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Regime diagram of thermal convection pattern under horizontal magnetic field in liquid metal

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The study on the nature of thermal convection in liquid metals under a magnetic field is important for the dynamics of planetary metallic cores. Electric current is induced when a flow of liquid metal crosses a magnetic field, and it generates Lorentz force. The Lorentz force changes the force balance, making the flow behavior different from no-magnetic field situations. In general, viscosity of liquid metals is very low and their flow easily becomes turbulent, but when a magnetic field is applied on liquid metals, it makes anisotropic flow structure with suppression of turbulence depending on its direction and intensity. To quantify the effect of magnetic field on flow patterns, we performed laboratory experiments of Rayleigh-Benard convection by using liquid gallium, with various intensities of a uniform horizontal magnetic field B. The vessel we used has a square geometry with aspect ratio five. Flow patterns with their time variation were visualized by ultrasonic velocity profiling method. The range of Rayleigh number (Ra) is from critical value to 100 times above it. The range of Chandrasekhar number (Q), which is proportional to the square of the intensity of B, is from 0 to 1000.

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) continuous transitions between roll numbers in the vessel, and (5) steady 2-D rolls. In (4), reversals of the flow direction in rolls were observed several times. These behaviors are summarized as a regime diagram of convection patterns in relation to Ra and Q. The key mechanisms for the variation are the enhancement of two-dimensionality and increase of roll number for larger Q situations. These flow regimes can be classified by Ra/Q, that is 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 (3) is observed where the ratio Ra/Q is lower than 100. Continuous transitions of roll numbers (4) are observed at Ra/Q between 10 and 30, and convection pattern keeps steady roll (5) at Ra/Q smaller than 10. We also performed numerical simulations of thermal convection with imposed horizontal magnetic field. Both the Prandlt number and magnetic Prandtl number of the working fluid are set small to simulate liquid metals. Our numerical result successfully reproduced all regimes that observed in the experiments.

Keywords: thermal convection, liquid metal, magnetic field, pattern