一様磁場下での液体金属の熱対流：変動する対流パターンの実測と数値計算による再現

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Thermal convection in liquid metals under a uniform magnetic field: visualization of flow patterns

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The study on the nature of thermal convection in liquid metals is essential for the dynamics of the Earth’s outer core, and the behavior of 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) 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. (2) 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. (3) At much higher Ra where turbulence is developed without magnetic field, 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. The vessel we used has a square geometry with aspect ratio five, and a uniform horizontal magnetic field is applied to the whole vessel. Flow patterns were visualized by ultrasonic velocity measurements, and time variations of convective flow structure were clearly observed. We found four flow regimes, that is, steady 2-dimensional rolls, oscillatory behavior of rolls, random reversals of the flow circulation in rolls, and large-scale flow, depending on Ra and the intensity of applied magnetic field. We analyzed details of the 3-dimensional structure in regimes of oscillation and random reversals by mapping the velocity field, and considered the cause of these variations.

We made up codes for numerical simulation of thermal convection to compare with the results obtained by these laboratory experiments. Furthermore, we analyzed the fine scale structure and short time variation relating to turbulence, those are difficult to obtain by laboratory experiments due to the limitation of measurements. The numerical simulation is performed for three dimensional square box, with no-slip boundary conditions at all boundaries, fixed temperature at the top and bottom, and insulating at side walls. The effect of applied magnetic field is also included. The Pr of the working fluid is that of liquid gallium. We used enough grid points to resolve the small-scale behavior without any assumption for the turbulence. Our numerical result reproduced several regimes of convection patterns as observed in the experiments. Statistical values, such as the relation of the circulation time and oscillation period, Ra dependence of the mean velocity and the oscillation frequency, are good agreement in both laboratory and numerical studies. This confirms that both of our laboratory experiment and numerical simulation are reliable ones.