Reversals of large-scale circulation at turbulent convection in rectangular boxes

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Abstract. The behavior of large-scale circulation appearing against the background of Rayleigh-Benard turbulent convection in rectangular cavities of various geometries (from a thin layer to a cubic cell) has been experimentally studied. It has been shown that the regimes of large-scale circulation with spontaneous reversals separated by long periods of quasistationary circulation appear both in a limited range of the Rayleigh number and in a limited range of the aspect ratio, which determines the ratio of the thickness of a cell to the side in the circulation plane. A regime without reversals is established in a thick layer, whereas a regime characterized by numerous changes in the direction of circulation, which are not separated by intervals with the stable direction of the large-scale flow, arises in a thin layer. The spectra of oscillations of the amplitude of large-scale circulation have been analyzed. It has been shown that a dominant frequency appears in the spectrum of oscillations of the cubic cell.

1. Introduction

Spontaneous reversals of a flow occur in various hydrodynamic systems, including large-scale flows in oceans, atmosphere, convective shells of stars or the liquid core of the Earth, where change in the direction of motion can lead to the reversals of the magnetic field. Investigations of reversals of the Earth’s magnetic field and attempts to develop simple models of a hydromagnetic dynamo, which would involve spontaneous changes in the large-scale field, significantly stimulate interest in the problem of reversals in the hydrodynamic systems in the end of the 20th century. Interest in this problem was refreshed after the detection of regimes with random reversals of the generated field in a dynamo experiment with a Karman flow between counterrotated discs performed by a French team (Ravelet et al., 2008). These works led to new attempts to detect spontaneous reversals of large-scale circulation in purely convective flows.

Experiments in quasi-two-dimensional turbulent flow (\( \Gamma \approx 0.3 \)) show that reversals appear only in a limited range of the Rayleigh number and numerical experiments for two-dimensional turbulent convection in a square region show that reversals appear only in certain ranges of the Prandtl and Rayleigh numbers (Sugiyama et al., 2010). It is worth noting that the picture of reversals of the large-scale flow in turbulent two-dimensional convection (Sugiyama et al., 2010) reproduces the picture of reversals obtained for supercritical convection in the Hele-Shaw cell 30 years ago (Lyubimov et al., 1977). Many open problems remain in the problem of reversals of large-scale circulation against turbulent convection. In particular, the role of the geometry of the cell remains unclear, the reversal mechanism has not yet been analyzed, and the question
concerning the existence of separated frequencies in the time spectra of lower spatial modes is yet unanswered (Zimin V.D., 1988).

2. Experimental setup

The experimental setup is a cubic cell with the side $D = 250$ mm whose horizontal walls are massive copper heat exchangers and vertical walls are made of 25 mm-thick Plexiglas. Two opposite walls of the cell are equipped with a system of vertical slots in which Plexiglas partitions are mounted, which separate a rectangular region with the thickness $d$ in the central part of the cube (see Fig.1). The experiments were performed with $d = 15, 25, 50, 125,$ and $250$ mm. The cube was completely filled by distilled water and the motion of water in the central cross section of the inner cell was investigated using particle image velocimetry (PIV). The temperature difference $\Delta T$ between the horizontal heat exchangers ranged from 10 to $30^\circ$ C.

![Figure 1. Scheme of the experimental box and coordinate system.](image)

The regime of the convective flow in the cell for a fixed Prandtl is determined by two parameters: the Rayleigh number $Ra$ and the aspect ratio $\Gamma$

$$Ra = \frac{g\beta D^3 \Delta T}{\nu \chi}, \quad \Gamma = \frac{d}{D},$$

where $g$ is the gravitational acceleration, $\beta$ is the thermal expansion coefficient, $\nu$ is the kinematic viscosity and $\chi$ is the thermal diffusivity. These parameters in the experiments varied in the ranges $2 \cdot 10^9 < Ra < 7 \cdot 10^9$ and $0.06 \leq \Gamma \leq 1$. The duration of several experiments reached 24 h.

The two-dimensional velocity field in the central cross section ($x0z$) of the cell used to calculate the vorticity component $\omega_y(x, z)$. The vorticity was expanded into the Fourier series

$$\omega_y(x, z) = \sum_{n,m} B_{nm}(t) \cos\left(\frac{\pi nx}{D}\right) \cos\left(\frac{\pi mz}{D}\right)$$

and, then, time variations of the amplitudes
of low modes were analyzed. The intensity of large-scale circulation is characterized by the amplitude $B_{11}(t)$; change in the sign of this amplitude corresponds to the inversion of large-scale circulation.

3. Results

The behavior of the amplitude of large-scale circulation was investigated for cavities with the aspect ratio $\Gamma = 0.06, 0.1, 0.2, 0.5$ and 1 with the imposed vertical temperature difference $\Delta T = 10, 20$ and $30^\circ$C. It was found that large-scale circulation appears in all cases against the background of developed turbulent convection. Three different behavior regimes of this circulation can be identified; they are exemplified in Fig.2.

Figure 2. Examples of time series for variations of the amplitude of the large-scale circulation: $\Gamma = 1.0$, $Ra = 4.4 \cdot 10^9$ (a); $\Gamma = 0.2$, $Ra = 4.4 \cdot 10^9$ (b); $\Gamma = 0.1$, $Ra = 6.6 \cdot 10^9$ (c).

Figure 3. Phase diagrams in the $Ra - \Gamma$ plane: crosses show convection with stable direction of circulation, circles correspond to detected reversals, triangles down shows the mixed regime.

The first regime is characterized by the pronounced large-scale circulation with the unchanged sign (circulation direction). In the example shown in Fig.2a, the amplitude of large-scale circulation oscillates around the statistically stable average value $\overline{B_{11}} = 0.27$ c$^{-1}$ with the variations of the amplitude of circulation in the range $0.1 < B_{11} < 0.4$ c$^{-1}$. The circulation direction remains unchanged during the entire experiment, i.e., for 6 h in this case, which corresponds to about 400 rotations of the large-scale vortex (the average rotation time of the large-scale vortex $\tau_D = 4\pi/\overline{B_{11}}$).

An example of the second regime is given in Fig.2b. In this case, large-scale circulation is characterized by the existence of time intervals with different circulation directions. Within one interval, the behavior of large-scale circulation is the same as in the first case. The durations of individual intervals are random and the transition from one circulation direction to another is sharp. Such sharp changes in circular direction are called reversals. In the presented example, 11 reversals were detected during the experiment (24 h). The durations of individual intervals with unchanged circular directions ranged from 10 min to 5.5 h.

The third regime exemplified in Fig.2c is called mixed. It is characterized by numerous changes in the direction of large-scale circulation, but they are not separated by intervals with quasi-stable circulation in one direction.

All experiments are indicated on the $(\Gamma - Ra)$ plane in Fig.3 by the marks corresponding to the observed circulation regime. According to the figure, the regime with reversals appears
in limited ranges of both the aspect ratio and Rayleigh number. It is seen that the regime without reversals is always observed for $\Gamma \geq 0.5$. Circulation with spontaneous reversals is most pronounced at $\Gamma = 0.2$ and moderate Rayleigh numbers. An increase in the Rayleigh number suppresses reversals and leads to the establishment of the first regime. A decrease in the aspect ratio $\Gamma$ (decrease in the thickness of the cell) leads to the implementation of the third, mixed circulation regime.

Change in the structure of the power spectrum with variation of the aspect ratio $\Gamma$ is illustrated in Fig.4, where the power spectra for the fixed Rayleigh number $Ra = 4.4 \cdot 10^9$ and various $\Gamma$ values. Fig.4 shows, that there is pronounced plateau in the low frequency part of spectrum in the regime without reversals ($\Gamma = 1$ and $\Gamma = 0.5$) and spectrum for cubic cell has pronounced peak. Energy of low-frequency oscillations almost independent of applied vertical temperature gradient in the regimes without reversals. In the case of circulation with reversals ($\Gamma = 0.2$, regime 2), the energy of low frequency oscillations increases strongly and almost the entire frequency range $\nu < \nu_D$ is characterized by a monotonically decreasing spectral energy density. In a thin gap ($\Gamma = 0.1$), regime 3 is established and the energy of oscillations increases by almost an order of magnitude (as compared to regime 2) throughout the low frequency range of the spectrum.

![Power spectra of oscillations of large-scale circulation](image)

**Figure 4.** Power spectra of oscillations of large-scale circulation for the cavities of various geometries and the fixed Rayleigh number $Ra = 4.4 \cdot 10^9$ at $\Gamma = 1.0$ (thick solid line), 0.5 (thin solid line), 0.2 (dashed line), 0.1 (dotted line) and 0.06 (down triangle).

Analysis of the oscillation spectra of large-scale circulation has indicated the appearance of the dominant oscillation frequency $\nu_M$ in the case of the cubic cell ($\Gamma = 1$). This frequency increases with the Rayleigh number, but is certainly related to the rotation frequency of the large-scale vortex. Figure 5 shows the spectra of oscillations of large-scale circulation in the cubic cell represented in the frequencies divided by the frequency $\nu_M$. The spectra almost coincide at the frequencies $\nu > \nu_M$ and decrease rapidly (according to a power law) at the frequencies $\nu > \nu_D$; the frequencies $\nu_M$ and $\nu_D$ are related as $\nu_D/\nu_M \approx 3$. 


Figure 5. Power spectra of oscillations of large-scale circulation for the cubic cell represented in the frequencies reduced to the frequency of the maximum $\nu_M$. $\Gamma = 1.0$ and $Ra = 6.6 \cdot 10^9$ (solid lines), $Ra = 4.4 \cdot 10^9$ (dashed lines) and $Ra = 2.2 \cdot 10^9$ (dotted lines).

4. Conclusions

The experimental studies of large-scale circulation of a fluid in the case of Rayleigh-Benard turbulent convection in rectangular regions of various geometries reveal three different regimes of large-scale circulation. The first regime is characterized by stable circulation whose intensity undergoes stochastic oscillations, but the circular direction remains unchanged. The second regime involves reversals, i.e., the alternation of time intervals with large-scale circulation in different directions. The durations of these intervals are random and the behavior of large-scale circulation within one interval is the same as in the first regime. The third, mixed regime is characterized by numerous changes in the direction of large-scale circulation, which are not separated by intervals with quasi-stable circulation in one direction. In this work, we have revealed a high sensitivity of the character of large-scale circulation to the transverse size of the cell (the thickness of the layer with the square cross section in the circulation plane). It has been shown that reversals are not observed at $\Gamma = 0.5$, whereas the regime with reversals in a thin layer ($\Gamma = 0.1$) changes to the mixed circulation regime.

References

Lyubimov, D. V., Putin, G. F. & Chernatynskii, V. I. 1977 On convective motions in a Haley-Shaw cell. Soviet Physics Doklady 22, 360–364.

Ravelet, F., Berhanu, M., Monchaux, R., Aumaître, S., Chiffaudel, A., Daviaud, F., Dubrulle, B., Bourgoin, M., Odier, P., Plihon, N., Pinton, J.-F., Volk, R., Fauve, S., Mordant, N. & Pétrélis, F. 2008 Chaotic Dynamos Generated by a Turbulent Flow of Liquid Sodium. Physical Review Letters 101, 074502.

Sugiyama, K., Ni, R., Stevens, R. J. A. M., Chan, T. S., Zhou, S.-Q., Xi, H.-D., Sun, C., Grossmann, S., Xia, K.-Q. & Lohse, D. 2010 Flow Reversals in Thermally Driven Turbulence. Physical Review Letters 105, 034503.

Zimin V.D., Frick P.G. 1988 Turbulent Convection. : Nauka.