

Periodic Boundary Motion in Thermal Turbulence

Jun Zhang^{1,2} and Albert Libchaber¹

¹Center for studies in Physics and Biology, Rockefeller University, New York, New York 10021

²Applied Mathematics Laboratory, Courant Institute, New York University, New York, New York 10012

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A free-floating plate is introduced in a Bénard convection cell with an open surface. It partially covers the cell and distorts the local heat flux, inducing a coherent flow that in turn moves the plate. Remarkably, the plate can be driven to a periodic motion even under the action of a turbulent fluid. The period of the oscillation depends on the coverage ratio, and on the Rayleigh number of the convective system. The plate oscillatory behavior observed in this experiment may be related to a geological model, in which continents drift in a quasiperiodic fashion.

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In Rayleigh-Bénard convection, a fluid heated from under becomes unstable due to buoyancy effects. One of the interesting aspects of this phenomenon is that, near onset, ordered patterns in space [1] and collective oscillations in time [2] are observed. Far above onset, this spatial and temporal order is lost; the fluid becomes turbulent, but a coherent large-scale flow can still maintain some aspects of low-dimensional dynamics [3]. In this paper, we show for the first time that, by introducing a free-moving boundary, a periodic state can be recovered. In such state, the floating boundary behaves like an oscillator. It raises the general question of low-dimensional behavior being restored by boundary conditions in turbulent states. Moreover, the observed phenomenon might illustrate, to a certain extent, the periodic migration of large continents over the convective mantle of the earth.

The experimental setup is shown in Fig. 1. It is a Bénard convection cell [4] with the addition of a free-moving floating plate at its open surface. The cell is a rectangular box with glass walls; the fluid inside is heated uniformly from under with a foil heater, powered by a dc source. The aspect ratio of the convective cell is varied, utilizing two adjustable vertical partitions of the same height as the glass walls. Not only is this a convenient method to vary the aspect ratio, but it also defines good thermal boundary conditions [5]. Various aspect ratios have been used, $L/h = 2.3$ to 7.2 , where L is the length between the two partition walls and h the depth of the fluid. The top of the cell is open and cooled by airflow at 20°C . Air is sucked from above using a bank of cooling fans. The cooling fans are separated from the convection cell using two layers of supporting grids, which prevent disturbances onto the fluid surface. To thermally insulate the lateral surfaces of the glass box, two layers of acrylic plastic separated by a 2 mm gap are added. The heat flux is thus essentially upward and the loss of heat through the four sides minimized. Overall, this setup is a thermal convection cell being cooled in a laminar hood.

The control parameter is the Rayleigh number [6]. It is adjusted from 10^7 to 4×10^8 . The working fluid is dis-

tilled water [7]. Temperature is measured using small thermistors [8] with precision better than 0.03°C . For the cell bottom, two thermistors are embedded in the aluminum bottom block. A typical temperature difference applied across the top and the bottom is about 5° . Visualization is achieved using a shadowgraph technique [9], which reveals thermal plumes and flow structure due to the density changes. We analyze the images using a time-lapse video recording; a computer program measures the floater position by detecting its edges.

Putting a free-moving floater in the system is not a simple task. The viscous drag force exerted on the floater by the convective flow is usually small compared to forces associated with surface tension. The floater will then not be freely driven by the convection, but rather stick to the side-walls. To overcome this difficulty, we use surface tension

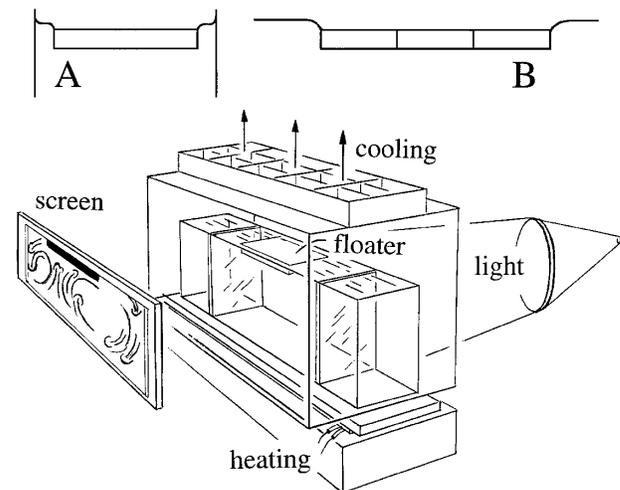


FIG. 1. Setup of the experiment. The convection cell (length 61 cm, width 7.7 cm, and height 12.7 cm) is heated from below uniformly. A laminar air tunnel for cooling is constructed using a bank of dc fans and supporting grids. A beam of light projects a shadowgraph of the flow pattern on a screen. Between the two vertical plates lies the convection cell. Inset A shows a side view of the floating plate, seen from the short side of the cell. B shows a group of three small floaters self-assembled together by capillary force, seen from the side of illumination.

effect to keep the floater away from the sidewalls. The plate is made of acrylic plastic [10] and is heavier than water. Its wetting property and sharp edges allow it to float, due to the meniscus effect (Fig. 1, inset A). The sidewalls of the cell, however, wet water. Because of the surface geometry, the interaction between the sidewalls and the plate is repulsive. This effect [11] causes the plate to stay at an effective distance from all sides, about 1 cm. Beyond this distance, the floater is free and its motion is merely subjected to the viscous drag of the convective flow. The fluid has to be maintained at high purity so that no pollution distorts the free motion of the floater. Given the size of the floater, it can move only along the long axis of the convection cell, since the lateral gaps are of the same order as the effective repulsive distance.

The heat flux is estimated from local temperature profiles measured by thermistors mounted on a moving stage, using the thermal conductivity of the fluids and of the floater material. We found that the heat flux (per unit area) is reduced significantly at the plate compared with the free surface, by a factor of 3.7 ± 0.6 [12]. The floater now behaves as a mobile “thermal blanket” over the fluid. If the floater is held fixed, hot upwelling flows are observed to form constantly right under the floater. Hot thermal plumes accumulate towards the bottom of the floater, and cold descending plumes form constantly at the free fluid surface.

When the floater is set free, the upwelling flow would entrain the floater in either direction. Remarkably, it is observed that the plate is driven into a regular motion by the turbulent convection. The plate oscillates between the left and right ends of the convection cell periodically. Figure 2(a) shows a series of shadowgraphs of the convection in the periodic state, where only half of a period is shown. The corresponding aspect ratio is 4.0, the Rayleigh number is 3.2×10^8 , and the coverage ratio (the length of the floater divided by the length of the cell L) is 0.38. The panel labeled (1) in Fig. 2(a) shows that an upwelling flow structure is well formed under the floater. The floater can move only to the right at this position, and the clockwise flow pattern at the right of the floater starts to entrain it. Panel (2) in Fig. 2(a) shows a typical flow pattern shortly after the floater has arrived at the right side of the cell. One observes that the upwelling structure has a slight drift to the right but the overall flow pattern is essentially unchanged during this transient time, which lasts about 100 s. In panel (3) of Fig. 2(a), one sees that an upwelling hot structure is forming under the plate, and the original flow structure starts to decay. One observes that the convection cell has four rolls [13]. Panel (4) in Fig. 2(a) is a picture taken when the plate starts to move back to the left. A counter-clockwise flow structure at the left of the plate has developed and the cell is now in a two-roll state. The time lapse between panels (1) and (4) is about 600 s. Figure 2(b) outlines the flow pattern according to the shadowgraphs shown in Fig. 2(a) and to the corresponding video recording. The process described goes on in a periodic fashion.

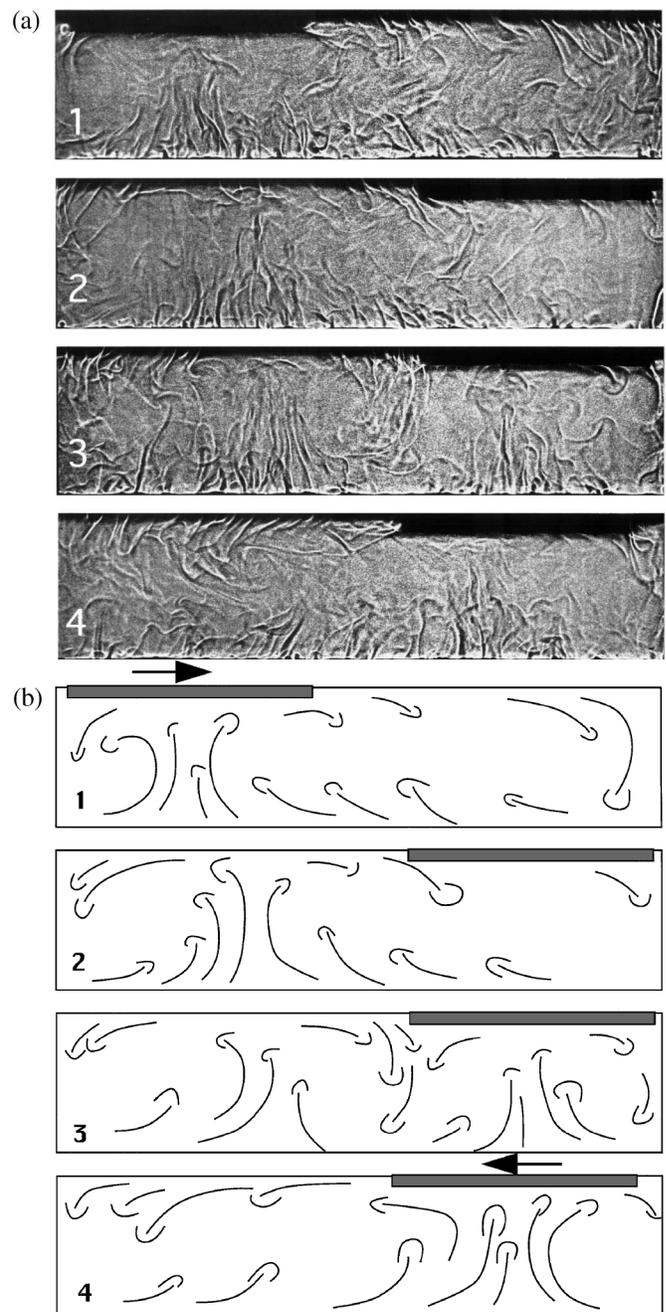


FIG. 2. (a) Four shadowgraphs at different times within half a period. (b) Sketches of the shadowgraphs illustrating the main flows. Aspect ratio is 4.0, coverage ratio 0.38, and Rayleigh number 3.2×10^8 .

The motion of the floating plate and the flow structure is closely coupled.

Figure 3 shows a time series of the floater motion for a cell aspect ratio of 3.3, Rayleigh number 2.0×10^8 , and coverage ratio 0.36. The oscillation period is $T = 1302 \pm 102$ s, averaged over 20 periods. We also notice that the oscillation is slightly asymmetrical, biased towards the left side. This is due to experimental imperfection, such as a very slight tilt of the cell bottom. The maximum speed

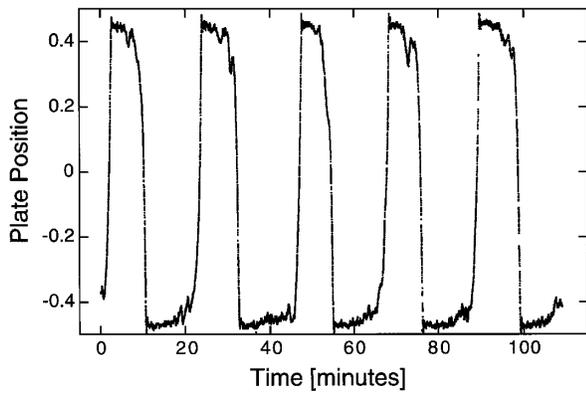


FIG. 3. Floater position, normalized by the cell length, versus time. The aspect ratio is 3.3, coverage ratio 0.36, and Rayleigh number 2.0×10^8 .

of the floater is about 1/3 of the typical flow speed (for instance, flow 5 mm/s, plate 1.5 mm/s). The maximum driving force can be estimated from the values of the bulk flow speed U and the viscous boundary layer thickness λ_v at the plate. The viscous boundary layer thickness is estimated as the distance over which the fluid speed adapts to the bulk speed. At $Ra = 2 \times 10^8$, $U = 4.5 \pm 1.5$ mm/s, and $\lambda_v = 1.0 \pm 0.3$ mm; the viscous driving force is $F = A\mu\delta U/\delta\lambda_v \sim A\mu U/\lambda_v$, where A is the total area of the plate bottom and μ the viscosity of the fluid. One gets $F \sim 4$ dyn [14]. During the oscillations, the temperature fluctuation is on the order of 0.3 °C for the bottom and 0.5 °C on the surface, measured at fixed points.

Shown by the shadowgraphs and time series of the plate motion, it is clear that a floater at the free surface of a convection cell produces a strong perturbation, and it tends to induce a convective flow pattern with hot fluid rising below the plate. The induced large-scale flow moves the floater to a new position, and, the bulk flow pattern must reorganize accordingly. Two different time scales are observed to be associated with the oscillatory state. The motion of the floater is at a fast time scale, which corresponds to the speed of the convecting fluid. It is followed by a relatively long time scale, the reorganization period for the flow when the floater is essentially at rest. The short time scale is not enough for the flow to reorganize effectively. The long time scale, on the order of 600 s, is consistent with the flow turnover time of convection in the cell, about 100 s. A few cycles are needed to reorganize the flow pattern. One notices also that before moving, the floater makes a few attempts, as seen in the time series. Also noticed is the corresponding Reynolds number on the order of 50, using an average floater size. For such Re , the motion once started is not only maintained by the flow, but also partially by inertia. It results in a clocklike behavior with long resting times. In short, the oscillation is a result of a two-way feedback mechanism: the boundary (floater) perturbs and changes the flow pattern, and the flow pattern repositions the boundary.

The period of the oscillation depends on many parameters. Among these, the floater size and the Rayleigh number are the most fundamental. Different floater sizes are realized by putting small identical floaters, as shown in Fig. 1, inset B. The interaction between them is attractive [11], and so they bond together as a single piece. They are not separable under the action of the convective flow, since the typical force of attraction is on the order of a few hundred dyn. Figure 4(a) shows the oscillation period versus the coverage ratio. A systematic decay in the period with increased floater size is observed. The smaller the floater, the longer the resting time. The measurement is averaged over 4–6 periods for each point presented in the figure. Figure 4(b) presents the period of oscillation as a function of the Rayleigh number, Ra . Two different floater sizes are used in the measurements, with coverage ratios of 0.36 and 0.48. A higher Ra gives rise to a higher convective speed [15], so that the transit time and the waiting time are both shortened. In the limited range of Ra and coverage ratio studied, the period of the oscillation seem to scale exponentially with both parameters.

For the range of Rayleigh number explored, $Ra = 10^7$ to 4×10^8 , and for all aspect ratios and coverage ratios reported here, the oscillatory motion is very robust, lasting for days. It is checked that the floater motion is driven

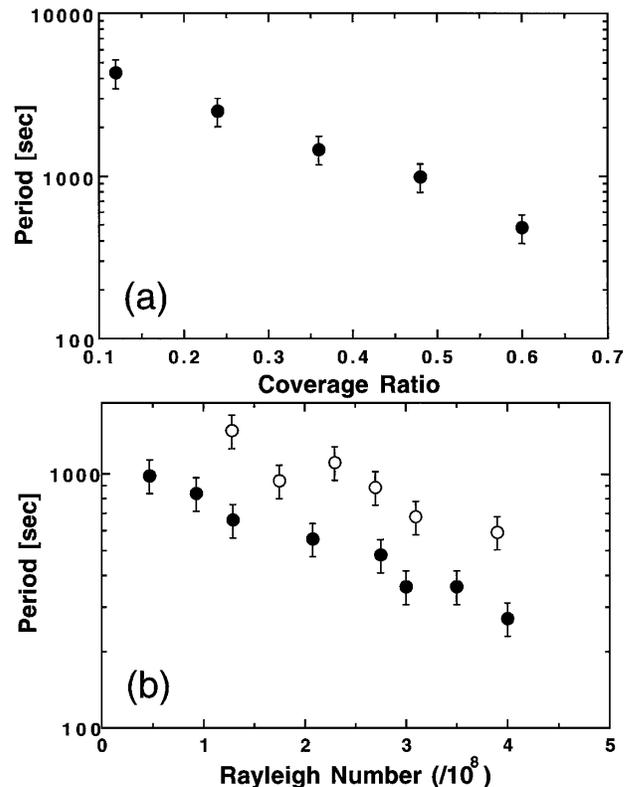


FIG. 4. (a) Period of oscillation of the floater as a function of the coverage ratio, where Rayleigh number is 10^8 . (b) Period as a function of the Rayleigh number. Open circles correspond to a floater of coverage ratio 0.36; close circles correspond to 0.48.

merely by the convective flow and not by other perturbations, such as the cooling system or surface tension effects.

The experimental result is reminiscent of a model proposed by Wilson, which suggests that continents have undergone quasiperiodic motion in plate tectonics processes [16]. In fact, the heat flux through continents is consistently smaller than that of the oceanic crust [17]. Continents act as thermal blankets over the convective mantle. Two-dimensional numerical simulations suggest that the interaction between the continents and mantle convection can give rise to oscillations [18].

In conclusion, we have observed periodic oscillations of a floater on the free surface of a convective cell. It is interesting that a regular, periodic solution can exist in the presence of a strong turbulent state. Such an ordered state is somewhat similar to the emergence of the large-scale circulation in the hard turbulent regime [19]. We further observe that the period of this oscillatory state strongly depends on the coverage ratio and on the Rayleigh number. In future work, we intend to study a large number of small floaters and study how the local flow perturbation at each plate affects the dynamics of this ensemble and its possible self-organization.

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- [5] The temperature jump is negligible at the boundaries, since the fluid is subjected to the same conditions on both sides of the partitions.
- [6] $Ra = \alpha g \Delta T h^3 / \kappa \nu$, where α is the thermal expansion coefficient, g the gravitational constant, ΔT the temperature drop between the bottom and the top, h the fluid depth, and κ and ν the thermal diffusivity and kinematic viscosity of the fluid, respectively. The Marangoni number, $Ma = (d\delta/dT)(dT/dh)h^2/\mu\kappa$, where δ and μ are the surface tension and dynamic viscosity of the fluid, respectively. In this experiment, $Ma/Ra \sim 5 \times 10^{-5}$, which is far from unity.
- [7] For water $\eta = 10^{-2}$ P, $\nu = 10^{-2}$ cm²/s, the Prandtl number is $Pr = 7$. The fluid is considered Boussinesq, since the fluid parameters remain constant over the temperature range applied in the experiment.
- [8] Thermometrics Inc., type AA6A8, 0.3 mm diameter and 0.8 mm long.
- [9] See, for example, A. Belmonte, A. Tilgner, and A. Libchaber, *Phys. Rev. E* **51**, 5681 (1995); W. Merzkirch, *Flow Visualization* (Academic, Orlando, 1987).
- [10] All plates are 0.6 cm thick, density 1.2 g/cm³. To study the effect of coverage, each small plate is 3.6 cm long, 6.1 cm wide. The thermal conductivity $K = 0.2$ W/mK.
- [11] H. Wu, N. Bowden, and G. M. Whitesides, *Appl. Phys. Lett.* **75**, 3222 (1999).
- [12] The local heat flux is $dQ/dt = AKdT/dy$, where A is the area, dT/dy the temperature gradient. The average heat flux through the bottom is measured at its thermal boundary layer, which is nonconvecting. Heat flux through the plate is measured using the temperature drop across the plate and its thermal conductivity. Assuming the heat loss through all sides is negligible, one gets the flux through the free surface.
- [13] When the aspect ratio is less than 3, the four-roll structure is not likely to form.
- [14] Since the plate is in contact with the free surface, differential surface tension forces are important. The typical difference in temperature across the plate along the direction of motion is of the order of 0.5 °C. Surface tension of water decreases with increased temperature at a rate 0.15 dyn/cm K, at 30 °C. It leads to a maximum differential driving force of 0.4 dyn.
- [15] The average flow speed increases with increased Ra ($U \sim Ra^{0.5}$), while the viscous boundary layer thickness decreases. Y.-B. Xin and K.-Q. Xia, *Phys. Rev. Lett.* **77**, 1266 (1996); A. Tilgner, A. Belmonte, and A. Libchaber, *Phys. Rev. E* **47**, 2253 (1993).
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