EXPERIMENTAL AND NUMERICAL STUDY OF OSCILLATORY CONVECTION IN FERROFLUIDS

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Introduction. Experimental studies of Rayleigh convection in a shallow disk have been conducted for a ferrofluid containing magnetite particles suspended in a kerosene carrier liquid. The oscillatory convection was observed in the entire investigated temperature region. The spiral and other wave regimes were revealed.

In zero magnetic fields and in the presence of temperature gradient the flux of magnetic particles in the studied system is influenced by the gravitational sedimentation as well as by Brownian and thermal diffusions. Due to thermal diffusion, the particles may migrate towards lower or higher temperature, corresponding to positive or negative Soret coefficients.

The temperature oscillations were registered using thermocouples. Visualization of convection patterns was provided by means of a liquid crystal sheet. Temporal evolution of the oscillations was analyzed using wavelets. The frequencies of temperature oscillations obtained under wavelet analysis were compared with the results of Fourier analysis and visual observations with the help of a video camera.

Explanation for the observed oscillatory convection is assumed to be concentration gradient of magnetic particles and their aggregates, in the studied fluid. To study the effects of initial concentration gradient of particles on convective instabilities, finite volume numerical simulations using a two-phase mixture model were carried out for the same setup.

1. Theory and background. In comparison to a pure fluid case, the dynamics and bifurcation scenario in binary mixtures are more complicated due to the extra degree of freedom associated with the concentration field [1]. The concentration gradients of magnetic particles may be developed due to the gravitational settling of magnetic particles and their aggregates or, when the temperature or the magnetic field gradients are present, due to thermal diffusion (Soret effect) and magnetophoresis, respectively.

In the absence of magnetic field, linear stability analysis [1] suggested that the convection instability for the positive values of the dimensionless separation ratio ψ, remains stationary and an oscillatory instability occurs only with negative values of the separation ratio. In the experiments oscillatory convection was observed in the entire investigated temperature region. Numerical simulations revealed the onset of either steady or unsteady oscillatory convection determined by the initial concentration gradient and the size of the particles in the fluid.

2. Experimental studies. Experiments were performed with a kerosene-based magnetic fluid having the following parameters: mean particles size 10 nm, magnetic phase concentration 10%, density $1.25 \cdot 10^3\,\mathrm{kg/m^3}$, dynamical viscosity 0.006 kg/ms, Prandtl number $6 \cdot 10^2$. To observe the convection patterns, a cylindrical fluid layer of thickness $h = 3.50 0.03$ mm and diameter 75 mm is used [2]. The bottom surface of the layer was a copper exchanger with the channels for

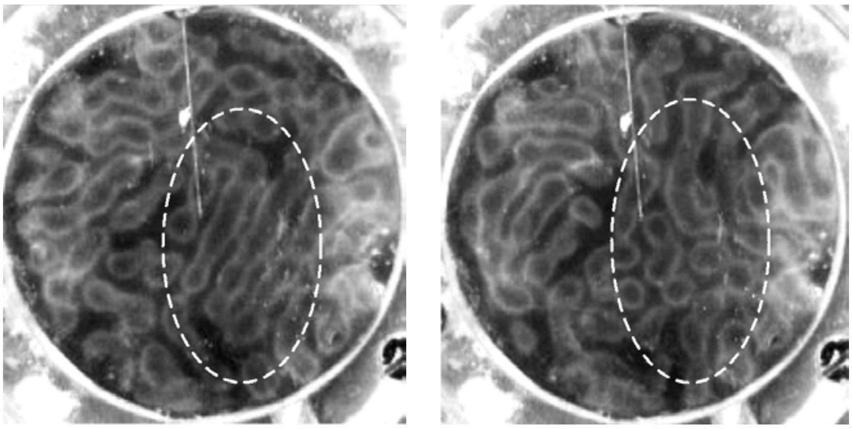

(a) (b)

Fig. 1. Liquid crystal surface photographs for $\Delta T = 2.1\Delta T_C$, where $\Delta T_C = 7.5$ is the critical temperature difference for the onset of Rayleigh convection. The time interval between snapshots (a) and (b) is 30 min. The temperature drop from cool (black) to warm (white) liquid is approximately 3 K. Each light (dark) strip in the photographs corresponds to the same handedness of two neighboring rolls.

constant-temperature circulating water. The top transparent heat exchanger was composed of Plexiglas parallel plates, which were separated by the gap for pumping thermostat water. The circular sidewall of the layer was made of Plexiglas. The liquid crystal sheet of 0.1 mm thick was used for visualization of convection patterns, so the ferrofluid is opaque to the light. The liquid crystal undergoes its entire color change from approximately 24 to 27°C from brown to blue color at an average temperature through the fluid layer 25°C.

The typical spatiotemporal patterns at $\Delta T = 2.1\Delta T_C$ are shown in Fig. 1. They consist of disordered convection rolls and cells, which spontaneously appear and disappear. The breaking-up of the roll pairs (Fig. 1*a*) and their subsequent partial recombination proceed through a cellular structure (Fig. 1*b*). Previously similar behavior was observed for a binary mixture and it is known as a "zipper state" [3]. The sample of temperature oscillations recorded at this ΔT is shown in Fig. 2*b*.

In order to study the nature of spatiotemporal variations of the temperature oscillations, wavelet analysis was conducted for temperature signals. The wavelet analysis gives information in the time-scale level and may be used to track the changes in the convection patterns as a function of the time. Wavelet-transform of the signal in Fig. 2*b* is presented in Fig. 2*d*. For comparison, a signal composed of five sinusoidal harmonics, corresponding to time periods of 4 h, 2 h, 1 h, 30 min and 10 min, and its wavelet transform are shown in Figs. 2*a* and *c*, respectively. The wavelet-analysis revealed that along with periods of 8–15 min there are periods from 1 to 6 hours. The existence of large and small periods is typical for other values of ΔT as well. As to the time evolution of patterns, there are slow movements of roll systems as a whole and a high-speed reconstruction of the convection rolls because of the cross-roll instability.

3. Numerical simulations. Numerical simulations were conducted using the finite volume simulation method. A simulation model was built on top of commercial Fluent software. In the model the ferrofluid is treated as a two-phase mixture of magnetic particles in a carrier phase. In the model the conservation equations for mass, momentum and energy are solved for the mixture phase. In addition, a mass conservation equation for the suspended particles and an algebraic expression for the relative velocity between the fluid and particles are solved [5]. More information about the theory and equations used in the model can be found from [4] and [5]. To study the effect of the concentration gradient within the fluid, the initial concentration of magnetic particles was varied. In order to avoid the complications caused by the large magnetic field gradients at the domain boundaries, the convection was studied in the absence of applied magnetic field. The simulations were carried out first for an initially homogeneous distribution of particles and then for an initial concentration gradient of $d\varphi/dz = -0.05$. The mean size of the magnetite particles in the studied fluid was 10 nm. In the simulations the particle diameter was varied from 10 to 100 nm in order to study the effect of larger particles or formation of clusters.

For single 10 nm particles there is now a significant sedimentation and the results were similar to those obtained with a homogeneous model. For larger particles or particle aggregates, when the initial sedimentation gradient was applied, the mixture model simulations revealed chaotic convection patterns, solid line in Fig. 3*a*. Close to critical Rayleigh numbers, competing actions of buoyancy and gravity lead to large fluctuations in the simulated heat flux signal. For an initially homogeneous fluid, dotted line in Fig. 3*a*, and for larger temperature differences, dashed line in Fig. 3*a*, a steady oscillatory convection was observed.

4. Discussion. Experimental studies of the Rayleigh convection in a shallow disk have been conducted for a ferrofluid containing magnetite particles suspended in a kerosene carrier liquid. The oscillatory convection was observed in the entire investigated temperature region. The spiral and other wave regimes were revealed. Wavelet analysis of the recorded temperature signal showed the presence of both low- and high-frequency reconstruction of the convection rolls because of the mean flow and cross-roll instability, respectively.

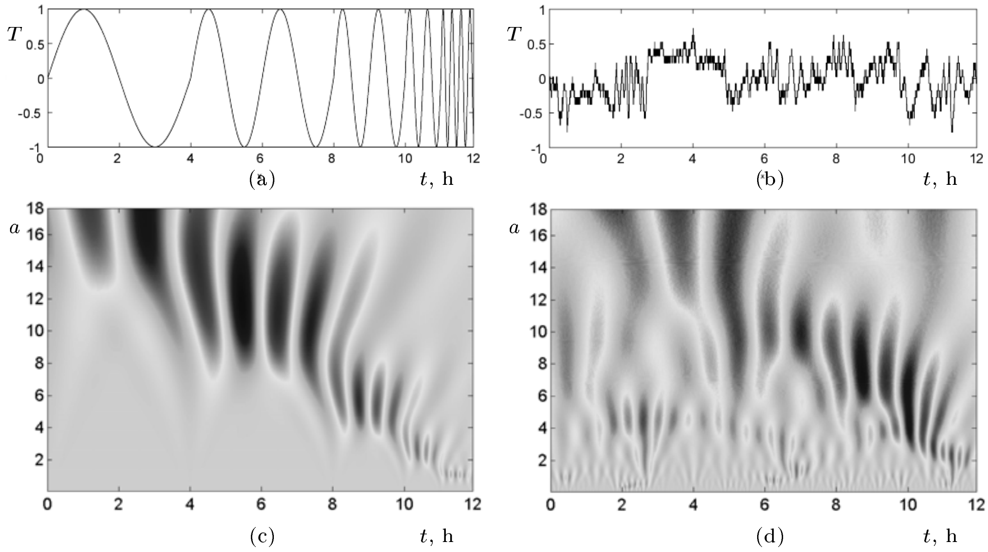
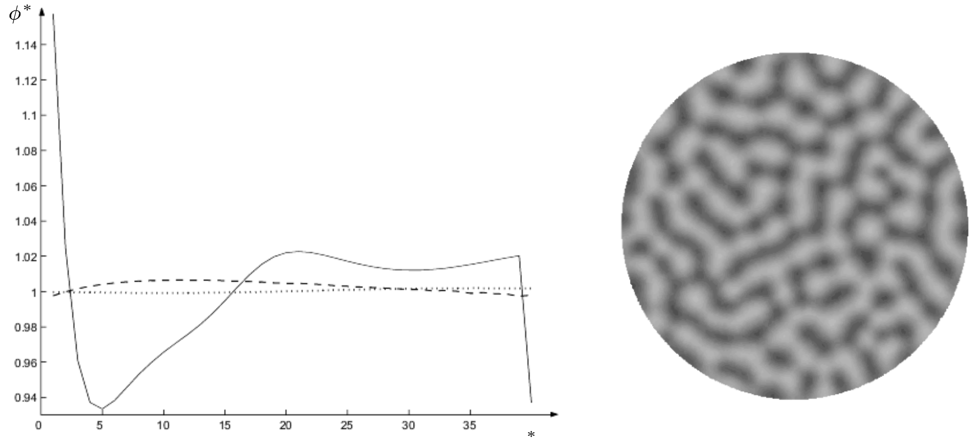


Fig. 2. (*a*) Signal composed of five sinusoidal harmonics, corresponding to time periods of 4 h, 2 h, 1 h, 30 min and 10 min, and (*c*) its wavelet transform. (*b*) Fluctuation component of the temperature oscillations recorded at $\Delta T = 2.1\Delta T_C$ and (*d*) corresponding wavelet transform.



(a)

(b)

Fig. 3. (*a*) Development of the normalized heat flux ϕ^* as a function of dimensionless time τ^*. Heat fluxes of different cases have been normalized using the mean value of heat flux of the corresponding case. Solid line represents the case with the initial concentration gradient $d\varphi/dz^* = -0.05$ and $\Delta T/\Delta T_c \approx 2$, dashed line is the case with $d\varphi/dz^* = -0.05$ and $\Delta T/\Delta T_c \approx 5$ and dotted line is the case with $\Delta T/\Delta T_c \approx 5$ for the initially homogeneous concentration of magnetic particles. (*b*) Snapshot of the simulated temperature contours for $\Delta T/\Delta T_c \approx 2$.

Mixture model computer simulations were carried out for the same setup to study the effects of the initial concentration gradient and the sedimentation of particles on the convective instabilities. For 100 nm particles, when the initial sedimentation gradient was applied, the simulations close to the critical temperature difference lead to chaotic convection patterns. In other cases, a steady oscillatory convection was observed.

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