TRANSITIONAL CONVECTIVE STRUCTURES IN A LIQUID LAYER WITH A DRIFT FLOW

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Abstract In this work we are concerned with numerical study of three-dimensional convective structures arising in a thin liquid layer heated from below and subjected to a horizontal drift flow. A free upper surface of the liquid contacts with a turbulent boundary layer of an air current which determines tangential surface stresses and heat emission. Basic parameters of the system correspond to the region of laminar-turbulent transition of the convective flow. The study is aimed at the explanation of former experiments by A. Ezersky and V. Chernov (1999) on transformations of the convective structures in a blown-off layer of silicon oil. Using reformulation of the basic equations, spectral decomposition along the horizontal coordinates, and discretization in the vertical direction we obtained established regimes observed in the experiment with increasing the airflow velocity: disordered cellular flow, elongated and merged cells, and longitudinal rolls.

STATEMENT OF THE PROBLEM

The contribution deals with the problem of structure formation in the gravity-capillary convection developing in a thin liquid layer in the presence of a horizontal shear flow. The liquid layer is heated from below and its free upper surface contacts a turbulent boundary layer of the air current. The problem is of interest for different natural and industrial applications, as well as for development of a general theory of pattern formation in fluids [1]. The term "transitional structures" implies that the parameters of the system belongs to the region of transition from laminar to turbulent convective flow, which is characterized by the onset of disorder in spatially periodic fields. The study is aimed at the explanation of experiments of the work [2] on transformations of the convective structures in a blown-off layer of silicon oil. It should be emphasized that, unlike a similar experiments with a gradually cooled layer of ethanol [3,4], we consider established flow regimes for each value of airflow velocity.

The standard equations for a three-dimensional convective flow in an incompressible fluid written in the Boussinesq approximation are used after special spectral reformulation. The hydrodynamic and temperature fields are represented as a superposition of oscillating and mean components. The equations are normalized through the layer depth H and the time scale H^2/ν_0, where ν_0 is the kinematic viscosity. The temperature scale is $\delta T=(T_1-T_0)$, where T_1 is a temperature of plate at the bottom of the layer, T_0 is a temperature of air in the uniform airflow. The dimensionless temperature is introduced by $\vartheta=(T-T_1)/\delta T$. A heat emission coefficient (the Biot number) b is determined by the thermal diffusion and radiation emission [3]. Conditions of fixed temperature, non-slip, and non-percolation are adopted at the bottom of the layer $z=0$, and conditions of heat emission, zero vertical velocity, and zero oscillating tangent stresses are adopted at the upper boundary $z=1$. The constant tangential stresses producing a drift flow are applied at $z=1$. The dimensionless parameters of the problem are the Grashof (Gr), Prandtl (Pr), Marangoni (Ma), and Reynolds (Re) numbers defined by

$$\mathrm{Gr}=\frac{\alpha_0 g(\delta T)H^3}{\nu_0^2},\quad \mathrm{Pr}=\frac{\nu_0}{\chi_0},\quad \mathrm{Ma}=\frac{\sigma_t(\delta T)H}{\rho_0\nu_0\chi_0},\quad \mathrm{Re}=\frac{U_s H}{\nu_0}, \tag{1}$$

where ρ_0, χ_0, α_0 are the density, thermal diffusivity, and thermal expansion coefficient of the liquid, respectively, g is the gravity acceleration, σ_t is the parameter of a linear temperature dependence of the surface tension, and U_s is the surface drift velocity of a hypothetic steady flow with a linear velocity profile the direction of which coincides with x-axis. The quantities U_s and b have been determined as explicit functions of the uniform airflow velocity U_∞.

SIMULATION OF THE TRANSITIONAL STRUCTURES

The computations were performed for the layer of silicon oil with $H=4\,\mathrm{mm}$, $\nu_0=0.0729\,\mathrm{cm^2s^{-1}}$, $\sigma_t=7\cdot10^{-5}\,\mathrm{Nm^{-1}K^{-1}}$, $\mathrm{Pr}=80$, $\mathrm{Ra}=17660$, Ma=9195 (data for the plate temperature $T_1=313\,\mathrm{K}$)). The air temperature was $T_0=293\,\mathrm{K}$. We used a spectral method in the treatment of work [5] with the periodicity conditions along the horizontal coordinates x and y together with discretization along the vertical coordinate z. There were 128-by-96 points in the FFT-procedure, 42-by-32 harmonics in the sought solution, and 40 discretization points along z-

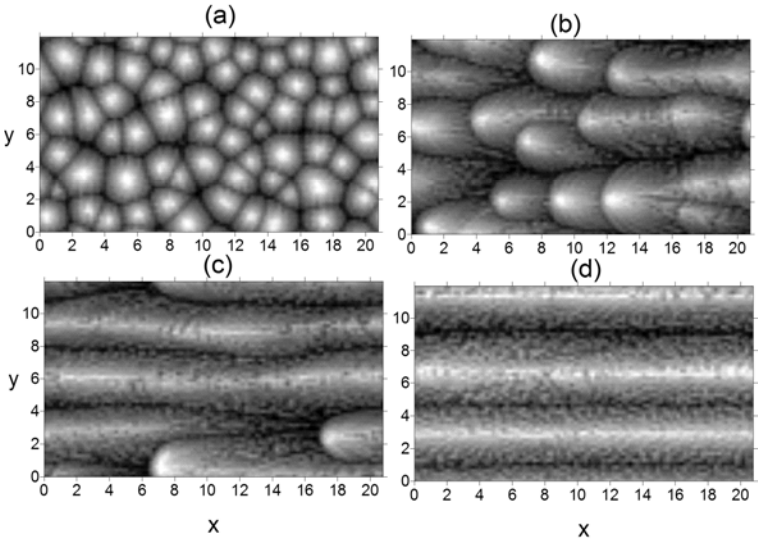

Figure 1. Patterns of total surface temperature in the established regimes of convection: (a) – disordered polygonal cells in the absence of blowing; (b) – elongated and enlarged cells at $U_\infty = 4\,\mathrm{m/s}$; (c) – merged cells and rolls with defects at $U_\infty = 6\,\mathrm{m/s}$; (d) – longitudinal rolls at $U_\infty = 8\,\mathrm{m/s}$. Drift flow direction coincides with direction of the x -axis.

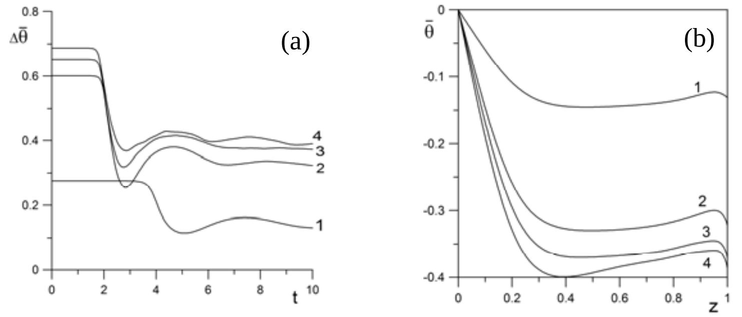

Figure 2. (a) **–** Time history of the mean temperature jump $\Delta\bar{\vartheta} = \bar{\vartheta}\big|_{z=0} - \bar{\vartheta}\big|_{z=1}$; (b) – vertical profiles of $\bar{\vartheta}$. The numbers $1 \div 4$ correspond to the same values of U_∞ as pictures (a), (b), (c), and (d) in Figure 1.

axis. The wavenumbers of the first harmonics were $k_{1x} = 0.3$ and $k_{1y} = 5.02$ (i.e., the spatial periods of the computational domain were 21 and 12.8). Initial mean velocity and mean temperature profiles corresponded to a steady-state: $\bar{u} = \mathrm{Re}\cdot z$ and $\bar{\vartheta} = -bz/(1+b)$. Initial flow perturbations were small and noisy.

The images of the total surface temperature ϑ drawn in the grayscale are presented in Fig. 1 (the white and black colors map the maximal and minimal values). The velocities of blowing U_∞ correspond to the drift flow Reynolds numbers $\mathrm{Re} = 0; 6.45; 13.4; 22.5$ (in order of increasing U_∞). Figure 2a shows that the convective cells are formed after saturation of the convective instability. As follows from Fig. 2b, cooling of the layer becomes stronger with increasing of U_∞ . In the absence of blowing (or at weak blowing) the polygonal disordered cells displayed in Fig. 1a are formed. Appearance of the drift flow gives rise to enlargement of the cells and their elongation downstream (Fig. 1b). Simultaneously some ordering of the cells takes place. Enlargement and merging of the cells leads to the formation of rolls the bounds of which may be branched (see Fig. 1c). Finally, the longitudinal rolls occur (Fig. 1d). Thus, the qualitative agreement of the computations with experiments of the work [2] has been confirmed.

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