MEASUREMENT OF PROFILES OF TEMPERATURE AND LOCAL VAPOR CONTENT NEAR A HEAT-GENERATING SURFACE IN WATER BOILING IN A LARGE VOLUME

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Results are presented of simultaneous measurement of temperature profiles and local vapor content in a boundary layer in the boiling of water.

In a number of boiling heat-transfer models for liquid boiling, use is made of data such as the local characteristics of the process, e.g., the frequency, separation diameter and growth rate of bubbles, and the density of vapor-generating centers. However, for sufficiently high heat flux, there is a merging of the vapor bubbles, and near the heat-transfer surface a region forms with a considerable volume vapor concentration, and the individual bubble model is open to serious doubt.

In order to understand the hydrodynamic and thermal processes near a heat-transfer surface and to create a physically well-founded heat-transfer model in developed boiling one must know the phase distribution laws. From the variation in vapor content in the wall layer one can determine the different regions on the boiling curve, and for large q the vapor content can also govern the crisis phenomenon.

The important parameters of bubble boiling are the thickness of the heated boundary layer adjacent to the heating surface and the temperature profile within this layer. Experimental investigations of temperature profiles in the boundary layer [1-4] have shown that there is a definite link between the heat-transfer coefficient and the thickness of the heated layer. The absolute values of δ are quite small (for $q = 233 \cdot 10^3$ W/m^2 δ is ~ 0.09 mm [3]) for small heat flux, and as the heat flux increases the values of δ decrease, which makes it considerably more difficult to determine these values experimentally.

The thickness of the heated layer is determined from the temperature profile in the liquid near the heat-transfer surface. The instantaneous temperature at any point in this layer is a variable which fluctuates with large amplitude and frequency. These temperature fluctuations are due to mixing of the liquid within the heated layer, caused by growth, merging, and separation of bubbles, which, in turn, is correlated with the bubble flux. It is very probable that the local vapor content is also the main factor in determining these characteristics of the boiling process. Therefore, one should expect a definite correlation between δ and $\bar{\varphi}$.

The present paper gives experimental data on simultaneous measurement of temperature profiles and local vapor content above a hot surface in water boiling at atmospheric pressure.

1. Experimental Equipment and Technique. To measure the distribution of phases the authors used a conductometric method, which is based on the use of differences in electrical conductivity between the liquid and the vapor [5, 6]. The average local vapor content as a function of time is determined as the ratio of the total dwell time of vapor at a given point to the total measurement time, i.e.,

$$\bar{\varphi}_l = \left(\sum_{i=1}^{n} \Delta\tau_i\right) / \tau, \tag{1}$$

where $\Delta\tau_i$ is the time for which the vapor phase is continuously present. The measurement cell (the face of the probe is the heat-transfer surface) is included in a series circuit whose elements are an ac oscillator and a load resistor. The signal taken from the resistor passes through an amplifier and then a discriminator which separates out the required signal amplitude part for subsequent reduction. The oscillator carrier frequency of the oscillator in the probe circuit was 4000 Hz.

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The carrier frequency was modulated by low-frequency signals from the passage of volumes of vapor through the probe face, and the signal amplitude varied from u_l to u_v. The discrimination level was set in the region 77-78% of $(u_l - u_v)$, according to [7], which derived the ratio $\bar{\varphi}_l$ and the true volume vapor content using synchronized high-speed photographs for various levels of discrimination. A more detailed account of the technique for measuring $\bar{\varphi}_l$ is given in [5].

For simultaneous measurement of temperature profiles and local vapor content we used a rake of 12 probes, at the center of which was located a Nichrome – Constantan thermocouple with electrode diameter 30 μm. The probes spanned an area of 6.4 × 6.4 mm and were located at the corners and the center of a cell of diameter 3.2 × 3.2 mm. For the vapor content measurement over the heat-transfer surface at constant height we used a rake of 9 probes spanning an area of 3.6 × 3.6 mm, located at the corners of a cell of size 1.8 × 1.8 mm. For traversing along the surface the probe rake was moved relative to the traverse axis in such a way that the minimum distance between lines of $\bar{\varphi}_l$ measurement was 0.3 mm, and the maximum distance was 0.7 mm. The distances between the probe traverse lines were determined from photography in two directions as the probes were moved relative to a fixed scale. The probes were made up with insulated Constantan wire of 0.2-mm diameter.

Location of the probe and the thermocouple in a single plane in setting up the probe rake was accomplished as follows. The thermocouple was attached rigidly to the rake, and the probe electrodes (i.e., the wires) could be moved and bent somewhat with respect to the thermocouple. A calibrated traverse mechanism (with divisions of 10 μm) was used to lower the entire rake of probes to the heated surface. The probes, on reaching the surface, penetrated inside the capillaries of the beryllium oxide until the thermocouple touched the surface. The moment of thermocouple contact was determined from the electrical contact. In this position epoxy resin was poured over the probe electrodes through a funnel. This position was the point of origin in conducting the tests ($h = 0$). The nine-probe rake was moved only horizontally at constant height 80 μm in steps of 0.1 mm over a length of 5 mm, and the 12-probe rake was moved only vertically in steps of 0.05 mm near the surface, and in steps of 0.2 mm for $h > 1$ mm.

The signal from the microthermocouple went to the amplifier, passed through a low-frequency filter, and was recorded on a type N-115 loop oscillograph. In this way we recorded the time-averaged temperature, obtained by filtering out the fluctuating components.

The heat-transfer surface was the face of a copper rod of diameter 20 mm, covered with a layer of nickel of thickness 5-7 μm. To measure the heat flux, four thermocouples were positioned along the upper part of the rod.

For a given heat flux the probes and the thermocouple were set up at a specific distance from the heat-transfer surface and the probes were connected, in turn, to the measurement instrument. The measurement time $\bar{\varphi}_l$ was 1 min, which was sufficient for statistical averaging of the results. The thermocouple readings were recorded over 2-3 min. The accuracy in determining local vapor content was 6-8% [7].

2. Experimental Results and Analysis. In the first series of tests we measured the distribution of local vapor content over the heat-transfer surface in an area of width 4.9 mm and length 5 mm, positioned at the center of the working section. The heat fluxes were $(349, 735, 930) \cdot 10^3$ W/m^2. In the second series of tests we measured, simultaneously, the temperature profiles and the local vapor content while the heat flux was varied from $490 \cdot 10^3$ to $1.13 \cdot 10^6$ W/m^2. The critical heat flux was $1.86 \cdot 10^6$ W/m^2. In the third series of tests we measured only the local vapor content for q equal to $1.13 \cdot 10^6$ and $1.44 \cdot 10^6$ W/m^2. The critical heat flux was $1.66 \cdot 10^6$ W/m^2. It was assumed that the chosen areas were representative of the whole heat-transfer surface in determining the actual vapor-generation centers.

a) Distribution of Vapor Content over the Heat-Transfer Surface. Using a physical model of boiling heat transfer, references [8, 9] have put forward a general correlation for the average resultant specific heat flux. In order to calculate individual heat-flux components one must average, over time and space, the fractions of surface occupied by the vapor and the liquid.

Tests to measure the surface-averaged vapor content were carried out at a constant height of 80 μm. To obtain the arithmetic average value $\bar{\varphi}$ a double averaging was performed: over the width of the area for all the probes, and along the length with steps of 0.1 mm, i.e., $\bar{\varphi}$ was obtained from 450 values of $\bar{\varphi}_l$.

Figure 1 shows $\bar{\varphi}$ as a function of the heat flux. The figure also shows the experimental data of [10] in terms of the relative fractions of the area in contact with the bubbles (line 1) and vapor (line 2). Since the vapor content was measured in a plane 0.08 mm distant from the wall, a distance greater than the thickness of

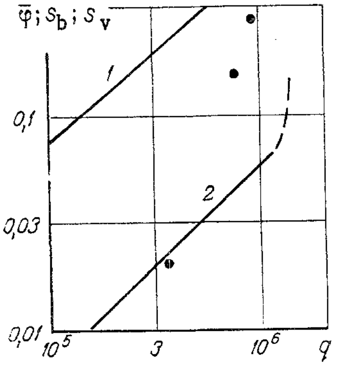

Fig. 1

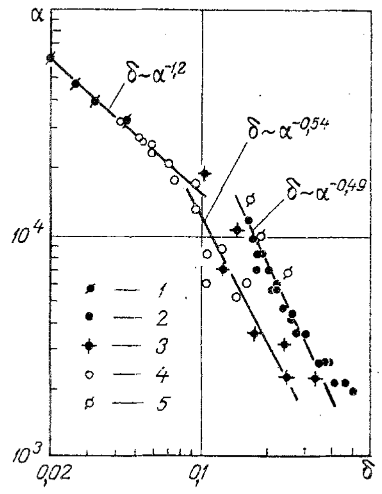

Fig. 2

Fig. 1. Ratios of the bubble contact area s_b (line 1), the vapor contact area s_v (line 2) with the surface [10], and the average vapor content as a function of heat flux q, W/m^2.

Fig. 2. Ratio between heat-transfer coefficient α, W/m^2·deg K, and extrapolated heated layer thickness δ, mm: 1) present data; 2-5) data of [1-4].

the microlayer under the bubbles in these conditions, the values of $\bar{\varphi}$ fall between lines 1 and 2, and with increase of q the values of $\bar{\varphi}$ draw near to the values of s_b.

Thus, from the measured vapor content one can obtain, to a certain approximation, the ratio of the fractions of surface occupied by vapor and liquid for different heat fluxes and pressures. These data can be used to determine the separate heat-flux components.

b) Temperature Profiles above the Heated Surface. The distribution of time-averaged temperature was measured up to h = 3 mm. Starting from h = 0.5-0.7 mm the thermocouple remained at a constant temperature, practically coincident with the saturation temperature. Values of surface temperature for h = 0 were obtained using a moving thermocouple and also by extrapolating the temperatures measured by the thermocouples in the copper rod. These two values showed good interagreement, which is evidence that the temperature measurements are reliable. Usually the extrapolated thickness of the heated layer was determined as the distance from the wall at which the tangent to the temperature profile at the surface intersects the line of constant liquid temperature in the enclosure [1-4]. The heat-transfer coefficient as a function of heated layer thickness is shown in Fig. 2. Figure 2 also shows the data of [1-4].

From Fig. 2 it can be seen that δ and α are linked for both regions by the expression

$$\delta \sim \alpha^{-n}. \tag{2}$$

For the first region n = 1.2, and for the second region the exponent n = 0.54 was proposed in [2], and the value n = 0.49 was proposed in [1]. Comparison of the present data with Eq. (2) shows that the data are in good agreement with this relation.

c) Local Vapor Content Profiles. The profiles of variation of vapor content with height are shown in Fig. 3. The points here are the average values of $\bar{\varphi}_l$, measured by the 12 probes. For comparison the experimental data of [11] are shown for one heat flux value. For q = 490 · 10^3 W/m^2 the vapor content increases smoothly to the value $\bar{\varphi}$ = 40% for h ≈ 1.6 mm, and $\bar{\varphi}$ remains practically unchanged at greater height. As the heat flux increases the maximum vapor content increases, while h_φ decreases. In the heat flux range investigated we find that

$$h_\varphi q = \text{const.} \tag{3}$$

The same relation between h_φ and q is obtained from the experimental data of [11].

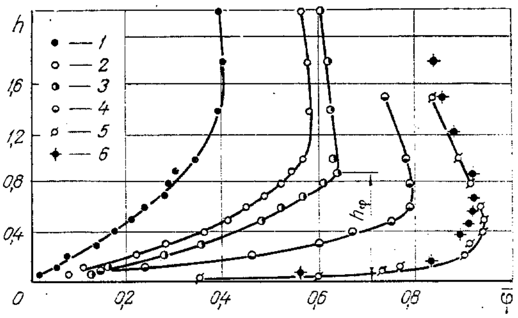

Fig. 3. Variation in vapor content with height h, mm, above the heat-transfer surface: 1-5) heat flux of (490, 668, 835, 1130, 1140) $\cdot 10^3$, respectively; 6) $1200 \cdot 10^3$ W/m^2.

Near the heat-transfer surface relatively low values of $\bar{\varphi}$ are observed. Therefore, in this region there is a layer with a considerable amount of liquid, and the region with increased volume concentration of vapor occupies the space above this layer. With increase of heat flux the density of active vapor-generation centers increases, the distance between the growing bubbles decreases, and the bubbles merge at earlier stages of growth, which leads to the region with enhanced vapor content being displaced toward the heat-transfer surface. This may explain relation (3) between h_φ and the heat flux.

Analysis of the variation in shape of the probe signal recorded by the oscillograph with varying distances from the heat-transfer surface and q = const shows that the same values of $\bar{\varphi}$ occurring at different h are due to different frequencies of liquid – vapor phase exchange. The smaller h is, the more frequent is the phase exchange, and the time for which a given phase is present decreases. This is evidence of strong mixing of liquid in the immediate vicinity of the heat surface, due to the formation of a large number of bubbles. With increase of heat flux the phase exchange frequency increases.

Thus, over the entire region of heat-flux variation there is a layer on the heat-transfer surface enriched with liquid, which also mainly determines the heat-transfer intensity in boiling.

Comparison of the experimental results with the data of [11], shown in Fig. 3, indicates good agreement both in the nature of the dependence of $\bar{\varphi}$ on h, and in the levels of $\bar{\varphi}$.

A feature of great interest in the heat-transfer process in bubble boiling is the layer of thickness h_φ (see Fig. 3) containing the maximum value of vapor content. As was noted above, the thickness of the heated liquid layer δ and the vapor content parameters are very probably the basic governing factors for the boiling process. Therefore, a definite relationship should exist between these factors.

Figure 4 shows the relation between the quantities δ, α, and the vapor content parameters. In the range of heat flux investigated the relationship between δ and h_φ(Fig. 4a) and α and $\varphi_{\max}$ (Fig. 4b) is given by the following expression:

$$\delta \sim h_\varphi^{0.7};\ \alpha \sim \varphi_{\max}. \qquad (4)$$

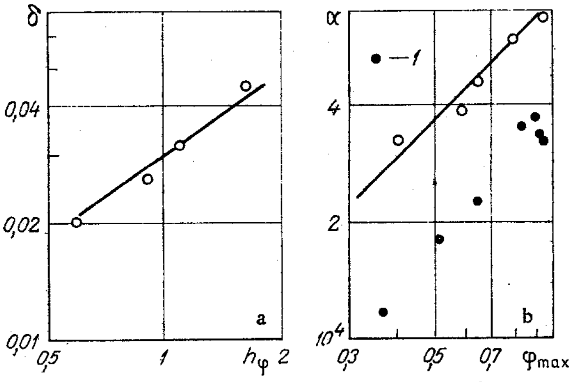

Fig. 4. Relation between δ, mm, α, W/m$^2\cdot$deg K, and the vapor content parameters: 1) data of [11].

The data of [11], presented in Fig. 4, show good agreement in basic character with our experimental results, but they differ in absolute magnitude. This may arise from two causes. Firstly, it is known that the quantities α and q_{cr} are greatly influenced by the surface conditions, which may possibly differ in our experiments and in [11]. This is confirmed indirectly by the different values of q_{cr} obtained in our tests ($1.66 \cdot 10^6$) and in the tests of [11] ($1.23 \cdot 10^6$ W/m^2), and also by the values of α at the same values of q. Secondly, the experimentally measured value of $\overline{\varphi}_l$ depends on the chosen level of discrimination (the level of the difference in amplitudes of sensor signal in the vapor u_v and in the liquid u_l, at which the time of liquid present at a given point is summed). In our tests the discrimination level was ~78% of ($u_l - u_b$), while in [11] it coincided with the amplitude of the sensor signal in the liquid.

NOTATION

α, heat-transfer coefficient; q, specific heat flux; q_{cr}, critical heat flux; δ, extrapolated thickness of heated thermal layer; $\overline{\varphi}$, $\overline{\varphi}_l$, average and local average vapor content; τ, time; s_b, s_v, area of surface contact of bubbles and vapor; h_φ, height at which the maximum vapor content value is attained; u_l, u_v, amplitude of sensor signal in the liquid and in the vapor.

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