drawn by analogy with the curve for $\omega_{\text{rot}}=0$. Note that this assumption refers to the case of relatively high vibration frequencies, $\omega_{\text{vib}}/\omega_{\text{rot}}>>1$, when there is no influence of the Coriolis force on the oscillating motion of the fluid (Kozlov 2004).

The use of a photochromic flow visualization technique, which does not perturb the liquid, make it possible to detect the periodicity along the two-dimensional rolls. In this case, the wavenumber was defined as $k=\sqrt{k_1^2+k_2^2}$. It should be noted that there is a qualitative difference between the dependences of the wave number on the rotation frequency: in the case of gravitational convection, the wave number increases (Fig.8), while in the case of thermovibrational convection at the large negative values of Ra the wave number practically does not change with the dimensionless frequency of rotation (Fig. 19), and moreover, with the rotation it has a lower value than in the absence of rotation. In part, this can be explained by the fact that under conditions of a strong stabilizing effect of gravity, the dimensionless wave number is very large, $k \sim 7$, already in the absence of rotation.

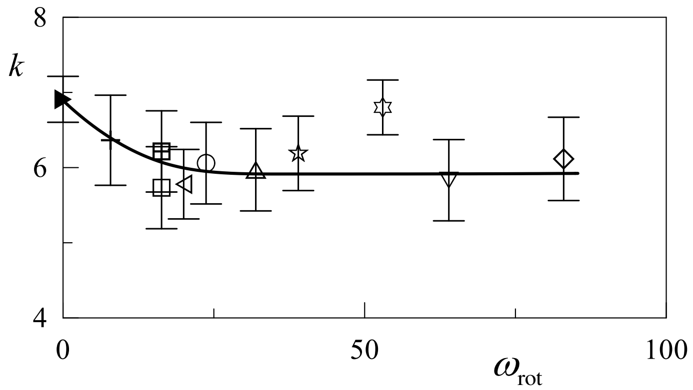


Fig.19 Dimensionless wavenumber vs the dimensionless frequency of rotation. The designations correspond to those used in Fig.15, the confidence intervals characterize the spread when the vibration frequency changes. $Ra = -1.3 \cdot 10^5$

As it has been shown in Fig.17, with an increase in the dimensionless rotation velocity, the thresholds shift to the area of larger values of the parameter R_v. Thus, the rotation raises the excitation threshold of both gravitational (Fig. 7), and thermovibrational convection.

To compare the influence of rotation on various mechanisms of thermal convection, gravitational and vibrational, it is convenient to present the threshold values of the corresponding control parameters, depending on the dimensionless velocity of rotation (Fig.20). At this, the control parameters are normalized to the threshold values in the absence of rotation. It is known that rotation has a stabilizing effect on the threshold of gravitational convection. The threshold value of the Rayleigh number in the limit of high rotation velocity ω increases according to the law $Ra = 18.8 \cdot \omega_{\text{rot}}^{4/3}$ (Boubnov and Golitsyn 2012). A solid line in Fig. 20 represents the threshold value of the ratio Ra/Ra^* versus the dimensionless velocity of rotation, where Ra^* is the critical value in the absence of rotation.

For the vibrational convection, an analogous threshold ratio R_v/R_v^* is shown by the points *2-4*; here R_v^* – the threshold of vibrational convection excitation in the absence of rotation, $\omega_{\text{rot}} = 0$, taking into account the value of the gravitational Rayleigh number (Fig.18). The empty points *2* and *3* correspond to different values of Ra (see Fig.17*c*), when the direction of the cavity rotation in the laboratory reference frame coincides with the direction of the inertial force field rotation. The filled points correspond to the case of the reverse direction of rotation with respect to the direction of circular vibrations of the cavity. As it can be seen, up to the experimental errors, the vibrational convection excitation thresholds for different directions of the layer rotation are consistent with each other.

In order to generalize the studies of the rotation influence on the thermal vibrational convection, it is interesting to present the excitation threshold of the averaged "vibrational" convection in a vertical layer rotating around a horizontal axis (Ivanova et al. 2003) on the plane of these parameters (points *1* in Fig.20). In this case, there is no static force field in the cavity reference frame, $Ra = 0$, and the averaged convection, which is determined by the same “vibrational” mechanism, is excited not by the cavity vibrations, but by the “tidal” oscillations of a non-isothermal fluid caused by the gravity field in a rotating reference frame. As it was shown in (Kozlov 2004), the problem in this statement differs from the considered classical vibrational convection only in that the cavity rotation velocity coincides with the oscillation frequency, $\omega_{\text{rot}} / \omega_{\text{osc}} = 1$, in this case, the Coriolis force affects the oscillations of the liquid, and hence the mechanism of vibrational thermal convection itself. From Fig.20 it can be seen that in this case the increase in the excitation threshold of the averaged convection with the rotation velocity in the area $\omega_{\rm rot} > 100$ happens according to law $R_{\rm v} / R_{\rm v}^{*} \sim \omega_{\rm rot}^{4/3}$, just as a rotation acts on gravitational convection in a layer in the classical case considered in (Chandrasekhar 1961). The theoretical analysis of the linear threshold of the thermal vibrational convection excitation (at $Ra = 0$) in a rotating plane layer in the case $\omega_{\rm rot} / \omega_{\rm vib} << 1$ has shown the relation $R_{\rm v} = 18 \cdot \omega_{\rm rot}^{4/3}$, (Kozlov 2004), represented by a dash-dotted line in the figure. The vibration parameter here is normalized to the threshold value $R_{\rm v}^{*} = 2129$ in the absence of rotation at $Ra = 0$. On the plane of the chosen parameters, the threshold curve of the thermal vibrational convection excitation at $\omega_{\rm rot} / \omega_{\rm vib} << 1$ is located in close proximity to the gravitational one.

Fig.20 gives a general idea of the influence of rotation on the excitation threshold of convection generated in a plane layer of liquid by the oscillating force field. The rotation of the cavity always leads to an increase in the excitation threshold of the vibroconvective instability: at the high frequency vibrations (the dash-dot curve) and when the oscillation frequency of the force field coincides with the rotation frequency (points *1*). Under conditions of a strong stabilizing effect of an external static field (points *2-4*), a number of features are observed: the critical value of the vibrational parameter increases with the rotation velocity, however, the wave number of the convective cells in the studied area $\omega_{\rm rot} < 100$ changes weakly.

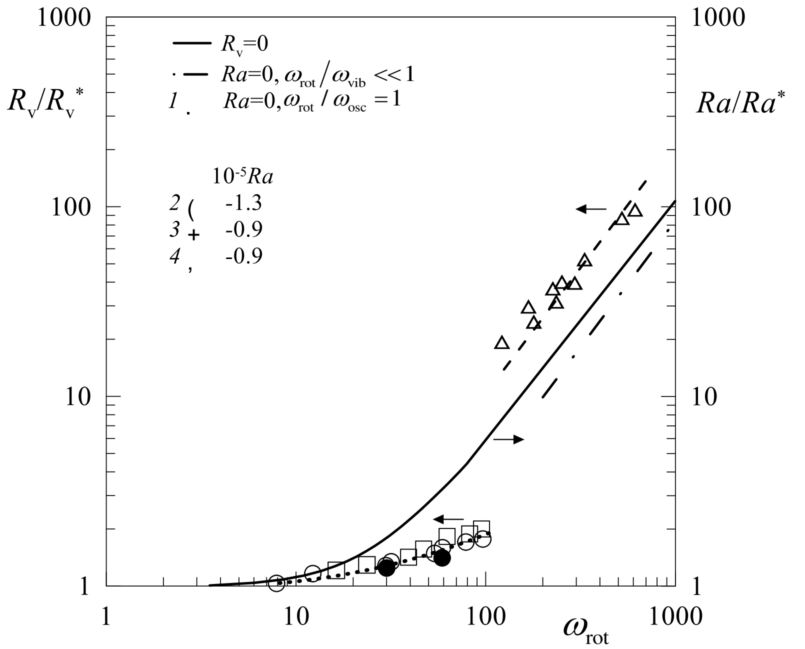


Fig. 20 Threshold values of the vibrational parameter and the gravitational Rayleigh number, normalized to threshold values in the absence of rotation, depending on the dimensionless velocity of rotation

The performed comparison testifies to the similarity of the influence of rotation on convective mechanisms of different nature, gravitational and thermovibrational, the change in the threshold values of the vibrational parameter with the dimensionless rotation velocity is similar to the change of the gravitational Rayleigh number.

Conclusion

An experimental study and a comparative analysis of the effect of rotation on the excitation threshold of thermal convection in a plane layer under the simultaneous action of two independent mechanisms (the classical Rayleigh mechanism and the thermovibrational one) were carried out for the first time. The analysis shows that in a rotating layer, under the action of only one of the convective mechanisms, at $R_{\rm v} = 0$ or $Ra = 0$, the dependences of the stability threshold on the rotation velocity in the area $\omega_{\rm rot} >> 1$ are similar, $Ra / Ra^{*} \sim \omega_{\rm rot}^{4/3}$ or $R_{\rm v} / R_{\rm v}^{*} \sim \omega_{\rm rot}^{4/3}$. It was found that in the region of a strong stabilizing action of the gravitational mechanism (at large negative values Ra) the rotation significantly increases the threshold of excitation of thermovibrational convection, at the same time in the investigated area, $\omega_{\rm rot} < 100$, the wavenumber of the convective cells is practically independent on the presence of rotation. It was expected that this feature could be explained by the anomalously high value of the wave number of convective structures even without rotation, which is specific for thermovibrational convection at large negative values Ra .

The obtained results and the analysis shed light on the features of thermal convection in rotating cavities under the simultaneous action of two mechanisms, gravitational and thermovibrational, and can be useful in the development of vibrational methods for controlling over heat and mass transfer, in particular, under microgravity conditions.

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Clinical trials: no any clinical trials were performed.

Authors' contributions: All authors contributed to the study conception and design. Victor Kozlov supervised the study. Kirill Rysin performed experiments and prepared the figures. Aleksei Vjatkin elaborated the experimental setup and technique. The first draft of the manuscript was written by Victor Kozlov and Kirill Rysin and all authors commented on previous draft versions of the manuscript. All authors read and approved the final manuscript.

Ethics approval: The work presented in this paper complies with all ethical standards.

Consent to participate: All authors agreed to participate in the research which has led to this manuscript.

Consent for publication: All authors agree to the publication of this manuscript.

References

Boubnov B.M., Golitsyn G.S.: Convection in Rotating Fluids. Fluid Mechanics and Its Applications (V 29). Springer Science & Business Media (2012)

Chandrasekhar S.: Hydrodynamic and Hydromagnetic Stability. Clarendon Press, Oxford University Press (1961)

Gershuni G.Z., Lyubimov D. V.: Thermal vibrational convection. N.Y., Wiley (1998)

Gershuni G.Z., Zhukhovitskii E.M.: Convective Stability of Incompressible Fluids (in Russian), Nauka, Moscow (1972)

Gershuni, G.Z., Zhukhovitsky, E.M.: Free thermal convection in a vibrational field under conditions of weightlessness. Sov. Phys. Dokl. **24**(9), 894–896 (1979)

Ivanova, A.A., Kozlov, V.G., Rylova, V.V.: Thermal convection in a plane layer rotating about a horizontal axis. Fluid Dyn. **38**(1), 9-17 (2003)

Ivanova, A.A., Kozlov, V.G.: Thermal vibrational convection in a cavity under nontranslational oscillations. Fluid Dyn. **38**(3), 372–386 (2003)

Kozlov, V.G.: Vibrational convection in a cavity undergoing spatial pendulum oscillations. Heat Transfer – Soviet Research **23**, 999–1008 (1991)

Kozlov, V.G.: Thermal vibrational convection in rotating cavities. Fluid Dyn. **39**(1), 3–11 (2004)

Kozlov, V., Vjatkin, A., Rysin, K., Sabirov, R.: Inertial waves and vibrational thermal convection. Proc. 66th Intern. Astronautical Congress (IAC2015). Israel, Jerusalem 697-704 (2015)

Kozlov, V. G., Rysin K. Y., Vjatkin A. A.: Vibroconvective stability of liquid in horizontal plane layer subject to circular translational vibrations. Microgravity Sci. Technol. **31**, 759–765 (2019)

Kozlov, V., Rysin, K., Vjatkin, A.: Vibroconvective patterns in a layer under translational vibrations of circular polarization. Fluids **6**, 108 (2021)

Lappa, M.: Thermal Convection: Patterns, Evolution and Stability. Wiley (2009)

Lappa, M.: Rotating Thermal Flows in Natural and Industrial Processes. Wiley (2012)

Mialdun, A.; Ryzhkov, I.I., Melnikov, D.E.; Shevtsova, V.: Experimental evidence of thermal vibrational convection in a nonuniformly heated fluid in a reduced gravity environment. Phys. Rev. Lett. **101**, 084501 (2008)

Pesch, W., Palaniappan, D., Tao, J., Busse, F.: Convection in heated fluid layers subjected to time-periodic horizontal accelerations. J. Fluid Mech. **596**, 313–332 2008

Rossby, H.T.: A study of Benard convection with and without rotation. J. Fluid Mech, **36**(2), 309–335 (1969)

Shevtsova, V., Ryzhkov, I., Melnikov, D., Gaponenko, Y., Mialdun, A.: Experimental and theoretical study of vibration-induced thermal convection in low gravity. J. Fluid Mech. **648**, 53-82. (2010)

Smorodin, B.L., Ishutov, S.M., Myznikova, B.I.: On the convection of a binary mixture in a horizontal layer under high-frequency vibrations. Microgravity Sci. Technol. **30**, 95–102 (2018)

Vorobev, A., Lyubimova, T.: Vibrational convection in a heterogeneous binary mixture. Part I. Time-averaged equations. J. Fluid Mech. **870**, 543–562 (2019)

Vjatkin, A. A., Ivanova, A. A., Kozlov, V. G., Rysin, K. Yu.: Effect of the tangential component of a force field on convection in a rotating plane layer. Izv. Atmos. Ocean. Phys. **53**, 187–194 (2017)

Zen’kovskaya, S.M., Simonenko, I.B.: Effect of high-frequency vibration on convection initiation. Fluid Dyn. **1**(5), 35–37 (1966)