TEMPERATURE FLUCTUATIONS IN A TWO-PHASE SUPERHEATED LAYER IN THE BOILING OF A LIQUID

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One of the basic parameters defining the intensity of heat transfer on the boundary separating liquid and vapor phases is the superheating of the liquid during boiling. In a two-phase boundary layer superheating constitutes a variable (fluctuating) quantity, which depends on several parameters of the system and is of a statistical nature. This paper is devoted to a study of the statistical nature of the fluctuations in the superheating of a liquid. Starting from experimental data obtained in measuring temperature fluctuations in a two-phase boundary layer during the boiling of water in contact with a heated surface, we carry out a statistical analysis of the amplitude of the fluctuations. Based on this analysis, we determine the average and the maximum superheating as a function of the distance to the heated wall. To determine the microstructure of the temperature fluctuations and to study their origin, we took high-speed pictures of the head of a thermocouple in contact with the two-phase medium. We established that the presence of various size amplitudes is associated, in the main, with two effects: the existence of a superheated layer on a bubble in the course of its growth and the convection of the liquid close to the bubble.

1. Description of the Problem. It is a known fact that the amount of superheating of a liquid during boiling determines the intensity of the vapor-phase formation process on the liquid–vapor interface. A study of superheating of the liquid phase in relation to the temperature of boiling is of interest in connection with the study of the mechanism of the boiling process. The nature of superheating during the formation of the vapor phase in the presence of a heating surface differs from the superheating of a liquid during homogeneous vapor formation [1-3]. This difference is contained, first of all, in the statistical nature of superheating. In the case of homogeneous vapor formation, superheating is associated with fluctuations in the state parameters in a microsystem; in the case of boiling at a heating surface there exist, in addition to these fluctuations, also the fluctuations arising from turbulence of the liquid owing to the formation of vapor bubbles on the heating surface. Temperature fluctuations in a two-phase boundary layer during the boiling of a liquid were investigated in [4-6]. It is evident from these papers that the character of the temperature fluctuations depends on the physicochemical properties of the liquid, on the heat flow at the heating surface, and on the quality and the form of the surface.

Earlier studies of the temperature fluctuations in a two-phase boundary layer [7-10] showed that the superheating fluctuations during the boiling of liquids have a statistical character with well-defined statistical parameters. It was shown by means of an amplitude and a harmonic analysis of the temperature fluctuations at various points of the boundary layer that the most probable superheating of a liquid is a function of distance on the heated surface for a constant heat flow. It was also shown in these papers that the maximum superheating can be substantially larger than the average superheating. The present paper is devoted to a further study of the nature of the fluctuations, their individual realizations, and the statistical character of the fluctuations in various regimes of boiling.

2. Analysis of the Temperature Field near a Vapor Bubble during Boiling on a Horizontal Surface. The analysis of the temperature fluctuations in a two-phase boundary layer during the boiling of water on a horizontal surface is based on an experimental measurement of the temperature fluctuations at various distances from the heating surface. To record the temperature fluctuations we used a Chromel–Alumel

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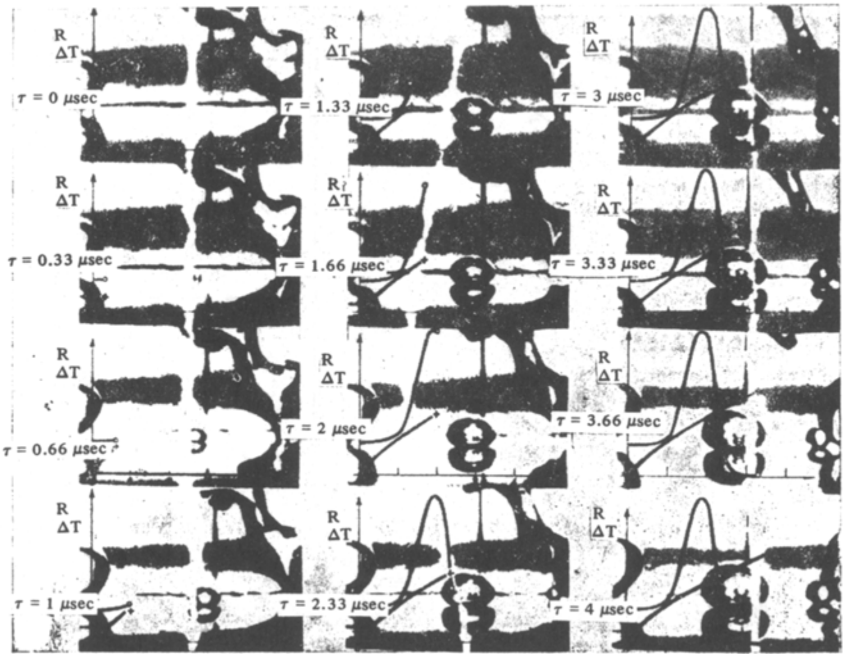

Fig. 1

microthermocouple made from 12.5-μ-diameter wires. The dynamic response of the thermocouple was determined by a specially developed method, described in [10]. The essence of this method is the following: a beam of light is directed onto the head of the thermocouple, behind which there is placed a photodiode. By covering the light beam with a specified frequency, a periodic heating and cooling of the thermocouple head is achieved. The frequency response of the thermocouple is determined by measuring the emf of the thermoelement, with a simultaneous recording of the light-beam intensity incident on the photodiode, and then comparing the resulting signals.

Measurement of the temperature fluctuations during boiling was made on the following experimental apparatus [10]. The polished surface, 6 cm^2 in area, of an experimental container served as the heating surface. Heat was supplied at the heating surface through a copper rod soldered to the outer horizontal side of the experimental container. The heat flow onto the heating surface was determined with the aid of five thermocouples placed along the copper rod. The temperature of the wall was determined by extrapolating the readings of these thermocouples up to the heating surface. A microthermocouple was placed on the lid of the experimental container, allowance being made for its motion in a horizontal plane. Vertical motion of the heat probe was realized by means of a microthermal screw, which made it possible, with sufficient accuracy, to determine the position of the head of the thermocouple with respect to the heating surface. The emf of the thermocouple was compensated by the emf corresponding to the boiling temperature and the difference obtained was fed to an amplifier. The signal, amplified 1000-fold, was then fed to an oscillograph or a special magnetophone.

The relative position of the thermocouple and a bubble during its growth was determined by a high-speed motion picture. For this purpose we used a "Neuss" motion-picture camera with two objective lenses. One of these was used to expose the interaction of the two-phase boundary layer with the microthermocouple, the other was directed at the oscillograph screen recording the microthermocouple signal. From the exposed films we determined the temperature field surrounding a bubble in the course of its growth. Successive frames from the film are shown in Fig. 1; these were taken for a heat flow of $q = 17.5$ W/cm^2 and a distance of the thermocouple from the heating surface equal to $\Delta x = 2.25$ mm. For the regime which is characterized by the presence of individual nuclei and corresponds to the heat-flow value $q = 8.65 \cdot 10^4$ W/m^2 and a pressure $p = 1$ atm, we made a series of film shots of a particular vapor-formation center with various thermocouple positions. The results of these measurements are shown in Fig. 2 for two different types of bubbles characterized by the same rate of growth. The thermocouple positions corresponded to the following distances from the heating surface: Point 1, $\Delta x = 0.5$ mm; Point 2, $\Delta x = 1.5$ mm; Point 3, $\Delta x = 2.5$ mm; Point 4, $\Delta x = 3.5$ mm; and Point 5, $\Delta x = 5.5$ mm. As is evident from these figures, the temperature field close to the bubbles completely repeats itself, i.e., the nature of the variation for the various realizations of individual bubbles

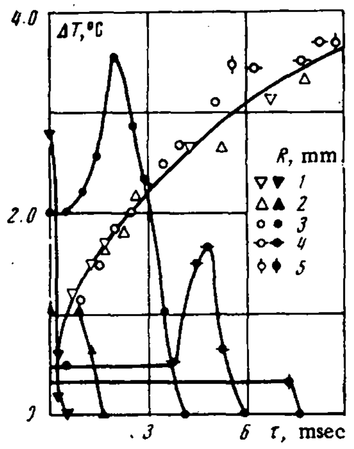

Fig. 2

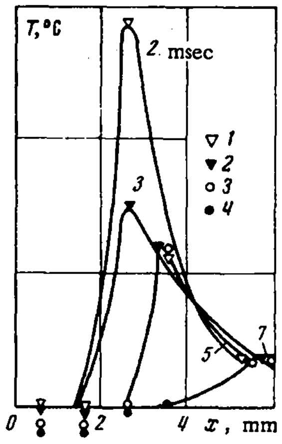

Fig. 3

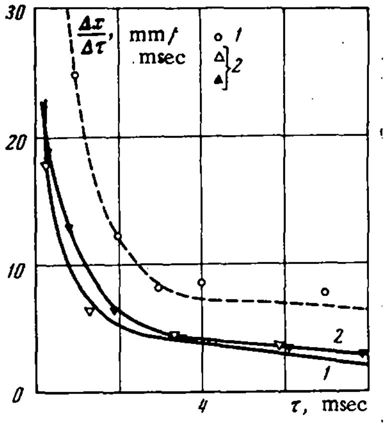

Fig. 4

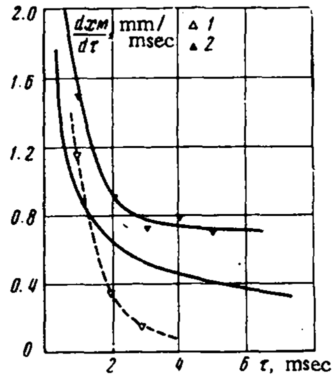

Fig. 5

is identical. This enables us to make the assumption that even for the various thermocouple positions the nature of the variation of the temperature field close to a bubble stays the same. Furthermore, this assumption makes it possible to draw temperature histograms on which the distance of the thermocouple from the heating surface appears as a parameter. These curves describe the variation of the temperature in spatial coordinates, where now the time of bubble growth appears as a parameter.

Figure 3 shows the variation of the temperature as a function of the distance to the heating surface for $\tau = 2$, 3, 5 msec for two different types of bubble. It is evident from these curves that there exists a thermal boundary layer surrounding a bubble. It is also known that the maximum temperature in the thermal boundary layer changes substantially with time as a result of the elimination of heat through the surface separating the phases and, also, thanks to the nonstationary heat conduction in the surrounding liquid. The second of these processes leads to a variation in the boundary-layer thickness. In estimating the boundary-layer thickness, it is necessary to take into account the fact that the results were obtained through measurement with a fixed thermometer, whereas the thermal boundary layer moves with respect to the thermometer with a speed equal to the rate of growth of the bubbles. The velocity of the liquid motion close to a bubble can be determined on the basis of measurements of the rate of bubble growth.

It can be seen from the curves in Fig. 3 that the boundary-layer thickness $\delta = 0.5$ mm for $\tau = 2$ msec. The rate at which the thermal boundary layer moves due to growth of the bubble amounts to $W = 0.8$ m/sec at the given time $\tau = 2$ msec. This means that the microthermocouple traverses the boundary layer in a time interval of $\tau = 0.63$ msec, which is close to the value of the time constant for the given thermocouple. It follows from this that a thermal element used for such rates of boundary-layer movement records only those temperature changes present in a boundary layer of thickness $\delta = 0.2$ mm. Therefore, in the measurements no thermal boundary layer can appear at distances less than $\Delta x = 1.5$ mm.

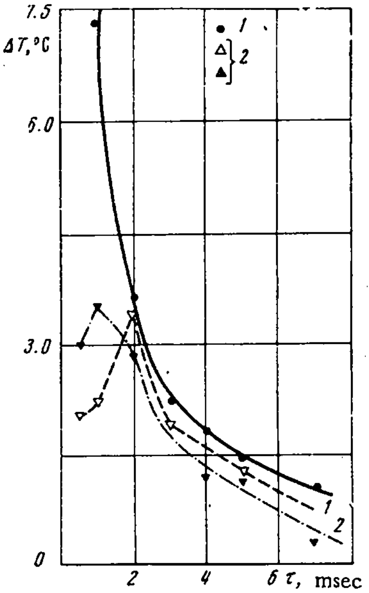

Fig. 6

On the basis of the measurements shown in Fig. 3 we can determine the rate at which the maximum temperature moves in the boundary layer. Figure 4 shows how the rate of change of this maximum varies as time increases. Curve 1 in this figure represents the rate of growth of a bubble plus the velocity of the heat wave; curve 2 is the rate $dR/d\tau$ of the bubbles 1 and 2. If from this rate we substract the rate of bubble growth, we obtain the velocity of the heat wave in the nonstationary boundary layer. The value of the velocity so obtained must be found to agree with bubble-growth theories based on the assumption of the existence of a thermal boundary layer surrounding a vapor bubble, controlling the rate and mechanism of growth of a bubble.

For the analysis of the temperature field surrounding a bubble, we start from the one-dimensional nonstationary heat-conduction equation

$$\partial T/\partial \tau = a\partial^2 T/\partial x^2 \tag{2.1}$$

and the following boundary and initial conditions:

$$\begin{aligned} &T(x=0,\ \tau \leqslant 0) = T_p \\ &T(x \leqslant \delta,\ \tau \leqslant 0) = T_p \\ &T(x > \delta,\ \tau \leqslant 0) = T_p \\ &T(x = 0,\ \tau > 0) = T_S \\ &T(x = \infty,\ \tau > 0) = T_S \end{aligned} \tag{2.2}$$

This makes it possible to introduce first-order impulse functions in place of the first two boundary and initial conditions, and to obtain the solution of Eq. (2.1) in the form

$$\frac{T(x,t) - T_S}{T_S} = \frac{\omega_2 x}{2(a\pi\tau^3)^{1/2}} e^{-x^2/4a\pi} \tag{2.3}$$

from which we can then obtain the speed at which the maximum temperature moves in the boundary layer:

$$dx_m/d\tau = (a/2\tau)^{1/2} \tag{2.4}$$

and the value of the maximum temperature

$$T(x_m, \tau) = \frac{\omega_2 T_S}{(2\pi e)^{1/2}} \frac{1}{\tau} \tag{2.5}$$

In Fig. 5 a comparison is made of the displacement rate of the maximum temperature in the thermal boundary layer, obtained on the basis of Eq. (2.4), with that obtained from experimental data. Also in this figure are shown the results obtained using the Mikić–Rohsenow relationship (see [11]). Figure 6 shows the variation of the maximum temperature in the immediate vicinity of a bubble during the period of its growth and also a comparison with Eq. (2.5) for the bubbles 1 and 2. Curve 1 in Fig. 5 is the experimentally obtained heat-wave velocity; curve 2 is based on the Mikić–Rohsenow model; curve 1 in Fig. 6 is based on Eq. (2.5) and curve 2 represents the experimental data for the bubbles 1 and 2.

The agreement of results of measurements of the temperature in the superheated boundary layer with the theory based on the existence of a nonstationary boundary layer surrounding a bubble confirms the assumption that the superheated liquid surrounding a bubble defines both the mechanism and the character of the bubble growth in the boiling process. It is well known that superheating of the liquid close to the heating surface represents a fluctuating quantity, the nature of which, for the existence of individual bubbles, can be described analytically with fairly good accuracy. A better description is possible only at a specified distance from the heating surface. At the start of bubble growth we obtain a maximum temperature in the boundary layer $T_{max}/\tau_0 = 24°C$, which is substantially larger than the wall temperature for a given heat flow. Therefore, the superheating value, obtained from wall-temperature measurements, represents only an average value of the superheating fluctuations in the immediate vicinity of the heated surface. We conclude, then, that in considering the superheating of a liquid close to a heating surface during boiling, it is necessary to take into account superheating fluctuations and their statistical character.

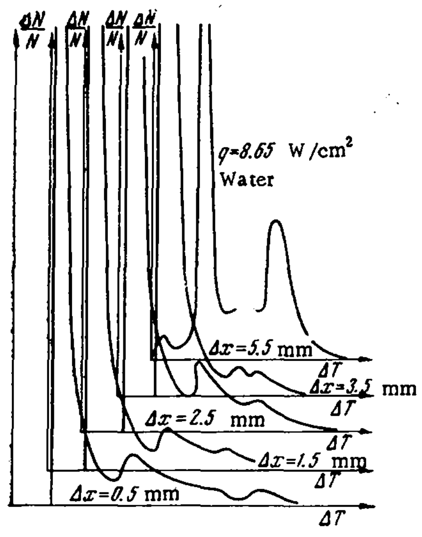

Fig. 7

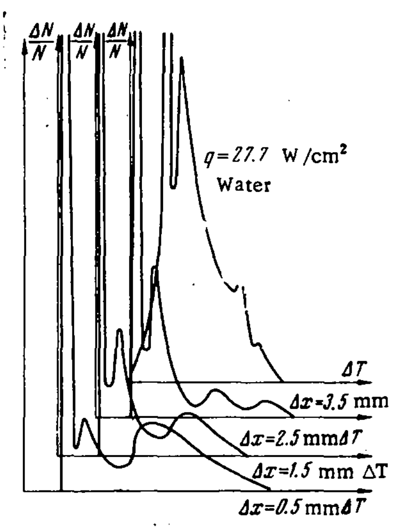

Fig. 8

3. Statistical Analysis of Superheating Fluctuations during Boiling. Bearing in mind the large number of diverse effects on the value of the individual parameters of a two-phase boundary layer, we can assume that all quantities which define the transfer of mass, energy, and momentum are of a statistical nature. A method has been worked out for statistically handling the superheating variables at each point of a two-phase flow. The microthermocouple signal was treated as a continuous random function; by statistically analyzing the amplitudes we can obtain a probability distribution for each amplitude of the signal in question. It is assumed here that the continuous random function considered satisfies the criterion of ergodicity. In the majority of cases the boundary-layer temperature fluctuations do satisfy this condition.

Amplitudinal Analysis. For each thermocouple position the thermocouple signal was entered into a measuring magnetophone in a flow of $\tau_0 = 15$ sec with a recording speed of $W_0 = 75$ cm/sec. The signal on the magnetophone film was fed through a linear amplifier and supplied as input to a frequency converter in which the signal was converted from analog to digital form, subsequent to which it was directed to a binary register. From the binary register the signal was fed to a digital computer, which carried out an amplitude analysis of the signal. Since the signal was slowed by a factor of 16 (the film was processed at a rate of 4.7 cm/sec), and since the oscillator in the circuit translating the signal into digital form worked at a frequency of 500 Hz, the duration of each discrete amplitude amounted to $\Delta\tau = 0.12$ msec. In the amplitude analysis we took 120,000 amplitudes, which corresponds to signal durations of $\tau_0 = 15$ sec.

If the number of amplitudes at level K for the value of the signal is H_K, where H is the total number of amplitudes considered, then the probability of the appearance of a K-th level amplitude in the total signal is

$$P(T_{K-1} \leqslant T \leqslant T_K) = H_K / H = \sum_K \Delta t_K / \Delta\tau, \tag{3.1}$$

Thus, for the probability density we have

$$P(T) = P(T_{K-1} \leqslant T \leqslant T_K)/\Delta T' \tag{3.2}$$

Temperature fluctuations were measured at the following five different thermocouple locations, $\Delta x =$ 0.5, 1.5, 2.5, 3.5, 5.5 mm, during the boiling of water at atmospheric pressure and with a heat flow of $q =$ 8.65 W/cm². The amplitude distributions obtained are shown in Fig. 7. Boiling under these conditions corresponds to a regime of separate, identical bubbles. The heating element location, selected exactly above the vapor-formation center, corresponded to the regime considered in the first part of our paper. It is evident from the amplitude distributions that there are two characteristics for the superheating of a liquid at each of the points considered. The smaller value of superheating corresponds to superheating of the liquid located at some distance from the surface, separating the phases, while the larger value corresponds to superheating in the thermal boundary layer surrounding the bubble. Superheating of the liquid located at a distance from the separation surface assumes a constant value, while the superheating in the thermal boundary layer is of the same nature as that obtained in considering the individual bubbles in the analysis of the films. Therefore the results shown in Fig. 7 relate to the temperature fluctuations exactly above the single vapor-formation center.

For well-developed bubble boiling, when the number of vapor-formation centers is uniformly distributed over the heating surface, the position of the thermocouple is observed to have a significantly smaller influence on the nature of the temperature fluctuations close to the heating surface. Figure 8 shows the amplitude distributions of the temperature fluctuations during the boiling of water with a heat flow of $q = 27.7$ W/cm^2. This regime of boiling corresponds to well-developed bubble boiling. Two values of superheating of the liquid are clearly visible. The smaller superheating value relates to the superheating of the surrounding liquid located at a specified distance from the phase-separation surface; the larger value corresponds to superheating in the thermal boundary layer. In this case significantly smaller superheating of the surrounding liquid is observed since for such a regime it represents an average superheating of the liquid. In its character and size the maximum superheating is equal to the superheating demonstrated in the case of single bubbles, thus confirming that the temperature fluctuation signal contains information concerning superheating in the thermal boundary layer.

Superheating of a liquid at some distance from the heating surface fluctuates over a range of amplitudes, which makes it possible to assume that the superheating of a liquid at a wall can be significantly larger than the superheating obtained by measuring the wall temperature.

Temperature fluctuations have a strictly defined character for various flow conditions in a two-phase mixture.

An analysis of temperature fluctuations in a two-phase flow makes it possible to determine an average local volumetric vapor content for a two-phase mixture.

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