EXPERIMENTAL STUDY OF INITIATION OF CONVECTION IN A SPHERICAL CAVITY FILLED WITH NANOFLUID

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Abstract: The stability of mechanical equilibrium in a spherical cavity filled with ferro-nanofluid heated from below is investigated experimentally. It is shown that when the temperature difference between the sphere poles is increased gradually the flow arises as a result of supercritical transition provided that nanofluid is well mixed before the start of the experiment. The subcritical transition from a motionless state arises if nanofluid remains at rest for a sufficiently long time (from one day to several weeks) prior to the experiment. The evolution of convection from a finite-amplitude excitation to a steady flow is described.

1. Introduction

In the present work we study the stability of mechanical equilibrium and the evolution of convective motions in a differentially heated spherical cavity filled with a ferrocolloid. It is known [1] that the loss of mechanical equilibrium in a single component fluid can lead to a gradual increase of the convective flow amplitude that is proportional to the square root of the supercriticality (i.e. of the parametric distance from a critical point). This scenario corresponds to a supercritical transition. However it is also possible for the transition to convection to occur abruptly. This is the case if a transition is subcritical so that a hysteresis is observed when the variation path of the control parameter is reversed. However in contrast to a classical case of subcritical bifurcation when both forward and reverse transitions are abrupt, in the case of multi-component nanofluids the reverse transition from the convective state to the state of rest occurs gradually [2-4]. The reason for this peculiar behaviour is that the stability of mechanical equilibrium in magnetic colloids in a gravitational field is influenced by a large number of factors such as buoyancy, thermodiffusion of various components of a liquid phase, thermophoresis and barometric sedimentation of solid particles and their aggregates and the variation of rotational viscosity of a fluid seeded with nano-particles. In many regards convective instability in nanofluids is similar to that observed in double diffusion systems [5, 6].

2. Experimental setup

The experimental setup consisted of a spherical cavity with the diameter of 16.0 ± 0.1 mm cut inside two plates made of organic glass and glued together to form a block with overall dimensions $53\times53\times18$ mm^3, see Figure 1. The block is placed between two flat parallel water-filled heat exchangers. The temperature of water in heat exchangers was controlled using two jet thermostats.

Four copper-constantan thermocouples located in the equatorial plane of a sphere were used to detect the structure of the arising convection flows, see Figure 1. Such an equidistant

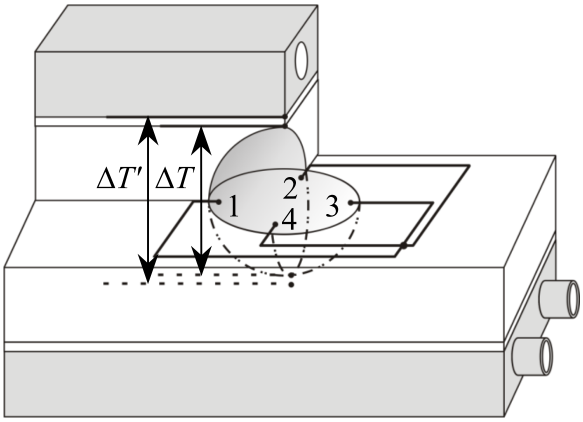

Figure 1: Schematic of the experimental setup: thermocouples 1–4 used for detecting the flow structure; $\Delta T'$ and ΔT are the temperature differences between the heat exchanger plates and poles of the sphere, respectively.

positioning of thermocouples enabled the detection of a single-vortex flow corresponding to the first instability mode in a sphere [7, 8] as well as of other structures including toroidal flows [7]. The digital data acquisition system "Thermodat T29BM1" was used for registering thermocouple readings with the accuracy of 0.01K. The data obtained in experiments lasting several days was automatically recorded on a computer hard drive via a USB port.

A single convection vortex with an arbitrarily oriented horizontal axis can be represented as a superposition of two base vortices with orthogonal axes oriented along the lines connecting thermocouples 1, 3 and 2, 4. Figure 2 shows one of such base vortices with the axis connecting thermocouples 1 and 3. The axis of a second base vortex (not shown) connecting thermocouples 2 and 4 forms the 90° angle with axis of the first (shown) vortex.

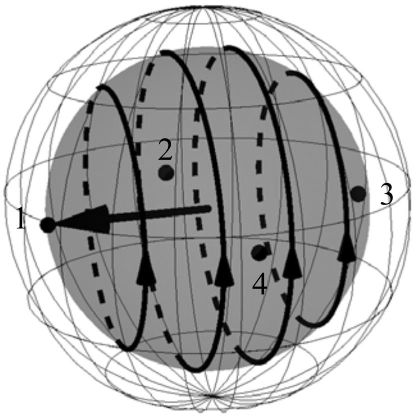

Figure 2: Schematic view of the first base vortex.

The thermal perturbations θ_{I} and θ_{II} induced by the orthogonal base vortices are given by $\theta_{\mathrm{I}} = \theta_1 - \theta_3$ and $\theta_{\mathrm{II}} = \theta_2 - \theta_4$, where θ_1, θ_2, θ_3 and θ_4 are the readings of the corresponding thermocouples. In the case of approximately linear vertical temperature profile in the central part of the sphere the orientation and intensity of a convection vortex can be described by the vector of angular velocity whose magnitude is proportional to the convective perturbation $\theta = \sqrt{\theta_I^2 + \theta_{II}^2}$.

An important characteristic of convective heat transfer is Nusselt number *Nu* that is the ratio of a full heat flux including convection and conduction components to the value of a conduction heat flux. In order to measure the heat flux organic glass plates were placed between the poles of a sphere and heat exchangers. Thermocouples were installed on both sides of the plates to register the temperature differences $\Delta T'$ between the heat exchangers and ΔT between the poles of the cavity. Nusselt number then was determined as $Nu = \Delta T_p/(k\Delta T)$, where $\Delta T_p = \Delta T' - \Delta T$ is the temperature difference across the plates and k is the empirical constant representing the ratio of thermal conductivities of a fluid and organic glass. The ferrofluid used in experiments had transformer oil base. The solid phase consisted of magnetite particles with the average size of 10 nm that were stabilised using oleic acid. The fluid density was 1.37×10^3 kg/m^3 and its dynamic viscosity was 0.069 Pa·s.

3. Results

As has been previously shown theoretically [7] and experimentally [8], a single-vortex convective motion in a spherical cavity filled with a one-component Newtonian fluid heated from below arises when the applied temperature difference exceeds the critical value ΔT_C as a result of supercritical bifurcation. A similar result was established here for a well-mixed multi-component ferrofluid. Specifically, in experiments with uniform ferrocolloid the threshold value of $\Delta T_C = 1.8 \pm 0.1$ K was reproduced in several independent runs using the method of convective pre-mixing: the experimental setup was turned sideways so that the heat exchanger plates that were maintained at the maximum possible temperature difference of $\Delta T' = 40$ K became vertical. They were kept in this position for an hour ensuring a strong convective flow inside the sphere. In contrast, when such a preliminary mixing was not performed the convection was found to establish abruptly and the hysteresis was observed when a gradual increase of the applied temperature difference was reversed.

The experiments with non-premixed fluid were performed using the fluid that remained in mechanical equilibrium for several days. After the start of heating the experiment proceeded with the incremental temperature increases of 2 K. After each temperature step the system was left to adjust to the new thermal condition for 24 hours. Once convection flow patterns were detected they were observed for a substantial time ranging from several days to several months.

Figure 3 shows the dependence of Nusselt number on the relative temperature difference $\Delta T/\Delta T_C$ between the poles of a sphere. Black squares along $\Delta T/\Delta T_C$ axis correspond to regimes where the abrupt transition was detected. Empty circles correspond to self-induced oscillations that are associated with the precession of the axis of the convection vortex in the equatorial plane. Black circles depict the regimes of stationary single-vortex convection when the orientation of the flow axis did not change with time.

The thin arrow at $\Delta T/\Delta T_C = 3.9$ in Figure 3 shows the abrupt transition to convective motion in a magnetic fluid that remained at rest in isothermal conditions for 34 days prior to the start of experiment. As seen in Figure 4, where the convective thermal perturbations θ_I и θ_{II} are presented as functions of time, 10 hours after the fixed temperature difference of $3.9\Delta T_C$ was applied quasi-harmonic oscillations with an increasing amplitude were established and existed for the next 27 hours. A similar transition was observed at $\Delta T/\Delta T_C = 2.0$ (thick arrow in Figure 3) for a fluid that remained isothermal and at rest for 3 days before the experiment. In this case the convective vortex with a precessing axis appeared 29 hours after the temperature difference was applied.

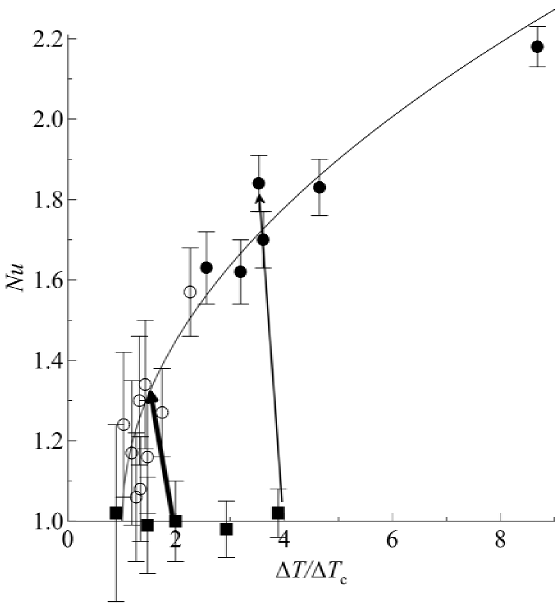

Figure 3: Nusselt number as a function of the relative temperature difference.

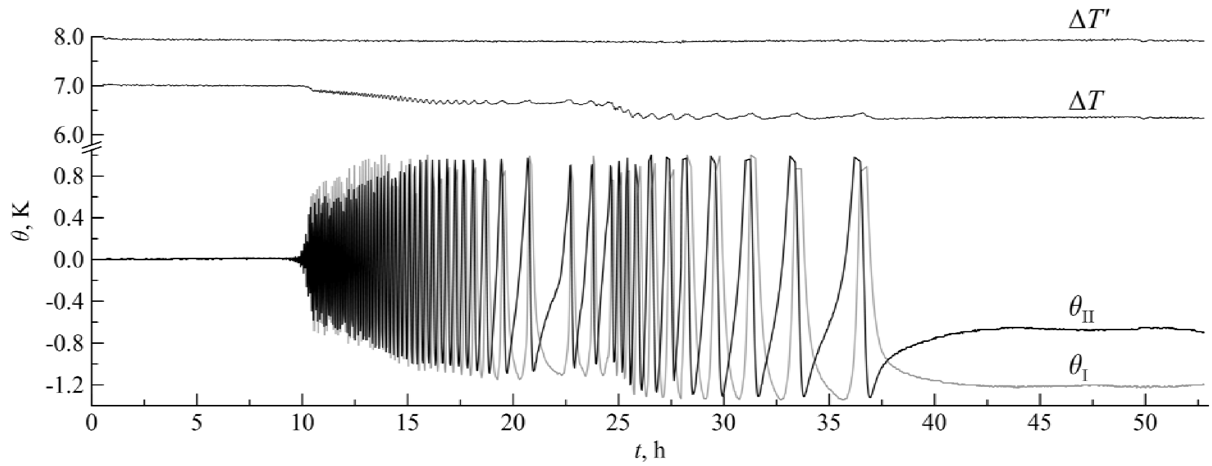

Figure 4: Thermogramm at $\Delta T/\Delta T_C = 3.9$.

The oscillations of the temperature difference between the poles of the cavity during the transient period seen in Figure 4 led to the variation of heat flux through a sphere. The corresponding variation of Nusselt number was around 5% between 15 and 24 hours after the convection flows were first detected. This increased to about 11% 15-24 hours after the start of convection, but finally died out after 53 hours so that the thermocouple readings remained unchanged for the next 10 days.

Figure 5 shows Morlet wavelet-transform of θ_I signal starting from the moment when convection flow was first detected. The horizontal axis corresponds to the observation time t and vertical the period of oscillations τ. The grey shade is used to show the amplitude of the. wavelet transform. In particular, the figure demonstrates that 7-12 hours after the start of oscillations they had the dominant period between 1 and 2, however at later times between 15 and 27 observation hours their period increased to approximately 3 hours.

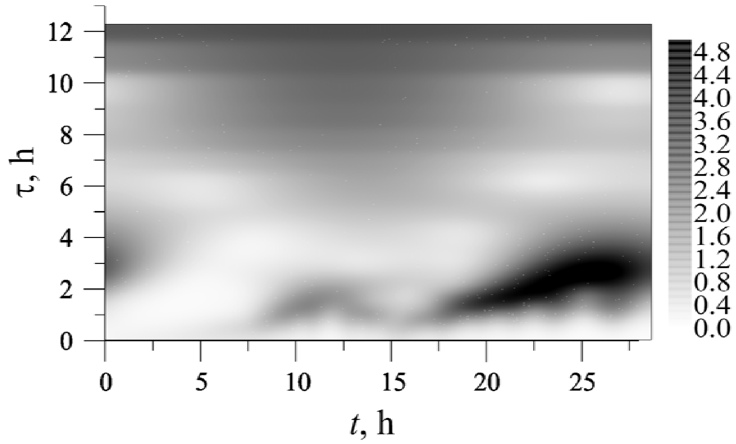

Figure 5: Morlet wavelet-transform at $\Delta T/\Delta T_C = 3.9$.

4. Conclusion

The current experimental investigation of the transition from mechanical equilibrium to convection flow in a spherical cavity filled with ferrofluid and heated from below showed that in a nanofluid that remained isothermal and at rest for several days convection flows arise abruptly and the hysteresis is observed in reverse transition to a stationary state. The depth of the hysteresis depends on the time the fluid stayed at rest before the start of the experiment: the critical temperature difference required to initiate convection increases with the duration of the period of rest prior to measurements. At the same time the reverse transition to a stationary state always occurs gradually at the same critical temperature difference. The likely explanation of such a peculiar behaviour is the presence of gravitational sedimentation of solid phase in a resting nanofluid that creates a stable density stratification that requires a stronger thermal forcing to initiate convection. At the same time convection leads to mixing of a nanofluid so that the reverse transition is not affected by the non-uniformity of solid phase concentration so that the ferrofluid behaves as a regular fluid.

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