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Thermal convection in a layer of magnetic colloid based on a single-component fluid

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ABSTRACT

Experiments on studying thermal gravitational convection in an undecane-based magnetic colloid layer are carried out. Undecane is a single-component carrier fluid. We use a cylindrical cavity with a diameter of 58 mm and a height of 2.4 mm to model a horizontal plane layer. Convection in the magnetic colloid layer heated from below is observed by means of a thermocouple system and a thermal imager. Several series of thermocouple measurements for a heat flux through the layer and thermal imaging survey for temperature fields at the magnetic colloid surface are performed at various average colloid temperatures. The average temperature increases from 20 to 55 °C in increments of 5 °C. A regime in the form of convective patterns consisting of stable downward flows in their centers and unstable upward flows along the edges is found in experiments. The Rayleigh number range for the regime shrinks as the average temperature increases. It can be seen from the convection regime map constructed in our study. We propose the hypothesis, according to which shrinkage of the Rayleigh number range and the instability of upward flows for this regime is due to the effect of aggregate sedimentation on convection in a horizontal magnetic colloid layer. Aggregate sizes decrease as the average colloid temperature rises.

1. Introduction

Fluids are used in the vast majority of scientific and technical problems as mass or heat transporters thanks to their main property - fluidity. An intention to enhance heat and mass transfer processes leads to the complication of fluid transporter composition. In particular, colloidal systems composed of solid particles and carrier fluids are produced. If these particles are made of magnetic materials (such as magnetite), the fluid acquires magnetic properties that help to control it by means of magnetic fields. Despite the obvious advantages of magnetic colloids over molecular fluids, there are serious difficulties in the production, operation, and behavior analysis of colloidal systems due to their complex composition. One of such problems is aggregate formation. Aggregates occur as a result of intermolecular and magnetic dipole-dipole interactions of solid magnetite particles. To stabilize the colloid and eliminate aggregation, producers add surfactants into its composition. Surfactant molecules cover each magnetite particle. There are various technologies to perform this procedure [1–4], but even the best of them cannot be 100% efficient. In spite of all, some particles will have defects in the molecular surfactant layer. Except defects in the surface surfactant layer, there are other factors that lead to the formation of aggregates such as a particle size distribution. So one should always take into account their presence and effect on fluid properties.

The shape and size of an aggregate depend on the interaction that has led to its formation. Magnetic dipole-dipole interactions result in occurrence of chain aggregates [5,6]. They are successive chains of individual particles. In the absence of an external magnetic field these chains curve and take nonlinear forms. Compact structures composed of several dozens of individual particles form due to van der Waals forces of intermolecular attractions. In [7] the structures are called quasi-spherical aggregates, which size depends on particle concentration. In particular, for 16% magnetic fluids it reaches 59 nm.

In the absence of a magnetic field heat and mass transfer in the magnetic colloid non-uniformly heated from below can be associated with thermal gravitational convection. It may occur because of the thermal expansion [8] and thermal diffusion (or the Soret effect [9]) effects, when a concentration gradient of solid particles arises in the fluid in addition to a temperature gradient. These phenomena produce an inhomogeneous density distribution if the fluid is non-uniformly heated. The temperature inhomogeneity growth can lead to a situation, when a density distribution

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becomes unstable and a motionless fluid state is replaced by convection. A similar situation is in the horizontal single-component molecular fluid layer heated from below due to the thermal expansion effect [8,10]. In multi-component colloidal media, fluid density inhomogeneities are associated with both thermal expansion and normal or anomalous thermal diffusion effects [11–14]. When the fluid is heated from below, normal thermal diffusion results in a directed upward concentration gradient of heavy solid particles. It leads to unstable density stratification. In magnetic colloids, normal thermal diffusion can play an important role due to large values of the Soret coefficient (for example, for a kerosene-based magnetic colloid it is equal to $S_T = 0.169\ \mathrm{K}^{-1}$) that is of two or four orders of magnitude larger than the Soret coefficient for molecular mixtures [14].

Working with colloids, one should not forget the particle sedimentation effect in a gravitational field. Sedimentation makes the motionless state of fluid medium more stable. In the horizontal colloidal fluid layer heated from below there is a competition between normal thermal diffusion and sedimentation in the presence of particle diffusion through the motionless array of the surrounding molecular fluid. The fluid is generally in the mechanical equilibrium state. As it was shown in [15], a redistribution of solid particles in suspensions at the motionless equilibrium state depends on the parameter $\beta = (v_S - v_T)H/D$, where v_S is the particle sedimentation velocity, v_T is the thermal diffusion velocity for upward particle movement in an opposite direction to a temperature gradient, H is the horizontal layer thickness, D is the particle diffusion coefficient. What the velocity v_S or v_T is greater defines the superiority of one effect - sedimentation or thermal diffusion - over the other, respectively.

For the colloidal fluid in the motion state, where a volumetric macroscopic fluid flow occurs in the cavity, a competition between thermal expansion, thermal diffusion and sedimentation effects can induce oscillatory convection regimes near the threshold of mechanical equilibrium instability [16–20]. Experimental observation of convection regimes near the instability threshold is a complex task because the temperature or velocity heterogeneities near the threshold are very weak. The authors of work [20] developed and applied a procedure for observing convection in a horizontal plane layer with a thermal imager. It allows for detecting temperature heterogeneities of 0.01 °C and greater. This made it possible to trace the oscillatory convection regime in a kerosene-based magnetic fluid, at which temperature perturbations moved with constant velocities along the nearly straight lines. In earlier experimental studies [21–23], which also dealt with convection in a horizontal magnetic fluid layer, the oscillatory regime was not found because sensitivity of experimental devices was not sufficient. To visualize temperature fields at a magnetic colloid surface, in these experiments the authors used a liquid crystal [21,22] or a more sensitive thermal imager but with no control over temperature at the upper boundary of a cavity [23].

The sedimentation effect in a magnetic colloid depends not only on a size of individual particles but also on the above-mentioned aggregates. An aggregate size may vary. Direct observation of aggregates is not possible at the moment because the fluid is opaque. We can talk about the presence of aggregates as well as about the change in their sizes only on the basis of indirect observations. Similar observations were carried out in study [24] dealing with the magnetoviscous effect. The effect concerns an increase in viscosity of the magnetic fluid under an applied magnetic field [25–28]. Using a special rheometer, the authors of [24] showed that the magnetoviscous effect weakened as shear rates in the magnetic fluid rose. They attributed this to the fact that sizes of chain aggregates gradually decrease as shear rates grow. Despite an external magnetic field remains constant, it reduces fluid viscosity.

An aggregate size can decrease not only with enhancing viscous stresses but with increasing the average fluid temperature or molecular kinetic energy. The present work is devoted to the latter effect on oscillatory convection regimes in a horizontal magnetic colloid layer.

2. Material and methods

2.1. Magnetic colloid used

An undecane-based magnetic fluid is applied as a test sample. The choice of undecane as a carrier fluid is justified by the fact that undecane is a single-component hydrocarbon fluid. In such a fluid there is no mass transfer due to thermal diffusion or molecular diffusion, as it occurs in multi-component fluids (kerosene, transformer oil, etc.). We use a colloid with solid magnetite particles that have an average size of 9 nm in a diameter and an oleic acid molecular layer covering their surfaces with a thickness of 2 nm.

The volume fraction of a magnetite solid phase is estimated through the measured value for magnetic fluid density and the reference values for undecane and magnetite densities [29–31]. In this case the sample is considered as a two-phase medium consisting of the solid (magnetite) and fluid (undecane) phases. This simplification is justified by the fact that oleic acid density in the sample slightly differs from undecane density in contrast to magnetite density. Besides, oleic acid molecules do not practically exist in an unbound state, where they are free from magnetite particles. The magnetite solid phase volume fraction calculated in such a way is 14% of the total sample volume.

In our research we track and detect variations of magnetic fluid physical properties such as density, viscosity, and thermal conductivity with the change in the average fluid temperature. Density was measured by a pycnometer prior to convective experiments. A capillary viscometer was applied for viscosity measurements. Fig. 1 a and b show the experimental data obtained at different magnetic colloid temperatures in the range of 10–50 °C. Thermal conductivity is directly determined in the convective experiment by the steady state plane layer method. The experimental setup used will be described below. Fig. 1 c represents results of thermal conductivity measurements. Several properties of the test fluid sample such as the volumetric thermal expansion coefficient or heat capacity were determined on the basis of the reference data for undecane and magnetite [29–31]. The colloid heat capacity defined is $1.3 \times 10^3\ \mathrm{J/(kg\,K)}$. Its volumetric thermal expansion coefficient is $0.9 \times 10^{-3}\ \mathrm{1/K}$.

2.2. Experimental apparatus

A Rayleigh-Benard geometry setup is commonly employed in studying convection excitation of non-uniformly heated fluids [32,33]. The horizontal plane layer model is the most simple, on the one hand, and informative, on the other hand. In our work we also use this model (Fig. 2). Horizontal layer 1 is formed by a cylindrical cavity with a diameter of 58 mm and a height of 2.4 mm. The magnetic colloid layer is confined at the top by the glass plate of lithium fluoride salt 2 with a diameter of 60 mm a thickness of 6.0 nm. The layer is confined at the bottom by aluminum plate 3 with a thickness of 2 mm. Cylindrical lateral boundary 4 is made of Plexiglas. A test fluid is injected through brass tubes 5 embedded in the lateral border into the layer. Plexiglas plate 6 with a thickness of 1 mm and copper heat exchanger 7 consecutively attach to the bottom surface of aluminum plate 3. Required temperature values at the upper and lower layer boundaries are established via liquid thermostats KRIO-VT-01.