EXPERIMENTAL STUDY OF TEMPERATURE PROFILES IN A THERMAL BOUNDARY LAYER DURING THE BOILING OF LIQUID IN A FREE VOLUME

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The results of an experimental investigation into the thermal boundary layer on a wire associated with boiling in a free volume are presented. The temperature profiles are illustrated and briefly analyzed. The effect of gas bubbles on the structure of the thermal boundary layer is demonstrated.

Investigations into the thermal boundary layer associated with boiling processes provide useful information for perfecting our theoretical concepts as to the mechanisms underlying heat transfer in boiling. Until recently, such investigations had mostly been carried out with thermocouple probes [1-3]. However, optical methods may also be used for studying the thermal boundary layer in boiling. One of the several possible methods of using the well-known Töpler optical technique, together with ordinary and motion-picture photography of the process, was described in [4]. A method of calculating the temperature profiles in a thermal boundary layer was also set out in that paper.

In this paper we shall present some experimental results relating to various modes of boiling and shall briefly analyze these. The experiments were carried out in water at atmospheric pressure. The working parts were a wire and a plate. We studied the boiling of saturated and underheated liquid.

A typical photograph of a thermal boundary in the free-convection mode is shown in Fig. 1. The light and dark interference bands correspond to isotherms. From the photographs we may determine the thickness of the thermal boundary layer δ_T, and estimate the influence of the mode of boiling and the heater geometry on this parameter. The correctness of the calculation based on the method of [4] was verified by comparing the excess temperature at the wire (obtained by direct measurements in a bridge or potentiometer circuit) with the calculation based on the interference bands. The mean-square deviation was 10-20%. Greater deviations occurred for small thermal fluxes, $q = 50{,}000\ W/m^2$. The results of some calculations of temperature profiles, obtained photographically in the free convection mode for various underheatings and thermal fluxes, are shown in Fig. 2. The analysis is presented in dimensionless coordinates. The continuous line gives the theoretical solution obtained in [6] for air ($Pr_a = 0.7$). The experimental conditions were matched to the theoretical analysis by incorporating a factor $Pr_l^{0.25}P_a^{0.25}$. The physical parameters were determined from the mean temperature of the thermal boundary layer.

The satisfactory agreement between the experimental data and the theoretical solution expressed in Fig. 2 serves as an additional confirmation of the validity of the method employed for analyzing the photographs of the thermal boundary layer. The photograph in Fig. 3a shows the thermal boundary layer for the boiling of an underheated liquid ($t_0 = 39.8°C$, $t_W = 118°C$, $q = 832{,}000\ W/m^2$, wire diameter 0.07 mm) in the "degassing" or "gas-bubble" mode [5]. This mode is characterized by an ideal spherical shape of the gas bubbles, and also a considerable local reduction in the wall temperature under the "stem" of the bubble. In Fig. 3b the results are given of an analysis of the interference pattern shown in Fig. 3a. The temperature axis y coincides with the axis of the bubble in the vertical plane. Along the y axis we have plotted the excess temperature $\theta = t - t_0$, where t_0 is the temperature of the main bulk of the liquid, t is the current temperature in the thermal boundary layer. We see from Fig. 3a, b that the temperature of the wire in the

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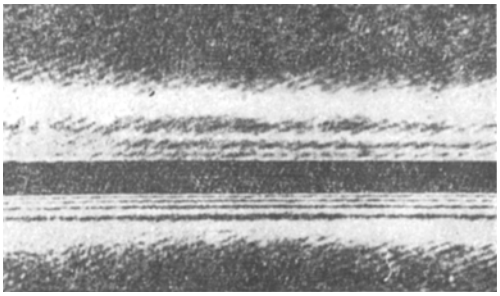

Fig. 1. Photograph of a thermal boundary layer for the boiling of underheated liquid ($q = 0.22 \cdot 10^6$ W/m^2; temperature of the liquid t_0 = 61°C; temperature of the wire 105°C; diameter 0.2 mm).

zone of action of the bubble, ~85°C, is much lower than its average temperature, 118°C. Knowing the average density of the thermal flux, the diameter of the heater, the dimensions of the zone of action of the bubble, and the local fall in temperature, we may calculate the intensification of heat transfer due to the release of heat through a single bubble. The calculation gives a local rise by a factor of two for the thermal flux in the zone of "thermal influence" of the bubble *ab*. If we estimate the proportion of the surface occupied by the "stem of the bubble" in the zone of "thermal influence," we may calculate the intensity of heat transfer through the bubble. An approximate estimate gives an "effective" heat-transfer coefficient through the bubble of $\alpha_e = 1.5 \cdot 10^5$ W/m$^2 \cdot$ deg. Line 2 in Fig. 3b lies in a horizontal plane and corresponds to the outer boundary of the thermal boundary layer under the lower generator of the wire. The thickness of the boundary layer necessary for the construction of line 2 is directly determined from the interference pattern of Fig. 3a. Curves 5, lying in the vertical cross sections, represent the temperature profiles along the length of the wire under the lower generator.

Curve 4 reflects the change in the excess temperature $\theta = t_w - t_0$ of the wire surface, also under the lower generator.

The foregoing analysis is quantitatively only approximate. For more accurate estimates it is desirable to combine longitudinal and transverse interference patterns, so as to allow for the temperature distribution around the heater perimeter.

The presence of light bands in the upper part of the bubble suggests the existence of convective heat transfer between the bubble and the cold liquid.

Visual observations showed that bubbles of this kind had a long life.

It was a more complicated matter to obtain a clear photographic picture of the thermal boundary layer in the bubble boiling of a saturated liquid.

One of the photographs of this mode of boiling is shown in Fig. 4. Such photographs are inadequate for constructing satisfactory temperature profiles (because of the thin thermal boundary layer). Nevertheless,

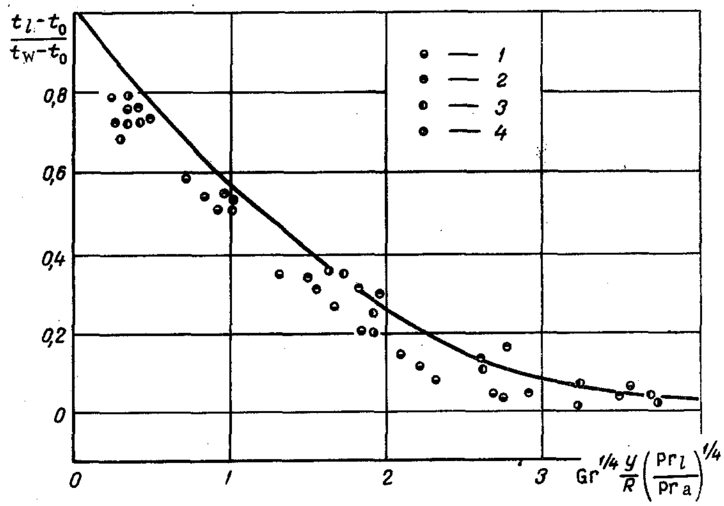

Fig. 2. Dimensionless temperature profiles of the thermal boundary layer on the lower generator of the wire in the free convection mode: 1) underheating 80°C; 2) underheating 60°C; 3) underheating 40°C; 4) underheating 20°C (the continuous line represents a theoretical solution of [6]).

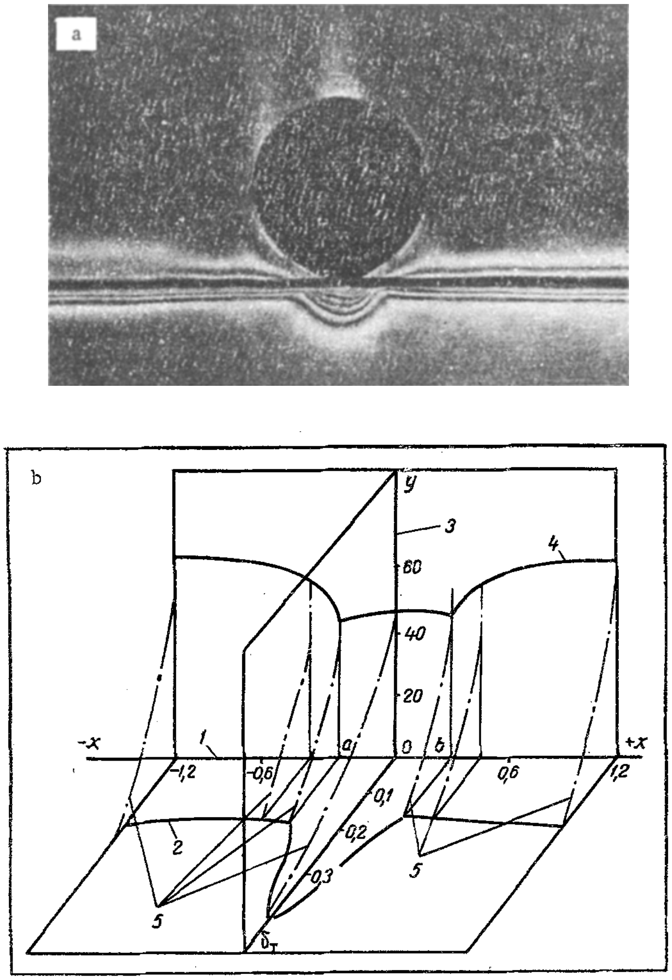

Fig. 3. a) Photograph of a gas bubble ($q = 0.96 \cdot 10^6$ W/m^2; liquid temperature $t_0 = 39.8$°C; wire temperature 118°C; wire diameter 0.07 mm); b) comparative temperature profiles and thicknesses of the boundary layer in the region of action of a single gas bubble: 1) axis of wire; 2) outer boundary of the thermal boundary layer on the side of the lower generator of the wire; 3) vertical axis of the bubble; 4) temperature distribution along the wire; 5) temperature profiles over the cross sections of the thermal boundary layer along the length of the wire. X, mm; δ_T, mm.

Fig. 4. Photograph of the thermal boundary layer while boiling ($q = 0.162 \cdot 10^6$ W/m^2, $t_W = 110.5$°C, $t_0 = 97.6$°C, wire diameter 0.4 mm).

we may still judge the general dimensions of the thermal boundary layer, its configuration in the zone of action of the vaporization centers, and so forth.

In the bubble boiling of a saturated liquid, practically linear temperature profiles are obtained in the thermal boundary layer. This indicates that, for this mode of boiling the heat transfer is mainly effected by thermal conduction through the thin boundary layer. The photographs presented in this paper represent particular cases, which are nevertheless the most characteristic of the corresponding modes of boiling. For each mode of heat transfer we took ordinary and motion-picture photographs of the process for various wire diameters and plate sizes, and different thermal fluxes and underheatings of the liquid. A check on the reproducibility of the pictures of the thermal boundary layer yielded excellent results.

Thus the use of the optical methods of Töpler for studying the thermal boundary layer during boiling supplements existing physical concepts as to the mechanism of heat transfer, and also provides additional quantitative characteristics (temperature profiles, thicknesses of the thermal boundary layer, etc.).

NOTATION

t_l	is the current temperature of liquid, °C;
t_0	is the bulk temperature of the liquid, °C;
t_w	is the temperature of the wire surface, °C;
Gr	is the Grashof number;
y	is the current coordinate from the lower generator of the wire, mm;
R	is the radius of the wire, mm;
$Pr_a = 0.7$	is the Prandtl number for air;
Pr	is the current Prandtl number for water;
δ_T	is the thickness of the thermal boundary layer on the lower generator of the wire, mm;
X	is the current coordinate along the axis of the wire, the origin of coordinates being at the center of the bubble.

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