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Thermal convection in low Prandtl number fluids: generation of oscillatory phenomena by numerical simulations

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The study on the nature of thermal convection in low Prandtl number (Pr) fluids is essential for the dynamics of the Earth's outer core, and the difference of the flow behavior from Pr~1 fluids like water and air is very important. In lower Pr fluids, the two-dimensional steady roll structure emerging at the onset of convective flow easily becomes time-dependent just above the critical Rayleigh number (Ra), and theoretical studies propose oscillatory instability such as "traveling-wave convection" in the direction of the roll axis. Transition to turbulence with increases in Ra in low Pr fluids occurs at much lower Ra than water or air, and large-scale flow is also expected to emerge easily.

Our laboratory experiments on thermal convection with liquid metal by using an ultrasonic velocity profile measurements visualized the flow pattern in a gallium layer with simultaneous measurements of the temperature fluctuations, from 10 to 200 times above the critical Ra (Yanagisawa et al., 2010). In those experiments, the presence of a roll-like structure with oscillatory behavior was established, even in the Ra range where the power spectrum of the temperature fluctuation shows features of developed turbulence. The flow structure was interpreted as a continuously developed one from the oscillatory instability of two-dimensional roll convection around the critical Ra. It was shown that both the velocity of the flows and the frequency of the oscillation increase proportional to the square root of Ra, and that the oscillation time of the roll structure is comparable to the time to complete one circulation of the flow.

We made up a code for numerical simulation of thermal convection to compare with the results obtained by the 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 rectangular box, with no-slip boundary conditions at all boundaries, fixed temperature at the top and bottom, and insulating at side walls. The range of Ra for numerical simulations is from critical value to 200 times above it. The material properties of the working fluid are those of liquid gallium and Pr=0.025. We used enough grid points to resolve the small-scale behavior without any assumption for the turbulence. Our numerical result reproduced oscillatory convection patterns as observed in the experiments. Statistical values, such as the relation of the circulation time and oscillation period, Rayleigh number 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. The series of numerical simulations with the increase in Ra revealed the onset point of oscillatory convection and subsequent transition to turbulence. The power spectrum densities calculated from the velocity and temperature dataset clearly indicate the feature of low Pr fluid, that is, temperature is more diffusive than momentum and the corner frequency is higher for velocity spectrum in the region of developed turbulence.

Keywords: thermal convection, low Prandtl number, numerical simulation, pattern, turbulence