THE INFLUENCE OF EXTERNAL UNIFORM MAGNETIC FIELD ON CONVECTION IN MAGNETIC FLUID FILLING A SPHERICAL CAVITY

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The influence of a uniform external magnetic field on convection flow instability and heat exchange in a spherical cavity filled with a magnetic fluid and heated from below is investigated experimentally. It is shown that a horizontal field orients the axis of a convection vortex along the vector of field intensity. It is also shown that the increase of the applied field weakens convection and eventually leads to its decay.

Introduction. Magnetic fluids can be used as effective heat carriers in various thermosiphons, energy converters and magnetic field generators [1, 2]. The application of such nano-suspensions is especially important when flows induced by gravity are weak (microelectronics) [3, 4] or gravity is absent (orbital stations) [5, 6]. Potential applications of ponderomotive forces induced in magnetic fluids also include modeling of centro-symmetric gravitational forces in the studies of ocean streams and gravi-capillary flows in microgravity [7]. A centro-symmetric force field can be created by a system of permanent magnets as it was done in magneto-convection experiments in a spherical shell [8]. Theoretical studies of magnetic fluid flows inside a sphere placed in a spatially uniform unsteady magnetic field were reported in [9].

It is commonly believed that a uniform magnetic field cannot have a significant influence on convective stability and heat transfer in magnetic fluid layers [10, 11]. Therefore, many past experimental and numerical studies had been conducted in cubic cavities, where the uniformity of the external field was distorted by the enclosure boundaries [11]. In a spherical cavity, the uniformity of a magnetic field cannot be destroyed by the effect of the boundary geometry [12]. However, theoretical and experimental studies of flows in a non-isothermal spherical enclosure show that a similar effect can be achieved due to the dependence of the fluid magnetisation on the temperature [13–15]. In this paper, we continue investigation on the influence of a uniform external magnetic field applied horizontally on the stability characteristics of magnetic fluid flows in a differentially heated spherical enclosure. Note that in addition to the destabilizing thermomagnetic effect and the stabilizing influence of gravitational sedimentation of particles and aggregates [16], an additional mechanism, a negative thermo-diffusion [17], suppressing convection in a layer heated from below, exists in a longitudinal magnetic field.

1. Experimental setup. The experimental setup is shown schematically in Fig. 1. A spherical cavity 1 of diameter 16.0 ± 0.1 mm was cut in a Plexiglas block 2 consisting of two identical plates with the overall dimensions 53 × 53 × 18 mm³. The block was placed between two aluminium heat exchangers 3, which were maintained at constant different temperatures by the water pumped through them.

In order to characterise convection instability, the equilibrium temperature field within the cavity was measured. When convection sets up, the axial symmetry
of the temperature distribution inside the cavity breaks. This enables one to detect the onset of instability by registering the deviation of the temperatures at the poles from the equilibrium values by comparing the temperature differences between two arbitrary points located straight above and below the poles in the block surrounding the cavity. Therefore, two 1 mm thick Plexiglas plates 4 were inserted between the poles and the heat exchangers. Differential copper-constantan thermocouples were then used to register the temperature difference $\Delta T$ between the poles and temperature drops $\Delta T_s = \Delta T'_s - \Delta T$ across the inserts, where $\Delta T'_s$ is the temperature difference between the heat exchangers. Thermocouple wires were 0.1 mm in diameter. The calibrated thermocouple output was $40 \mu V/K$. As shown in [18], when the ratio of thermal conductivities of the fluid to the solid is close to unity, that was indeed the case for magnetic fluid and Plexiglas, the inserts could be very thin.

Four equidistant 3 mm long thermocouples were placed in the equatorial plane of the cavity. A single convection vortex with the horizontal axis of arbitrary orientation corresponding to the first instability mode in a sphere [18, 19] can be represented as a superposition of two orthogonal basic vortices. Temperature components $\Theta_i$ of such basic vortices, where $i = 1 \div 4$ are the thermocouple numbers, were measured relative to a common juncture denoted by the symbol ‘0’ in Fig. 1. This enabled us to detect higher supercritical harmonics [19].

A schematic diagram of the experimental setup is shown in Fig. 2. The temperature difference in the cavity 1 was maintained by jet thermostats KRIOT-01 2 with an accuracy of 0.02 K. The cavity was placed in a uniform magnetic field created by Helmholtz coils 3 that were powered by a DC source GPR-11H30D 4. The maximum magnetic field $H$ created at the center of the coils was 56.2 kA/m. The coils had an average diameter of 300 mm and wiring of height along a radius of 130 mm. The working zone within the coils had a diameter of 200 mm.

The thermocouple readings were recorded using the data acquisition device “Thermodat” 5 connected to a computer 6. The data acquisition protocol was driven by the software package “TermoNet”. The data was saved every 5 s that is one-two orders of magnitude smaller than the characteristic flow times.
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Fig. 3. Oscillatory regime initiated via strong subcritical excitation at \( H = 0 \)
\( \Delta T/\Delta T_c = 1.1 \).

Fig. 4. Readings of thermocouples located in the equatorial plane, as shown in the
bottom right-hand diagram for \( H = 0 \) and \( H = 7.2 \) kA/m (to the left and to the right
of the vertical dashed line, respectively) at \( \Delta T/\Delta T_c = 3.2 \). The bottom left-hand diagram
shows the vector of the angular velocity \( \omega \) of a convection vortex, which can have arbitrary
direction in the absence of magnetic field. When a magnetic field is switched on, the
vector of the angular velocity \( \omega \) draws up along to the magnetic force lines, as shown in
the bottom right-hand diagram.

(during the first 16 hours since the start of experiment) and then started to increase
leading to strongly nonlinear oscillations.

In order to ensure homogeneous initial conditions before the magnetic field
was switched on, in each experiment, the fluid was being mixed for several hours
by side heating applying the temperature difference \( \Delta T' = 40 \div 50 \) K.

Fig. 4 shows thermocouple readings of the temperature components of the
basic vortices of \( \Theta_i \) located, as shown, in a bottom right-hand diagram. The
vertical dashed line denotes the moment when a uniform horizontal external field
was applied. The temperature difference between the two heat exchangers was
maintained constant, and the temperature difference between the poles of the
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temperature difference of $\Delta T \approx 2.6 \Delta T_c$, convection decays at $H = 50 \text{kA/m}$, and at $\Delta T/\Delta T_c \approx 1.6$ the conduction state is restored at $H = 20 \text{kA/m}$.

Therefore, the horizontal magnetic field not only orients the axis of a convection vortex, but also inhibits the development of convective perturbations along the field thus strengthening the stability of mechanical equilibrium. A similar effect was reported in [24] for a vertical fluid layer heated from below and exposed to a horizontal magnetic field.

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