Journal of Engineering Physics and Thermophysics, Vol. 64, No. 4, 1993

MOTION OF A TEMPERATURE AUTOWAVE UPON CHANGE OF BOILING REGIMES ON A MASSIVE HEATED PLATE

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UDC 536.248.2.001.5

The critical change in the temperature of a 120 mm long and 15 mm thick brass plate at different distances from the nitrogen boiling surface is investigated experimentally.

With the onset of burnout, one or several sites of a new regime are first formed on the boiling surface, which expand and displace the former boiling regime [1, 2]. The self-sustaining propagation of the temperature wave front observed upon change of boiling regimes is related to the type of thermal autowaves (TAW) of change which are realized in bistable systems [3]. This means that to one value of the heat transfer rate there correspond two steady states with different temperatures (bubble and film boiling regimes) [4, 5].

Familiar experimental investigations into the process of the replacement of boiling regimes have been carried out on thin electrically heated filaments. Besides the high-speed cine-photography of vapor film boundary motion over the boiling surface [6-8], the thermographical technique was employed, which allowed one to indirectly assess the value of w by the change in the mean temperature of the filament [1, 2]. The publications mentioned do not furnish information about the actual distribution of temperature in the TAW front or about the effect of two-dimensionality in boiling on a massive ("thick") surface [5].

The concern of the present work is to experimentally determine the two-dimensional temperature field characteristics in a heated metal plate upon change of boiling regimes on its surface. Proceeding from the possibilities of measuring-recording instrumentation, on the one hand, and the characteristics of the spatial-temporal scales of the process, on the other hand, brass LS59-1 was selected as the material for the plate, and liquid nitrogen, boiling at atmospheric pressure, as the coolant.

Rectangular plate 1 (Fig. 1) had the dimensions $10 \times 15 \times 120$ mm. On one of the sides measuring 10×120 mm, main electric heater III with a maximum power of 250 W was glued. Nitrogen boiled on the opposite side of the plate; its remaining sides were thermally insulated with foam plastic and tufnol II. Sixteen copper-constantan thermocouples IV were positioned in three longitudinal cross sections located at the distances x = 1, 7 and 13 mm from the boiling surface (according to the centers of the holes). The distance between the centers was $\Delta y = 20$ mm.

Two additional electric heaters V of dimensions 10×10 mm were glued to the side of the plate opposite to that with thermocouple leads. They were used to initiate bubble boiling crisis. Each of them had a maximum power of 35 W. All the electric heaters were fed by direct current from controlled sources; current and voltage were measured by digital instruments.

Thermocouple signals were preliminarily strengthened by F7029/4 and F116/1 amplifiers. The levels of signals were substantially different for the groups of thermocouples with x = 1, 7 and 13 mm, and therefore the gain coefficients 1000, 500 and 200 were employed, respectively. This made it possible to obtain close levels of signals at the inlet to the measuring-recording system K200/4 and operate on one measuring limit of the analog-digital converter. The frequency of cyclic sampling of the system commutation channels was 0.1 sec.

In Fig. 1 we show the change in the mean (with respect to y) stationary temperatures of the metal in three longitudinal cross sections with increase in the power of uniform heating of the plate in the stable bubble boiling regime. The value of q_{cr1} is equal to (163 ± 5) kW/m^2. The transverse temperature gradient rises from $\overline{K} \approx 0.3$ to $\approx$

Physicotechnical Institute of Low Temperatures, Kharkov. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 64, No. 4, pp. 387-392, April, 1993. Original article submitted February 26, 1992.

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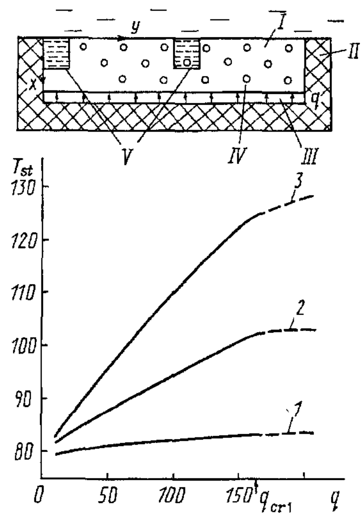


Fig. 1. Schematic of the experimental arrangement and dependence of the stationary temperature of the metal on the heat transfer rate: 1) x = 1 mm; 2) 7; 3) 13. T_{st}, K; q, kW/m^2.

3.5 K/mm in the range q = 9.4-156 kW/m^2. Estimation of the thermal conductivity coefficient yields λ= 35-55 W/(mK); according to [8], at T=70-100 K λ = 50-60 W/(mK) for this type of brass. Taking into consideration the approximate character of the estimate, the agreement between the data can be regarded as satisfactory.

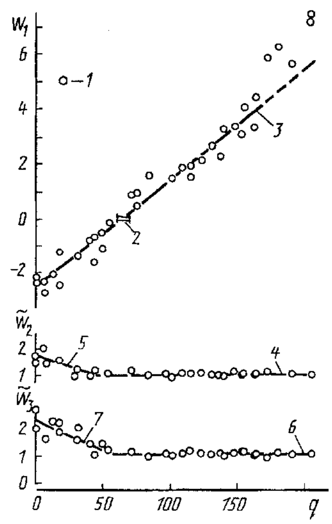
The heating of the plate for the bubble boiling crisis was initiated in two ways. When $q<q_{cr1}$, after the stationary distribution of T had been developed, we supplied power to one of the additional electric heaters, producing local superheating of the metal. Noting the start of the irreversible critical process, we switched off the initiator and recorded the propagation of the "hot" zone along the uniformly heated plate.

As the heat transfer rate decreased from 156 to 80 kW/m^2, the power needed for crisis initiation increased from about 15 to about 30 W. At $q = q^*$ = 60-70 kW/m^2 the TAW formed in the vicinity of the initiator came to a halt, and after the initiator had been switched off, a stationary bistable state was observed, i.e., stable coexistence of boiling regimes (a temperature wave with a fixed front).

In the second case, a stationary temperature field was achieved under the conditions of q = 156 W/m^2 with a small power of heat liberation (4-8 W) on one of the initiators. The local superheating of the plate was insufficient for the crisis to be initiated. Therefore, the heat flux from the main electric heater was upped from 156 kW/m^2 to $q = 163-206\ kW/m^2 > q_{cr1}$. In this case, on the basic process of "hot" zone propagation along the plate relaxation of a small transverse temperature perturbation was superimposed. In Fig. 1 the dashed lines show the data on the brass temperature ahead of the heating TAW front.

In film boiling crisis, the natural initiators of local lowering of T and vapor film disintegration are the ends of a uniformly heated boiling surface where heat losses through the insulation are maximal. Therefore, some time after the heat transfer rate was lowered from the region $q>q^*$ to the region $0 \le q < q^*$, it was two opposing TAW that began their motion almost simultaneously from the ends of the surface to its center, i.e., the collapse of the "hot" zone took place.

In processing experimental data, we determined the linear velocity of the TAW front $w = \frac{dy}{d\tau}$ at three longitudinal sections of the plate (x_1 = 1 mm; x_2 = 7 mm; x_3 = 13 mm), the mean steepness of the front $\Gamma = \frac{dT}{dy}$ at the same sections and the mean transverse temperature gradient of the metal $K = \frac{dT}{dx}$ at a cross section passing through the front and moving with it. When determining the value of w in the case of $q>q^*$, the instant of TAW arrival at the point with the coordinate y_i was related to the instant of $T_i(\tau)$ deviation from the horizontal and to the start of temperature growth. Since for $q<q^*$ it was difficult to precisely determine the instant of time when T_i ceases to



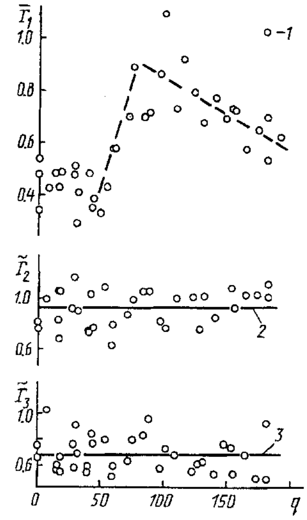


Fig. 2. TAW front velocity vs heat transfer rate: 1) experimental data; 2) zone with $q = q^*$; 3-7) see the text. w is in mm/sec; q is in kW/m^2.

Fig. 3. Mean TAW front steepness vs heat transfer rate: 1) experimental data; 2, 3) see the text; the dashed lines are drawn for clarity. $\overline{\Gamma}$ is in K/mm.

decrease, here the arrival of the front was related to the instant of attainment of a certain value of $T_i = T_{st}(q) + \delta T$, where the value of δT was selected in the range 15-25 K. In this case the velocity w depended little on the choice of δT; theoretically, any point of the TAW front should have the same velocity.

The relation $y_i = y_i(\tau_c)$ derived experimentally is close to a linear one in all of the cases, i.e., the velocity of the front can be considered constant in time and along the coordinate y: $y_i = A + w\tau$. The values of Γ and K were also determined (due to the discrete nature of the data on $T = T(x, y)$) within the framework of a linear approximation: $T(x, \tau = \text{const}) = B + \Gamma y$; $T(y, \tau = \text{const}) = C + Kx$. The time-averaged values of the gradients $\overline{\Gamma}$ and $\overline{K}$ are presented below.

Analysis of the possible errors in determining the characteristics of TAW has shown that the errors encountered in the measurements of temperature, time and coordinates are relatively small and that the main contribution to the considerable (as will be shown below) scatter of the data comes from the above-described procedure of linearizing the actual relations. Moreover, the very process studied seems to be not entirely uniform along the plate length because of local heating nonuniformities, properties of the metal, etc. Nevertheless, the experimental procedure we used and the approximate approach to the determination of w, $\overline{T}$ and $\overline{K}$ give the possibility of obtaining useful information on critical transition processes and on the order of the quantities characterizing these processes.

From Fig. 2 it is seen that the dependence of the TAW front velocity in the metal layer adjacent to the boiling surface on q is close to a linear one. Approximation of the data on w_1 within the range $0 \le q < q_{rc1}$ gives $w_1 = -2.536 + 3.938 \times 10^{-2} q$, where w_1 is in mm/sec and q in kW/m^2 (line 3). Here, positive values of w_1 correspond to expansion of the "hot" zone (bubble boiling crisis), negative values correspond to collapse (film boiling crisis), and the value $w_1 = 0$ corresponds to stationary coexistence of boiling regimes. The points obtained for $q > q_{rc1}$ lie somewhat higher than the extension of curve 3; this seems to be associated with the change in the means of crisis initiation. It should be noted that in the region $w_1 < 0$ our relation $w_1 = w_1(q)$ differs qualitatively from that observed in the works of other authors [2, 6, 7]. In the case of boiling on small-diameter cylinders the velocity $w < 0$ falls quickly with a decrease in q from $q = q^*$ and tends to $-\infty$ as q approaches zero. In our opinion, this is associated with the very small thermal inertia of such specimens and the virtually one-dimensional character of the process of their cooling. It is evident that the change of boiling regimes on a massive specimen with a considerable thermal resource physically cannot be infinitely fast and the quantity w should have a finite value even at $q = 0$.

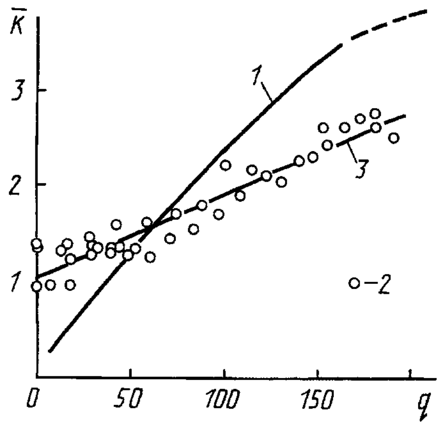


Fig. 4. Mean transverse temperature gradient of metal vs heat transfer rate: 1) "stationary" gradient $\overline{K}_{st}$; 2) experimental data on $\overline{K}_d$. $\overline{K}$, K/min.

To compare the TAW front velocities at different distances from the boiling surface, the relative velocities $\tilde{w}_2 = \frac{w_2}{w_1}$ and $\tilde{w}_3 = \frac{w_3}{w_1}$ were calculated. Averaging of the values of $\tilde{w}$ for $q>q^*$, where the heat transfer rate does not influence the velocity ratio, yields $\tilde{w}_2 = 1.016\ \ 0.054$ (line 4 in Fig. 2); $\tilde{w}_3 = 1.082\ \ 0.058$ (line 6). Slight growth in the TAW front velocity with increase in x cannot be regarded as valid since it lies within the error of determining front velocities. Conversely, when $0 \le q < q^*$, the values of $\tilde{w}_2$ and $\tilde{w}_3$ grow reliably with decreasing heat transfer rate and the faster, the farther the section is from the boiling surface. Approximation of the data in this region of q yields $\tilde{w}_2 = 1.765 - 1.770 \times 10^{-2} q$ (line 5 in Fig. 2); $\tilde{w}_3 = 2.312 - 2.195 \times 10^{-2} q$ (line 7), where q is in kW/m^2. Thus, in the case of film boiling crisis the TAW front velocity in metal increases with distance from the plate surface. Simultaneously, the deviation of the function $w = w(q)$ from the linear one also increases.

The range of the metal temperature within which the mean steepness of the TAW front was calculated was limited from above by the value T = 250 K. As is seen from Fig. 3, when $q>q^*$ a decrease in the value of $\overline{\Gamma}_1$ with the growth of the heat transfer rate and, correspondingly, of the TAW front velocity occurs. The faster the thermal autowave, the flatter its front. When $0 \le q < q^*$, one fails to reveal an equally unequivocal dependence $\Gamma_1 = \Gamma_1(q)$. It is not excluded that in this region of the values of q the characteristics of the longitudinal metal temperature distribution in the course of replacement of regimes is influenced by a certain initial nonuniformity of the distribution. One can hardly avoid this in the course of experiments since it is impossible to attain a steady initial state in the film boiling regime (the corresponding values of T_{st} are too high). It is possible that precisely the initial nonuniformity, which increases with approach to q = 0, limits the decrease of Γ_1 when $q<30$ kW/m^2, although here the absolute value of the TAW front velocity continues to grow.

The relative values $\tilde{\Gamma}_2 = \frac{\Gamma_2}{\Gamma_1}$ and $\tilde{\Gamma}_3 = \frac{\Gamma_3}{\Gamma_1}$ do not display a certain dependence on the heat transfer rate (Fig. 3). Nevertheless, in the case of considerable scatter of the data, one can see that the mean steepness of the TAW front decreases with increase in the distance from the boiling surface: $\tilde{\Gamma}_2 = 0.920 \pm 0.140$(line 2 in Fig. 3); $\tilde{\Gamma}_3 = 0.678 \pm 0.138$(line 3). A certain contribution to this can be made by the growth of the thermal conductivity of brass with the temperature rise occurring with increase in the distance from the cooled surface of the plate.

The mean temperature gradient of metal in transverse sections of the plate, through which the TAW front passes, increases with q (see Fig. 4). However, the relation $\overline{K}_d = \overline{K}_d(q)$ for this "dynamic" gradient differs from that obtained on the basis of the data of Fig. 1. Approximation of this relation gives $\overline{K}_d = 1.034 + 8.74 \times 10^{-3} q$ (line 3 in Fig. 4), where q is in kW/m^2, whereas $\overline{K}_{st}(q=0)=0$. Approximate equality of $\overline{K}_d$ and the stationary gradient $\overline{K}_{st}$ is observed only in the region $q \approx q^*$, i.e., when $w \approx 0$. In the case of expansion of the "hot" zone (bubble boiling crisis) $\overline{K}_d < \overline{K}_{st}$, since growth of the temperature at each transverse section begins in the metal layer adjacent to the boiling surface. By contrast, in the case of film boiling crisis $0 \le q \le q^*$ the temperature of this layer begins to decrease before that inside the plate, and $\overline{K}_d > \overline{K}_{st}$.

Thus, on the basis of direct measurements we estimated for the first time the characteristics of a two-dimensional nonstationary temperature field after change of boiling regimes on a heated-plate surface. The results obtained can be used for calculating transient processes in the cooling systems of thermal and electric power equipment and also in cryogenic technology.

NOTATION

A, B, C, constants; Γ, TAW front steepness; K, transverse temperature gradient; q, heat flux density; T, temperature; w, TAW front velocity; x, y, coordinates; λ, thermal conductivity; τ, time. Indices: cr1, bubble boiling crisis; cr2, film boiling crisis; c, characteristic value; st, stationary value; $^-$, mean value; $^\sim$, relative value; 1, 2, 3, numbers of longitudinal sections of the plate.

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