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Microgravity experiments on thermomagnetic convection in magnetic fluids

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Abstract

We have investigated the onset and the flow profile of thermomagnetic convection in a cylindrical fluid layer. Under microgravity conditions provided by the use of sounding rockets and at the drop tower 'Bremen' (ZARM, University of Bremen, Germany) the experiments could be carried out with periodic boundary conditions in which the vertical force of gravity, that normally produces three-dimensional flow, is made negligible, thus permitting the establishment of counter-rotating vortices.

1. Introduction

In our experiments a magnetic fluid is enclosed in a hollow cylindrical container heated from the center and cooled at the outer surface. The temperature difference between inner and outer cylinder gives rise to a gradient in magnetization in the fluid. In addition the fluid is under the influence of an azimuthal magnetic field with radial gradient (see Fig. 1(a)). The gradient of magnetization and the gradient of magnetic field strength are antiparallel. If a volume element of the fluid is displaced adiabatically from a region near the inner to a region near the outer cylinder, i.e. from a region with low to one with high magnetization, the displaced volume element will be surrounded by fluid with higher magnetization, so the volume element feels a resulting force antiparallel to the field gradient. Therefore this force is directed in the direction of the initial displacement. In the same way it can be understood that a volume element displaced radially inward will also feel a resulting force in the direction of displacement. Such forces always acting in the direction of a displacement have destabilizing character, since they can amplify random disturbations of the fluid layer. Therefore they can drive a convective flow in the fluid.

The destabilizing effect is opposed by viscous friction and thermal conductivity. The situation of the system is described by a dimensionless parameter, the so-called magnetic Rayleigh number [1,2]

$$R_{\mathrm{m}} = \frac{\mu_0 K G \Delta T d^3}{\kappa \eta}, \qquad (1)$$

where μ_0 denotes the vacuum permeability, $K = -\partial M / \partial T$ the pyromagnetic constant, G the magnetic field gradient, ΔT the temperature difference between the cylinders, d the thickness of the fluid layer, κ the thermometric conductivity and η the dynamic viscosity of the fluid. If this parameter exceeds a certain critical value R_{m}^* then convection will set in. If the experiments are carried out under microgravity the geometry of the set-up described before favours periodic boundary conditions which are not feasible in a ground-based experiment (see Fig. 1(a)). Such boundary conditions are highly interesting for a comparison of the experimental results with numerical calculations carried out by Polevikov and Fertman in 1977 [1,3]. They predicted that the resulting flow pattern for magnetic Rayleigh numbers above the critical value should consist of counter-rotating axial vortices with a diameter equal to the thickness of the fluid layer (see Fig. 1(a)).

2. Experiments

In our experiments the fluid was enclosed between two concentric cylinders (see Fig. 1(a)). The inner cylinder is heated by an electric heater, while the outer one is cooled with a latent heat reservoir. The flow profile of the convective flow has been investigated by measuring the temperature distribution on the inner surface of the outer cylinder by means of small thermistors (see Fig. 1(b)). The periodic temperature distribution along azimuthal lines around the cylinder produced by hot fluid streaming towards the outer cylinder and cold fluid streaming to the inner one (see Fig. 1(a)) gives information about size and number of vortices. In addition the amplitude of the temperature variation is proportional to the amplitude of convection α. Since

$$\alpha^2 \propto R_{\mathrm{m}} - R_{\mathrm{m}}^* \qquad (2)$$

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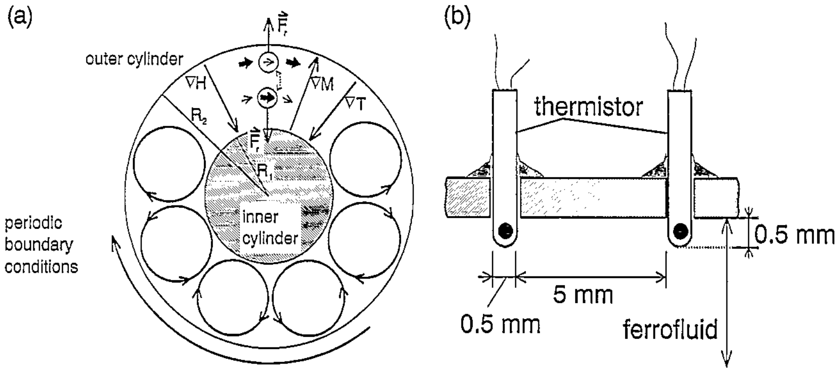

Fig. 1. (a) The origin of a destabilizing magnetic force in a cylindrical fluid layer under the influence of radial temperature and magnetic field gradients. (b) The use of microthermistors placed in the wall of the outer cylinder provides information about the temperature distribution.

an extrapolation of the measured linear relation between α^2 and R_m to $\alpha^2 = 0$ provides the value of R_m^*.

The value of the magnetic Rayleigh number required for the onset of convection and the flow pattern of the convective flow have been investigated in several microgravity experiments. These experiments were carried out with sounding rockets and at the drop tower 'Bremen' (ZARM, University of Bremen, Germany). For the drop experiments it must be considered that the magnetic convection has to be established within the 4.75 s of microgravity time provided. Therefore it is necessary to reduce the relaxation time for the build-up of convection

$$\tau = d^2/\nu \tag{3}$$

(d is the fluid layer thickness, ν is the kinematic viscosity of the fluid) to a value appropriate for such short experiment times. With a fluid layer thickness of $d = 7$ mm and a fluid with a kinematic viscosity of $\nu = 100$ mm^2/s the relaxation time becomes $\tau = 0.5$ s. Therefore 0.5 s must be provided for the decrease of gravitational convection and another 0.5 s for the build-up of thermomagnetic convection. So enough time for the investigation of the convective flow remains.

3. Results

If one intends to combine the results of drop tower and sounding rocket experiments it becomes necessary to prove that the time available at the drop tower is long enough to establish the thermomagnetic convection. Therefore in Fig. 2 the amplitude of convection α normalized to its maximum value is shown as a function of time after the azimuthal magnetic field is switched on. It is obvious that α approaches a limit for times above 2 s. Therefore the temperature distribution measured at the end of the experiment time provided by the drop tower can be used for the determination of the flow profile and of the amplitude of convection for the certain magnetic Rayleigh number.

An example for a temperature distribution measured along an azimuthal line around the cylinder for $R_m > R_m^*$ is shown in Fig. 3 together with the corresponding flow profile. The flow profile agrees well with the predictions in Ref. [1]. Fig. 4 shows the linear relation between the square of the amplitude of convection and the magnetic Rayleigh number. The extrapolation to $\alpha^2 = 0$ provides a

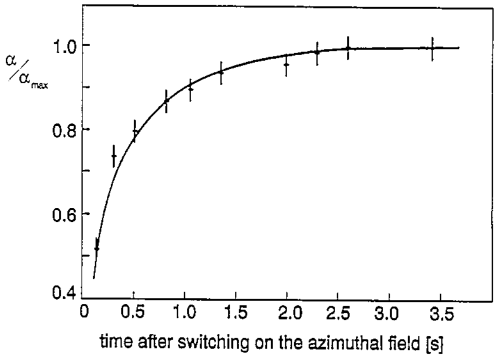

Fig. 2. Time dependence of the amplitude of convection after the azimuthal magnetic field is switched on measured at the drop tower 'Bremen'.

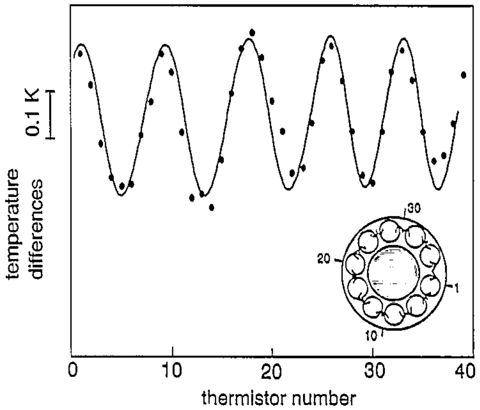

Fig. 3. The temperature distribution along an azimuthal line around the outer cylinder measured during a sounding rocket experiment. The inset shows the corresponding flow pattern.

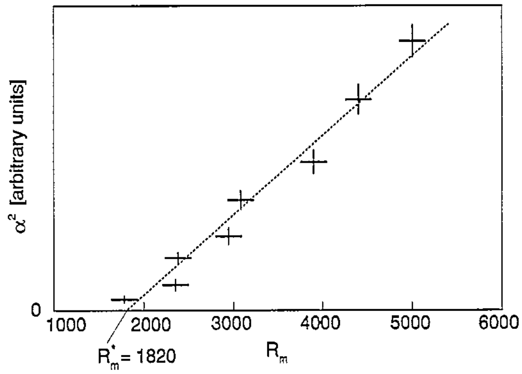

Fig. 4. The linear dependence of the square of the amplitude of convection on the magnetic Rayleigh number measured in drop tower experiments. The extrapolation to $\alpha^2 = 0$ provides the critical magnetic Rayleigh number.

value for the critical magnetic Rayleigh number about $R_m^* = 1820 \pm 100$. An excellent agreement with the theoretical prediction of $R_m^* = 1880$ is found.

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References

[1] V.K. Polevikov and V.E. Fertman, Magnetohydrodynamics 13 (1977) 11.

[2] L. Schwab, Thesis, Universität München (1989).

[3] B.M. Berkovsky and V.K. Polevikov, Numerical Experiments on Convection (Minsk, 1988) (in Russian).