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# Drift of a Free-floating Body in a Convective Layer Heated by Radiation

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**Abstract.** The one-dimensional dynamics of a disk floating freely at a fixed depth in a layer of liquid under conditions of natural convection caused by radiation heating was studied experimentally. It was shown that the dynamics of the disk depends on its optical properties. A disk with a light-reflecting surface demonstrated quasi-periodic motions along the cell. The period of oscillations depends on both the length of the cell and the immersion depth of the disk. The light-absorbing or transparent disk is pressed against the side wall after brief wanderings and remains there until the end of the experiment.

**Keywords:** turbulent convection, floating bodies, radiation heating.

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Thermogravitational convection governs the dynamics of various geophysical systems, such as the atmosphere, ocean, and mantle, and provides efficient transport of heat and various impurities [1]. The variety of studies of convective flows is caused by the fact that their formation and characteristics significantly depend on the intensity and orientation of heating, geometric parameters of the problem, fluid properties, boundary and initial conditions [2–4]. Recently, researchers have begun to pay attention to the behavior of convective systems involving a free-floating body (or set of bodies). The complex dynamics of such systems is determined by the mutual influence of the floating body and the convective flow. The floating body blocks the heat and momentum transfer and changes the structure of the flow, while the flow, due to viscous stresses, moves the body.

For instance, the motion of an insulating plate on the free surface of a liquid layer heated from below and cooled from above (Rayleigh-Bénard convection) has been studied experimentally [5–7] and numerically (in the infinitely large Prandtl number approximation) [8]. A more general formulation provides a plate with isothermal horizontal boundaries, floating inside the convective layer [9–12]. In such a system, the character of body motion and the structure of the flow significantly depend on the Rayleigh number, the geometry of the cell and the plate. Regular,

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periodic motions of the body from one edge of the cell to the other were observed in the limited range of governing parameters. Changing the distance between the plate and the isothermal boundary, the length of the cell and the heating rate lead to significant changes in the dynamics of the floating body. Transient regimes, in which periodic oscillations occur irregularly, and chaotic regimes, in which there are no intervals of regular oscillations, are observed. In addition to changing the structure of the flow, the insulating body inside the fluid can significantly affect the heat exchange [10–12].

In addition to the main control parameters, such as Rayleigh and Prandtl numbers and aspect ratios, the type and even the way of implementation of boundary conditions can have a great influence. Thus, for a developed Rayleigh-Bénard convection, the transition from a boundary condition of the first kind (isothermal boundaries), to a condition of the second kind (constant heat flux) leads to fundamental structural changes, namely to the appearance of convective cells with a size much larger than the layer thickness [13]. This raises the question of how the dynamics of the convective layer with a free-floating body will change in the case of boundary conditions for temperature of the second kind. For natural systems, the main source of heat is solar radiation, so the realization of heating the lower boundary by radiation is of particular interest. This paper presents first results of an experimental study of the motion of free-floating bodies with different optical properties in the convective layer above the underlying surface heated by radiation.

## 1. Experimental setup

Experiments are performed in a rectangular cavity with length $L = 500$ mm, width $W = 100$ mm and height $H = 180$ mm. The scheme of the experimental setup is shown in Fig. 1. Two vertical plexiglass baffles are placed inside the cavity, which separate the working area of length $L_1$. By changing the position of the baffles, the value of the layer length $L_1$ can be varied in a wide enough range. In the experiments, the width and height of the layer were fixed ($W = 100$ mm, $H_1 = 40$ mm), and the length $L_1$ varied from 180 to 350 mm.

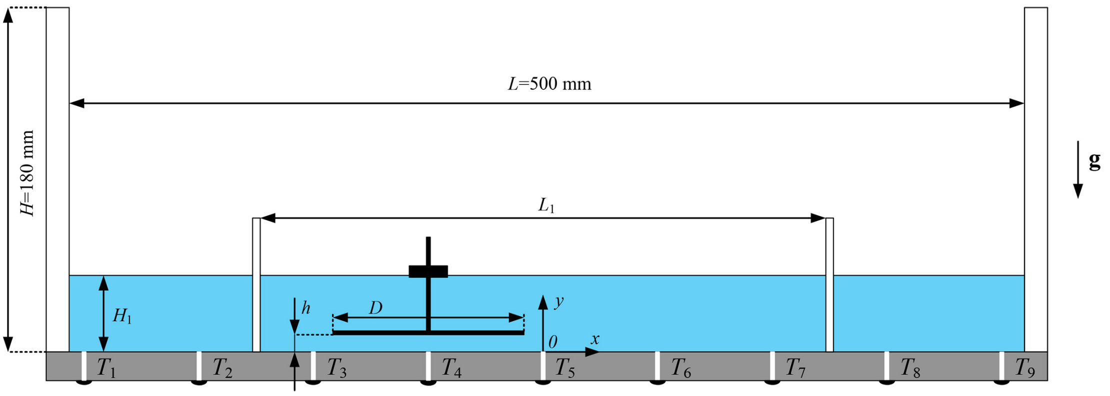


Fig. 1. Schematic diagram of the experimental setup

The base of the model is made of 10 mm thick fiberglass and acts as a heater. For radiation heating, the surface of the base that is in contact with the water is painted in black matte color. The bottom surface is heated by the light from a LED panel. The infrared component in the spectrum of the LEDs used is practically absent. In the experiments, the upper boundary is free and cooling is realized as a result of convective heat transfer at the water-air boundary. There are nine holes in the base, spaced 50 mm apart, in which copper-constantan thermocouples are installed to measure the temperature near the bottom. Thermocouples are labeled $T_i$, where the lower index shows the location of the thermocouple. The thermocouples are numbered from left to right (see Fig. 1).

Two copper-constantan thermocouples located near the side walls were used to monitor the free surface temperature. Temperature measurements were recorded with a National Instruments NI 9213 measuring board at frequency of 1 Hz.

Distilled water was used as the working fluid. Physical properties of the fluid is characterized by Prandtl number $\mathrm{Pr} = \nu/\chi$, where $\nu$ is the kinematic viscosity and $\chi$ is the thermal diffusivity. Temperature variations in the presented study were relatively small (several degrees), so we assume that value of Prandtl number is constant ($\mathrm{Pr} = 6.5$). The free-floating body is a plexiglass disk of 1 mm thickness and diameter $D = 98$ mm, slightly smaller than the width of the cavity. The body was immersed to a given depth by means of a thin rod placed in the center of the disk. At the rod was fixed a washer of porous material, which remains on the free surface of the liquid due to the action of surface tension forces. By moving the washer along the rod, the immersion depth of the disk can be adjusted. In the case of radiation heating, the optical properties of the disk surface play a fundamentally important role, so three options were considered: a transparent disk, a disk with a blackened surface and a disk with a light-reflecting surface (Fig. 2). The motion of the disk was recorded on a CCD video camera at time intervals of 6 seconds. The duration of the experiments varied from 10 to 24 hours.

(a) (b) (c)

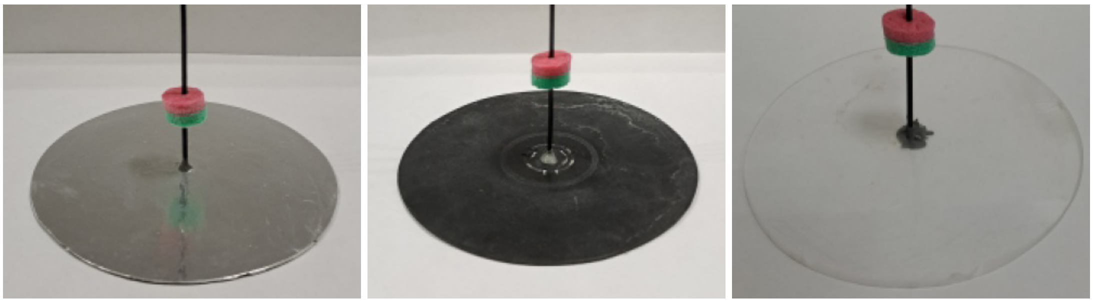

Fig. 2. Free-floating bodies with optically different surface properties: (a) reflective, (b) absorbing, and (c) transparent

After switching on the LEDs and the beginning of heating the bottom by radiation in the cavity, a convective flow is formed. Due to the fact that the heat flux at the upper boundary of the layer is determined by the temperature difference between the water and the surrounding air, and the heating power is fixed, there is an imbalance of heat fluxes at the boundaries. As a result, the average temperature of the liquid grows to a certain value, after reaching which, the heat fluxes are balanced, and the system under study enters a quasi-stationary state. The time of reaching the quasi-stationary state is more than five hours. The main parameters of the experimental runs are presented in Tab. 1, where $\Delta T = T_b - T_t$ is the time-averaged temperature difference in the layer ($T_b$ and $T_t$ are the mean bottom and open surface temperatures). As the main control parameter we used Rayleigh number $\mathrm{Ra} = g\beta H_1^3 \Delta T/\nu\chi$, where g is the gravity acceleration, $\beta$ is the thermal expansion coefficient.

Due to the imbalance of heat fluxes at the upper and lower boundaries, the mean temperature

Table 1. Main parameters of experimental runs

| Optical properties of the disk | $L_1$, mm | $H_1$, mm | $h$, mm | $\Delta T$, $^o$C | Ra |
|---|---|---|---|---|---|
| reflecting | 180 | 40 | 4 | 0.8 | $8.9 \cdot 10^5$ |
| | 250 | | 8 | 0.9 | $1.0 \cdot 10^6$ |
| | 350 | | 15 | 1.0 | $1.1 \cdot 10^6$ |
| absorbing | 180 | | 4 | 1.0 | $1.1 \cdot 10^6$ |
| | | | 8 | 1.0 | $1.1 \cdot 10^6$ |
| transparent | 180 | | 4 | 1.1 | $1.2 \cdot 10^6$ |
| | | | 8 | 1.1 | $1.2 \cdot 10^6$ |

of the liquid changes during the experiment, we consider deviations of temperature from the mean temperature of the liquid: $T_i - T_0$, where $T_0 = (T_b + T_t)/2$. Note that as the length of the cell $L_1$ changes, the number of thermocouples inside the cell changes as well. To analyze the dynamics of the free-floating disk, the readings of thermocouples near the left boundary ($T_3$ or $T_4$), near the right boundary ($T_6$ or $T_7$) and in the center of the cavity $T_5$ were used.

## 2. Results

Since the disk floating in the layer can absorb a substantial part of the heat flux that provides heating of the bottom, the optical properties of the disk significantly affect the behavior of the entire system. Three variants were consecutively considered: a transparent disk, a disk with a blackened surface, and a disk with a light-reflecting surface. For the first two variants, despite the fundamental difference in the type of surface, the behavior of the floating body was similar. After switching on the radiation flux, the disk moves several times from one wall of the cavity to the opposite one, and then it stops at one of the walls and remains there until the end of the experiment (Fig. 3).

(a)

(b)

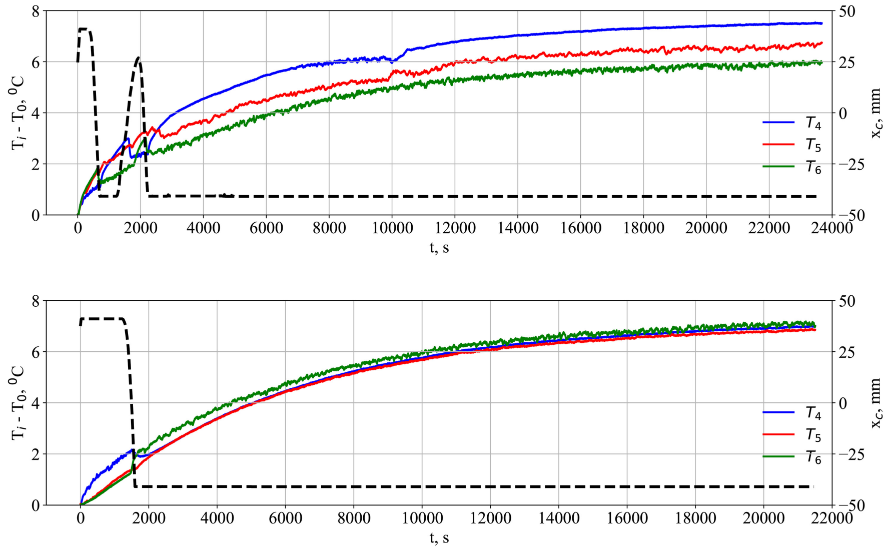


Fig. 3. Temperature variations at three points at the bottom of the cavity (colored lines) and the position of the disk (dashed line): (a) — transparent disk ($L_1$ = 180 mm, $h$ = 4 mm) and (b) — absorbing (blackened) disk ($L_1$ = 180 mm, $h$ = 8 mm)

Fig. 4 shows the time dependence of disk position and temperature at three points on the bottom, in quasi-stationary mode, after the final stop of the disk. The transparent disk transmits radiation, blocking the vertical heat and momentum fluxes, due to which there is a "greenhouse" effect and the liquid under the disk warms up more (Fig. 4a). For the blackened disk, the situation is more complicated. Its upper surface is heated by the radiation flux, just like the bottom surface, so upward convective flows are always formed above it. Immediately after shifting the disk to a new position, the temperature under the disk decreases because it blocks the radiation heat flux, but the disk itself is heated. Therefore, if it remains stationary long enough, the fluid below disk also begins to warm up by conduction, and eventually the temperature below the blackened disk may become even slightly higher than the temperature of the bottom away from the disk (Fig. 4b). High-frequency temperature pulsations are associated with the formation and displacement of small-scale convective structures, thermals, and plumes.

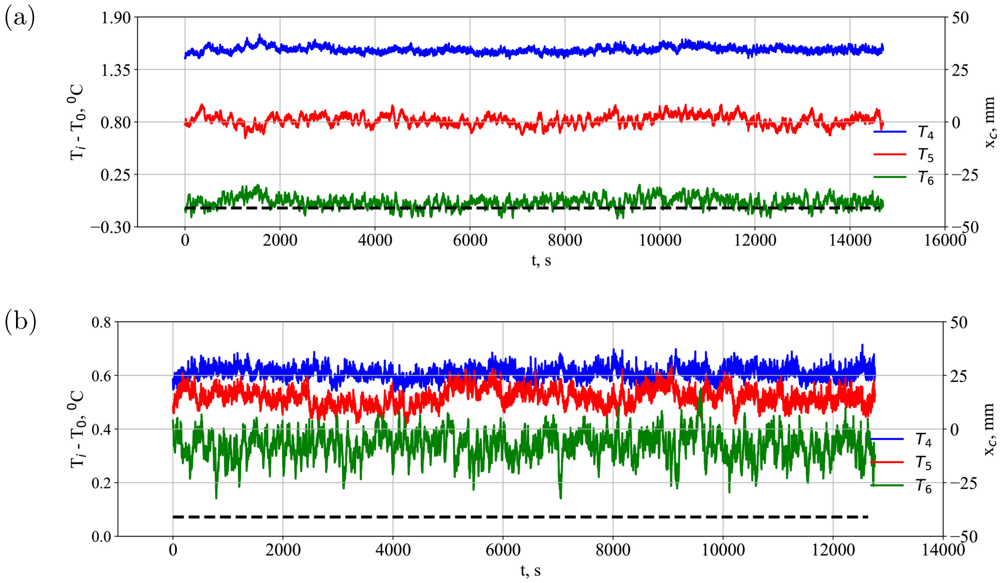


Fig. 4. Position of the center of the disk (dashed line) and temperature at three points on the lower boundary (colored lines) for $L_1$ = 180 mm, $h$ = 4 mm: (a) — transparent disk, (b) — blackened disk

The drift of the disk in the system under consideration is caused by the fluid flow, which leads to a nonzero integral value of viscous stresses on its surface. A detailed explanation of the causes of the fixed position of the disk near the wall requires the reconstruction of the flow structure. However, based on the results obtained in [9, 10, 12], some assumptions can be made. The blackened disk is heated by radiation and is actually a floating heater, i.e., an upward convective flow is formed above it. The asymmetric position of this flow relative to the center of the disk should lead to its displacement toward one of the walls. The fact that the disk remains near the wall for a long time (several hours) indicates that the convective flow at this position of the disk is stable and does not change its structure. In the case of transparent disk, the resulting flow also presses the disk against the wall. As noted above, the fluid under the transparent disk is relatively overheated, while above it, due to blocking of vertical heat flux, the fluid should be relatively cold, so we can expect the formation of an ascending flow around the disk and a descending flow in the central part.

The disk with a reflective surface blocks the radiative flux, which leads to cooling of the bottom under the disk. At the same time, in contrast to the blackened disk, the disk itself is not directly heated by radiation. Almost immediately after the radiative heating is turned on, a quasi-periodic drift of the disk from one wall to the other begins (Fig. 5a). The apparent trend for increasing bottom temperature (Fig. 5b) is a result of increasing average fluid temperature, due to the imbalance of heat fluxes at the bottom and top boundaries of the layer. The heat flux at the bottom, due to radiative heating, is almost independent of time, while the heat flux at the upper boundary depends on the temperature difference between the water and the surrounding air. At the initial moment of time it is equal to zero, and then as the water warms up, it becomes equal to the heat flux at the bottom. As a result, the thermal balance is achieved and the quasi-stationary state is reached.

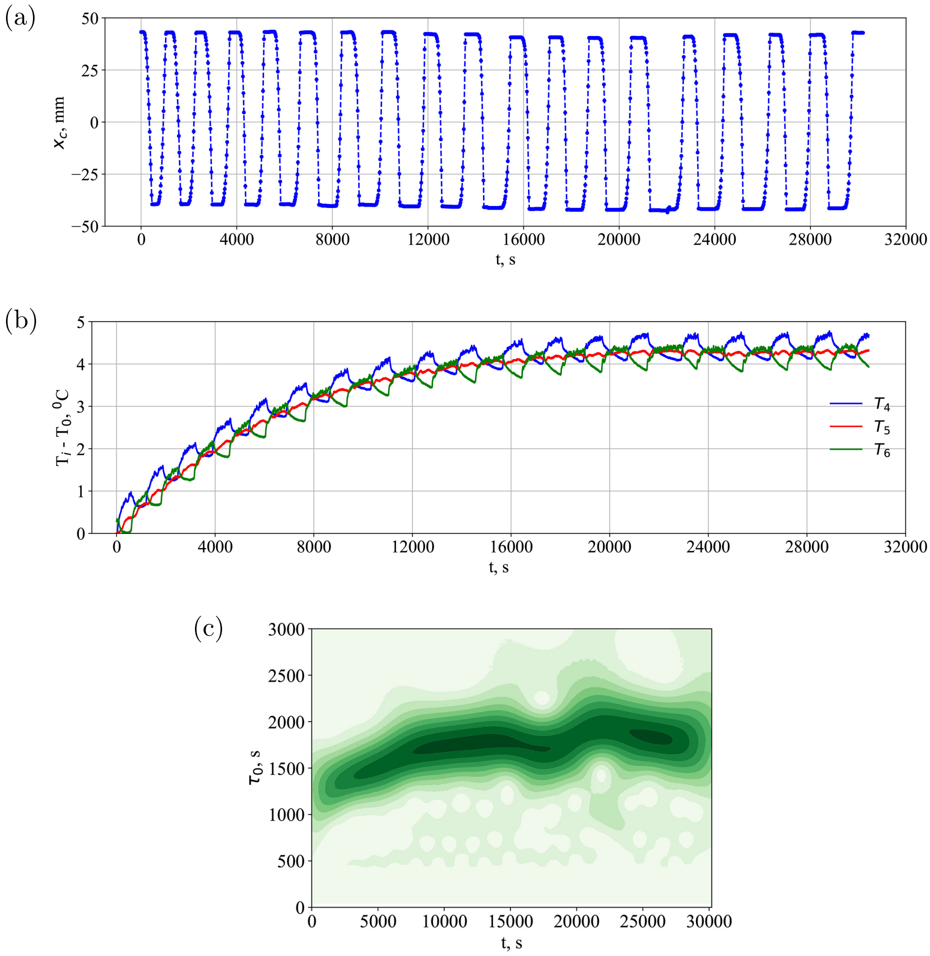


Fig. 5. Periodic mode (reflecting disk). Disk center displacements (a), temperature variations at the lower boundary (b), and a wavelet spectrogram of the disk position (c) for $L_1 = 180$ mm, $h = 4$ mm

Along with the monotonic temperature increase, there are temperature variations associated with the disk drift. The temperature deviation from the average for $T_4$ and $T_6$ is largest at the side walls, due to stops of the disk. The fluid is cooled under the disk, because of the blocking of radiative heating, and heated at the other wall. The temperature in the central part ($T_5$) is weakly affected by the disk, since the time of disk motion over the thermocouple is substantially less than the rest time at the walls.

The continuous wavelet transform [14, 15] is used to analyze the spectral properties of the temporal signal. The wavelet transform is defined as

$$W_f(\tau_0, t) = \tau_0^{-1} \int_{-\infty}^{\infty} f(t')\, \psi^* \left( \frac{t - t'}{\tau_0} \right) dt', \tag{1}$$

where $\psi(t) = \exp(-t^2 + \imath 2\pi t)$ is the complex Morlet wavelet, $t$ is the time and $\tau_0$ is the oscillation period. Wavelet analysis allows us to track changes in the spectral structure of $\tau_0$ with time. Fig. 5c shows a wavelet spectrogram of the disk position variation over the entire time interval. In the non-stationary regime, the period of disk drift increases, and in the stationary regime it equals approximately 1700 s (Fig. 5c). In [9] it was shown that the period of oscillation of the disk is proportional to Rayleigh number. Therefore, such a slow motion of the disk seems to be associated with a relatively small value of Rayleigh number.

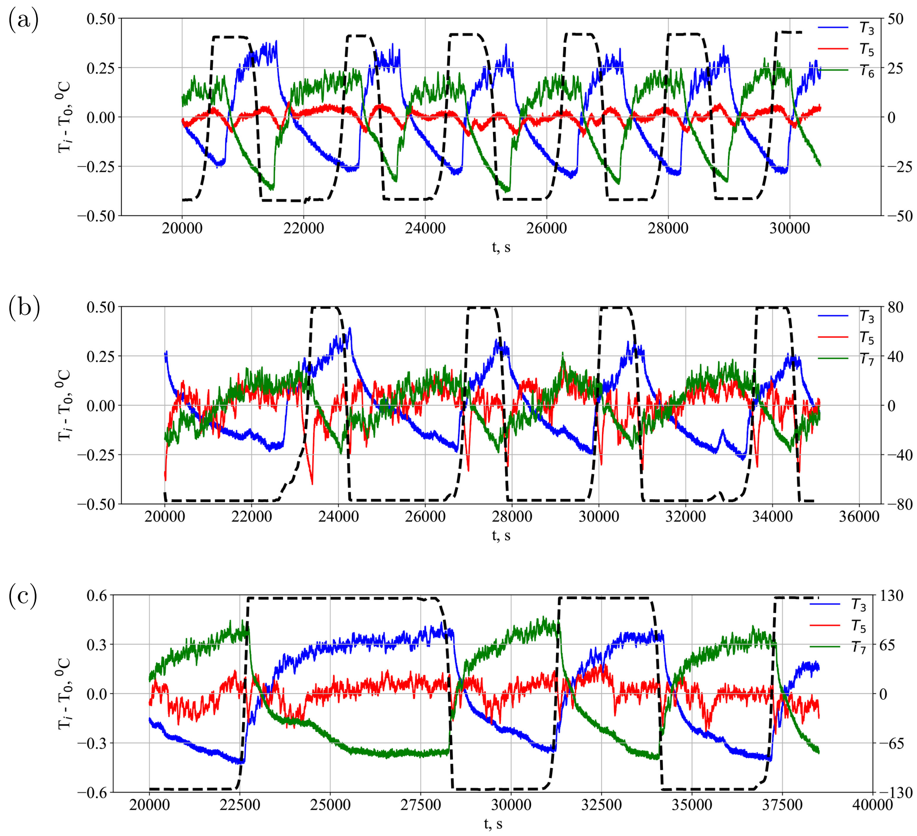


Fig. 6. Displacements of the center of the disk (dashed line) and temperature at the lower boundary for $h = 4$ mm: (a) — $L_1 = 180$ mm, (b) — $L_1 = 250$ mm, (c) — $L_1 = 350$ mm

The structure of the flows and, as a consequence, the period of disk drift significantly depend on the values of aspect ratios ($\Gamma_1 = L_1/H_1$ and $\Gamma_2 = L_1/D$). At homogeneous heating and cooling, varying $\Gamma_1$ [9] and $\Gamma_2$ [10] leads to crucial changes in disk dynamics. Starting from some values of $\Gamma_1$ ($\Gamma_1 > 4.25$) or $\Gamma_2$ ($\Gamma_2 > 1.7$), the disk drift becomes non-periodic. During radiative heating and cooling at the free boundary, in the case of a disk with a reflecting surface, periodic motions persist even for significantly large values of $\Gamma_1$ and $\Gamma_2$, with the period of motions increasing with $\Gamma_2$ (Fig. 6, Fig 7). Note that as $\Gamma_2$ increases, the time intervals between disk drifts from one wall to another become very large (Fig. 7); therefore, even a sufficiently long experimental realization (more than 10 hours) is not enough to accurately establish the disk motion period. The change in the period of disc motion with increasing $\Gamma_1$ is more complex. Increasing of $h$ at fixed $L_1$ leads to a decrease in the drift period, but after reaching some value of $h$, the period increases significantly.

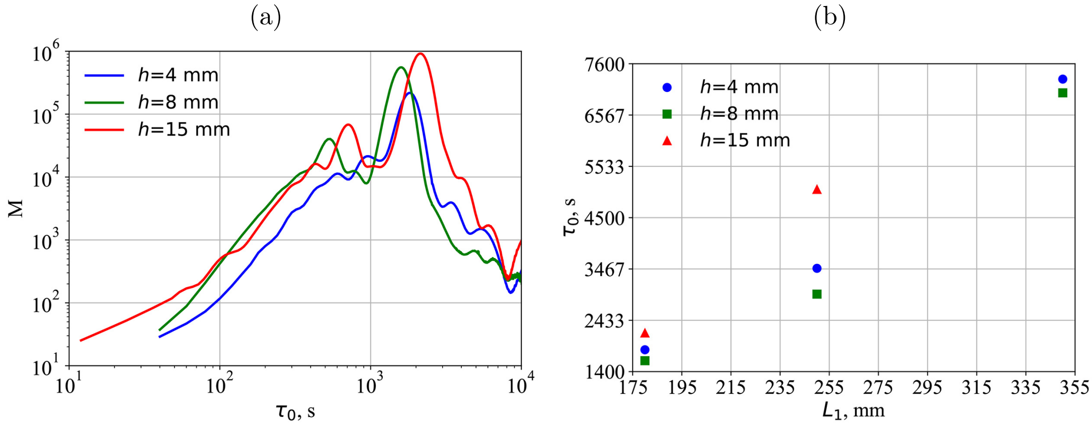


Fig. 7. Integral wavelet spectrum for $L_1 = 180$ mm (a) and the dependence of the disk drift period on the cavity length (b)

## Conclusions

One-dimensional dynamics of a free-floating horizontally extended disk, held at a given height, in developed natural convection caused by radiation heating is studied experimentally. It is shown that the dynamics of the body depends on the absorbing/reflecting properties of its surface.

If the disk floats close enough to the underlying absorbing surface and itself absorbs the radiation, the disk drifts to one of the side walls and remains there for a long time. A large-scale circulation is formed in the layer, which holds the disk against the wall. If the gap between the disk and the bottom is small, the convection is not qualitatively different from convection in the same cavity without the disk — the only difference is that in part of the cavity, the bottom is "elevated" (with the same heating as the rest of the underlying surface).

If the disk is transparent to the radiation flux, the problem becomes equivalent to the problem of a disk floating in a convective layer with constant heat release on the lower surface. Qualitatively, this configuration is similar to the one considered earlier in [9, 10], and one would expect a periodic motion of the disk. However, experiments have shown that in this case, too, the disk has a stable position near one of the walls. A possible reason for such unexpected behavior of the transparent disk, in contrast to earlier studies, is the transition to boundary conditions of the second kind, which fundamentally affect the structure of flows in the cavity.

In all experiments with a reflecting surface, in contrast to the disk in a cavity with a fixed temperature difference [9, 10], quasi-periodic drifts of the floating disk were observed, with the period of oscillations being significantly dependent on the geometry of the cavity and the depth of the disk immersion.

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# Движения свободноплавающих тел в конвективном слое с радиационным нагревом

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**Аннотация.** Экспериментально изучена одномерная динамика диска, свободно плавающего на фиксированной высоте в слое жидкости в условиях естественной конвекции, вызванной радиационным нагревом. Эксперименты показали, что динамика диска зависит от его оптических свойств. Обнаружено, что квазипериодические движения тела наблюдаются только в случае светоотражающей поверхности. Период колебаний при этом зависит как от длины полости, так и от глубины погружения диска. Светопоглощающий, либо прозрачный диск, после непродолжительных блужданий прижимается к боковой стенке и остается там до конца эксперимента.

**Ключевые слова:** турбулентная конвекция, плавающее тело, радиационный нагрев.