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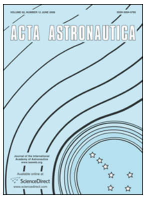

Convection of liquid with internal heat release in a rotating container ☆

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ABSTRACT

The convection of heat-generating fluid in a rotating horizontal cylinder is experimentally investigated. The threshold of convection excitation, the structure of convective flows and the heat transfer in the cylinder depending on the heat release capacity, liquid viscosity and aspect ratio of the cavity are studied. It is found that the average convection is excited by the thermovibrational mechanism —the gravity force, rotating in the cavity frame, produces the oscillations of non-isothermal fluid relative to the wall, which in turn result in excitation of mean convective flows. It is shown that the structure of convective flows depends on the dimensionless velocity of rotation. At relatively low rotation velocity the convection develops in the form of a periodic system of vortices regularly distributed along the cylinder axis. The threshold of excitation (critical value of vibration parameter) of three-dimensional vortex structures grows with rotation velocity. Above some definite rotation velocity the convection develops as two-dimensional rolls parallel to the axis of rotation. The threshold of two-dimensional structures excitation does not depend on the rotation velocity. Besides the structure of thermal convective flows the analysis of the relatively weak currents generated by the inertial waves below the threshold of convection is performed.

1. Introduction

Thermal convection in rotating systems is an actual problem widely spread in nature [1]. The convection in stars, atmospheres and cores of the planets could be an example. The specificity of these problems is connected with the action of inertial forces on non-uniformly heated medium. Systematic analysis of thermal convection in rotating systems could be found in [2]. In the presence of steady gravity field the thermal convection is determined by the gravitational Rayleigh number $Ra_g = g\beta\Theta h^3/\nu\chi$, Prandtl number $Pr = \nu/\chi$, Taylor number $Ta = 4\Omega^2 h^4/\nu^2$ and Froude parameter $Fr = \Omega^2 R/g$. Here ν, χ and β—coefficients of kinematic viscosity, thermal diffusivity and thermal expansion respectively, h—thickness of the layer, R—characteristic distance from the axis of rotation, Ω—angular velocity, and Θ—the temperature difference between the layer boundaries. Taylor number characterizes the action of the Coriolis force on the convective flows. It is demonstrated that Coriolis force has strong stabilizing effect on 3D cellular vortexes. The centrifugal force of inertia can play both stabilizing role, if the temperature gradient in the fluid is directed to the axis of rotation, and destabilizing in another case, when the centrifugal thermal convection appears. The action of the centrifugal force could be characterized by a centrifugal Rayleigh number $Ra = \Omega^2 R\beta\Theta h^3/\nu\chi$.

The properties of thermal convection become qualitatively new if the cavity rotates in the external force field directed perpendicular to the axis of rotation. The case of the rotation around the horizontal axis could be an example. The gravity force performs rotation in the cavity frame and acts as an oscillating force. It is known that the action of oscillating force on the non-uniformly heated fluid leads to the averaged convective motion (thermovibrational mechanism in the

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Nomenclature

C	mass concentration of the aqueous solution of glycerol, %
c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
Fr	Froude number
g	gravity acceleration, m s^{-2}
h	thickness of the layer, m
l	length of the cylinder, m
N	dimensionless frequency of liquid oscillation
Nu	Nusselt number
n	rotation frequency, rps
n^*	critical rotation frequency, rps
Pr	Prandtl number
q	specific heat release capacity, W m^{-3}
R	radius of the cylinder, m
Ra	centrifugal Rayleigh number
Ra_g	gravitational Rayleigh number
R_v	vibrational parameter
T_1	temperature on the cavity axis, °C
T_2	temperature of the internal cavity boundary, °C
T_3	temperature in the water jacket, °C
Ta	Taylor number
β	thermal expansion coefficient, K^{-1}
χ	thermal diffusivity, m^2 s^{-1}
φ	the angle between the characteristic surface of inertial wave and the axis of rotation, deg
λ	thermal conductivity, W m^{-1} K^{-1}
ν	kinematical viscosity, m^2 s^{-1}
Θ	temperature on the axis relative to the side wall of the cylinder, K
ρ	liquid density, kg m^{-3}
Ω	angular velocity of rotation, rad s^{-1}
ω	dimensionless rotation velocity

absence of rotation is described in [3]). The equations of vibrational thermal convection in rotating systems were obtained in [4] by the averaging method. The averaged effect of the gravity on the non-isothermal fluid in a rotating cavity is characterized by a modified vibrational parameter $R_v=(g\beta\Theta h)^2\ /2\nu\chi\Omega^2$. Other governing parameters are a centrifugal Rayleigh number and a dimensionless rotation velocity $\omega=\sqrt{Ta}/2\ =\Omega h^2/\nu$. A detailed experimental study of thermal vibrational convection with rotation is performed in a coaxial hori-zontal gap rotating around its own axis [5]. It is shown that thermal vibrational convection could appear even in a stably stratified (in the centrifugal field) fluid. Great interest in the study of the averaged effect of external force fields on the con-vective processes in rotating systems is determined by a wide class of natural objects. An example of such influence is the gravitational action of massive satellites which cause the tidal oscillations in the atmospheres and liquid cores of the planets.

The article is devoted to experimental study of thermal convection of liquid with uniform internal heating in rotating cavity started in [6]. The problem is considered from the point of view of thermal vibrational convection—mean flows of non-isothermal liquid excited by oscillating (in the cavity frame) force field.

2. Experiment

2.1. Research facility

The cavity is a Plexiglas cylindrical tube 1 (Fig. 1) closed on both sides with the flanges 2. The length of the cavity is $l=170$ mm, the inner radius varies, $R=18$ and 22 mm. The heat release is provided by an alternating electric current passing through the fluid in the cavity. The flanges are equipped with copper electrodes inside. The liquid (water and aqueous glycerol mixtures) is added with sulfate of copper (up to 5%) for better conductivity.

The temperature in the cavity is measured using the resistance thermometers. One of them is placed in a thin glass capillary and measures the temperature T_1 on the cavity axis; another one measures the temperature T_2 on the internal cylindrical boundary. Both sensors are made of thin copper wire and are extended along the entire cavity length and thus measure the average temperature.

The temperature at the outer boundary of the cell is kept constant. For this the cell is placed in a Plexiglas tube 3 (Fig. 1) of larger diameter closed by flanges on the end faces. The water from the jet thermostat is pumped in the gap between the pipes (water jacket). The coolant temperature T_3 is also controlled by the temperature sensor.

The system of the bearings and seals allows the cylindrical cavity to rotate freely with the outer boundary 3 motionless. The rotation is set by stepper motor 4; the rotation rate n varies from 0.01 to 2 rps.

The signal from the temperature sensors is processed by device Termodat 5 which rotates with the cavity and is transmitted to the computer with the help of a multichannel electrical collector 6. The temperature measurement error does not exceed 0.1 K. The collector is also used to power the Termodat and to apply voltage to the cell.

2.2. Experimental technique

The experiments are performed with water (Prandtl number varies in the interval $Pr=4.5–6$) and aqueous

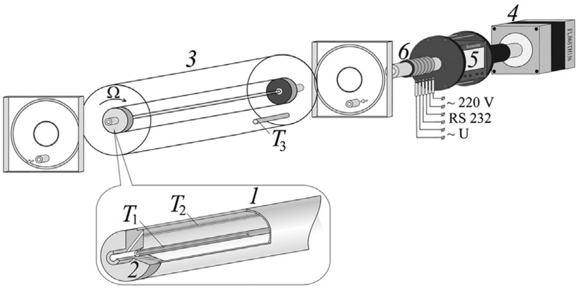

Fig. 1. Facility scheme.