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EXPERIMENTAL INVESTIGATION OF THERMOCAPILLARY CONVECTION INDUCED BY A LOCAL TEMPERATURE INHOMOGENEITY NEAR THE LIQUID SURFACE.

2. RADIATION-INDUCED SOURCE OF HEAT

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The structure and stability of a thermocapillary flow from a concentrated source of heat induced by radiation and located near the free surface of the liquid filling a deep reservoir are experimentally studied. Absolute stability of this flow for all depths and powers of the heat source is found. The profile of the liquid surface near the heat spot is considered experimentally.

Key words: *thermocapillary convection, source of heat.*

Introduction. It is known that a temperature inhomogeneity at the interface generates a convective flow called a thermocapillary flow. The reasons for the emergence of such an inhomogeneity can be accidental (inhomogeneous front of the dissolution process or chemical reaction with heat release) or deliberate (source of heat or cold on the surface). One of the methods of deliberate generation of the thermal inhomogeneity is electromagnetic irradiation of the interface surface in the range of absorption frequencies with a nonuniform distribution of intensity in the beam. Such a situation is frequently encountered in many applications and engineering processes [1–3]. Special interest in induction of thermocapillary convection by means of radiation is caused by the fact that this is the situation with growing of crystals onboard spacecraft [4, 5]. Because of its nongravitational character, it is this type of convection that starts to play the governing role and leads to origination of a nonuniform crystallization front and, as a consequence, to violation of the homogeneous structure of single crystals.

The topic of research itself is not new. There are some theoretical and experimental papers on the structure and stability of the flow from a radiation-induced source of heat [6–8]. In those studies, however, the properties of the liquid and the radiation wavelength were specially chosen to have the absorption factor as high as possible. In this case, the temperature inhomogeneity is concentrated in a very narrow surface layer. In the authors' opinion, this simulates the case of a concentrated heat source located directly at the interface. The case of an "immersed" heat spot is of no less interest, because it allows additional regulation of intensity and structure of the liquid flow.

In the present paper, we describe the results of an experimental study of a thermocapillary flow in a deep reservoir, which is generated by a concentrated source of heat induced by radiation and located near the free surface of the liquid. A significant difference of the flow structure and stability from the case of a solid source of heat (see [9]) is demonstrated. The role of boundary conditions on the heat-source surface is discussed.

Experimental Setup and Measurement Technique. The layout of the experimental setup is shown in Fig. 1. The source of light (SL), which is a lamp with a filament in the form of a circle, is located in the focal plane of a converging lens L_1. Then, the light beam passes through an infrared filter F and is directed, by means of a pivoted mirror (PM), to a converging lens L_2. The resultant converging light flux is directed to the liquid surface.

The working liquid in this set of experiments was decane. Preliminary studies showed that the integral absorption factor in the infrared range for decane is $\alpha = 0.06$ mm^{-1}. This means that the intensity of the light

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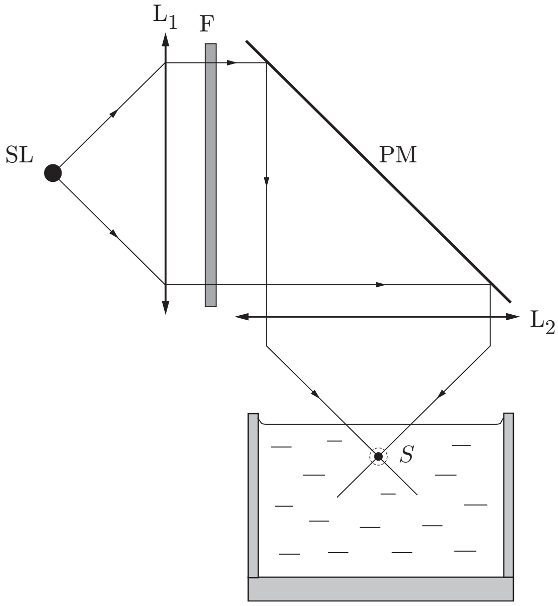

Fig. 1. Layout of the experimental setup.

flux at a depth of about 20 mm is approximately 30% of intensity of incident radiation. This is the characteristic penetration depth. Each element of the liquid on the path of radiation releases an amount of heat proportional to the energy absorbed. The latter, in turn, depends on the density of the light flux incident onto this element of the liquid. As is seen from Fig. 1, the radiation-flux density is distributed nonuniformly and acquires the maximum values in the vicinity of the point S, which is the center of the image of the lamp filament. Hence, the heat-release maximum, being a concentrated source of heat, is localized in this region. The distribution of the light-flux density near the point S was preliminary measured to determine the size of the heat source. A sensor for light-flux intensity, which was a soot-coated piece of copper foil 0.5 × 0.5 mm, was placed on the path of radiation. The junction of a copper–Constantan thermocouple was welded to the foil; the signal from this thermocouple was measured by a microvoltmeter. The second junction was located in a thermostatted reservoir. With the help of a two-coordinate traversing gear, the sensor was placed to the region of light-flux propagation. The distance from the length at which the light-flux density reached a maximum was assumed to be the center of the heat source. The boundaries of the heat source were assumed to be the coordinates where the light-flux density was 30% of the maximum value. With such a criterion, the geometric size of the heat source was as follows: diameter 10 mm and height 5 mm.

The power of the heat source was preliminary measured by a comparative calorimetric method based on comparing the heating rates of a moderate volume of the liquid by unknown and reference sources of heat. Based on the research results, the calibration curve was constructed for the power of the radiation-induced heat source versus the voltage applied to the incandescent lamp. It turned out that the power of the heat source can vary from 0 to 3 W within the range of the operating voltage of the lamp.

The experiment was performed as follows. The convective chamber was filled by the working liquid. The experimental setup made it possible to move the chamber with the liquid in the vertical direction relative to the lens L_2 (see Fig. 1). By micrometric adjustment, the dish was set at such a height that the center of the light source was located on the liquid surface. This position of the source was assumed to be its zero immersion depth. Then, a certain voltage was applied to the incandescent lamp. The structure of the arising convective flow and the shape of the liquid surface were studied during the experiment with fixed power and immersion depth of the light source of heat. The methods of flow visualization and investigation of the liquid-surface shape are similar to those described in [9].

Experimental Results. Figure 2 shows the photograph of the vertical section of the flow in the plane of the center of the heat source with a certain fixed power, which is located on the liquid surface. The centrifugal flow is concentrated in a narrow subsurface region, whereas the reverse flow occupies the entire volume of the liquid.

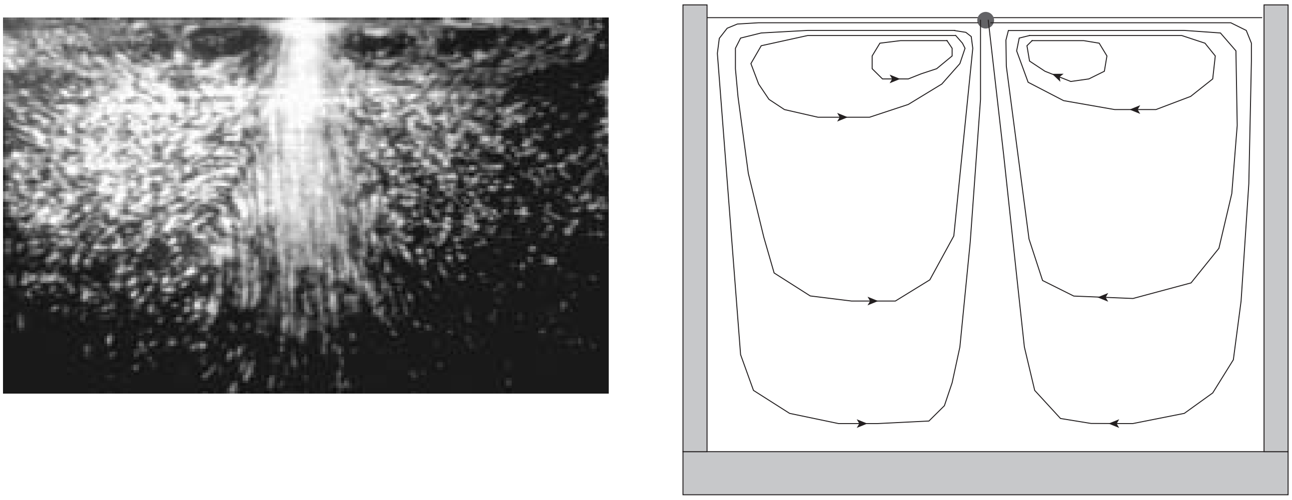

Fig. 2. Vertical section of the flow in the plane of the center of the heat source.

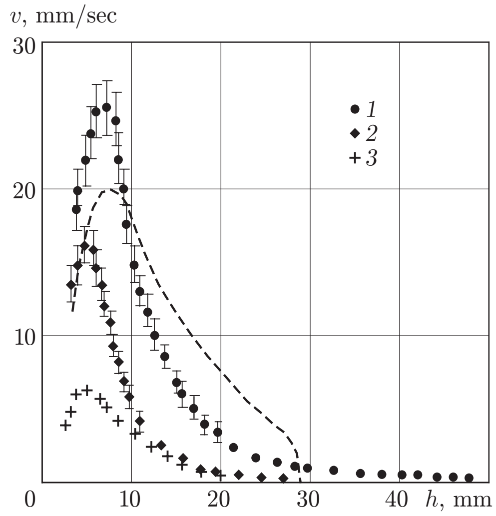

Fig. 3. Radial velocity of the flow on the liquid surface versus the radial coordinate for the heat-source power $P = 0.6$ W and the immersion depth of the center of the heat source $h_0 = 0$ (1), 5 (2), and 10 mm (3); the dashed curve is a similar dependence for the solid source of heat with $h_0 = 1$ mm and $P = 0.6$ W.

A typical feature of such a flow is the central upward vertical flow propagating from the bottom to the liquid surface. The liquid flow along the surface has a radially symmetric structure and occupies the entire volume of the liquid (edges of the photograph).

Figure 3 shows the radial component of velocity as a function of the radial coordinate for three different positions of the heat source relative to the liquid surface. As the center of the light source moves inward the liquid, the flow velocity on the surface rapidly decreases. The values of velocity far from the source for large immersion depths are not marked on the graph because they practically coincide with the coordinate axis in this scale. Such a distribution of velocity on the liquid surface and throughout its volume is typical of all powers and immersion depths of the light source. Only the value of flow velocity is changed as these parameters are varied. Such a flow structure is absolutely stable for all values of power that can be reached in an experiment. The dashed curve in Fig. 3 shows a similar dependence for the case of a solid source of heat (see [9]). The flow localization typical of the case with a solid source of heat is not observed here.

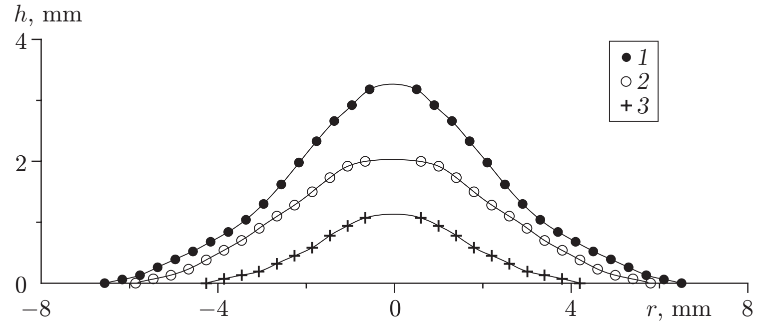

Fig. 4. Profile of the liquid surface for different positions of the 0.6-W heat source for $h_0 = 0$ (1), 5 (2), and 10 mm (3).

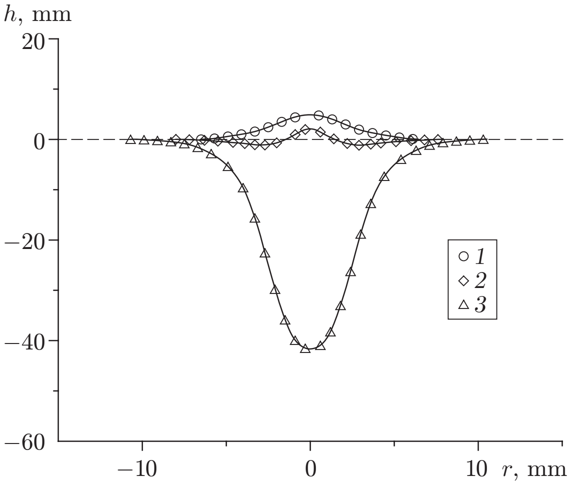

Fig. 5. Profile of the liquid surface for $P = 1.2$ W and the liquid-layer thickness $h = 10$ (1), 2 (2), and 1 mm (3).

Figure 4 shows the plot illustrating the profile of the liquid surface in the vicinity of the heat source for different positions of the latter relative to the interface. The curvature has always the same sign: the liquid surface is convex toward the gas phase. For all values of heat-source power and its positions, the surface shape remains stationary. The pattern of free-surface deformation observed is significantly different from the case of an immersed solid source of heat (see [9]) and does not coincide with the results of other investigations [6–8]. An analysis of works dealing with the profile of the irradiated liquid surface shows that the surface is always concave toward the liquid phase. In all these cases, however, there is some solid boundary near the liquid surface (the lower boundary of the flat layer in [6–8] and the upper surface of the heat source in the experiments of [9]), which seems to be responsible for the difference observed. To check this assumption, we studied the influence of the liquid-layer thickness on the flow structure and interface shape.

Figure 5 shows the profiles of the liquid surface in the vicinity of a 1.2-W light source for different values of the liquid-layer thickness. Down to the depth $h = 10$ mm, the surface profile is unchanged. With further decrease in the layer thickness, there appears a surface region with the opposite curvature; beginning from $h \approx 1$ mm, the surface acquires the shape concave toward the liquid phase. The shape of the surface is always stationary. The flow structure is similar to that observed for the solid source of heat (dashed curve in Fig. 3).

Conclusions. The results described in both parts of the paper show that the structure of the thermocapillary flow significantly depends on the nature of the heat source. This refers both to the structure of the main flow and to its stability. In the case of the solid source of heat, the flow is always localized, i.e., has a finite size of the convective cell both on the liquid surface and in its volume. In the case of a radiation-induced source, the picture is different: the cell is bounded by nothing (except for the dish walls). In theoretical works [10–14] dealing with the thermocapillary flow induced by a point source of heat, the main flow is always an infinite surface flow in terms of the radial coordinate, which is proportional to $1/r^n$. The test results described in the paper show that one should take into account the specific features of the source itself when calculating the main flow. The difference in experimental results is, apparently, caused by the difference in boundary conditions for velocity on the heat-source surface. The light source is permeable for liquid fluxes and is similar, in this aspect, to the point source considered in theoretical studies, which is responsible for the similarity of the results for the main flow.

The difference in conditions for velocity on the surface seems also to be the reason for the difference in stability of the thermocapillary flow. The no-slip condition at the boundary of the solid source of heat favors the origination of disturbances near the heater surface, which leads to flow instability observed in a local region immediately above the heat source and, as a consequence, to emergence of surface waves. The thermocapillary flow from a light source whose boundaries are absolutely permeable is more stable.

It is of interest to compare the data on the flow structure observed with the results of some theoretical investigations. It follows from the information in the present work that the thermocapillary flow is axisymmetric regardless of the type of the heat source. Even the emergence of surface waves (in the case with the solid source of heat) does not violate the symmetry. At the same time, it is shown in some theoretical papers [12–14] that the thermocapillary flow from a point source of heat on the surface of a semi-infinite liquid becomes unstable (in some works, absolutely unstable) to azimuthal disturbances already at low Marangoni numbers, which, in the authors' opinion, is the reason for replacement of the axisymmetric flow by a flow with an azimuthal component of velocity on the surface (the so-called "daisy"-type flow). The authors' confidence in correctness of their results is supported by the data of an experimental study of a capillary flow from a concentrated source of a surfactant [15]. These experiments evidenced the absolute instability of the axisymmetric flow to such disturbances. The results of the present study show that this is not the case for thermocapillary convection. The reason for the different types of behavior of the system in the case of obvious identity of the nature of capillary forces caused by the dependence of surface tension on temperature or concentration of the admixture has to be clarified yet.

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