Convection of heat-generating fluid in a rotating cylinder subjected to transversal vibrations

Alexey A. Vjatkin Victor G. Kozlov Rustam R. Sabirov
vjatkin_aa@pspu.ru kozlov@pspu.ru sabirov@pspu.ru

Abstract

The paper is devoted to the experimental study of the effect of vibrations on the convection of heat-generating fluid in a rotating horizontal cylinder. The case of translational vibration perpendicular to the axis of rotation is considered. Experiments are carried out in cavities of different sizes with vibrations of varying intensity; heat transfer and the structure of emerging flows are studied.

For fast rotation in the absence of vibration under the action of centrifugal inertia force the axial temperature profile in the cylinder has a maximum on the cylinder's axis. In a centrifugal field this temperature distribution is stable – the liquid is in a state of mechanical equilibrium. Vibrations perpendicular to the axis of rotation are able to disturb the equilibrium state when the rotational and vibrational frequencies are similar. For this case the temperature in the center of the cavity decreases indicating the development of the flows transferring heat from the center. The value of the heat transfer is a nonmonotonic function of the frequency difference, so special attention is given to the study of the complicated heat transfer curve.

It is shown that a key role in the development of convection belongs to the centrifugal and vibrational mechanisms. Research results are summarized in the plane of the control parameters – vibrational and centrifugal Rayleigh numbers.

1 Formulation of the problem

The averaged convection of heat-generating fluid in a horizontal rotating cylinder from the point of view of "vibrational hydrodynamics" was studied in [1],[2]. In this paper the effects of vibrations on the mechanical quasi-equilibrium of heat-generating fluid are studied. Such equilibrium is reached at the cavity rapid rotation and caused by the stabilizing action of the centrifugal inertial force. The cylinder with isothermal outer boundary filled with heat-generating fluid rotates around a horizontal axis of symmetry. Vibrations are specified in the horizontal plane; their direction is perpendicular to the axis of rotation. Vibrational mechanism of thermal convection in the rotating cavities is described theoretically in [3].

2 Experimental tecnique and procedure

Experiments are carried out using the equipment (fig. 1), which is described in details in [2],[4]. The working cavity *1* is formed by a Plexiglas cylinder closed on both sides with caprolan flanges. On the inner sides of flanges round copper electrodes with an area equal to the cross-sectional area of the cylinder are fixed. Two cylinders with lengths $l = 159$ and 254 mm and diameters $d = 36$ and 44 mm respectively are used. Heat release in the cell is ensured by passing an alternating electric current through the liquid, temperature measurement is performed by integral RTDs. The temperature is controlled at the axis and at the inner wall of the cavity. The temperature outside the cylinder is kept constant by washing the cavity with the thermostated water. "Termodat" *2* – temperature measuring device – rotates together with the cylinder. Data from the measuring device is read through the electrical collector *3*. The rotation is provided by a stepper motor *4*.

A mechanical vibrator (fig. 2) is used for vibrating the above-described experimental setup. The desk *1* moves along two parallel horizontal rails *2*. To reduce the friction at this part of vibrator the linear bearings are used. The oscillations are given by a crank mechanism, consisting of a disc *3* with an eccentric axis, and a long connecting rod *4*. The rotation of the disk is produced by the servomotor ESTUN EMG-15APA22 with the servo amplifier PRONET-E-15A ensuring the maintenance of the rotational speed with an accuracy of at least 0.2%.

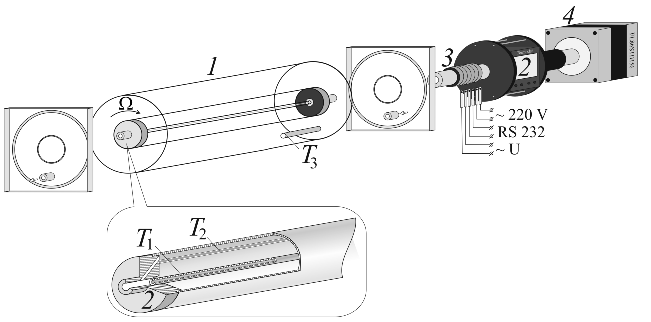

Figure 1: The cuvette scheme

As the working fluids water and an aqueous glycerol solution with a concentration of 50 % are used in the experiments. The frequency and the amplitude of vibration are changed in the range of $f_{vib} = \Omega_{vib}/2\pi$ = 1 - 10 Hz, b = 0.1 - 10 mm. The amplitude is measured using an optical cathetometer B-630 with the accuracy 0.1 mm.

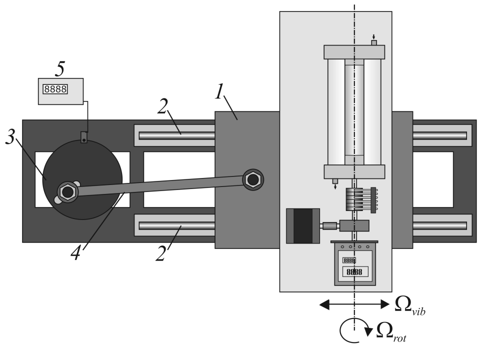

Figure 2: Research facility (top view)

Before starting the experiment the cuvette is provided in a relatively fast rotation (with velocity 2 - 4 rps), the electric current is passed through the fluid. The experiment starts after the state of stationary temperature distribution in the cell (not less than 60 minutes). Then the transverse vibrations with frequency higher than the speed of rotation are set. During the experiment the oscillation frequency is lowered stepwise. Measurements are taken at each step after the establishing of steady state of convection in the cell (15 minutes). At one amplitude of vibration the measurements are made at different values of the rotational speed $f_{rot} = \Omega_{rot}/2\pi$ = 2, 3 and 4 rps.

3 Experimental Results

Consider the results of experiments with the water in the cavity with radius $R = 22$ mm and length $L = 254$ mm. In the range of high speed the equilibrium may be upset by the weak averaged flow generated by inertial wave [2] that occurs on a background of hot liquid column oscillation near the ends of the cavity. With decreasing f_{rot} the intensity of averaged currents increases. This effect increases with increasing viscosity of the working solution.

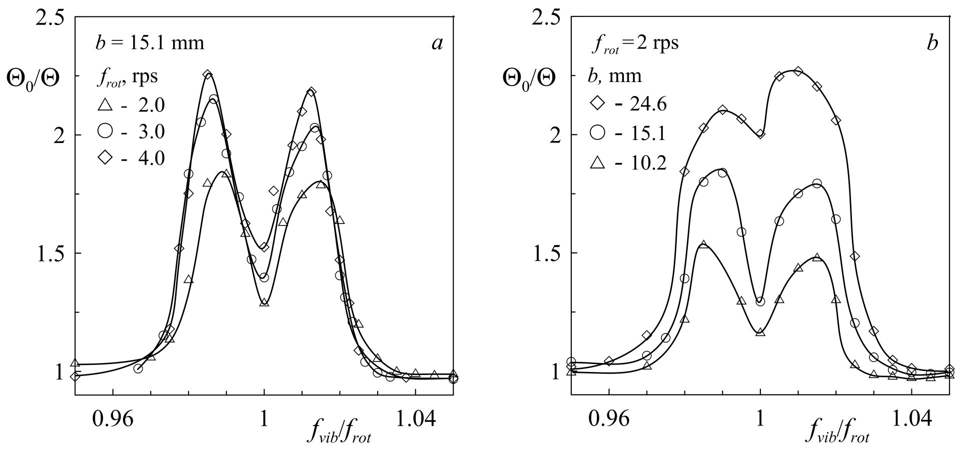

Figure 3: The dependence of the heat transfer on the dimensionless frequency vibrations at a constant amplitude (a) and frequency (b)

To study the effect of vibrations on the heat sink from the center of the cavity the characteristics of heat transfer, defined as Θ_0/Θ is selected. Here Θ - temperature of fluid on the axis relative to the cylindrical wall of the cavity measured in the experiment, Θ_0 - theoretical value calculated by the formula $\Theta_0 = qR^2/4\lambda$ [1]. In the absence of vibration the difference between the theoretical and experimental values does not exceed 2%, which indicates the absence of convection. The vibrations influence the convection of heat-generating fluid at frequencies close to the speed of rotation (fig. 3). Heat transfer curve is of a complicated form – at an exact match of vibrational and rotational frequencies the minimum of heat transfer is detected. Although $\Theta_0/\Theta \neq 1$, its value has minimum compared to the $f_{rot}/f_{vib} = 1.02$ and 0.98, where the maximums of heat transfer are observed.

With intensity of the vibration impact the width of area in which the heat transfer is different from the molecular one and the height of the heat transfer peaks increase. Heat transfer at the exact coincidence of frequencies also increases with the amplitude and the frequency of vibration (fig. 4).

To visualize the convective flows plastic light scattering particles with a diameter of 50 microns are used. The mass fraction of the particles is less than 0.15 %. The visualizer density is less than the density of the working solution, during rapid rotation in the absence of vibrations, the particles accumulate along the axis of the cavity. The same distribution of the particles is observed in the experiments with vibrations in areas far from the frequencies coincidence. At $f_{rot}/f_{vib} = 1$, the particles are distributed in the form of the column along the cavity axis at distance from it (fig. 5, a). The column is motionless in a cavity frame. The photo shows the band of particles above the glass capillary located at the axis and containing a temperature sensor.

The vibrations with the frequency coinciding with the speed of rotation leads to the formation of force field static in the cavity frame [3]. The same way as if the cylindrical

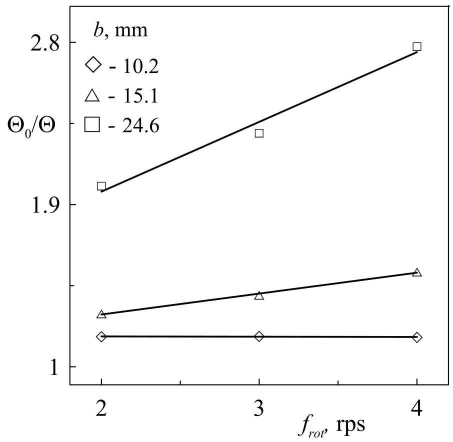

Figure 4: The dependence of heat transfer on the velocity of rotation at $f_{rot}/f_{vib} = 1$

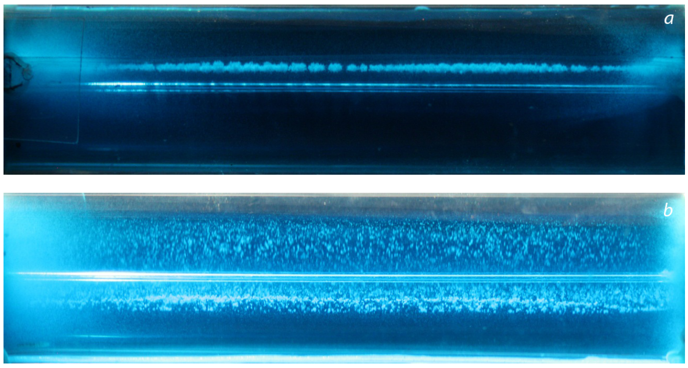

Figure 5: Photos of convective structures; $b = 10.2$ mm, $f_{rot} = 3$ rps; $f_{vib} = 3$ (a) and 2.95 (b) Hz

cell was rotated about an axis shifted relative to axis of symmetry. Thus, the structures of flows are similar in the case of gravitational convection of heat-generating fluid in a fixed horizontal cylinder (in the form of two crescent-shaped vortices) and convection in experiments with vibrations with frequency equal to the rotational velocity. The only difference is that in the latter case the centrifugal force of inertia provides a strong stabilizing effect. It should be noted that, when the axis of rotation is horizontal, the external static force field (gravity) can also have an impact [3] at low speed. In the above experiments $f_{rot} =$ 2, 3 and 4 rps, as follows from [1],[2] at such velocities this effect does not appear Thus, in the cavity frame the liquid is under the action of two force components: the first – static, associated with the vibrations, the second – centrifugal one.

At $f_{rot}/f_{vib} \approx 1.02$ and 0.98 heat transfer in the cavity is maximal. The temperature at the cylinder axis is lower than at $f_{rot}/f_{vib} = 1$. The experiments with visualization show (fig. 5, b), that the temperature drop is associated with the occurrence of the azimuthal rotation of the hot inner column of working fluid relative to the cavity: fluid on the axis rotates at an angular speed different from the speed of the cylindrical wall of the cuvette. This is because if $f_{rot}/f_{vib} \neq 1$ force field generated by the action of vibration rotates slowly relative to the cavity at a velocity equal to $|\, f_{rot} - f_{vib} \,|$ in the direction of cylinder rotation, or in the opposite one. Particles of the visualizer unlike the case $f_{rot}/f_{vib} = 1$ are located in a cloud rotating with a leading or lagging flow.

4 Discussion

Following [1] consider the effect of translational vibrations of the cavity in the direction perpendicular to the axis of rotation from the position of vibrational mechanics, i.e. consider an averaged effect of vibrations. The inertial field $b\Omega_{vib}^2 \underline{i}$ caused by the translational vibrations with frequency $\Omega_{vib} \equiv 2\pi f_{vib}$ is represented as the sum of two circularly polarized inertial fields rotating in opposite directions with a frequency Ω_{vib}. In the cavity frame these fields with the amplitude $b\Omega_{vib}^2/2$ rotate with the frequencies $\Omega_{vib} + \Omega_{rot}$ and $\Omega_{vib} - \Omega_{rot}$, causing the fluctuations of non-isothermal fluid. The proposed mechanical model explains the nature of the intensification of heat transfer at $f_{rot}/f_{vib} = 1$. The frequency of rotation of one of the fields coincides with the cavity rotational frequency and in the cavity frame the field becomes stationary creating a uniform force field $b\Omega_{vib}^2/2$. This field breaks the axial symmetry of the centrifugal force field. The second vibrating component rotates with a frequency of $2\Omega_{rot}$, causing the fluid oscillations. Experiments [2] show that this effect is weak, thus the static in the cavity frame force field plays a key role while the averaged action of oscillating component is insignificant. This allows to conclude that in the conditions of this experiment centrifugal and indicated static (in the cavity frame) fields are the determining ones. The effect can be characterized by two Rayleigh numbers: centrifugal $Ra_c = \Omega_{rot}^2 \beta \Theta R^4/\nu\chi$ and vibrational $Ra_v = b\Omega_{rot}^2 \beta \Theta R^3/\nu\chi$, where Θ – characteristic temperature difference. In the problem of fluid with internal heat release with a volumetric density of heat sources q these parameters can be written as:

$$Ra_c = \Omega_{rot}^2 \beta q R^6/\nu\chi^2\rho c_p,\ Ra_v = b\Omega_{vib}^2 \beta q R^5/\nu\chi^2\rho c_p \tag{1}$$

where β, ν, χ – coefficients of thermal expansion, kinematic viscosity and thermal diffusivity of fluid, ρ – density, c_p – specific heat at constant pressure.

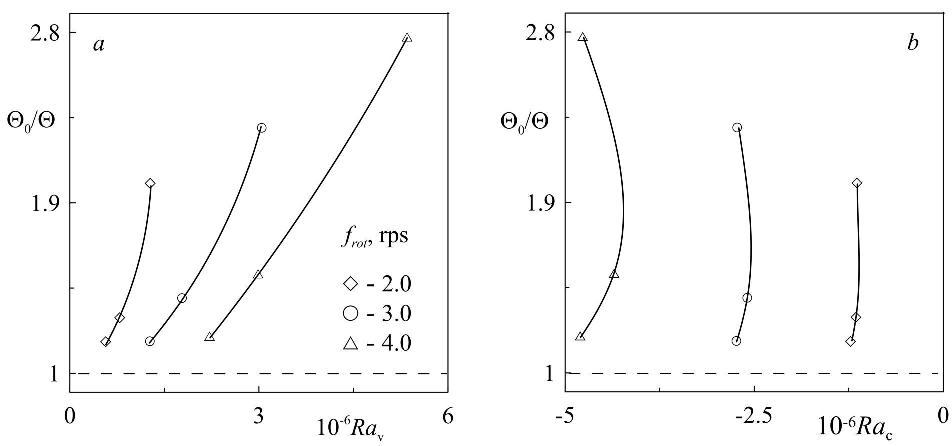

Figure 6: Heat transfer in the plane of the control parameters

Let us consider the effect of vibrations at a frequency coinciding with the frequency of rotation on the temperature of the liquid at the axis of the cavity (fig. 6). The ratio of the vibrational and centrifugal mechanisms is characterized by the relative amplitude of oscillations b/R. With the amplitude increasing the contribution of Ra_v (vibrational mechanism) to the heat transfer significantly increases (fig. 6, *a*), while the influence of Ra_c (centrifugal mechanism) stays nearly unchanged (fig. 6, *b*).

Isolines of heat transfer values Θ_0/Θ are presented in the plane of indicated Rayleigh numbers. As expected heat sink increases with Ra_v at constant Ra_c. Note that the extrapolation of the curves to intersection with the axis Ra_c gives the positive values of Ra_v.

In this extreme case, the centrifugal convection provides heat transfer in the absence of vibration component.

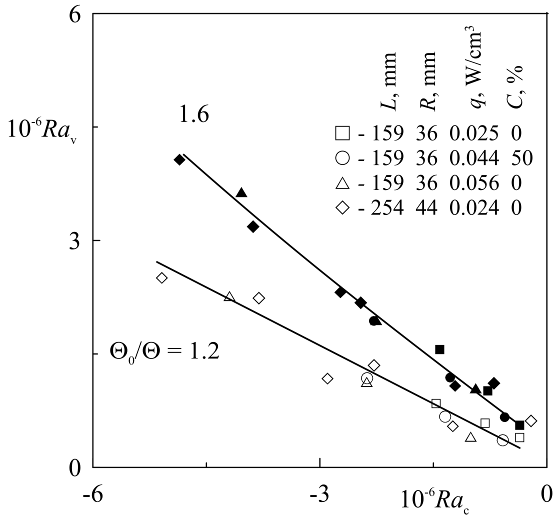

Figure 7: Isolines of heat transfer in the plane of the control parameters

5 Conclusion

Thermal convection of liquid in horizontal cylindrical layer uniformly rotating around its own axis and performing transverse translational oscillations is investigated experimentally. It is found that the vibration impact with frequency equal to the speed of rotation causes an intense heat sink from the central area of the cavity It is shown that the convection is associated with the generation of inertial force field static in the cavity frame.

Acknowledgements

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Victor G. Kozlov, Alexey A. Vjatkin, The Laboratory of Vibrational Hydromechanics, Perm State Humanitarian-Pedagogical University, Perm, Russia