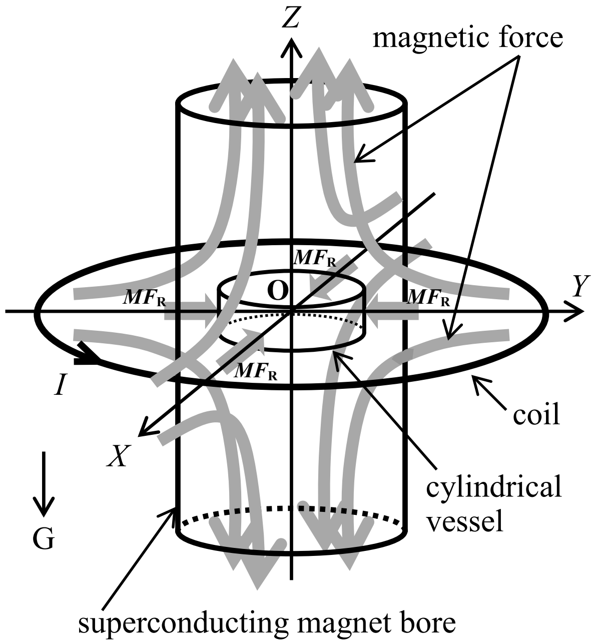
13. Benard Water Convection in a Cylindrical Vessel where Axisymmetric Magnetic Force Is Applied at the Superconducting Magnet Center (Videos 29–32)

<Explanation>

In a solenoidal superconducting magnet, the magnetic force functions axisymmetrically to the magnet bore. The radial component of magnetic force lessens as it gets closer to the center axis and becomes zero in the center (r = 0). As shown in the diagram below, the direction of magnetic force is plane-symmetrical to the horizontal plane that passes through the round coil center.



Assume a fluid to be water and it is put in a shallow cylindrical vessel, and three-dimensional computation of Rayleigh-Benard convection is performed under the conditions of cooling on the upper surface and heating on the lower surface. In such a case, the aspect ratio (diameter/height) of the vessel is 8.0, Pr = 6.0, and Ra = 7020. The result of this computation becomes a steady solution and an axisymmetrical roll is formed according to the shape of the cylindrical vessel.

Based on the result of this computation, we examined time-serial variations in the magnetothermal convection pattern with the use of the three-dimensional computation method while 4 different intensities of magnetic force were applied. In the center of the vessel sidewall, the intensity of magnetic force was set at (A) 5.0 times the gravity, (B) 1.0 times, (C) 0.5 times, and (D) 0.1 times, respectively. The non-dimensional number γ that denotes the intensity of magnetic force is (A) $\gamma = -2665840$, (B) $\gamma = -533169$, (C) $\gamma = -266584$, and (D) $\gamma = -53316.9$, respectively. The numerical computation employed the non-dimensionalized momentum equation, equation of energy, and equation of continuity, to be solved with the aid of the HSMAC explicit method. The magnetic force was obtained using Biot-Savart's law.

<Results of computation>

Videos show the thermal distribution over the horizontal cross section that passes through the center of the shallow vessel, viewed from above.

(A) In this case, the strongest magnetic force (5 times the gravity) was applied sideways (**Video 29**). We can see that a low-temperature fluid is concentrated in the center of the vessel and a high-temperature fluid moves to the vicinity of the sidewall. This is because the magnetic force is in proportion to the volume susceptibility (product of density and mass susceptibility), and therefore the effect of the magnetic force becomes stronger as the temperature of a fluid with large density becomes lower. Since water is diamagnetic, a fluid at a lower temperature tends to move toward the vessel center, where the magnetic force is weak, and a fluid at a higher temperature tends to move toward the peripheral area of the vessel.

(B) In this case, a magnetic force equal to the gravitational force was applied (**Video 30**). Similarly to (A), a low-temperature fluid is concentrated in the center of the vessel and a high-temperature fluid moves to the vicinity of the sidewall. However, since the magnetic force is somewhat weak, the low-temperature fluid an not be held in the center of the vessel in a steady state. Thus generation and destruction of an axisymmetrical pattern are reciprocally repeated.

(C) In this case, a magnetic force 0.5 times the gravity was applied (**Video 31**). A high-temperature fluid satys around the vessel's periphery. However, the intensity of magnetic force is not strong enough to transport the low-temperature fluid to the vicinity of the vessel center. As a result, the flow goes on in an unstable state. Finally, convection in a three-times symmetric spoke pattern appears.

(D) In this case, a magnetic force 0.1 times the gravity was applied (**Video 32**). The intensity of the magnetic force is weaker than that in case (C). A high-temperature fluid can be held only around the vessel periphery, and it also seems to be concentrated around the vessel center as well. This is because the intensity of the magnetic force is too weak to transport the low-temperature fluid to the center. It is assumed that a pattern of Rayleigh-Benard convection was still maintained as the initial condition. The convection turns into a three-times symmetric spoke pattern and is led to a steady solution.

A similar spoke pattern appears even when the aspect ratio is 10. Refer to [2] for more details.

<Place of execution>

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<Research papers>

[1] S. Maki, C. Udagawa, S. Morimoto, and Y. Tanimoto,
"Induction of rhythmic flow with a vertical magnetic force",
Journal of the Physical Society of Japan **82**, pp. 033402-1-4, (2013).

[2] S. Maki, C. Udagawa, S. Morimoto, and Y. Tanimoto,
"Periodical oscillation phenomena observed in salt-water oscillator experiments under small gravity conditions",
Microgravity Science and Technology, in press.