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Interaction of gravitational and magnetic mechanisms of convection in a vertical layer of a magnetic fluid

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Abstract

Mixed thermo-gravitational and thermo-magnetic convection in a vertical layer of non-conducting magnetic fluid is investigated. Various convection patterns found computationally are confirmed experimentally.

Keywords: Ferrofluid; Magnetic convection; Gravitational convection

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1. Introduction

The study of heat transfer characteristics of magnetic fluids is of primary interest in designing cooling systems operating in zero-gravity environment. However, in realistic spacecraft conditions the effective gravity is almost never zero due to various micro-accelerations associated with equipment vibrations (high frequency gravity modulation) or maneuvering of the ship (quasi-static gravity modulation) [1]. Therefore it is important to study combined convection caused by the competing gravitational and magnetic mechanisms.

Investigation of such an interaction at normal gravity is a challenging experimental task. For example, studies [2,3] did not detect any significant influence of a transverse magnetic field on the stability of a shear flow in a vertical layer of a magnetic fluid heated from a side (Fig. 1a). The major reason for this was that thick (~1 cm) layers of fluid were used in experiments [2,3], where gravitational convection dominated the flow. An earlier theoretical investigation [4] was also inconclusive as it was performed assuming that horizontal convection rolls similar to those observed in pure gravitational convection form a major perturbation pattern. However, more recent experimental studies [5] and a linear stability analysis of two- and three-dimensional disturbance patterns [6] showed that the most dangerous perturbations disrupting a vertical shear flow have the shape of vertical rolls (Fig. 1b). They are caused by the thermo-magnetic effects. The further investigation of the interaction between gravitational and thermo-magnetic convection mechanisms is the goal of the present work.

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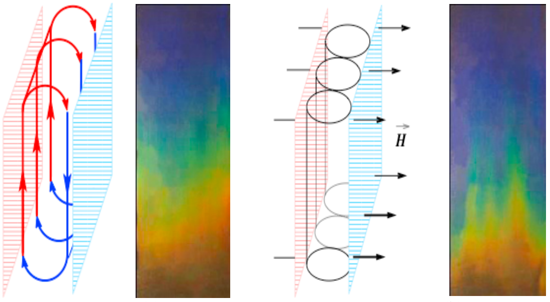


(a) (b)

Fig. 1. Qualitative diagrams and photos of (a) shear flow and (b) thermo-magnetic vertical rolls at $\Delta T = 22$ K and $H = 0$ kA/m and $H = 11$ kA/m, respectively. The temperature variation from cool (brown) to warm (blue) liquid is approximately 4 K. Magnetic field is perpendicular to the plane of photographs.

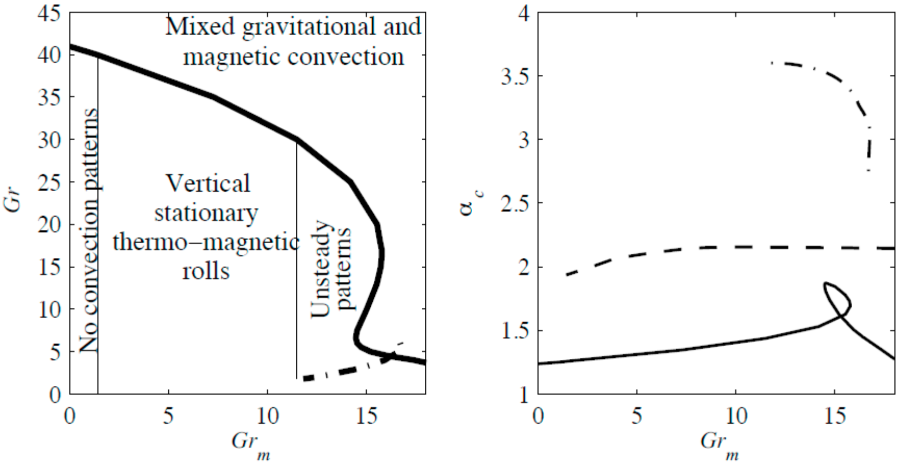
2. Experimental setup

A simple geometry of a tall and wide vertical cavity heated from one side and placed in a perpendicular magnetic field was chosen. Two vertical slots (referred as Cavity 1 and Cavity 2 below) with the thicknesses of 3.5 mm and 6.0 mm and the heights of 75 and 255 mm (aspect ratios of 21 and 42, respectively) with heated vertical walls made of copper and brass were used in experiments. The cool transparent walls were made of Plexiglas. Since a magnetite-based ferrofluid is not transparent, a heat-sensitive liquid-crystal films with working temperatures in the range of 24–27^{0}C and 18–22^{0}C were glued to the inner side of transparent walls to visualize the thermal field. When the flow is relatively slow the relationship between the transverse velocity component and the convective distortion of the temperature field is approximately linear. Therefore color variations from brown (cool) to blue (warm) in a liquid-crystal thermo-indicator were compared with a non-convective state to identify the flow pattern and estimate its intensity.

Experiments were performed with two kerosene-based magnetic fluids with magnetic saturation $M_S = 55$ and 70 kA/m, mean particles size of 10 nm, magnetic phase concentration 10 % and 14 %, density $\rho = 1.25 \cdot 10^3$ and $1.44 \cdot 10^3$ kg/m^3 and dynamic viscosity $\eta = 0.006$ and 0.008 kg/(m·s), respectively. Homogeneous magnetic field $H \le 40$ kA/m was generated by a Helmholtz coil.

3. Results and discussion

The destabilization of the primary flow in magnetic fluids is caused by two major physical mechanisms: the action of the ponderomotive magnetic force and the buoyancy force. The computational stability map of a shear flow in an infinite vertical layer placed in the uniform horizontal magnetic field (see Fig. 1b) is shown in Fig. 2, where $Gr_m = \rho\mu_0 K^2\theta^2 d^2/\eta(1+\chi)$ and $Gr = \rho^2\beta\theta g d^3/\eta^2$ are the magnetic and gravitational Grashof numbers, respectively. Here μ_0 is the permeability of vacuum, β is the coefficient of thermal expansion, K is the pyromagnetic coefficient, χ is the differential magnetic susceptibility, $2d$ is the thickness of a fluid layer and 2θ is the temperature difference between the heated and cooled enclosure walls. For small values of Gr_m and large values of Gr the thermo-gravitational instability mechanism dominates (left top corner of Fig 2a). In high Prandtl number fluids such as a typical kerosene-based ferrocolloid the thermo-gravitational instability takes the form of two counter-propagating waves. They are almost insensitive to a magnetic field when Gr_m is small in comparison to Gr. However as the ratio Gr_m/Gr increases along the top solid line in Fig. 2a the thermo-magnetic effects intensify significantly and eventually become dominant. It is noteworthy that although the dominant physical mechanism of instability changes, this happens in a continuous way. The only observable indication that such a change has indeed occurred is in the qualitative behavior of the disturbance wave-number: as Gr_m increases so does the wavenumber of thermo-gravitational waves. However this trend is reversed once thermo-gravitational waves are replaced with thermo-magnetic waves, see the solid line in Fig. 2b. The energy analysis of various convection patterns found numerically at a number of points selected along the solid line in Fig. 2a confirms that the energy driving convection patterns is contributed by the buoyancy near the left end of the curve and by the magnetic forcing near its right end [7]. The transition from the buoyancy to magnetically driven patterns occurs between the two turning points of the curve.



(a) (b)

Fig. 2. Parametric map (a) and wavenumbers (b) of the dominant convection patterns for an infinite vertical layer of a ferrofluid. The solid, dashed and dash-dotted lines correspond to mixed gravitational and magnetic convection, vertical magneto-convection rolls and thermo-magnetic waves, respectively.

At low to moderate values of the gravitational Grashof numbers (the middle region in Fig. 2a) the stationary vertical thermo-magnetic rolls (cf. Fig 1b), dominate the flow. Their wavenumbers remain almost constant for the increasing values of Gr_m, see the dashed line in Fig. 2b.

The spatial orientation of the instability patterns detected numerically is strongly related to the physical mechanisms causing them: the propagating thermal or thermo-magnetic instability waves form horizontal or inclined convection rolls, while stationary magneto-convection rolls are vertical. The time-dependent combination of these three basic patterns is observable in the corresponding parametric region located to the right of the vertical roll region in Fig. 2a. The wavenumbers of the most rapidly growing patterns of each type are shown in Fig 2b and the examples of the corresponding experimentally observed combined flow fields are presented in Fig. 3.

Note that magnetic particle aggregates are formed in a magnetic fluid. Their number and sizes depend on the experimental conditions and affect the rotational viscosity of the fluid. Therefore the values of the gravitational and magnetic Grashof numbers change with time. This complicates the comparison of the experimental results with values computed assuming constant viscosity. While such variations of fluid properties do not affect the qualitative behavior of the flow they alter its quantitative characteristics. This discrepancy presents a fundamental difficulty in comparing computationally and experimentally obtained critical values of parameters at which the transition from one convection pattern to another occurs. Therefore the computed critical values of Gr and Gr_m should only be considered as estimates of their experimentally determined counterparts.

Figures 3 and 4 show photographs of instantaneous spatial convection patterns observed in fluid layers with different height-to-thickness ratios. The red/brown regions in the photographs correspond to a convection flow of a cool fluid away from the enclosure's cool wall while the blue/green strips show the location where warm fluid impinges the photographed cool surface. Therefore each blue/green-red/brown pair corresponds to an individual convection roll.

When the contributions of ponderomotive and buoyancy forces are comparable (i.e. the values of Gr and Gr_m are similar) a complex oscillatory flow pattern, consisting of vertical rolls with patches of horizontal and inclined rolls, was observed experimentally in a thinner layer (Cavity 1), see Fig. 3. This is in agreement with computational findings. At the larger values of Gr the oscillatory instability of vertical rolls detected in Cavity 2, see Fig. 4, manifests itself via the periodic variation of their wavelength: the number of rolls in the lower half of the cavity doubles and halves over a period of several seconds. In a stronger magnetic field the inclined rolls are formed that drift slightly down in the direction perpendicular to their axes with the speed of about 3-4 mm/s, consistent with numerical predictions of [6].

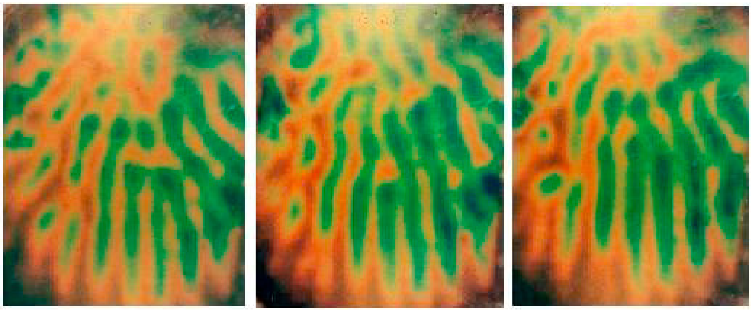


Fig. 3. Unsteady patterns for $(Gr_m, Gr) \approx (15,15)$ in Cavity 1. The time interval between snapshots is 2 min.

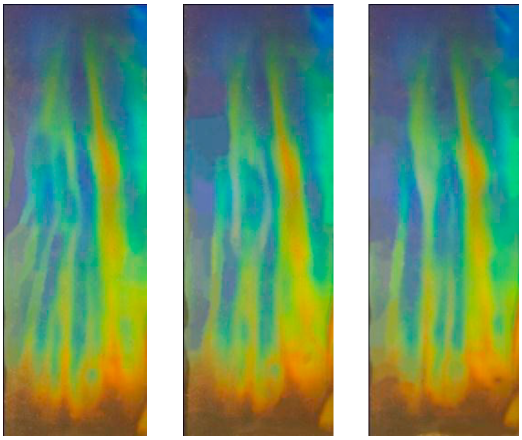


Fig. 4. Traveling rolls for $(Gr_m, Gr) \approx (20,35)$ in Cavity 2. The time intervals between snapshots are 30 and 50 s. The arrow shows the direction of roll motion.

4. Conclusions

The existence of computationally predicted stationary vertical magneto-convective rolls and propagating inclined thermo-magnetic patterns was confirmed experimentally. Experimental observations in a thicker layer also indicated that the arising convection patterns are influenced by thermal stratification and are most profound in the colder lower part of the cavity.

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