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Research Article

Wave Convection Regimes in an Inclined Layer of Nano Fluid

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Abstract

The experimental investigation of thermogravitational convection has been carried out for an inclined layer of nanofluid heated from below. It is shown that when the Rayleigh convection arises in the dependence of inclination angles and temperature drops are observed the regimes of traveling rolls with the cross-roll instability, the attenuation of secondary flow partially or throughout the layer, climbing and gliding dislocations. The maps of flow regimes have been built; the convective heat transfer has been investigated.

***Keywords**: Convection; magnetic fluid; wave regimes; heat transfer.*

Introduction

Studying of artificial nanofluids representing colloidal dispersions of ferromagnetic nanoparticles suspended in a liquid carrier was started in the 1930s (Elmore W. C. 1938) The interest to magnetic colloids increased considerably in the 60s , when their industrial production became to be possible . To date, many monographs and reviews are devoted to study properties and applications of magnetic nanofluids in various areas (Blum E. J. *et al*, 1989; Odenbach S., 2009).

In magnetic colloids the average particle size of solid phase, e.g., magnetite, is about 10 nm. As liquid carriers normally kerosene, various synthetic oils and water are used. For prevention of aggregation due to the dipole – dipole interaction between single – named particles, they are coated with a stabilizing layer of surface – active agent.

It should be noted that convective motions of a single liquid in an inclined layer, embosomed between two parallel planar surfaces, kept at constant different temperatures, have studied in reasonable detail, both theoretically and experimentally (Gershuni G. Z.,*et al*, 1989 ; Pivovarov D. E.,*et al* ,2009) and the references therein . In nanofluids unlike single – component fluids at the instability of a primary rising – drop flow the irregular spatially – temporal behavior has been detected (Bozhko A. A., *et al* ,2003; Bozhko A. A., *et al* ,2009) . Unlike developed turbulence this behavior observed in a number of liquid and gas systems (Kolodner P. ,*et al* ,1988 ; Donzelli G., *et al* ,2009) near the instability threshold of the basic state, is placed to so – called spatially – temporal chaos where in convective structures the characteristic wave number is kept.

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Experimental procedure

The design of a convection chamber and the measurement procedure were significantly influenced by the fact that the used in the experiments nanofluid on basis of magnetite is opaque in layers with thickness more than tenths of a millimeter. This fact does not allow to use the methods of visualize marks and particles, as well as the laser Doppler navigator for direct determination of velocity fields and pictures of convective flows. For this reason optical methods recording refractive index fields and related temperature and concentration fields in transparent fluids cannot be used. As a result, conventional methods of studying of convection are narrowed to measure temperature fields and heat flows.

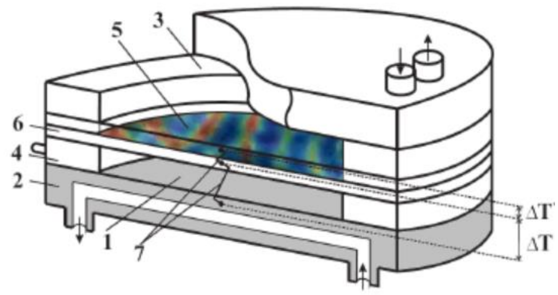

Fig. 1 Convention chamber: 1 – nanofluid; 2 ,3 – cooper and plexiglass heat exchangers; 4 – annular frame; 5 – thermal sensitive liquid – crystalline film; 6 – protective plate; 7 – thermocouples

On basis of these factors for studying of convection in plane layers after a series of exploratory experiments the construction of a convection chamber was chosen, shown on figure 1. Measuring cell 1 having disk shape, with height 3.5 ± 0.1 mm and with diameter 75 mm, was limited from one of the wide sides by copper plate of a heat exchanger 2 with thickness 10 mm and with diameter 98 mm. Longitudinal parallel channels were drilled in the plate so as to arrange the counter flows of thermostatic fluid in adjacent apertures and, consequently, to optimize the maximal uniformity of the heat exchanger's temperature.

From above transparent heat exchanger 3 was adjacent to cavity 1, consisting of two parallel plates from organic glass with thickness 2 mm, separated by a gap with height 10 mm, which served as a channel for thermostatic liquid. From the sides cavity 1 was surrounded by circular frame 4 from organic glass, its thickness assigned height of the layer. At that in the working cavity at the absence of convection, the uniform transverse temperature gradient set.

In the experiments, magnetic nanofluids on basis of kerosene with the average particle size 10 nm stabilized by oleic acid with density $1.55{\cdot}10^3$ kg/m^3, dynamic viscosity $9.0{\cdot}10^{-3}$ Pa·sec and the Prandtl number 51 were used.

Thermal conductivity factors of copper and plexiglas are $4.0{\cdot}10^2$ and 0.19 W/(m·K). The nanofluid applied in the experiments had thermal conductivity factor 0.21 W/(m·K). The ratio of thermal conductivity factors of fluid and plexiglas was 1.1, and liquid and copper was $5.3{\cdot}10^{-4}$. Thus, a cooper array with high accuracy satisfied the approximation of infinite thermal conductivity, often used theoretically.

To assess the structure of convective motions, thermal sensitive liquid crystal film 5 with thickness 0.1 mm was used, changing its color from green to brown over blue with increasing of temperature in a range of 24 – 27 °C; an error of a thermal indicator was ± 0.5 K.

Using differential thermocouples 7, their seals were located on the boundaries of the fluid layer and the protective plate, temperature differences ΔT on the liquid and $\Delta T'$ on the organic glass plate were determined.

Experiment results

As it is known, at deviation of a layer from its horizontal equilibrium, mechanical equilibrium in isothermal fluid becomes to be impossible, and a flow occurs, at which fluid floats along the heated and descends along the cooled walls (figure 2 a). While rising of a certain temperature difference, depending on the angle of slope, against the main lifting – lowering flow the movement of the Rayleigh nature develops in a threshold way as a system of convective rolls and their axes are extended towards the primary flow (figure 2 b).

Figures 3, 5, 8 show the maps of flow regimes in an inclined heated from below layer of ferrocolloid. Along abscissa the angle of inclination of a layer α is laid off, along vertical axis – temperature difference ΔT, referred to the threshold drop ΔT_C = 8.1 K, responsorial to the stability crisis of mechanical quasiequilibrium at the horizontal (α = 0) orientation of a layer.

Figure 3 shows a threshold curve $\Delta T_C(\alpha)$ shown by black dots. Below the curve a primary thermogravitational flow (figure 2 a) is stable. Above the curve $\Delta T_C(\alpha)$ on the basic lifting – drop flow the motion in the form of the Rayleigh rolls and cells superposes. The specified on the line of stability dispersion is due to the vibrational nature of the convective instability and at slop angles $\alpha > 20^0$ is due to an amendment arising due to the formation of the longitudinal temperature drop in the cavity of limited dimensions.

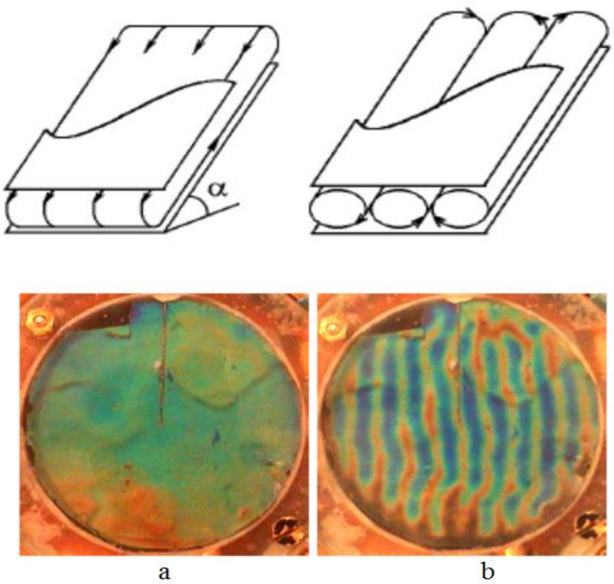

Fig. 2 Structures of convective motions and temperature distribution on a liquid crystal film in an inclined nanofluid layer heated from below: a – basic lifting – drop flow; b – the Rayleigh component. The photos were taken from the upper heat exchanger at $\alpha = 10^0$ and ΔT: (a) 8 K; (b) 16 K

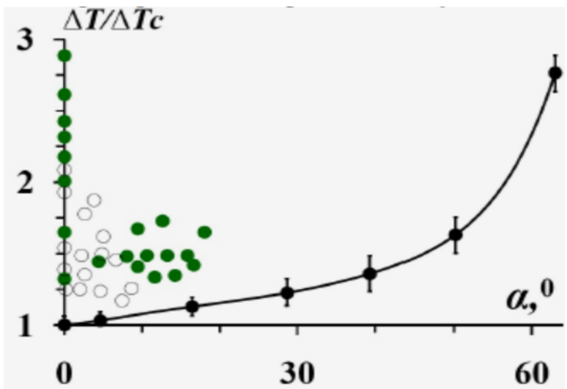

Fig. 3 A cross – roll region of instability in an inclined heated from below layer of nanofluid: dispersion dots – the stability boundary of a primary flow; colorless circles – target – formed and spiral convective rolls; solid circles –extended convective rolls

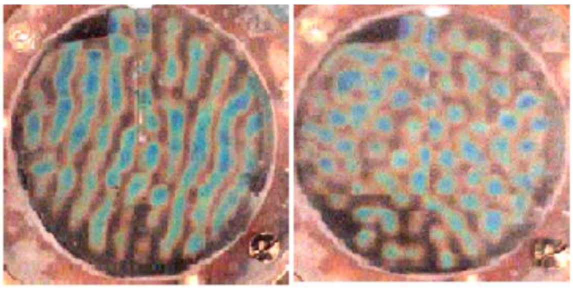

Fig. 4 Cross – roll instability of convective rolls at $\alpha = 5^0$, $\Delta T/\Delta T_C = 1.4$; the interval between shots is 6 minutes

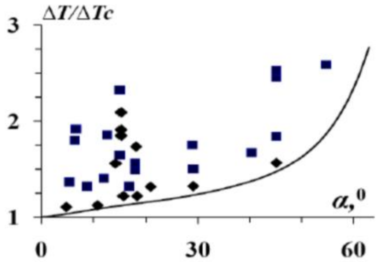

Fig.5 The area of amplitude modulation of the Rayleigh convection in an inclined heated from below layer of nanofluid: rhombuses –spontaneous decay and excitation of convection throughout the layer; squares – floating convective "spots"

In the whole seized by the experiments above critical range of parameters, the Rayleigh component showed irregular in space and time modulation.

In contrast to the linear theory (Gershuni G. Z., *et al*, 1989) at small slop angles the cross – roll instability of rolls and spiral domains having the same form as in the horizontal cavity persists.

In the realizations marked by empty circles, rearrangements occurred in the system of spiral and short rolls as at $\alpha = 0$ (Bozhko A. A., *et al* , 2000 ; Bozhko A. A., *et al* , 2007).

Figure 4 shows a typical decay of rolls at $\alpha = 5^0$ (solid circles on figure 3), which over time restore again ("zipper state" mode (Kolodner P.,*et al* , 1988 ; Bestehorn M., *et al* ,1990)).

With increasing values α and ΔT the orienting effect of a lifting – drop flow increases, and consequently, the ratio of the Rayleigh elements along this flow increases.

At the values of parameters α and ΔT presented on figure 5, there are convective modes in which the modulation of rolls is so deep that in some areas of the cuvette, the Rayleigh convection for a time completely extinguishes.

In the shown on figure 6 realization, the longitudinal convective rolls during 10 – 15 minutes occur mostly only in the upper half of the inclined layer – blue – green and brown stripes on the fragment on (a). The brown solid, i.e. cold spot on the figure means that the transverse convective heat inflow from the heated lower boundary of the layer to the upper in this area is absent. Thus, the Rayleigh rolls and cells carrying this heat transfer are absent under the brown spot. On the next step (figure 6 b) the Rayleigh rolls in the upper half of the cuvette disappear, but are excited in the lower part of the cavity. Figure 6 c corresponds to a phase of the process, in which the roll convection dies out along the whole field. Later the irregular exchange of the roll – structure intensities moving with the states of the almost died Rayleigh convection can be carried out both between the top and the bottom, and between the left and the right areas of the layer. The discussed states are shown on figure 5 by black rhombuses.

In the inclined layer of nanofluid, the quasiperiodic motion of the Rayleigh convection front from one wall of the cuvette to the other and back occurs spontaneously, continues unabated throughout the experiment and is accompanied by several tens cycles of decay and reappearance of the roll convection. Such irregular repetitive transitions from the convective limited conditions to the heat transfer regime were also observed in a horizontal heated from below layer of spirit solution in water (Ahlers G.,*et al* , 1996) and in nanofluids (Donzelli G.,*et al* , 2009; Terehov V.I.,,*et al*,2010). Note that the condition discussed here can be referred also to the modes with movement of a domain wall (Gershuni G. Z.,*et al*, 1989) or with the distribution of the convectional front (Getling A.V., *et al*, 1999).

In the described above mode, the "spot" which does not contain convective rolls, at some point of time covers the whole field of the cuvette. By blue squares on figure 5 the "limited states" are shown (Kolodner P., *et al*, 1988; Bestehorn M.,*et al*, 1990),in which the Rayleigh convection dies out for a time in one or several areas of a smaller scale, randomly moving along the cavity.

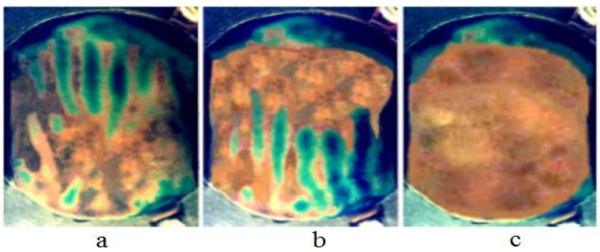

Fig. 6 Wave mode accompanied by partial or complete disappearance and following appearance of the Rayleigh convection at $\alpha = 15^0$, $\Delta T/\Delta T_C = 1.8$; the time between shots is 15 min

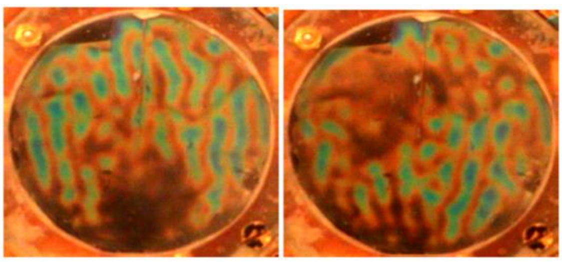

Fig. 7 Migratory non convective “spots” at $\alpha = 10^0$, $\Delta T/\Delta T_C = 2.3$; the time between shots is 6 min

An example of this mode when $\alpha = 10^0$ is shown on figure 7. On the left fragment the brown spot, indicating the area in which the Rayleigh convection is absent, is located at the bottom of the cuvette, and then the non convectional "spot" moves up. In the cleared from the "spot" areas, the structure consists of short convective rolls and cells.

At large slope angles to the horizon ($\alpha \geq 15°$) the spontaneous decay and the following appearance of convection occur on the system of extended convective rolls, located along the longwave lifting – drop flow.

At significant temperature gradients the most significant mechanism of the unsteady behavior of the Rayleigh component becomes the motion of convective rolls and defects. By blue triangles on figure 8 the modes of modulated traveling waves are shown, which can be classified as "glittering states" (Kolodner P., *et al*, 1988; Bestehorn M.,*et al*, 1990). A distinguishing feature of such regimes is irregular change not only the amplitude, but also the spatial period of the Rayleigh convective rolls (figure 9). On the right half of the shot on figure 9 a of this series, there are three longitudinal lines corresponding to the six convection rollers. As time passes in the upper flattened region, a new couple of rolls is born and spreads down (blue line), shown on figure 9 b by an arrow.

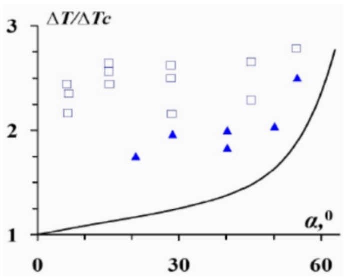

Fig. 8 Area of running convective rolls in an inclined heated from below layer of nanofluid: triangles – "flickering states"; squares – rolls with dislocations

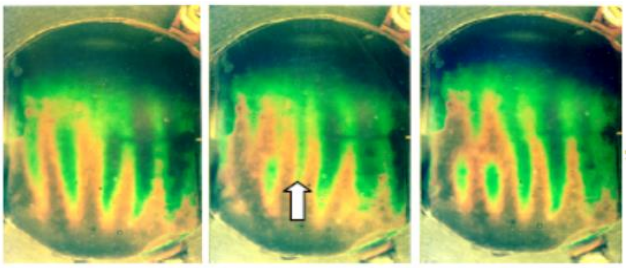

Fig. 9 "Flickering states" at $\alpha = 55^0$, $\Delta T/\Delta T_C = 2.5$; the time between shots is 2 min

This couple of rollers can be observed as the dislocation "climb" because its movement occurs along the rolls' system (Millan– Rodriguez J.,*et al* ,1995; Getling A.V.,*et al*, 1999). At the same time, at the left edge of the cuvette "glittering" of the temperature field also occurs. The picture of the flow in this part of the cuvette is complicated by the fact that, along with the "glittering", also a "limited" state as dark areas without the Rayleigh convection appears (figure 9 b, c). The observations show, however, that exactly these dark areas are necessary for the appearance of the dislocation climbs, causing the divergence of rolls.

At high temperature gradients ΔT the coverage of large areas of the cuvette by dark non convective spots stops and the movement of convective rolls and defects becomes to be a distinguishing mechanism of the unsteady behavior of the Rayleigh component. The corresponding modes are indicated on the map of figure 8 by empty squares, and the typical sequence of the change of convective structures in these modes is shown on figure 10. As in the process described above, in the flattened region of figure 10 a, a new blue strip – a couple of convective rolls – is born and begins its moving down spreading the neighboring rolls. Initially, the movement of this couple has the form of dislocation climb. However, near the center of the cavity, one of the former blue stripes clambers with a new couple of rolls (figure 10 b), and the so – called "pinning" (attaching) effect takes place (Millan – Rodriguez J.,*et al*,1995). Then there is a sliding shift of the defect to the left towards the direction which is perpendicular to the rolls' axes, and following climbing down (figure 10 c). As well as shown on figure 9, in the discussed mode the total number of rolls varies with time.

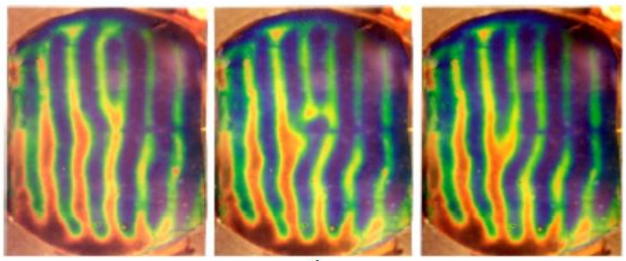

Fig. 10 Modulated convective rolls at $\alpha = 15^0$, $\Delta T/\Delta T_C = 2.4$; the time between shots is 1 min.

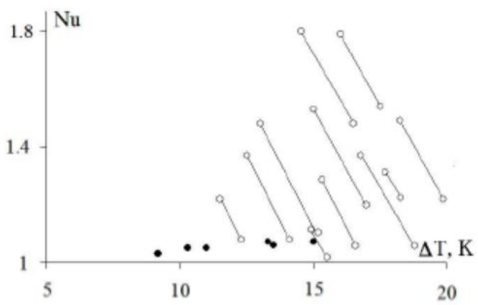

Fig. 11 Convective heat transfer in an inclined layer of nanofluid at $\alpha = 15^0$; black dots are corresponded to the primary flow in the case of gradually increasing ΔT

The series of photos given above also illustrate the effect of temperature stratification (Shaidurov G. F.,*et al*,1959; Kutateladze S. S.,*et al*,1984) generated by the base lifting – drop flow in an inclined layer of limited length. Due to the accumulation of heat at the top and cold at the bottom of the polar regions – blue and brown (light and dark in black and white) of the arc along the top and the bottom edges of the cavity on figures 9, 10, the longitudinal temperature gradient occurs. As a result an additional control parameter – the stratified Rayleigh number occurs (Gershuni G. Z.,*et al*,1989; Kutateladze S. S.,*et al*,1984) On the figures corresponding to a small slope angle $\alpha \leq 15°$ (figure 6, 10), the longitudinal temperature stratification appears as narrow lines at the poles of the convective camera. As slope of the cavity increases, length of the boundary perturbed by the temperature areas increases significantly, and in a vertically oriented cavity their height reaches a half the length of the cuvette.

Changing of a dimensionless heat flow through a layer of nanofluid with increasing of the cross temperature drop ΔT for a fixed slope angle is shown on figure 11. The Nusselt number Nu, which is equal to the ratio of the total heat flow, including convection and molecular components, to the purely molecular heat transfer, was calculated from the expression: $Nu = k\Delta T'/\Delta T$, where k – an empirical constant having the meaning of the ratio of effective thermal conductivities of liquid and fluorine plastic and calculated upon the absence of convection from the equation $k\Delta T' = \Delta T$.

Note that for small slope angles $\alpha \leq 15°$ convection can occur rigidly and with hysteresis (dark spots). Sloping segments connect minimum and maximum values of the Nusselt numbers at fluctuations of the heat flow in the case of fixed temperature values on heat exchangers. Segments with minimum values of $Nu \approx 1$ correspond to the regime of limited states or to the distribution of the convection front. In these modes, in certain areas or along the whole field of the cuvette the linear temperature distribution corresponding to a basic lifting – drop flow can be installed aperiodically.

Conclusions

Thus, in the inclined layer of nanofluid in the entire region of control parameters the wave convectional modes were observed. The appearance of the states where convection can partially or completely disappear indicates the presence of significant density inhomogeneities (Gluhov A. F.,*et al*,1999). Increasing of the concentration effects in comparison with the case of the horizontal orientation of the layer (Bozhko A. A.,*et al*,2000; Bozhko A. A.,*et al*,2007) can be due to two factors. Firstly, as a slope angle rises, effective (barometric) height of the cavity increases. Secondly, a background flow, as in the case of mixture separation in the thermal diffusive column (Blum E. J.,*et al*,1989) increases the heterogeneity of the colloid along the cavity.

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