EXPERIMENTS ON FERROFLUID CONVECTION IN A SPHERICAL CAVITY

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Introduction. The study of ferrofluid convection in a spherical cavity is very interesting for understanding the uniform external magnetic field action on convective instability, flows and heat transfer. This geometry also allows to understand magneto-viscous, concentration and induction effects. The present investigations were performed to examine the influence of an external homogeneous magnetic field on gravitational, natural and thermomagnetic convection in the magnetic fluid and their mutual impact. The profound effect of gravity sedimentation of magnetic particles and their aggregates on the convective instability and the shape of fluid motion has been revealed under heating from below. The influence of magnetic disturbances induced by temperature inhomogenities of magnetization on thermomagnetic instability and heat transfer was considered theoretically and experimentally.

1. On experimental and theoretical apparatus. As known, if there is a uniform temperature gradient in a solid body at infinity, the isotherms in a fluid sphere, which cut out therein, become horizontal before the attainment of the critical Rayleigh number $\mathrm{Ra_c}$ [1]. At the critical Rayleigh number the replacement of heat-conducting regime by convection takes place. When the thermal conductivities of the fluid and solid body are about unity, the heat exchangers may be installed closely to the cavity [2]. The ratio of ferrofluid and Plexiglass thermal conductivities is 1.3 that enables to place the heat exchangers close to the spherical cavity.

A spherical cavity of 16 mm in diameter was cut in a Plexiglass block. Its poles were pressed to aluminium heat exchangers through the parallel plexiglass plates of 1 mm thick. The temperatures of pumping thermostat water were fixed with the accuracy of 0.05 K. With the help of differential thermocouples the temperature perturbations θ_1, θ_2 being in proportion to temperature rectangular components of the basic vortices, which rotate around mutually orthogonal axes, were registered in the equatorial plane of the fluid cavity. The temperature differences θ_3 and ΔT were measured between the cavity poles and the heat exchangers.

Experiments were performed with a kerosene-based magnetic fluid having the following parameters: magnetic saturation $M_\mathrm{S} = 48$ kA/m, initial susceptibility $\chi = 5.7$, mean particles size 10 nm, density $1.25 \cdot 10^3$ kg/m^3, dynamical viscosity in zero magnetic field 0.006 kg/m $\cdot$ s. A uniform magnetic field was generated by a Helmholtz coil set or an electromagnet. The magnetizing forces were changed from 0 before 120 kA/m.

In spherical geometry, there are a number of critical motions accounted for lower levels of the spectrum of convective instability [1, 2, 3, 4]. Thus, in the case of an opaque magnetic fluid the measuring of transverse heat flux through the fluid is a more foolproof method of convection threshold determination than the registration of various flow patterns. In order to register the heat flux. the temperature difference across the solid layers $T_\mathrm{S} = \Delta T - \theta_3$ was compared with the temperature difference through the fluid θ_3 [5].

Theoretical study was carried out under the assumption of constant temperature gradient and magnetic field in the solid body at infinity. The viscosity and thermal conductivities of the fluid and solid medium were invariable. The linear dependence of magnetization on the temperature and the magnetic field strength was used. The distributions of velocity, magnetic field, pressure and magnetization were defined from the system of equations of hydrodynamics and continuum electrodynamics [6]. The solutions of the system were expanded by Legendre polynomials. The reason of magnetic field distortions in the spherical geometry is considered to be the heterogeneity of magnetization because of the non-isothermal medium.

2. The influence of gravity sedimentation of aggregates on convection. The minimal Rayleigh number for a homogeneous liquid at spherical cavity heating from below corresponds to the plane stationary circular motion with zero range rates [1, 2]. The tests on visualization of the flows provided with a water-glyceric fluid in the described above sphere have shown that the convection motion arises softly, without hysteresis, and represents a horizontal stationary vortex with the axis passing through the centre of the cavity. In contrast to this, the convection in the ferrofluid develops in a finite-amplitude manner, with hysteresis, and has an oscillatory character.

The critical temperature difference ΔT_c, corresponding to the convection threshould, was about 1 K for the situation of gradually decrease of temperature drops. When the convection originates from the subcritical region, ΔT_c was nearly 1.5 K. Both critical values are of much higher estimations (~ 0.1 K) for the first bifurcation at $\mathrm{Ra_c} \sim 350$ (a convective parameter taken from the experiments). For the temperature oscillations of θ_1 and θ_2 there are turns of the axis of horizontal roll. In zero magnetic fields with the increasing of ΔT the near-threshold quasi-harmonic temperature oscillations changed to non-sinusoidal (with a larger time period) and relaxation ones. Then a stationary flow was formed. A similar behavior was also observed in the presence of vertical magnetic field.

Fig. 1 presents the execution behaviour of the convective system in the presence of vertical magnetic field with $H = 32$ kA/m. As non-dimensional temperatures were used $\Theta_1 = \theta 1/\Delta T$ and $\Theta_2 = \theta_2/\Delta T$. In the center of the cavity, where the temperature field is close to linear, they play the roles of angular velocities of horizontal temperature vortices. The point of the origin corresponds to equilibrium of the system. The directions of affix movement are shown by arrows. The vector connecting the point of the origin with the affix has a direction and length,

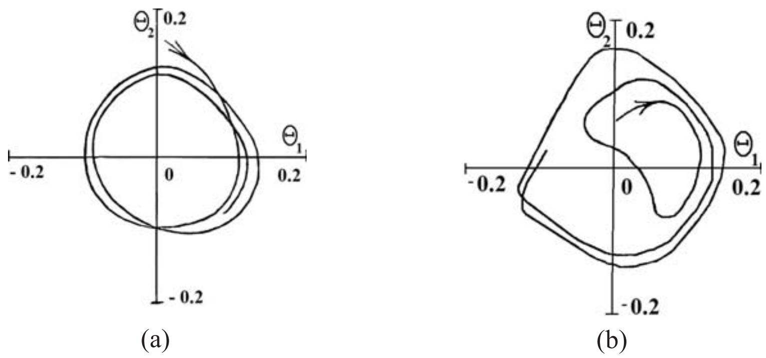
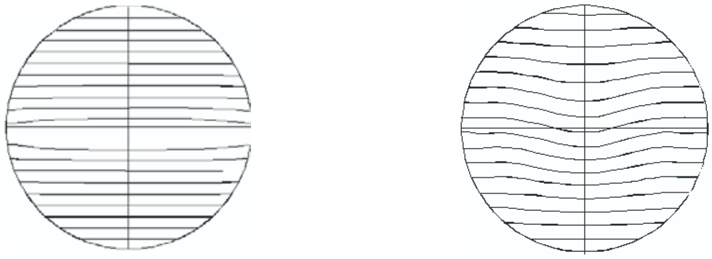


Fig. 1. Phase-plane portraits for a spherical ferrofluid cavity heated from below and subjected to a vertical magnetic field with $H = 32$ kA/m for $\Delta T/\Delta T_c$: (*a*) 1.7, (*b*) 2.5. Here $\Delta T_c = 1.5$ K is critical temperature difference.



(a) (b)

Fig. 2. The isolines of the module of magnetic field strength (a) and the temperature (b) for magnetic conductivity $\mu = 5$.

which denote the orientation and the value of the angular velocity of the vortex. The limit cycle in the form of ellipse corresponds to near-threshold quasi-harmonic oscillations (Fig. 1a). At a higher temperature drop when the non-sinusoidal temperature oscillations take place the movement of the affix is visible as a rectangle phase portrait (Fig. 1b).

3. The influence of magnetic field distortion on convection. The theoretical solutions for the non-isothermal sphere have shown that the magnetic disturbances induced by temperature heterogeneities of magnetization excite a nonthreshold weak convective motion which turns out an avalanche flow upon reaching the critical parameter. Similar nonthreshold flows arose at slight inclination of the cylinder [7] or in a slightly mis-shapen sphere [3]. In numerical simulations [8] the nonthreshold convection was induced by the magnetic field distortions in a square geometry subjected to the external uniform magnetic field, where the cause of the distortions was the walls of the cavity.

Fig. 2 presents the profile of the spherical ferrofluid cavity when heated from below. The isolines of the module of magnetic field strength are shown in Fig. 2a. In contrast to the definitely horizontal and parallel to each other lines in the isothermal state, there is an appreciable deformation of the force lines especially in the centre of the sphere. This is pictured for the ratio of dimensionless parameters of magnetic field distortion and the magnetic field at infinity equalling unity. The isotherms for such situation are illustrated in Fig. 2b. They correspond to a convective pattern which is superposition of two asymmetric relatives to equator tores.

As shown in [9], the ratio of magnetic and gravitational Rayleigh numbers is proportional to the ratio of the applied temperature difference to the characteristic height of the convection cavity. When the cavity height is 16 mm, the buoyancy forces are much more than magnetic ones. Moreover, at small values of ΔT, as in the present experiment, the stabilizing role of gravity sedimentation of aggregates acts on the foreground that is confirmed by the conservative value of the critical temperature and the oscillatory regimes near the onset of convection. Thus the induction effects are weakly observed at the heating from below.

On the contrary to the heating from below, the thermomagnetic convection in the presence of vertical magnetic field and at the heating from above arises without a clear threshold (Fig. 3). The intensity of the initial flow and the effective heat flux, respectively, increase with the rise of the magnetic field strength. The heat flux is proportional to the temperature difference T_{S} through the solid layers. As seen from the graph, the modifications due to the nonthreshold primary motion amount to one fourth of the applied temperatures at strong magnetic fields. Bifurcations from one forms of convection motion to the other – a proper thermomag-

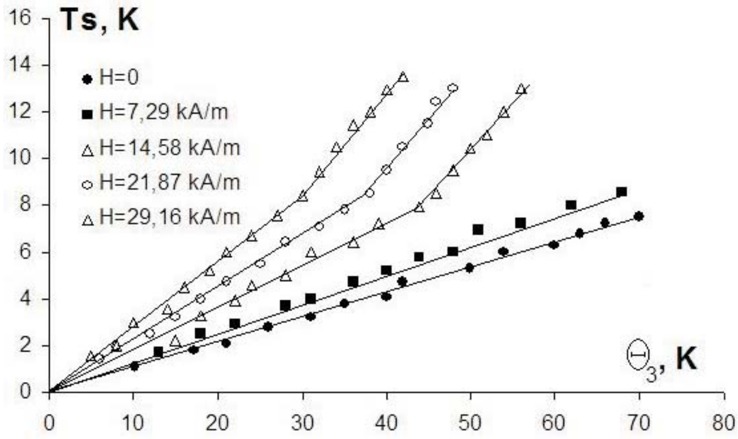


Fig. 3. Heat transfer versus the applied temperature difference at fixed values of the magnetic field H in a ferrofluid sphere at the heating from above.

netic flow – take place at larger temperature differences. The critical temperatures corresponding to thermomagnetic convection are diminished with the increasing of the magnetic field as in the experiments with the horizontal layer [9].

4. Conclusion. As the experimental and theoretical investigations show, when study the ferrofluid convection in a spherical volume subjected to a uniform magnetic field, it is necessary to take into account the effects of gravity settling of magnetic particles and the magnetic field distortions due to the temperature dependence of magnetization.

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