# ON FEATURES OF MAGNETIC CONVECTION IN FERROFLUID

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Summary Experiments were performed to examine the influence of external homogeneous magnetic field on ferrofluid convection. The results indicate that with the help of a magnetic field it is possible to control the stability and the form of convection motions. A number of non-linear regimes of convection, e.g. spiral-defect chaos, blinking and localized states were observed.

Magnetically driven convection in insulating media is actively investigated last years due to uses in the field of materials processing, e.g. crystal growth from protein solution and paramagnetic melts. The magnetic body force in magneto-polarized liquids is not the pondermotive force of magnetohydrodynamics, which requires a conducting fluid, but arises simply from the force of a nonuniform magnetic field on the molecular dipoles. This force is independent of gravity and its greatest utility will surely be in microgravity environments. However, for diamagnetic and paramagnetic materials, the pondermotive force exerted by a typical magnet is insignificant compared to gravity-induced buoyancy one. Therefore, a ferrofluids (colloidal suspension of monodomain particles), which has the susceptibility thousand times higher then natural fluids, are very convenient medium for ground-based modeling of magnetic convection.
The experiment was performed to examine the influence of external homogeneous magnetic fields on convective instability, heat transfer and flow patterns in ferrofluid layer heated from one wide side and cooled from another in a range of inclination angles from $\alpha = 0^0$ (heating from below) to $180^0$ (heating from above). Visualization of flow structures is provided by a temperature-sensitive liquid crystal. The heat transport was measured by integral or local temperature sensor.
The influence of an externally applied magnetic field upon a buoyant convection within a magnetic fluid is characterized by two main factors. The first one is the driving force connected with a spatial variation in magnetization and it is realized in transversal field. The second factor is comparatively weak suppressive force arising due to interaction between applied field and distortions of magnetization induced by a convection motion. The demagnetizing effect is primarily researched as related to horizontal fluid layer subjected to a longitudinal field.
The experiment also shown that the sedimentation effects due to the settling of magnetic particles and their aggregates in gravity field can play the material role in magnetic fluid convection. The competitive action of thermal and concentration density gradients results in oscillatory and traveling wave, mostly spatiotemporally chaotic, convection in the entire region of control parameters [1]. Besides, under definite conditions the gradients of concentration nature may influence on convection instability. For example, in the absence of magnetic field in contrast to a single component fluid, the thermal convection in ferrofluid appears “hard” and with hystersis, and the patterns consist of disordered convection rolls and cells, which prominently feature the persistent spontaneous appearance and disappearance of spirals irregularly in time and in space (fig. 1(a)).
At laboratory tests to intensify the magnetic body forces in comparison with gravity buoyancy ones it is necessary to create the conditions when magnetic Rayleigh number $Ra_M = \mu_0(\beta_m M\Delta Th)^2/\rho\nu a(1+\chi)$ exceeds or compares with gravitational parameter $Ra = g\beta\Delta Th^3/\nu a$. Here $\beta_m$, M, $\nu$, $\chi$, a are relative pyromagnetic coefficient, magnetization, kinematic viscosity, differential susceptibility, thermal conductivity of magnetic fluid, $\mu_o$ -permeability of free space, $\Delta T$ - temperature difference across the layer, h – layer thickness, g and $\beta$ - acceleration due to gravity and thermal expansion coefficient. The ratio $Ra_M/Ra \sim M^2\Delta T/h$ shows that it is need to use the layers with small thickness, the great temperature drops and liquids with high magnetization.

**Ferrofluid convection in the presence of transversal magnetic field**

The experiments on convection instability of horizontal ferrofluid layer in the presence of transversal magnetic field revealed that the behaviour of system strongly depends on value of magnetic Rayleigh number. To control $Ra_M$ the colloids with different values of magnetic saturation $M_S$, i.e. with the different concentrations of magnetic phase, are taken in our experiments. Under concept overview [2], in concentrated ferrofluid with $M_S = 48$ kA/m and $Ra_M \sim 3\cdot10^3$ the driving forces prevail over suppress ones. In this case the magnetic forces facilitate the onset of convection and increase its intensity of motion. At moderate magnetic fields critical temperature difference of convection onset decreases twice and heat transport across fluid layer is intensified three times even under layer heating from above. Under inclination of ferrofluid layer from $\alpha = 0^0$ to $180^0$ the magnetic field also renders destabilising effect on the development of Rayleigh roll motion.
In weak concentration colloid ($M_S = 18$ kA/m), when $Ra_M \sim 50$, the concentration drops of density overwhelm thermomagnetic and buoyancy stirring and begin to render essential stabilizing influence on the convective instability. In the presence of magnetic field the convection starts via subcritical bifurcation and with hysteresis; critical temperature differences and depth of hysteresis increase with the rise of magnetic field strength. The rate of fluid movement and the heat transfer at the heating from below are distinctly decreased.
One should note that unicellular buoyancy driven shear flow in a vertical layer subjected to transversal magnetic field breaks down due to excitation of the thermomagnetic rolls, aligned with the direction of the basic motion. Thus, in this situation the magnetic field influences on the instability, heat transfer but also on structure of secondary flow.

**Ferrofluid convection in the presence of longitudinal magnetic field**

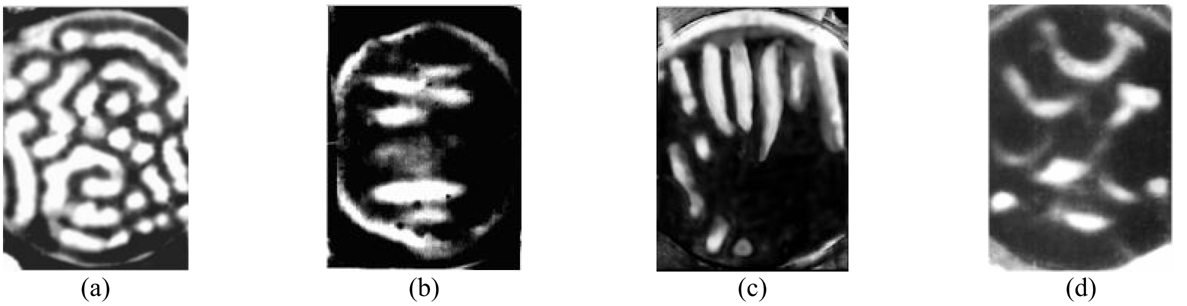
In accordance with the theory [3], the convection threshold in horizontal ferrofluid layer heated from below and subjected to longitudinal magnetic field does not depend upon magnetic field strength and the convection rolls in magnetic field align themselves so that their axes tend to be parallel to the imposed field. However, in contrast to linear theory in the entire region of control parameters only oscillatory traveling wave convection is observed. The confined states when the regions with conductivity and convection heat transfer are irregular changed in different parts of container occur not far from the onset of convection (fig. 1(b)). At highest values of control parameters the traveling rolls known as "blinking state" [4] arise.

**Ferrofluid convection in an inclined layer**

A similar orientation effect as in the case of a longitudinal magnetic field occurs in a liquid stream in the presence of Rayleigh instability. The thermally driven shear flow in an inclined layer draws up convection rolls in the direction of inclination. In the absence of magnetic field the multiplicity of nonlinear wave regimes as in the case of longitudinal magnetic field are observed (fig. 1(c)). The repeated transients involving roll convection and pure shear flow are also revealed.

**Interaction of gravitational and magnetic mechanisms of convection in an inclined layer**

In contrast to the horizontal layer, the action of longitudinal magnetic field orientated perpendicular to flux velocity of base shear motion can lead to completely stabilization of Rayleigh roll convection in the case of inclined layer. Near the stability boundaries of basic thermally driven shear flow the complicated patterns and different types of chaotic localized states (or pulses) take place (fig. 1(d)) because of hydrodynamic and magnetic interplay.



(a) (b) (c) (d)

Figure 1. Liquid crystal surface photographs for Rayleigh convection in ferrofluid layer at: (a) $\alpha = 0°$, $H = 0$, $\Delta T/\Delta T_C = 1.5$; (b) $\alpha = 0°$, $H = 17$ kA/m, $\Delta T/\Delta T_C = 1.3$; (c) $\alpha = 15^0$, $H = 0$, $\Delta T/\Delta T_C = 1.8$; (d) $\alpha = 25°$, $H = 1$ kA/m, $\Delta T/\Delta T_C = 2$; $\Delta T_C = 5.1$ K – critical temperature difference of the onset of Rayleigh convection in the absence of magnetic field. Temperature drop from cool (black) to warm (white) liquid is approximately 3 K. Each light (dark) strip in photographs corresponds to the same handedness of two neighboring rolls. Magnetic field is directed aflat to the plane of photographs from the left to the right.

## CONCLUSION

Thus, the ferrofluid may be used as modeling fluid to study thermomagnetic convection mechanism that can act in all diamagnetic and paramagnetic media. On the other hand, it offers a new magnetic field controllable system for the study of so-called spatio-temporal chaos near the convection threshold [5], which previously have been studied experimentally in gases, binary mixtures, nematic liquid crystals and so on.

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