Random reversals of flow direction in Rayleigh-Bénard convection of liquid metal under a uniform magnetic field

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We performed laboratory experiments of Rayleigh-Bénard convection by using liquid gallium, in the range of Rayleigh number (Ra) from critical value to 100 times above it, under various intensities of a uniform horizontal magnetic field B. The range of Chandrasekhar number (Q) is from 0 to 1000. The vessel we used has a square geometry with aspect ratio five. Flow patterns were visualized by ultrasonic velocity profiling method, and time variations of convective flow structure were clearly observed. We recognized five flow regimes depending on Ra and Q, that is, (1) isotropic large-scale cell pattern, (2) anisotropic cell with larger flow velocity perpendicular to B, (3) short-period oscillatory behavior of rolls aligned in the direction of B, (4) rolls with random reversals of the flow direction, and (5) steady 2-D rolls. In the regime (4), a roll-like structure is dominant for most of the duration and the flow keeps its two-dimensionality, while an emergence of new circulation near the wall triggers the global reorganization of the pattern causing reversal of the flow direction. The reversals of the flow occur randomly with the typical time interval between reversals much longer than the circulation time.

Keywords: Rayleigh-Bénard convection, liquid metal, horizontal magnetic field, flow reversal

1 INTRODUCTION

The study on the nature of thermal convection in liquid metals is essential for the dynamics of Earth's outer core and many engineering topics, and the behavior of turbulent flow under a magnetic field is very important. In highly conductive (low Prandtl number (Pr)) fluids like liquid metals, theoretical studies propose following features [1-2]. (a) Two-dimensional steady roll structure emerging at the onset of convective flow easily becomes time-dependent just above the critical Rayleigh number (Ra) at the condition without external magnetic field, and producing oscillatory instability such as "traveling-wave convection" in the direction of the roll axis. (b) Under a horizontal magnetic field, the axis of the roll structure at the onset of convection is forced to align in the direction of the magnetic field, and the Ra for transition to time-dependent flow regime is increased. (c) At much higher Ra where turbulence is developed, suppression of turbulence and formation of anisotropic flow structure are expected under a magnetic filed. These features are confirmed in our laboratory experiments by visualizing flow patterns in liquid metals [3-5].

On the other hand, 'flow reversals' in Rayleigh-Bénard convection has been an active topic in this decade [6]. The occurrence of spontaneous reversals of the mean flow direction in turbulent thermal convection in water and gas is established. The observed reversals occur at irregular intervals, with the time-scales much longer than the turnover time of the convection [7-8]. Most experimental investigations on flow reversals are made in cylinders or rectangular boxes with small aspect ratios, in which the flow pattern is basically a single circulation and is strongly restricted by the sidewalls of the vessels. Experiments with larger aspect ratio geometries would be helpful to understand, whether flow reversals can occur in situations with several horizontal coexisting circulations. The working fluids in the reported experiments have mainly been water and gas, whose Pr are around one. Liquid metals were used in some experiments [9], but obvious flow reversals have not been established with liquid metals. Here, we report several regimes of flow pattern including newly found flow reversals in liquid metal layer of larger aspect ratio, under the effect of horizontal magnetic field. We classified the flow regimes and clarified the condition for the occurrence of reversals in this system.

2 APARATUS AND SETTING

The vessel we used has a square geometry with aspect ratio five (Fig. 1) [10]. The top and bottom plates are made of copper, and the temperature of each plate is maintained by circulating water. Liquid gallium is used as the working fluid. Ultrasonic transducers for the UVP are set in holes in the Teflon sidewalls, and are in direct contact with the liquid gallium. The flow velocities of the gallium were measured along four lines from the ultrasonic transducers (uv1-uv4); these four transducers were switched on in order for 1.25 s periods, and the sampling for the lines was taken place at 5 s intervals. The UVP measures the projected flow velocity along each line. We used a Helmholtz coil system to apply a uniform magnetic field. The direction of magnetic field is horizontal in this study, and its intensity is controlled by an electric power supply.

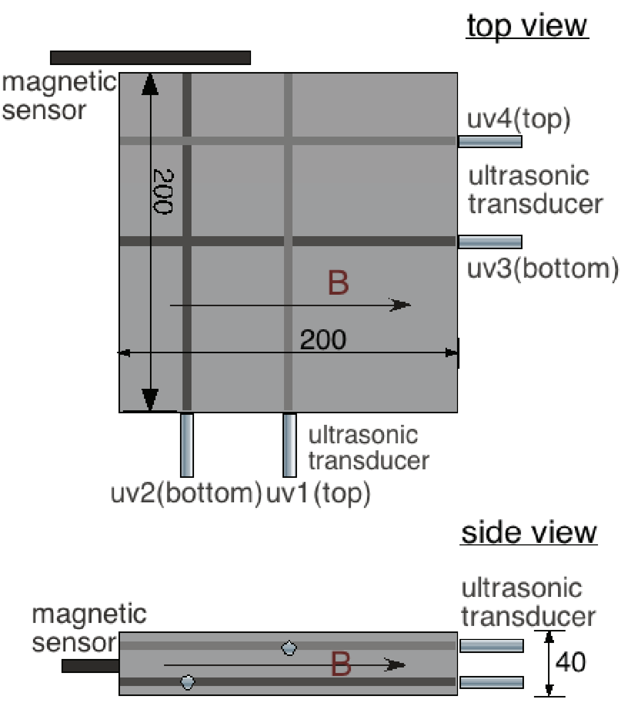

Figure 1: Geometry of the vessel and measurement lines with ultrasonic beam. Liquid gallium is filled in the vessel. The numbers are the dimensions in mm.

3 RESULTS

We found five flow regimes depending on Ra and the intensity of applied magnetic field B. Intensity of the magnetic field can be evaluated by Chandrasekhar number (Q), which is proportional to the square of B. Q is identical to the square of Hartmann number (Ha). At a fixed value of Ra with the increase in Q, those regimes are, (1) isotropic large-scale cell pattern, (2) anisotropic cell with larger flow velocity in the direction perpendicular to B, (3) short-period oscillatory behavior of rolls aligned in the direction of B, (4) random reversals of the flow direction with very long time-scale, and (5) steady 2-dimensional rolls. We note the detail of each regime. In the following figures, the direction and magnitude of the flow velocity are shown in color, blue (minus) shows a flow toward each transducer and red (plus) flow away from it. Ra is fixed at 1.4×10^4, about one order above the critical Ra, in the following examples.

3.1 Isotropic large-scale cell

This regime is observed for the case without magnetic field or under a weak magnetic field. The flow is strongly time-dependent, and there is no obvious structure in time-averaged field. Flow velocities are the same order in both directions as shown in Fig. 2. It is a kind of organized flow pattern in turbulence for low Pr fluid.

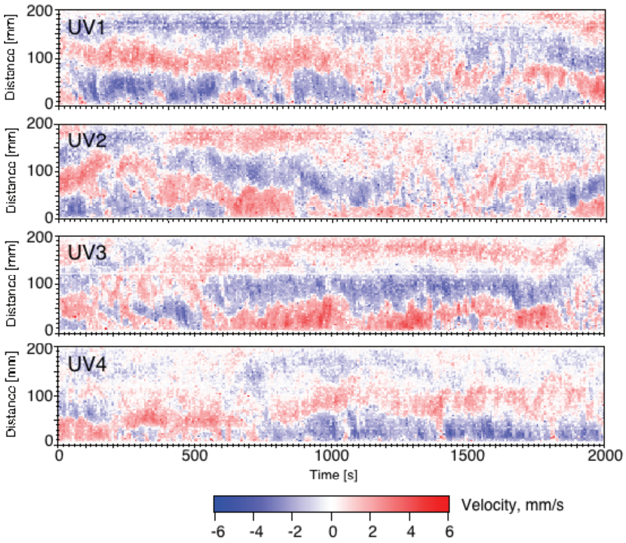

Figure 2: Time-space map of the horizontal flow velocity at $Ra=1.4 \times 10^4$ with Q=0, for 2000 seconds. Isotropic large-scale cell pattern.

3.2 Anisotropic cell with larger flow velocity perpendicular to B

In this flow regime, the average velocity is larger for uv1-2 than uv3-4, which is the effect of the applied magnetic field, but no clear roll-like structure exists (Fig. 3). The flow pattern is broader than four-roll structure in the next regime, and it shows large amplitude of fluctuations. Three-dimensionality of the flow structure is strong. This regime can be thought as a transition state between isotropic cells and aligned rolls.

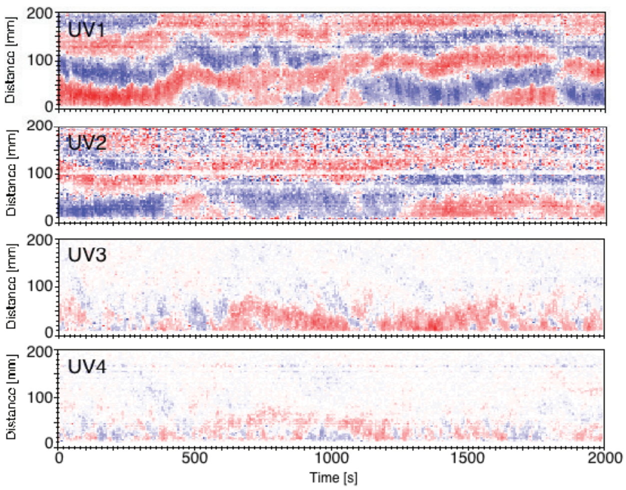

Figure 3: $Ra=1.4 \times 10^4$ with $Q=7.7 \times 10^1$. Anisotropic cell pattern.

3.3 Rolls with short-period of oscillation

More organized, roll-like pattern emerges at moderate values of Q as shown in Fig. 4. Four clusters of velocities are observed with opposite signs in uv1 and uv2 (due to the different height of them, uv1: top, uv2: bottom), which suggests the existence of a nearly two-dimensional roll-like structure with the axis parallel to the direction of the applied magnetic field. In this example, the sign of the flow velocity indicates that there exist upwelling flows at both sidewalls and in the central part of the vessel. One noteworthy feature of these profiles is that the pattern shows periodic fluctuations, suggesting the presence of oscillation of the roll structure. Its typical period is about 70 s for the case here. The period does not depend on Q much, as far as the oscillatory behavior of four-roll is observed, but the spatial range of its horizontal fluctuation gets shorter as Q increases. As the circulation time of the flow for a roll is 30-40 s (length of one circulation for four roll structure ~ 180 mm, and the typical flow velocity 5-6 mm/s), this oscillation period is about two times of the circulation time. This time ratio is almost equal for the other cases with different Ra.

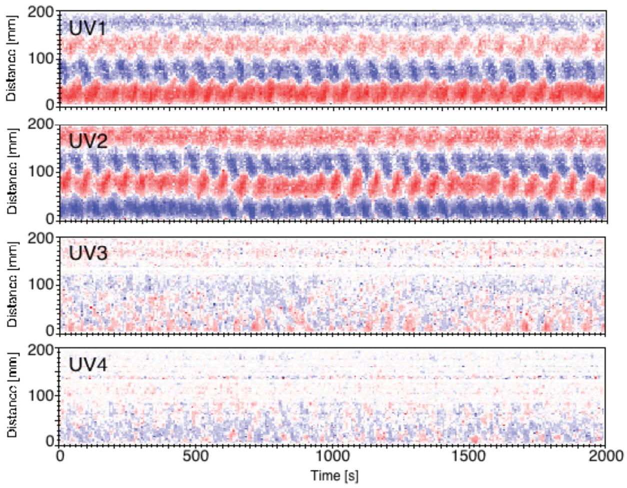

Figure 4: Ra=1.4x10^4 with Q=1.5x10^2. Rolls with short-period of oscillation. The mean direction of the roll is parallel to B.

3.4 Rolls with random reversals of flow direction

The pattern in Fig. 5 shows the regime with irregular reversals of the flow direction. A four-roll structure with axis parallel to the magnetic field is dominant, but the profiles show two reversals of flow direction with non-periodic intervals. Reversals repeat throughout the duration of the experiment (longer than 20,000 s). One flow structure dominantly observed is the four-roll pattern with red patches around 0-50 mm in uv1, which shows upwelling flows at both sidewalls and the center as indicated in Fig. 6 (a). The other dominant flow structure is also a four-roll pattern with the flow direction opposite to this (Fig. 6 (b)). The fraction of time that the flows show either of these four-roll states is relatively large, and the transition between the two patterns occurs over a shorter time than the four-roll state is maintained. Flow velocities in uv3-4 become larger at the timing of reversals; hence two-dimensionality of the flow structure becomes weaker. The transition proceeds as follows: a small circulation emerges at a corner of the vessel in either sidewall. It grows up to the fifth roll, and expands horizontally for a while, then the global flow reverses with a reorganization of the whole pattern. In this case with 20,000 s of the duration, the average time between intervals is 800 s. The average intervals of the flow reversal are much longer than the circulation time.

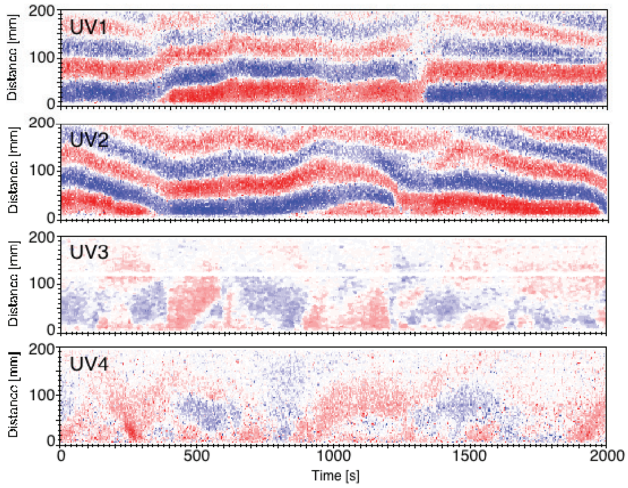

Figure 5: Ra=1.4x10^4 with Q=1.0x10^3. Random reversals of the flow direction.

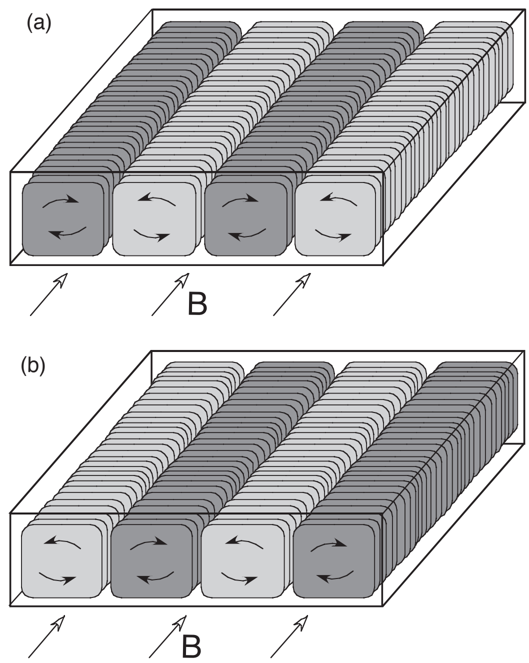

Figure 6: Schematic view of the flow patterns with four rolls. These patterns correspond to (a) t ~ 600 s, and (b) t ~ 1500 s in Fig. 4.

3.5 Steady 2-D rolls

With a higher intensity of B, the flow pattern keeps almost steady roll structure whose axis is parallel to the magnetic field. Either pattern in Fig. 6 (a) or (b) lasts for a long time.

4 DISCUSSIONS

A regime diagram of convection patterns under a horizontal magnetic field is established in relation to Ra and Q. These flow regimes can be classified by the ratio of buoyancy force to the Lorentz force. If buoyancy force is much larger than Lorentz force, the flow is turbulent and isotropic structure is dominant. Short-period of oscillation is observed where this ratio is lower than 100. Random reversals are observed at lower ratio.

The geometry of the vessel is also important for the occurrence of flow reversals; we did not observe spontaneous flow reversals in a narrower vessel. Fluctuations of flow pattern in a narrower vessel are limited to induce oscillatory behavior of roll-like structure [5], but fluctuations in a wider vessel can cause global reorganizations of the flow pattern as shown in the present experiments. This may be due to the larger variation of the flow in a wider vessel, such as the emergence of new circulations.

Applying a horizontal magnetic field of adequate intensity for horizontally wide fluid layer may be essential for the occurrence of flow reversals in liquid metal Rayleigh-Bénard convection.

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