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Thermal “Vibrational” Convection in Thick Rotating Horizontal Annulus

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Abstract **-** This paper presents the results of an experimental study of thermal convection in a thick rotating horizontal annulus. The boundaries of the annulus have different temperatures; the inner one is hotter. Thus, the centrifugal mechanism of thermal convection plays a stabilizing role. It is found that with a decrease in the rotation rate, a non-isothermal liquid loses its stability. Two-dimensional rolls, elongated along the axis of rotation, appear in a threshold manner. These rolls are steady in the frame of the rotating cavity and belong to the thermal “vibrational” convection – the averaged convection excited by an oscillating force field. In the case under consideration, the gravitational field is responsible for the excitation of the vibrational convection; it rotates in the cavity framework and excites oscillations of the non-isothermal fluid. This conclusion is supported by the good agreement between the threshold of steady convection excitation and the results of linear stability theory, as well as by the similarity with thermovibrational convection in a thin layer, which was previously studied experimentally and theoretically. In parallel with two-dimensional steady convective rolls, fluid oscillations result in the excitation of inertial waves. The latter excites steady toroidal vortices of relatively low intensity in the annulus. A new phenomenon that we find in thick annulus experiments is two-dimensional oscillatory convective patterns that appear below the threshold of steady thermovibrational convection excitation. It is found that in the cavity frame, these rolls oscillate with a frequency that is two times less than the rotation rate. Both convective regimes, steady and oscillatory, lead to a significant increase in heat transfer.

Keywords**:** thermal convection, rotation, annulus, heat transfer

1. Introduction

Thermal convection in rotating systems is an actual scientific and technological problem [1, 2]. The governing complicating factors in rotating systems are determined by centrifugal and Coriolis forces. One more specific mechanism of thermal convection is the “thermovibrational” one [3], that is caused by the oscillations of non-isothermal liquid. The vibration could excite the oscillating inertial force fields, that excites the oscillations of the non-isothermal liquids. In practice, the convective processes often occur under conditions when the force fields periodically change in magnitude and direction. In the rotating systems, the vibrational mechanism gets a number of very specific features [4] because the Coriolis force determines not only the steady flows but also the oscillatory ones – the engine of thermal vibrational convection.

Thus, the oscillating force fields could be an effective instrument for controlling heat and mass transfer. In the case of cavity rotation around a horizontal axis, the thermal vibrational convection forms a special class of problems. The gravitational force field rotates in the cavity reference frame and plays the role of an oscillating force; the non-isothermal liquid performs oscillations although there are no any vibrations. In such a statement, the equations obtained by the averaging method [4] describe the steady convection that corresponds to the thermovibrational one. The experimental and theoretical studies of steady convection in rotating around the horizontal axis cavities [5-7] prove the efficiency of this convection excitation mechanism and the correctness of the theoretical model.

Let us consider the thermal vibrational convection of a liquid layer formed by two horizontal coaxial cylindrical surfaces having different temperatures and rotating around the symmetry axis with the same angular velocity. This problem has been systematically studied in thin layers experimentally and theoreticall+y [6, 7]. The latter includes a linear stability analysis and a numerical study of stationary convection and heat transfer in the supercritical region of parameters. In the case of thin layers, the experimental and theoretical results are in good agreement in the area of high dimensionless rotation velocities.

The purpose of this article is an experimental study of the averaged convection in a rotating thick horizontal annulus with isothermal boundaries of different temperatures. In this case, the inner boundary has a higher temperature, i.e., centrifugal convection plays a stabilizing role. Studies have revealed a number of new features of the dynamics of a nonisothermal fluid in a rotating cavity: along with the threshold appearance of two-dimensional rolls of a thermovibrational nature, toroidal vortex flows excited by inertial waves appear in the annulus. A qualitatively new phenomenon is the threshold excitation of the convective equilibrium oscillatory instability, which under certain conditions occurs before the excitation threshold of thermovibrational convection.

2. Experimental setup and procedure

A detailed description of the experimental features is given in [8]. The coaxial gap with relative radius $R = d/D$, filled with fluid rotates contraclockwise around a horizontal axis with a rotation velocity Ω. The working fluids are water and water-glycerol solutions with a mass fraction $C = 25$ and 50 %. The gap is formed by an inner aluminum cylinder *1* and an outer plexiglass tube *2* which diameters are shown in Fig. 1. The cavity length is 210 mm. A change in the annulus thickness is carried out by changing the diameter of the aluminum cylinder; in a thin annulus the diameter of the inner boundary is 60 mm. The cylinder *1* presents a hot heat exchanger and is equipped with an electric heater made of a nichrome wire. The heater is located in the cavity made along the heat exchanger axis and occupies the entire length of the cylinder.

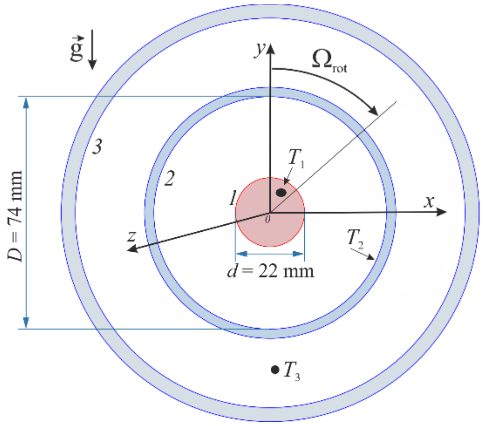

Fig. 1: Cuvette scheme.

The plexiglass tube presenting the outer boundary of the annulus and the inner heat exchanger are strictly coaxial, which is provided by the grooves in the flanges used to close the cavity ends. An outer cold heat exchanger is formed as a cavity between the plexiglass tube and another tube *3* of a greater diameter. This auxiliary cavity is connected to a jet thermostat which pumps water of preset temperature and cools the outer boundary of the working gap.

The heater in the inner heat exchanger is installed in compliance with the requirements of the electrical insulation and good thermal contact with the aluminum cylinder, which, along with a good thermal conductivity of aluminum, provides high uniformity of the inner boundary temperature T_1. This temperature is measured with thermo-resistors made of copper wire and located in the aluminum massive (Fig. 1). The temperature T_2 of the outer annulus boundary is also measured with the copper thermo-resistors. These sensors are glued with a thin adhesive film along the generatrix of the plexiglass tube from its inner side. The temperature T_3 of the coolant in the outer heat exchanger is set by a thermostat and kept constant during the experiment. The signals of thermosensors are processed by a devise Termodat and transmitted to a PC.

The annulus can rotate about the horizontal axis with the various velocity Ω_{rot} while the outer tube *3* (Fig. 1) stays immovable. At the beginning of the experiment, the temperature of the coolant is installed, the heater's electrical supply with a stabilized DC source is turned on, and the cavity is set to a relatively rapid rotation with a stepper motor which provides the high accuracy of the rotation velocity maintenance. After establishing a stationary convection mod, the rotation velocity is reduced with a step value of 0.05-0.20 rps, depending on the experimental task. The electrical current through the heater, the electrical supply of the device Termodat, and the transition of the thermosensors signals are implemented using a multi-channel electrical collector.

The structure of convective flows in thin cylindrical layers is studied using a thermochromic film glued to the surface of an aluminum heat exchanger. The film color depends on its temperature. The convection appearance is accompanied with the temperature inhomogeneity, which is visualized by the film color inhomogeneity. The observations are carried out from the side of the cylindrical wall of the cavity. In the thick layer, the convective flows are studied using PIV-method. In this purpose, plastic particles of 50 microns in size of almost neutral buoyancy are added to the liquid. The particles scatter light from a thin laser knife that cuts the layer in cross section. In this case the observations are curried out from the side of the transparent end of the cavity using a high-speed camera. The position of the observer corresponds to the

3. Experimental Result

Earlier in [6,7] the excitation threshold of thermal convection in a thin cylindrical layer of liquid rotating around the horizontal axis of symmetry was studied. It was shown that, regardless of the direction of heating in the layer, the excitation of "vibrational" thermal convection is possible, despite the absence of the cavity oscillations. The source of the nonisothermal fluid oscillations in this formulation of the problem was the gravitational field rotating in the cavity reference frame. In the further presentation of the results, we restrict ourselves to the case of heating the layer from the inside.

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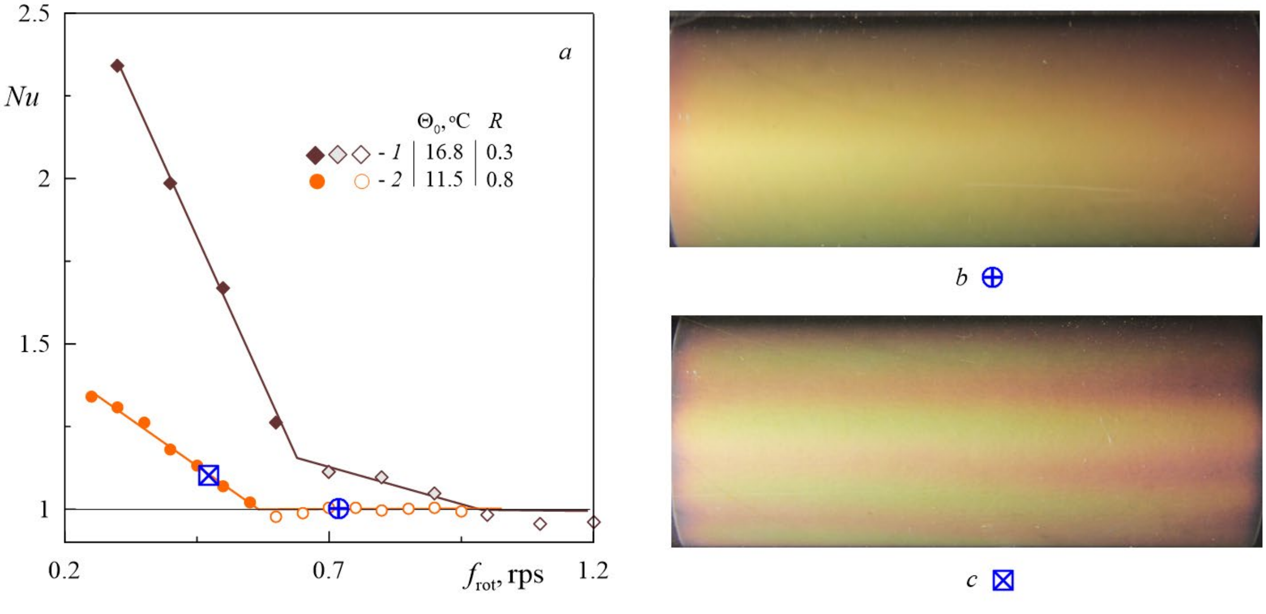

Fig. 2: Dependence of the Nusselt number on the cuvette rotation velocity (*a*); photos of the thermochromic film on the surface of the internal heat exchanger: heat-conductive (*b*) and convective (*c*) modes;
points *1*: $C = 50\%$, $R = 0.3$; points *2*: $C = 50\%$, $R = 0.8$.

At relatively fast rotation, the centrifugal force of inertia leads to a mechanical equilibrium of the liquid layer. On heat transfer curves (Fig. 2*a*) thermal conduction mode (the Nusselt number Nu equals 1) is marked with empty symbols. In the photo Fig. 2*b* the uniform color of the thermochromic film at the inner boundary of the layer indicates the absence of convection. The break in the curves indicates a heat transfer crisis associated with the convective flows appearance. In the thin layer the convection is excited in the form of a system of two-dimensional rolls elongated along the axis of rotation (Fig.

2*c*). It should be noted that the change in the heat transfer in the layers of different relative thicknesses is different. In the thick layer two heat transfer crises are observed. Vibrational convective structures in a thick layer correspond to a section of the curve with filled points *1*.

In thick layers, as it had been mentioned, the convective structures are studied using the PIV-method. A camera installed at the end of the cuvette makes it possible to obtain a successive series of frames and to follow the movement of light-scattering particles in the plane of a thin light knife that cuts the layer in cross section. The liquid is observed in the laboratory reference frame. To switch to the cavity reference frame, each photo is rotated around the axis in such a way that the layer boundaries remain motionless. Further, the frames are formed into consecutive pairs and the instantaneous fields of the fluid velocity are determined. In Fig. 3 the color shows the field of the average vorticity, while the arrows show the velocity of the fluid parts. A system of convective rolls extended along the axis of rotation is formed in the layer. The blue areas correspond to the cyclonic swirl of the roll (the direction coincides with the direction of the layer rotation), the red areas correspond to the anticyclonic one. An azimuthal inhomogeneity is observed in the intensity of vortex structures.

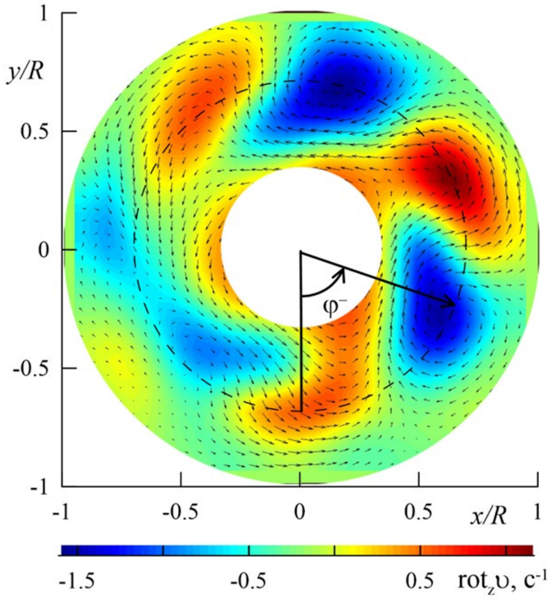

Fig. 3: Average vorticity field.

It is found that the convective structures in Fig. 3 rebuilt periodically over time. The oscillation period of the convective flows system is two periods of the cavity rotation. In the rearrangement process, the centers of the convective rolls are immobile in the reference frame of the cavity. There is no description of this mode of convection in rotating cavities in the literature.

4. Analysis

In [4, 6] It has been theoretically and experimentally shown that convection is described by a vibrational R_v and a centrifugal Ra Rayleigh numbers having the following forms:

$$Ra = \Omega^2 R \beta \Theta h^3 / \nu \chi \quad (1)$$

$$R_{\mathrm{v}} = (g \beta \Theta h)^2 / 2 \nu \chi \Omega^2 \quad (2)$$

The threshold curves corresponding to the heat transfer crises (brakes in Fig. 2*a*), are shown in Fig. 4. The left and right graphs differ in the range of control parameters. Points *1* and *2* corresponds to the results presented in Fig. 2*a.* Thermal conductive mode – area *I*. Threshold points *3* and *4* are obtained in experiments with thin and thick cylindrical layer respectively. The thick layers provide the large values of control parameters Ra и R_v.

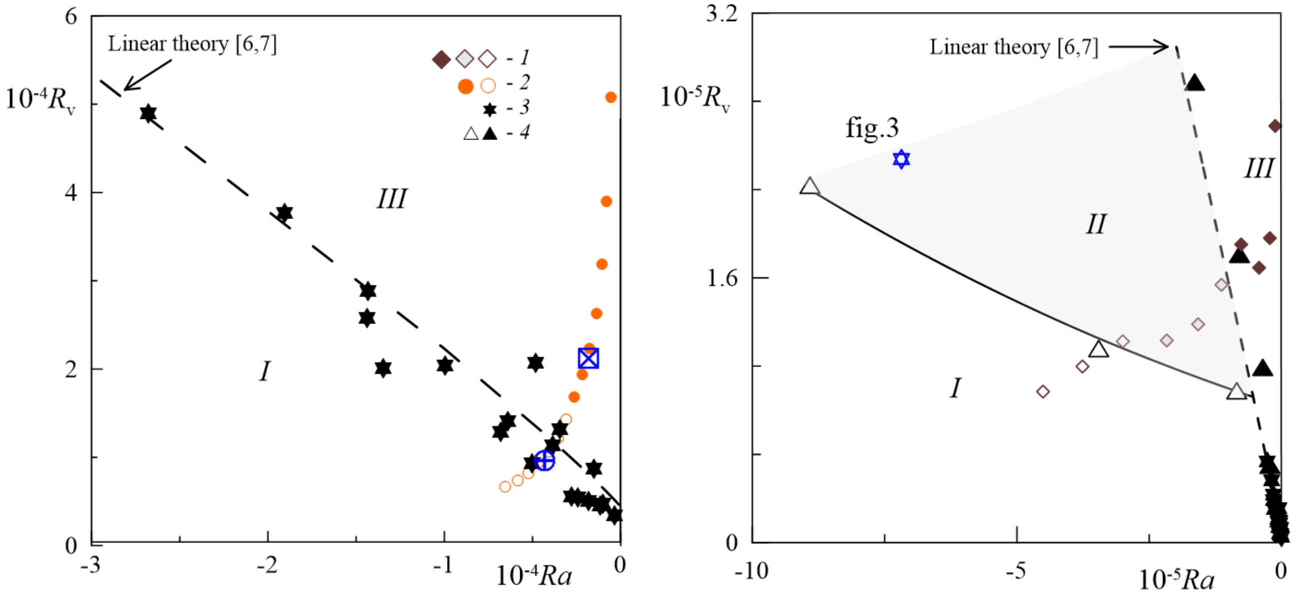

Fig. 4: Threshold curves on the plane of control parameters.

The structures of "vibrational" thermal convection exist in the area *III* on the plane of control parameters [6,7]. In the case of a thin layer, this convection mode occurs against the background of mechanical quasi-equilibrium of the liquid (points *3*). In the thick layers, up to the threshold of "vibrational" convection, an oscillatory convective regime arises. It should be noted that the threshold curves corresponding to vibrational thermal convection, obtained in cavities with different relative radii, agree satisfactorily with each other and with the results of the linear theory (dashed line). This indicates the dominant role of the thermal vibration mechanism of convection excitation in the specified range of parameters. The physical mechanism of convection generation in the area *II* remains to be seen.

5. Conclusion

The thermal convection in a rotating thick horizontal annulus with isothermal boundaries of different temperatures has been experimentally studied. The inner boundary has a higher temperature, at this, the centrifugal convection plays a stabilizing role, and the vibrational convective mechanism is responsible for the excitation of convective flows. The threshold of thermovibrational convection excitation is in good agreement with the predictions of linear stability theory. A number of new features of the oscillatory dynamics of a nonisothermal fluid in a rotating cavity are revealed: along with the threshold appearance of two-dimensional rolls of a thermovibrational nature, toroidal vortex flows appear. The latter flows are excited by inertial waves in the annular space and have relatively low intensity. A qualitatively new phenomenon – threshold excitation of oscillatory instability of convective equilibrium – was discovered in experiments with a thick ring. Two-dimensional oscillating convective patterns appear below the excitation threshold of stationary thermal vibrational convection. It is established that in the reference frame of the cavity, these rollers oscillate with a frequency that is two times less than the rotation speed. Both convective regimes, stationary and oscillatory, lead to a significant increase in heat transfer.

Acknowledgements

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