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Vibrational convection of heat-generating fluid in a rotating horizontal cylinder. The role of relative cavity length

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A B S T R A C T

Thermal convection of fluid with internal heat sources in a rotating horizontal cylinder with isothermal boundary and adiabatic ends is investigated experimentally. Under the action of gravity nonisothermal liquid oscillates in the cavity frame. These tidal oscillations generate the average mass force and, as a result, excite convection. The steady convection developing by this mechanism is called thermal vibrational. Centrifugal force in the considered case plays a stabilizing role. The objects of studying are the excitation thresholds of the averaged convection, heat transfer and the structure of convective flows. The parameters varying in the experiments are heat release rate, relative length of the cylinder and rotation velocity. It is found that the inertial waves which are generated near the ends of the cavity by tidal oscillations of nonisothermal liquid effect the convection. The intensity of flows excited by these waves is relatively low, but significant especially below the threshold of thermal vibrational convection. It is shown that the influence of inertial waves on heat transfer and structure of convective flows strongly depends on the cavity aspect ratio.

1. Introduction

Geo- and astrophysical applications occupy especial place in studies of thermal convection under rotation [1,2]. This interest is first of all connected to the convective processes in stars, planetary atmospheres and cores. Intricacy of these systems modeling is connected either with their size or necessity to take in account such factors as internal heat generation, MHD-effects, the force action of satellites, inertial waves, propagating in rotating fluids, and others. Despite this, great number of experimental works, containing significant simplifications and assumptions, set as one of the purposes modeling of core and atmospheric processes. The review of some of these works is presented in [3]. The number of laboratory experiments modeling the Earth's core is described. The paper gives the comparison of experiments and considers their advantages and disadvantages according to dynamical similarity with the corresponding geophysical processes in the core. A number of studies of Earth's core convection and other geodynamical processes are generalized in monograph [4]. The studies of convection in the planet's cores are inseparably linked with dynamo models and possible magnetic field generation mechanisms in Earth's and other planets' cores. This line of researches is reflected mostly in theoretical papers [5,6].

The influence of planets' satellites on the convection in cores and atmospheres is less intensively studied. The action of satellite's gravity field on hydrodynamic processes of planet is oscillatory one (tidal oscillations) It is known that the action of oscillating force field on non-isothermal liquid or multiphase medium can be the reason of variable averaged effects appearance [7,8]. The perturbing action of external force in experiment can be modeled by the rotation about a horizontal

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Nomenclature

b	the amplitude of vibrations, m
C	mass concentration of the aqueous solution of glycerol, %
c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
g	gravity acceleration, m s^{-2}
h	thickness of the layer, m
l	length of the cylinder, m
N	dimensionless frequency of liquid oscillation
n	rotation frequency, rps
Pr	Prandtl number
q	specific heat release capacity, W m^{-3}
R	radius of the cylinder, m
Ra	centrifugal Rayleigh number
R_v	vibration parameter
T_{in}	temperature on the cavity axis, °C
T_{ex}	temperature of the internal cavity boundary, °C
T_{sh}	temperature in the water jacket, °C
β	thermal expansion coefficient, K^{-1}
γ	the cavity relative length
χ	thermal diffusivity, m^2 s^{-1}
φ	the angle between the characteristic surface of inertial wave and the axis of rotation, deg.
λ	spatial half-period of inertial wave
κ	thermal conductivity, W m^{-1} K^{-1}
ν	kinematic 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_v	the frequency of vibration, rad s^{-1}
ω	dimensionless rotation velocity

axis. In this case the gravity force rotates in the cavity frame and determines the liquid's oscillations. This approach is realized in a number of experimental works [9–11]. It is shown that thermal convection develops even in the liquid stably stratified in centrifugal field.

The theory of thermal vibrational convection [7] built in the approximation small amplitudes of liquid's oscillations in the cavity frame tells that under the action of translational vibrations of container the averaged convection is determined by the vibrational parameter $Ra_v = (b\Omega_v\beta\Theta h)^2/2\nu\chi$ and dimensionless frequency of vibration $\omega_v = \Omega_v h^2/\nu$. The parameter ω_v characterizes the ratio of the cavity size and the Stokes boundary layer and does not affect the averaged convection in the limit $\omega_v >> 1$. It plays an important role in case of finite frequency of external field modulation [12], at $\omega_v \le 1$ the vibrational convective mechanism weakens with frequency decrease because the viscosity strongly suppresses the liquid oscillations.

In rotating cavities thermal convection acquires a number of specific features connected with the action of inertial forces, the centrifugal and Coriolis ones. The theory of thermal vibrational convection in rotating cavities [13] takes into account the effect of inertial forces on steady and oscillatory liquid flows. It is shown that the averaged action of gravity on non-isothermal fluid in a cavity rotating about a horizontal axis is characterized by modified vibrational parameter $R_v = (g\beta\Theta h)^2/2\nu\chi\Omega^2$. Other control parameters are centrifugal Rayleigh number $Ra = \Omega^2 R\beta\Theta h^3/\nu\chi$ and dimensionless velocity of rotation $\omega = \Omega h^2/\nu$, where R is characteristic distance from the rotational axis. It is worth mentioning that the dimensionless velocity of rotation ω characterizes the ratio of the cavity size and the Ekman boundary layer and could be different from the frequency of force field oscillations ω_v. At $\omega >> 1$ the Coriolis force results in continuous suppression of thermal convection with ω growth [13]. The interesting feature of the vibrational convection under consideration is that the cavity vibrations are absent and the oscillations of nonisothermal liquid are induced by external static force field, which performs rotation in the cavity frame. In this specific case the values of parameters ω and ω_v coincide.

One more manifestation of liquid's oscillations relative to the rotating cavity is a generation of inertial waves [14]. In last decade the interest to the investigation of internal inertial waves significantly rises. Among the works the studies of isothermal case prevail. The disturbing factors leading to the inertial waves generation are variable, e.g. vibrations, precession of the rotational axis, modulations of the rotational velocity and others. The inertial waves, appearing under such conditions in the containing fluid, are able to induce some averaged flows. The review of works on this problem is given in [15]. The results of further researches are presented in [16]. The theoretical and experimental study of inertial waves in a trapezoidal enclosure in 2D case is considered.

In the present paper the action of external force field on thermal convection of liquid with internal heat release in a rotating horizontal cylindrical cavity is studied experimentally. The research develops the investigation started in [10,11], where the excitation of the averaged convection of liquid with internal heat release in rotating horizontal cylinder was discovered and was demonstrated that the averaged convection in the cavity of the definite aspect ratio is determined by parameters R_v, Ra and ω. In contrast to those papers the main attention here is paid to subcritical regime of convection and to the action of inertial waves and the cavity aspect ratio on the excitation threshold and the structure of thermal vibrational convection.

2. Experiment

2.1. Experimental facility

The installation consists of a horizontal cavity 1, electric collector, stepper motor and measuring complex (Fig. 1a). A multi-channel device Termodat 2, disposed at the same axis with the cavity, rotates with it and provides the temperature measuring. The data are taken from device by a pair of sliding contacts of electrical collector 3. The signal converted by an adapter is transmitted to the PC. The temperature measurements are displayed on a monitor in real time. Electrical supply