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EXPERIMENTAL STUDY OF THE EFFECT OF GAS-PHASE THICKNESS ON STABILITY AND STRUCTURE OF THE FLOW IN A TWO-LAYER LIQUID–GAS SYSTEM

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The stability of a two-layer liquid–gas system with a variable ratio of layer thicknesses is experimentally studied. It is found that the critical value of the Marangoni number and the characteristic size of convective structures depend on the ratio of thicknesses of the gas and liquid phases. For ratios higher than ten, the gas layer can be considered as infinite.

Key words: *thermocapillary convection, two-layer system.*

Introduction. It is known that the nonuniform distribution of temperature or density of surface-active agents on the free surface of the liquid or at the interface of two immiscible liquids generates shear stresses, which cause liquid motion. The first studies of this phenomenon were performed long ago in pioneering works of Pearson, Sterling, and Scriven. Nevertheless, though the story is more than 100 years old, the interest in processes near the interface did not decay but got new qualitative development recently (detailed historical reviews can be found in [1, 2]). The reason is that the effects considered can significantly influence the intensity of many heat- and mass-transfer processes on interfaces of heterogeneous substances used in chemical industry, metallurgy, power engineering, and other branches of industry. These studies are particularly important for the development of space material science because of the nongravitational character of surface effects. In addition, the interest in studying interface-convection phenomena is stimulated by current advances in such research fields as the theory of self-organization in nonequilibrium systems, synergetics, theory of oscillations, and dynamics of nonlinear systems.

Most papers deal with the Marangoni instability in flat layers of the liquid for the following reasons: theoretical and experimental research techniques can be easily implemented and devices of this geometry are widely used in technological processes. It is normally assumed that the liquid layer borders on a semi-infinite gas layer whose thermal and viscous properties are usually neglected. Allowance for the gas-phase properties reduces to varying boundary conditions for the temperature at the upper boundary of the liquid layer. The solution of the problem in this classical formulation [3–6] shows that disturbances giving rise to a hexagonal cellular structure of the flow are most dangerous, which is confirmed by experimental results.

As is shown in the review of papers published on this topic, however, there are some experimental studies [7, 8] where different supercritical flow structures were observed. Several reasons for the disagreement with the theory were proposed; one of them implies that it is necessary to take into account the gas-phase characteristics. This initiated some theoretical works [9, 10] where the stability of a two-layer liquid–gas system under conditions of a uniform vertical temperature gradient was considered. It turned out that the stability is affected by the ratio of sizes and thermophysical parameters of the liquid and gas phases. The influence of the ratio of sizes and thermal conductivities of the gas and liquid phases on the threshold of stability and space-time parameters of convective flows arising in the liquid layer was considered in [10]. Golovin et al. [10] concluded that the critical Marangoni number decreases as the gas-phase thickness decreases and the most dangerous disturbances are shifted to the long-wave region and presented a chart of stability illustrating the regions of existence of various supercritical flows.

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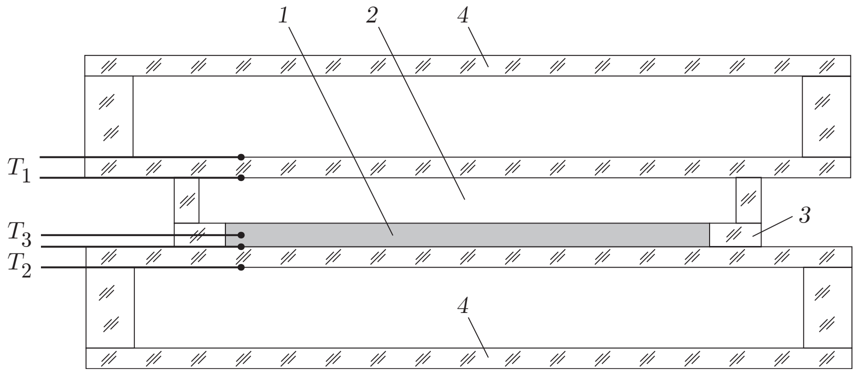

Fig. 1. Layout of the experimental setup: 1) liquid layer; 2) gas layer; 3) frame; 4) heat exchangers.

Experimental studies of two-layer systems were performed either for the case of two liquid phases or for liquid–gas systems; in the latter case, however, the issue of the influence of the air-layer thickness was not considered specially. No systematic experimental study of stability of the liquid–gas system with commensurable phase thicknesses was performed.

Results of an experimental investigation of stability of a two-layer liquid–gas system are described in the present paper. The effect of the ratio of layer thicknesses on the threshold of stability and convective flow structure is considered.

Experimental Setup and Measurement Technique. The layout of the experimental setup is shown in Fig. 1. The convective chamber containing layers of the liquid phase (1) and gas phase (2) is bounded on butt-end faces by a transparent Plexiglas frame (3) with an inner size of 220×220 mm. The frame consists of two parts, each of them being responsible for the thickness of the gas or liquid phase. The liquid-layer thickness was constant and equal to 4 mm. Frames with the ratios of the liquid- and gas-phase thicknesses 1 : 1, 1 : 2, 1 : 3, 1 : 4, and 1 : 10 were used in the experiments; the case of an unbounded gas phase was also considered. The top and the bottom of the chamber were bounded by transparent Plexiglas heat exchangers (4) whose temperature was maintained constant with the help of two water ultrathermostats.

The working liquid was chosen to be *n*-decane for the following reasons. The surface tension of the liquid should not be very high to avoid generation of an adsorbed film of the surface-active agent at the interface, which can weaken thermocapillary convection or make it impossible. The liquid should be homogeneous because the presence of admixtures of organic compounds with long carbon radicals, which normally have lower surface tension, can lead to formation of adsorbed films. The presence of such films can reduce the intensity of convective fluxes on the surface or lead to their complete stabilization. The dependence of surface tension on temperature should be rather strong to obtain rather intense flows. The liquid should not be too volatile because this can lead to significant changes in the thickness of the liquid layer during the experiment. Intense evaporation can also produce high gradients of surface tension, associated with nonuniform evaporation from the surface. All these requirements are satisfied by *n*-decane with surface tension of 23.9 mN/m (at 20°C) and temperature coefficient of surface tension of 0.092 mN/(m $\cdot$ K).

In the course of experiments, differential copper–Constantan thermocouples were used to measure the temperature of the horizontal boundaries of the system (T_1 and T_2 in Fig. 1), temperature difference on the horizontal wall of the heat exchanger on the side of the liquid (T_2) and on the half-thickness of the liquid layer (T_3). The ratio T_2/T_3 allows one to register the crisis of the thermal flow for determining the critical temperature gradient corresponding to emergence of a convective flow in the liquid. Addition of a small number of light-scattering particles (aluminum powder) into the liquid under study allows one to observe the structures of convective flows.

Results of the Experimental Study. The experiments showed that a decrease in the gas-phase thickness reduces the critical vertical temperature gradient at which convective motion arises. Figure 2 shows the critical Marangoni number as a function of the ratio $\bar{h}$ of the liquid- and gas-phase thicknesses. The case $\bar{h} = 0$ refers to an infinitely large thickness of the gas layer. The Marangoni number was found by the formula

$$\mathrm{Ma} = A\sigma_T h^2/(\eta\chi),$$

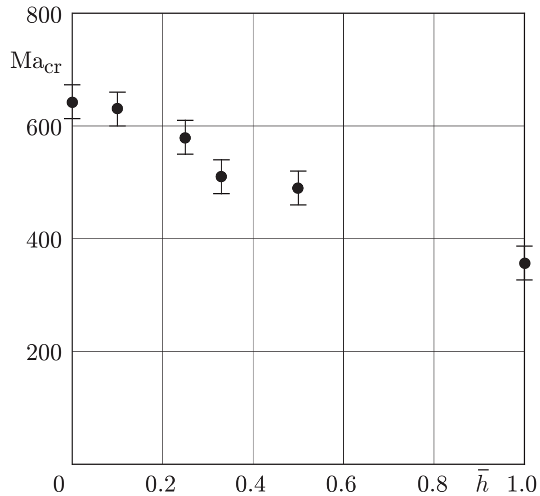

Fig. 2. Critical value of the Marangoni number versus the ratio of liquid- and gas-phase thicknesses.

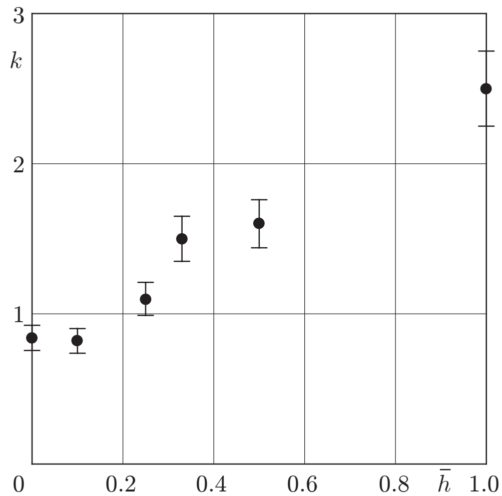

Fig. 3. Dimensionless wavenumber versus the ratio of liquid- and gas-phase thicknesses.

where A is the temperature gradient in the liquid layer, $\sigma_T = 0.092$ mN/(m·K) is the temperature coefficient of surface tension, h is the liquid-layer thickness, $\eta = 0.91$ Pa·sec is the dynamic viscosity of the liquid, and $\chi = 5.6 \cdot 10^{-7}$ m^2/sec is the thermal diffusivity of the liquid.

It is seen from Fig. 2 that the critical Marangoni number ceases to change when the gas-phase thickness is approximately ten times greater than the liquid-layer thickness. Thus, if the gas layer has a greater thickness, it can be considered as infinite.

Visual observations of the convective flow structure show that the liquid flow has a hexagonal structure of type l for all ratios of the thicknesses of the liquid layers. The liquid ascends at the center of the cell and descends at the edges. As the gas-layer thickness decreases, the characteristic size of convective structure changes. Figure 3 shows the dimensionless wavenumber versus the ratio of thicknesses of the liquid and gas phases. The wavenumber was found as

$$k = 2\pi h/\lambda,$$

where λ is the characteristic cell size, which was assumed to be the distance between the opposite faces of the hexagon. The size of convective structures decreases as the gas-layer thickness decreases.

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