Laminar-turbulent transitions at natural convection in flat and annular vertical fluid layers

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Abstract. The evolution of the local characteristics of natural convective boundary layers along the longitudinal coordinate is studied experimentally. The spatial forms of secondary flows in boundary layers on the walls of the plane and annular vertical liquid layer heated to different temperatures and in the core of the layers are studied. Hot walls are transparent, which allows video recording in two planes. In the regions of the laminar, transition, and turbulent boundary layer, local fields of velocity and temperature and local heat fluxes are measured.

1. Introduction
The flat vertical liquid layer, enclosed between parallel walls heated to different temperatures, is the canonical object in studies of the stability of free convective boundary layers (BL) and laminar-turbulent transition (LTT) in buoyancy-induced convection problems [1-4]. In a series of studies performed at the Institute of Thermophysics SB RAS, the flow structure in laminar regimes and their stability was investigated. Then developed turbulent flow regimes were studied. The most important results of these investigations were summarized in the review [1] and were taken into account in setting up problems for further studies aimed at a comprehensive investigation of laminar-turbulent transitions [5-7]. This work aims at continuing studies of the local characteristics of a natural convective boundary layer and qualitative reconstruction of the spatial form of flow on the wall of a flat vertical layer. The investigations are carried out under conditions when the boundary layers on the hot and cold walls develop to a large extent autonomously, in contrast to the case of thin layers [2-4]. In order to study the effect of hydrodynamic interaction of boundary layers on the features of LTP, a stand "Annular vertical layer-12" has been created. In the annular layer, the effect of the end walls and corner zones on the flow along the walls is excluded. On this stand, LTP studies are carried out in the boundary layers and turbulization processes of the stably stratified core of the layer at different liquid layer heights.

2. Result and Discussion
At the "Flat vertical layer" stand, experiments are carried out at a layer thickness of 58 mm, a width of 160 mm, and in the layer height range of 95 ≤ H ≤ 660 mm. The working liquid is ethyl alcohol with Pr = 16. With these dimensions of the layers, the boundary layers on the walls develop practically autonomously in the zones of laminar boundary layers that are stable up to Raₓ ≤ (5 ± 0.5)×10⁸. At Raₓ
a - General form  \( b - h = 150 \text{ mm}, \quad Ra_x = 7.4 \times 10^8 \)  
\( c - h = 333 \text{ mm}, \quad Ra_x = 8.1 \times 10^9 \)

**Figure 1.** Time scans of the signal of one line of the matrix of the video camera in two sections along the height of the layer: the height of the liquid layer \( H = 635 \text{ mm}, \quad Ra_H = 5.6 \times 10^{10} \)

\( \geq 6 \times 10^8 \), there are two-dimensional secondary vortices (the wavelength is \( \lambda_x \)) with axes transversal to the main stream, which are clearly visible in the range \( 10^8 \leq Ra_x \leq 2.3 \times 10^9 \) (figure 1a). The scenario of the appearance, development, and ascent of the first vortex in the region of the upper boundary of the laminar BL unambiguously shows that there is no exact value of \( Ra_x = (\beta g/a) \Delta T m x^3 \), at which the LTT zone begins. There is a finite region \( Ra_x \), in which the first vortex forms and detaches. In the place of a floating and detached vortex, the following vortex is formed. Digital video recording allow observing this process and even create a generalized portrait of the first vortex that appears on the upper boundary of the laminar boundary layer (figure 1b). In the plane of the heated vertical wall, one can see a chain of previously emerged vortices (second, third, etc.) and the evolution of their spatial form (figure 1a).

Further downstream at \( Ra_x > 2.3 \times 10^9 \) the vortices are bent, i.e. they lose stability with respect to perturbations of the "stationary" type along the transverse coordinate \( z \) with a certain wavelength \( \lambda_z = (1+1.5) \lambda_x \). At the next stage, deformations and breakthrough of the leading edge of curved secondary vortices occur on the crests of these waves. It looks like the formation of \( \Lambda \)-structures (figure 1a). Then follow the collapse zones of ordered secondary vortices and three-dimensional mixing - the turbulent boundary layer, \( Ra_x > (1.1 \pm 0.05) \times 10^{10} \). The breakthrough of the leading edge of the floating vortices is accompanied by the formation of jets of a heated liquid that are transformed into mushroom-like thermals (figure 1c). The velocities of the motion of the secondary vortices as a whole are close to the maximum average velocity of the ascending stream in the transition region of the boundary layer development. This type of flow is maintained up to the upper insulated end, which limits the working volume from above, or to the free boundary of the liquid at \( H \geq 250 \text{ mm} \).

At the stand "Annular vertical layer-12" experiments were carried out in annular layers with a maximum height of \( H = 1473 \text{ mm} \) and a thickness \( \Delta R = 12.65 \text{ mm} \) in the range of Rayleigh numbers \( 10^8 \leq Ra_H \leq 10^{12} \). The internal diameter is \( \approx 141.1 \text{ mm} \). The effect of the relative dimensions of the layers on LTT for a discrete set of layer heights equal to \( H/2, H/4, H/8 \) was studied. In these cases, the upper boundary of the layers was free. The investigations were carried out in steady continuous many
day cooling and heating of the layer boundaries. The liquid layer is enclosed between the glass tubes. The temperature drop is created by pumping cold liquid in the inner tube and hot liquid in the gap between the walls of the outer tube and a transparent plexiglas box of the square cross-section.

With these parameters, the boundary layers developing on the hot and cold walls interact hydrodynamically. As a result, in addition to the instabilities characteristic of the autonomous development of the BL (figures 2, 3a), instability appears at the boundary of the counter flows (figure 3b). Secondary vortices of this type in the central part of the layer drift upward with a velocity much lower than the rate of emergence of wall-type vortices of the first type. This type of instability is observed at all the heights of the liquid layers studied and over a wide range of temperature differences. Their spatial structure is strongly influenced by the development and evolution of vortices of the first type appearing in the near-wall region. Near a hot wall buoyant vortices first have an annular shape. Near a cold wall, similar vortices are shifted downward. Then, almost independently of the temperature drop, an azimuthal instability is observed at the leading edge of the vortices and a structure similar to the Λ-structure appears (figure 2). At the next stage, structures of a mushroom shape are formed. Those processes at a qualitative level are similar to those observed in a flat layer.

The evolution of near-wall currents downstream changes the characteristics of the opposing descending and elevating interacting currents. The flow acquires a pronounced three-dimensional nonstationary character with increasing \( \text{Ra}_H \). In the central part, sporadically, secondary vortices arise and helical-shaped longitudinal vortices oscillate in the azimuthal and radial directions (figure 4). In Figure 4, the position of the frames along the height of the layer from the bottom is \( z = 180-260 \text{ mm} \) with the height of the layer \( H = 1470 \text{ mm} \) and with a temperature difference between the thermostats, which corresponds to the value \( \text{Ra}_H \approx 10^{12} \). The helical longitudinal vortices have the spatial form of a
double helix in which they intertwine upward the flow of heated liquid and the counter flow of cold liquid. Each of these streams periodically touches the hot and then the cold walls. The velocity and temperature profiles were measured, and the statistical characteristics of the velocity and temperature fields were determined; examples are shown in figures 5-8. Here are the data obtained at the height of the liquid layer $H = 1470$ mm and at $Ra_H \approx 10^{12}$. A characteristic feature of natural convection, even in the regimes of the developed turbulent flow of velocity and temperature pulsation, is low-frequency (figures 6, 7).

Since the experiments are carried out in layers with walls of relatively low thermal conductivity, the question naturally arises of the conjugate heat transfer and its effect on the parameters of the BL. The process of conjugate heat transfer and the penetration of temperature pulsations into the wall during the movement of secondary vortices are numerically studied. Numerical simulation was carried out by the finite element method. A complete system of equations for nonstationary buoyancy-induced convection for a two-dimensional flow in a plane layer in a conjugate formulation are solved. With the geometry of the computational domain, similar to the experimental working part of a stand, the regular structure of the secondary flow observed experimentally is reproduced. Non-stationary temperature fields and local heat fluxes in a liquid and a streamlined wall of finite thermal conductivity are studied (figure 9). At figure 9c $t_1 = 157$ s and $t_2 = 153$ s correspond to the passage of the head and stern parts
of the emerging secondary vortex. From the data obtained, it is possible to estimate the depth of penetration of the temperature perturbations and the phase shifts of the thermal wave along the wall thickness.

In experiments with a free upper boundary, the presence of a longitudinal temperature gradient leads to the development of buoyancy-thermocapillary induced convection. The influence of the thermocapillary effect is manifested in thin near-surface layers. In the upper ends of vertical layers, this type of flow occurs, but does not affect the development of a boundary layer on a vertical cold wall.

3. Conclusions
It has been shown experimentally that, at a qualitative level, the scenarios of instabilities in the boundary layers on vertical walls in the planar and annular layers coincide at the initial stage. But the processes of turbulence of the core of a liquid layers differ significantly, depending on the distances between vertical walls heated to different temperatures [5, 6]. In a thick layer with a stably stratified core, there is a tendency to form non-stationary vortices due to side heating. In a thinner ring layer, the transition to turbulent flows in the layers as a whole is caused by the hydrodynamic interaction of the ascending flow on the hot wall and the descending flow on the cold wall. In this case, the instability develops in the boundary layers, characteristic for the case of a separate vertical wall or for non-interacting multidirectional boundary layers on the walls of a flat vertical layer (figure 2). Breakthroughs of hot liquid on the leading edges of secondary vortices form longitudinal trickles and mushroom-shaped structures. In addition, there are vortices on the boundary of the opposing streams. As a result of the interaction of these types of instability, a topologically complicated flow in the form of a double helix appears in the core of the annular layer, in which flows of heated and cold liquids move towards each other.

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