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NONUNIFORM STEADY STATES OF THE BOILING PROCESS IN THE TRANSITION REGION BETWEEN THE NUCLEATE AND FILM REGIMES

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Abstract—An investigation of the process of boiling on thin metallic filaments in the transition region between the nucleate and film regimes is carried out. It is shown that, depending on the mode of power supply (constant current, constant voltage and constant electric resistance regimes), different nonuniform states (the state of 'mixed' boiling) occur in the region which significantly distort the form of the boiling curve. The inadequacy of traditional approaches for the correct measurement of the heat transfer coefficients in the transition region and also of the critical heat fluxes is shown. Experimental procedures which preclude the occurrence of spatially nonuniform states are described, and some estimates of the critical heat fluxes are given.

NOMENCLATURE

d,	heating element diameter;
J,	current strength;
$\bar{J}$,	magnitude of current corresponding to neutral equilibrium position;
L,	total length of heating element;
l,	linear dimension;
q,	heat flux;
$\bar{q}, q_1, q_2$,	mean integral heat flux, heat flux from the zone of nucleate and film regimes, respectively;
$q_{\text{cr }1}, q_{\text{cr }2}$,	critical values of heat flux;
R,	electric resistance;
$\bar{T}, T_1, T_2$,	mean integral temperature of the heating element, temperature in the zone of nucleate and film regimes, respectively;
V,	voltage.

Greek symbols

α_1, α_2,	heat transfer coefficient in the zone of nucleate and film regimes, respectively;
λ,	thermal conductivity of the heating element;
θ,	dimensionless parameter.

INTRODUCTION

THE UNDERSTANDING of the processes occurring on a heat generating surface in the transition region between the nucleate and film boiling regimes is of fundamental importance for the physical description of boiling. This problem has, nevertheless, received scant attention from investigators interested in research on boiling. It would hardly be wrong to say that even an unambiguous insight into the nature of the transitional regime has not been gained thus far. Some of the authors [1, 2] regard it to be a separate regime, coexisting with the nucleate and film ones, which is realized within the range of temperatures that lie between those corresponding to the first and the second critical heat fluxes, and within which the heat transfer undergoes a monotonous variation from the nucleate to film boiling. Other authors [3-5] claim that mixed boiling occurs in the transitional region, i.e. the zones of nucleate and film boiling regimes coexist on the surface of a heat generating element (HGE).

Based on the theoretical and experimental information dealing with autowave processes in boiling, the conclusion has been drawn [6, 7] that the usual technical means of controlling the temperature regime of a HGE are insufficient to provide reliable information on the true boiling curve in the transitional region. The uniform boiling regime in this region is unstable. This causes the occurrence of nonuniform steady states of the boiling process on the surface, such as standing temperature waves. This paper contributes to the development of research into this type of boiling, the study of the effect of heat supply modes on the character and stability of nonuniform boiling regimes in the transitional region, the development of means for suppressing the occurrence of nonuniform states, and accumulation of information on the true transition boiling curve.

The subject of investigation was a heat generating element (HGE) in the form of an electrically heated filament placed in a pool of working liquid. The choice of this kind of heater was dictated by the possibility and ease with which different modes of heat supply can be realized. This, as will be evident from what follows, is of principal importance for the problems considered in the paper. The specific features of the transition from nucleate to film boiling regimes have been studied under the three different conditions of heater-temperature behaviour control. For the constant current regime (J = const), electric power was supplied by a current stabilizer [7], i.e. the parameter which varied in the experiments was the strength of the current passed through the element. The second method, the constant voltage regime (V = const), was realized with the aid of a voltage stabilizer so that the variable parameter is the voltage drop across the element. And, finally, the third method is the regime of the constant electric resistance of the element, i.e. constant mean-integral temperature. In this case, the electric power was supplied with the aid of a tracker system that maintained the ratio V/J constant and allowed it to be raised [8].

Despite the academic nature of the system studied, the basic qualitative conclusions of this work seem to be of general importance and can be applied to any type of HGE.

CONSTANT CURRENT REGIME (J = const)

Despite the uncertainties in the information about boiling heat transfer on solid surfaces mentioned earlier, it is unquestionably true and generally agreed that the heat transfer law represented by the coordinates 'heat flux (q)–surface temperature (T)' is not a unique function of q. This means that the heat supply to the element in the q = const regime fails to provide information on the transitional region, since the boiling curve branch corresponding to this region is the branch of the steady states that are unstable with respect to small disturbances.

All that has just been said of the q = const regime applies fully to the J = const regime in the case of electric power supply to the element. These regimes become completely identical if the heater is made from a material with a small thermal resistance coefficient (nichrome, manganin, constantan, etc.).

The above familiar statements are illustrated in Fig. 1, where the results are plotted for boiling on a platinum filament 100 μm in diameter, for the J = const regime. The 'ab' line shows uniform nucleate boiling, the 'cd' line uniform film boiling; the arrows 'be' and 'cf' mark the jump-wise transitions between the steady state regimes. For a nichrome heater, the boiling curve is close to the given one, but is distinguished by a decrease in the value of $q_{cr\,2}$ down to 60 W cm^{-2} which is explained by the approach of the J = const regime to the q = const one. Not having information on the transitional region, these regimes of heterogeneous boiling control were thought to allow the determination of its boundaries, i.e. the rather accurate measurement of the values of $q_{cr\,1}$ and $q_{cr\,2}$. However, treated on the basis of the theory of wave processes in boiling [6, 7], this conclusion gives rise to serious objections. It follows from this theory that the critical heat fluxes in media, boiling on solid surfaces and containing the sources of rather strong thermal disturbances (a boiling liquid is precisely this kind of a medium), are impossible to achieve in principle: before these are attained, a spontaneous change of boiling regimes by the autowave mechanism will have occurred in the system with the result that the measured and true critical heat fluxes will be the more at variance the higher the amplitudes of disturbances in the medium and the longer their lifetimes on the surface (or, in conventional concepts, the higher the vapour content in the medium and the larger the size of vapour bubbles, the shorter is the thermal response of the element). The magnitude of the critical heat fluxes will also depend on the method used to control the element's temperature behaviour since that determines the character of the system's adjustment to the disturbances. (For further details see below.) The above seems to be the most likely reason for the marked spread in the reported data on the critical heat fluxes. Figure 1 shows that the jump-wise transitions between the steady states (shown by arrows) occur and develop not over the entire surface of the element at a time, but have a distinct autowave character. Reducing the disturbing factors (such as transition to a subcooled liquid boiling, which corresponds to the conditions of small vapour phase concentration in its volume, or screening of the heater to prevent the effect of rising vapour bubbles) leads to an increase of the values of $q_{cr\,1}$ up to 100–150 W cm^{-2}, however, the 'bc' transition retains the wave mechanism, i.e. even the methods mentioned fail to provide for the possibility of attaining the true value of the first critical heat flux.

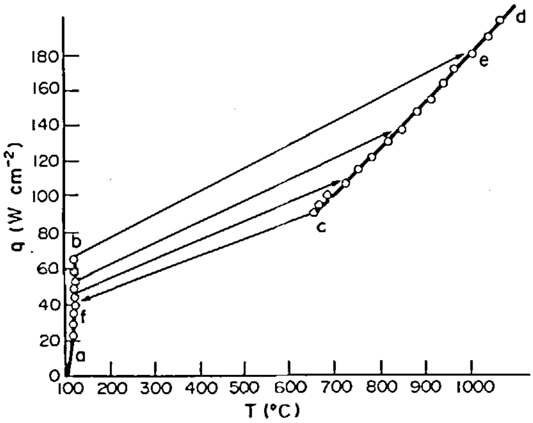

FIG. 1. Boiling curve obtained in the constant current regime (J = const). A platinum filament 100 μm in diameter and 7.2 cm long.

The difference of $q_{cr\,2}$ from the true value is still greater. This is due to the fact that, because of the heat drain along the electrodes, there are always cold end patches on the electrically heated wire which are continuous sources of local disturbances. For this reason, the transition from film to nucleate boiling occurs in the autowave regime at the currents that are smaller than the current of 'neutral equilibrium', $\bar{J}$ (dashed line 'mn' in Fig. 2) at which the both regimes may coexist in a stationary fashion forming a substantially nonuniform domain structure of the temperature field on the element surface. (For details see refs. [6, 7].) It follows from the above that $q_{cr\,2}$ can be brought more closely to the true value by employing artificial heating of the end patches of the element. (This experimental procedure was resorted to intuitively, but quite justifiably, in ref. [9].) But just as in the case of $q_{cr\,1}$, even this preventive measure cannot provide true values of $q_{cr\,2}$ because of the presence of random

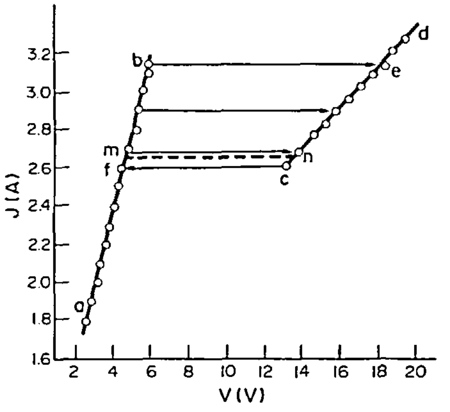

FIG. 2. The voltage–current characteristic of the heating element in the J = const regime.

thermal disturbances that induce the wave transition process. The results are given in Fig. 2 in the form of the voltage–current characteristic (VCC) of the heating element.

CONSTANT VOLTAGE REGIME (V = const)

For a heater made of a metal that has a zero thermal resistance coefficient, the V = const, just as the J = const, regime is identical to that of q = const.

Consider the case V = const, using as an example the process of boiling on a platinum filament (Fig. 3) under the same conditions as those used in the case of J = const (Fig. 1). As seen from the figure, the boiling curve of V = const is distinguished by the presence of a new segment 'bc', which precedes film boiling. This shows up most clearly in the VCC (Fig. 4): within the segment 'bc' a change in the voltage does not lead to a change in the steady-state value of the current strength, i.e. the system automatically adjusts its current as a consequence of the heater temperature-field rearrangement which changes the electric resistance of the heater so that the ratio V/R remains constant. A comparison of Fig. 4 with Fig. 2 shows that the magnitude of the current in the segment 'bc' coincides with the value of J.

The appearance of the 'bc' segment on the boiling curve and VCC in the V = const regime finds a simple explanation within the framework of the theory of autowave processes [6, 7]. This segment corresponds to the nonuniform steady states of the type of the standing temperature waves that separate the coexisting nucleate and film boiling zones on the heater. The correlation relating the dimensions of these zones to a change in the voltage varies so that at the point 'b' the entire element becomes encompassed by nucleate boiling, while at the point 'c' it is covered by film boiling regime. These nonuniform steady states are stable in contrast to the 'neutral equilibrium' states (J = const regime). This is evidenced by the character of transition processes occurring in response to the introduced disturbance (Fig. 5): when the voltage increases or decreases within the interval 'bc' in a jumpwise fashion the unsteady-state processes terminate by attaining the initial current level, and on removing the disturbances the initial state becomes completely restored with the same relationship between the dimensions of the high- and low-temperature zones.

The above can be clarified with the aid of the following qualitative reasoning. It is known from the preceding section that the uniform steady state of nucleate boiling, corresponding to point A (Figs. 3 and

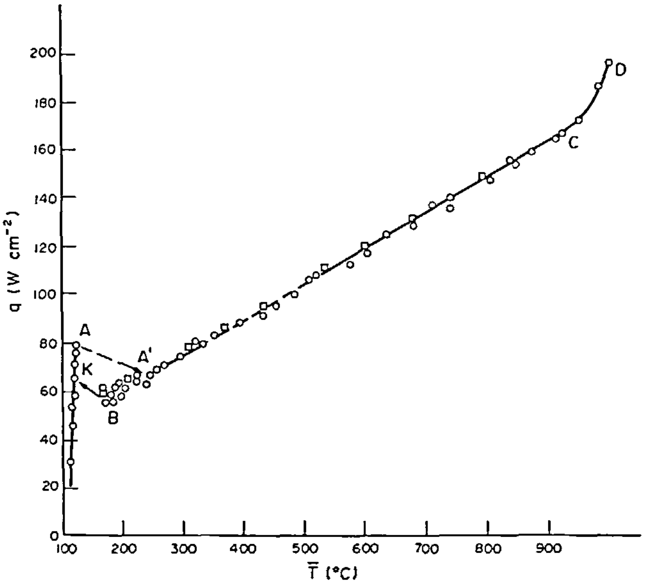

FIG. 3. The boiling curve obtained in the constant voltage regime. A platinum wire 100 μm in diameter, 7.2 cm long. ○, experimental data; □, calculation by equations (2) and (3).

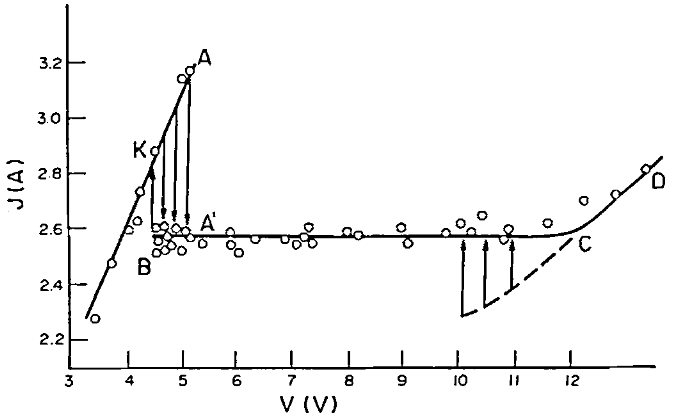

FIG. 4. The voltage–current characteristic of the V = const regime.

4), loses its stability in response to a local disturbance, with the result that the zone of film boiling develops on the element which spreads spontaneously over the element's surface. In the J = const regime, the motion continues until the wave completely displaces the nucleate regime, while in the V = const regime the transitional process develops in another fashion: an increase in the dimensions of the high-temperature film regime zone naturally results in the rise of the internal electric resistance of the element, and thus, to a decrease of the current strength in the course of wave motion. As a consequence, the wave process is characterized by a decrease in velocity of the wave front up to its complete termination at $J = \bar{J}$ (the 'aa' process). Similar transitional processes will occur over the entire segment 'bc' on a jump-wise increase or decrease of the voltage. This is reflected in the behaviour of dynamic curves in Fig. 5. The motion of nonuniform steady states from 'c' to 'b' is accompanied by an increase in the size of the nucleate boiling zone; at the point 'b' the last spot of film regime disappears (the process along the arrow 'bk'). Similar jump-wise transitions should have been also observed from the side of the film boiling branch (dashed-dotted line 'cc' in Fig. 4). However, permanent end disturbances on the filament make the transition from the nonuniform steady state to the film boiling branch continuous.

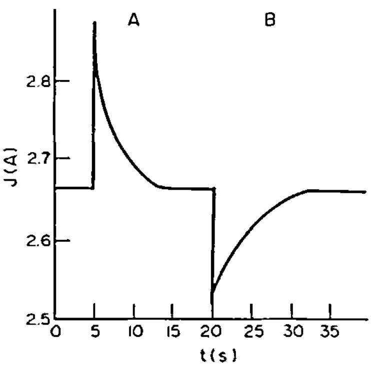

FIG. 5. The behaviour of current passing through a heater with (A) and without (B) disturbances.

We can illustrate the above qualitative picture by applying a quantitative analysis based on the theoretical correlations from ref. [7]. First, we shall calculate the minimum size of the last spot of the opposite regime which disappears step-wise with a further change of the parameter. (In our case it is the size of the film boiling zone at point 'b' in Figs. 3 and 4.) It follows from this theory that such a minimum size, $l_{\min}$, should be commensurable with the width of the standing wave front, i.e.

$$l_{\min} \sim \frac{(d\lambda)^{1/2}}{[\alpha_2\theta(1-\theta)^2+\alpha_1\theta^2(1-\theta)]^{1/2}} \tag{1}$$

where d and λ are the diameter and thermal conductivity of the element, respectively; α_1 and α_2 are the heat transfer coefficients in the nucleate and film regimes, θ is the dimensionless temperature, $0 \leqslant \theta \leqslant 1$ [6, 7]. The values of α_1 and α_2 can be obtained from the boiling curve recorded in the J = const regime (Fig. 1) for $J = \bar{J}$, since it is at this current strength that the above nonuniform steady states are realized. Calculation by equation (1) yields $l_{\min}$ = 0.4 cm, which is very close to the experimental width of the film regime zone at point 'b', i.e. 0.3 cm.*

Now it is possible to calculate the location of the segment of nonuniform steady states on the boiling curve and compare it with the experimental segment 'bc' of Fig. 6. Since this region of the filament has two zones with different boiling regimes, the measured temperatures and heat fluxes are mean-integral ones. These can be easily calculated by the formulae

$$\bar{T} = \frac{T_1(L-l)+T_2 l}{L}, \tag{2}$$

$$\bar{q} = \frac{q_1(L-l)+q_2 l}{L} \tag{3}$$

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* Evidently, this zone is substantially thermal, i.e. a certain characteristic dimension of it is referred to.

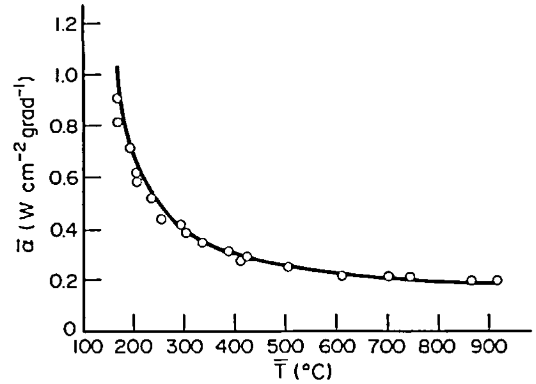

FIG. 6. The dependence of the heat transfer coefficient on the mean-integral temperature of the heating element: ○, experimental data; ——, prediction.

where L is the total length of the element, l is the size of the film boiling zone which varies within the range $l_{\min} \leqslant l \leqslant L - l_{\min}$; T_1, T_2, q_1, q_2 are the temperatures and specific heat fluxes of the nucleate and film boiling, respectively, at $J = \bar{J}$ [which are determined from the boiling curve in the J = const regime (Fig. 1)]. The results of the calculation of $\bar{q} = q(\bar{T})$ by equations (2) and (3) are presented in Fig. 3. (In Fig. 6 these data are given in the coordinates $\bar{\alpha}$–$\bar{T}$, where $\bar{\alpha}$ is the mean integral heat transfer coefficient.) As is seen, there is practically complete coincidence between the experimental and calculated data. It should be noted that the segment 'bc' has a linear nature which also follows from equations (2) and (3):

$$q = \frac{q_1T_2 - q_2T_1}{T_2 - T_1} + \frac{q_2 - q_1}{T_2 - T_1}\bar{T}.$$

The above analysis leads to a number of important methodological conclusions.

(i) The high-temperature branch of the boiling curve obtained in the V = const regime involves a segment which quantitatively does not reflect the actual position of the film boiling branch. This segment corresponds to the occurrence on the HGE of temperature-nonuniform steady states.

(ii) The magnitude of the second critical heat flux ($q_{\mathrm{cr}\,2}$) measured in these experiments cannot be considered as a true value of q_{cr}. This value corresponds to such a mean-integral flux, at which the last portion of film boiling disappears in a jump from the element, the latter being almost completely encompassed by that time by nucleate boiling. The value of $q_{\min}$ can be calculated from equation (3) as

$$q_{\min} = \frac{q_1(L - l_{\min}) + q_2 l_{\min}}{L}.$$

(iii) The magnitude of the first critical heat flux measured in the V = const regime cannot coincide with its true value for the same reasons as in the J = const regime. An increase of this value in the case of the first control regime, as compared with the second one (see Figs. 1 and 3), is due to a certain increase in the system stability to local disturbances* because of the weak negative reverse coupling between the disturbances and the heat flux: the appearance of a hot disturbing spot on the element surface is accompanied in the V = const regime by a decrease in the mean-integral thermal stress, while in the J = const regime the mean-integral thermal stress increases.

Before concluding the discussion of the processes occurring on the HGE with heat supply in the V = const regime by a decrease in the mean-integral and consider a certain applied aspect which follows from these results. For the reasons considered above, the rearrangement of the boiling regime spontaneously sustains a constant current in the heater in a wide range of voltages. In other words, the system acts as a very simple current stabilizer. Devices with a similar VCC that are used as current stabilizers are known in electrical engineering. One such device, which has found increasing use, is the ballast tube, the basic element of which is an iron wire placed in a glass vessel filled with hydrogen.† The similar properties of the VCCs of the ballast tube and of the HGE operating in a mixed boiling regime have provided the basis for the development of a new technique of current stabilization which uses the specific features of boiling processes [10].

CONSTANT ELECTRIC RESISTANCE REGIME (R = const)

The processes that occur on the heating element with thermal power supply in the regime of stabilized resistance of the element are very similar to those realized in the V = const regime. However, a closer reverse temperature coupling‡ results in the appearance of new specific features. This regime was used in a number of works [4, 5] for the establishment of the boiling curve form in the transitional region. To what extent the use of these methods for the construction of the full boiling curve is admissible will be seen from the results given below.

Figure 7 shows the form of the boiling curve obtained on a 0.1 mm wire. In the presence and position of characteristic branches it is identical with the boiling curves obtained in refs. [4, 5]§ and is characterized by

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* The authors consider it their duty to note that Adiutori has intuitively arrived at a similar conclusion [16].

† Recently it has been shown [11] that the capability of the ballast tube to keep the electric current constant on a change in voltage is also associated with the presence of autowave processes in the system.

‡ In the V = const regime, the passive negative reverse temperature coupling spans the whole system which results from the dependence of heat flux (current through a heater) on the surface temperature (electric resistance), while in the R = const regime the active negative reverse coupling is confined within the temperature control block.

§ Similar curves are given also for the case of vapour heating [12, 13], which is believed to provide the isothermicity of the HGE surface and the constancy of its temperature.

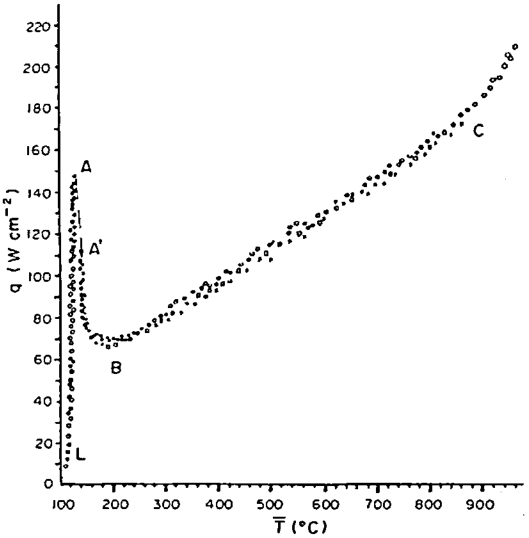

Fig. 7. The boiling curve obtained in the constant electric resistance regime (R = const). A platinum wire 100 μm in dia and 3.5 cm long (□, data of Fig. 3).

the presence of the nucleate boiling branch (LA), the branch with a negative angle of slope (A'B) and the branch (BC) on which the heat flux increases again with the surface temperature.

We will show that the obtained temperature dependence of the heat flux is strongly distorted over the curve segment AA'BC due to the presence in this region of longitudinal nonuniform steady-state temperature profiles, i.e. standing waves.

Presenting the data of Fig. 7 in the coordinates of VCC (Fig. 8) and comparing the latter with the VCC obtained in the V = const regime (Fig. 4), it is seen that in this case also the curve has a distinct portion of current stabilization ('bc') which shows the existence on the element of nonuniform steady states, i.e. the mixed boiling regime.

Thus the data on the trends in heat transfer on the boiling curve segment BC obtained in the R = const regime contain practically no new information on the system behaviour as compared with the results obtained in the V = const regime. This conclusion is fully confirmed by the experimental data (Fig. 7).

Of particular interest is the curve segment AB which was lacking on the earlier boiling curves (Fig. 7). Visual observations show that at the point A' on the heating element an isolated film regime spot is formed, the temperature in which is much below that in the film boiling zone on the branch BC ($T = T_{20}$ at $J = \bar{J}$).

Interest in studies of these states is engendered by the possibility which arises for the measurement of the true values of $q_{cr\,2}$ and $T_{cr\,2}$. However, a direct measurement of the fluxes and temperatures in the film regime spot over the segment 'ab' is still difficult, so an indirect method is described below. It is as follows: calculation of the required temperature T_2 is possible if the values of the mean temperature (T), the nucleate boiling temperature (T_1) and of the size of the nonuniformity zone (l) are known. The information on the value of T can be obtained, just as before, by assuming that T_1 is determined only by the strength of the current passing through the heater.

The values of $l = l(\bar{T})$ are determined directly by measuring the geometrical dimensions of the zone. The results are presented in Fig. 9.

As can be seen, the dependence obtained has two distinct regions (KL and LM) which correspond to different laws governing the growth of the film regime spot. In the region LM corresponding to the segment BC on the boiling curve, the mean temperature of the heating element increases mainly due to the increase of the size of the film regime zone at relatively constant temperature. The region KL is characterized, on the other hand, by a considerable change of temperature in the film regime spot.

These results show that not only on the segment BC of the boiling curve, but on the segment 'AB' also (Fig. 7) a thermally nonuniform boiling regime is developed on the HGE. Thus, the boiling curve obtained under the conditions when the mean-integral temperature

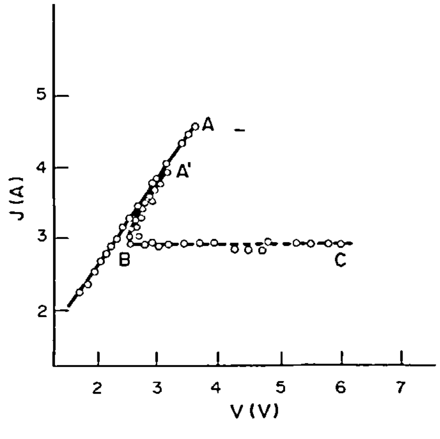

Fig. 8. The voltage–current characteristic (the R = const regime).

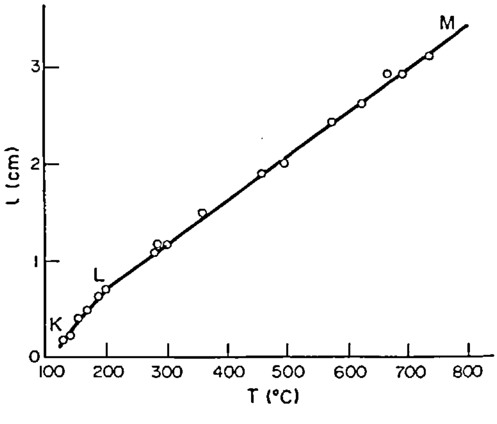

Fig. 9. The dependence of the size of the film regime zone on the mean-integral temperature (T). A platinum wire 100 μm in diameter and 3.5 cm long.

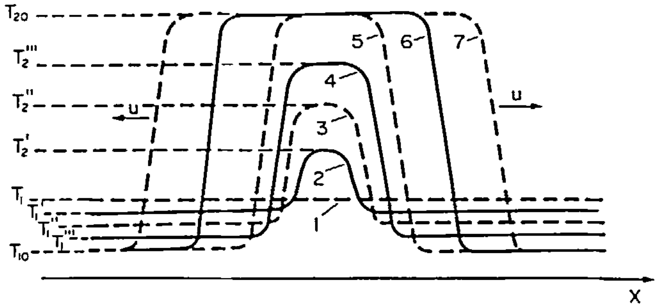

FIG. 10. A qualitative picture of the film regime zone formation (the R = const regime).

of the heating element is maintained constant (the R = const regime) does not contain true information on the region of transition boiling.

In what follows, a qualitative description of the formation of nonuniform steady states in the R = const regime is given. An increase of the mean-integral surface temperature above some value (point A in Fig. 7) leads to the jump-wise appearance of a film regime zone on the heating element. Since the heat transfer coefficient in the film boiling regime is much lower than in the nucleate regime, the temperature in the film regime spot and, consequently, the mean-integral resistance increase. Making up for the higher electric resistance, the tracker system decreases the electric current in the heater in such a way as to leave the mean-integral resistance of the heating element unchanged and equal to that prescribed ('AA″ process in Fig. 7). A decrease in the current leads to a decrease of the temperature and of the energy generated over the nucleate boiling segment. The process terminates by the development of a steady and stable, spatially nonuniform temperature profile on the heating element (Fig. 10, curve 2). With a further increase of the mean-integral resistance (mean heater temperature), the temperature in the film regime spot, as well as its size, increase still further, while the temperature and the size of the nucleate regime zone decrease (curves 3 and 4, Fig. 10). In Fig. 7, the points corresponding to the position of the system in the course of the described temperature profile rearrangement are on the boiling curve segment A'B.

The growth of temperature in the film regime spot will terminate when a standing wave forms on the heater, the temperature in the front of which varies from T_{10} to T_{20}. (The stationary value of the current will become equal to J.) With a further increase in the prescribed value of the mean-integral resistance (Fig. 10, curves 5–7) the steady states are developed just as in the case of the V = const regime over the segment 'BC'. Note, that the value of the critical heat flux at the point A for the R = const regime is still higher than for the V = const regime. This can be attributed to the stabilizing effect of the stronger reverse coupling. However, in this regime too it is impossible to obtain the true value of $q_{cr\,1}$ for the same reasons which were considered in the previous section.

Let us calculate the position of the branch 'AC' in the same way as for the mixed boiling branch in the V = const regime. Figure 11 shows the experimental and calculated dependences of the mean heat transfer coefficient on the integral heat flux. The good coincidence between the calculated and measured results testifies quantitatively to the fact that the physical concepts developed correctly reflect the processes that take place on the heating element.

In conclusion an interesting feature observed in the process of jump-wise transition AA' will be mentioned. Taking the general concepts as a basis, it could have been expected that the transition from one boiling branch to the other would be accompanied by hysteresis effects. (In moving along the temperature in the backward direction the transition to the nucleate boiling branch should have taken place at the temperature lower than $T_{A'}$.) However, one fails to observe this phenomenon experimentally. This is due to the fact that in the region of temperatures close to the critical ones, irregular fluctuations occur in the system between the stationary points on the branches LA and A'B (spontaneous jumps) (Fig. 7), which seems to be attributed to an extremely narrow hysteresis loop.

ON THE FORM OF THE BOILING CURVE

The main aim of this part of the work is to consider the possibilities for the experimental determination of

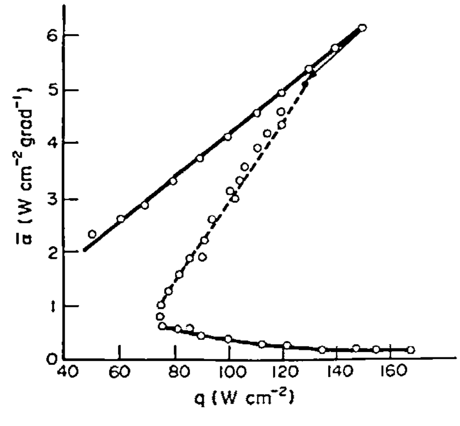

FIG. 11. Experimental (O) and predicted (— — —) heat transfer coefficients.

the true form of the boiling curve and the values of its characteristic points.

According to the ideas developed in refs. [6, 7] and in the present work, in order to obtain the true values of the critical heat fluxes, it is necessary to realize conditions in the system such that the outer and inherent disturbances of the system are at a minimum.

In those cases when it is required to determine the maximum heat flux ($q_{cr\,1}$), the heat generating element should be made in such a way as to prevent the appearance of local superheats due to the non-uniformity of heat flux distribution along the element. As has been remarked above, the true value of $q_{cr\,1}$ can be approached by suppressing the perturbing factors, for instance, by decreasing the dimensions of vapour bubbles (subcooling of liquid, external effects) and/or by improving the regimes of controlling the temperature state of the element, etc.

It is much more difficult to obtain the true value of $q_{cr\,2}$. It has been shown above that the measured values of q_{min} correspond either to the states of 'neutral equilibrium' (J = const), or to the conditions of disappearance of mixed boiling (V = const, R = const). From the standpoint of the theory of autowave processes, the achievement of the minimum heat fluxes requires the absence of sections with reduced temperature in the experimental system. In the vast majority of cases, such sections exist at the ends of the heating element due to conductive heat losses. Thus, a technique which would have allowed a steady operation in the region of low heat fluxes should involve the provision of a longitudinally uniform temperature profile. Practically, it is much easier to provide 'hot spots' at the ends of the test section, i.e. local zones with elevated surface temperature that 'block' the wave of the nucleate regime.

An experimental study of heat transfer near minimum critical heat fluxes has been carried out on the facility described above. Just as before, the heat generating element was a platinum wire. The 'hot ends' were provided in several ways, one being that suggested in ref. [9]. It has turned out, however, that this method applies only for filaments the diameters of which exceed 200–300 μm. This is attributed to their mechanical strength and stability against high temperatures. In order to effect experimentation on thin wires, the present authors have suggested and tested a number of techniques as described below.

The scheme of the heating element connection and the sequence of measurements are shown in Fig. 12.

A 100 μm platinum filament 8–10 cm long (1) was provided, at a distance of about 2 cm from the current leads (2), with a transversely placed point-welded segment of a 50 μm diameter platinum wire (3) to serve as leads for measuring the voltage drop across the test section. So that the heat regime could be assigned, the test section was shunted, through massive current leads (4), by a variable resistor made from manganin (R_m).

The experiments were carried out as follows: the heating element in the J = const regime was supplied with a heat flux that ensured stable film boiling. By closing the shunting circuit and varying the value of R_m, a decrease in the heat flux on the test section was achieved down to the value at which the film boiling regime becomes unstable. Knowing the value of the total current J, of the current passing through the shunt J_m and the voltage drop V_1, one can calculate the value of the heat flux and the temperature of the heating element over the test section.

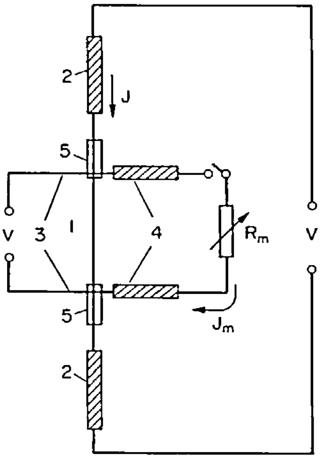

FIG. 12. A schematic of the test section of an experimental set-up used in experiments with 'hot ends'.

Subsequently one other version of the method has been devised which consists of compensating for the heat losses through the potential leads by decreasing the local heat transfer at their points of attachment. This was accomplished by encasing the working filament, at the places of attachment of leads, in quartz capillaries [Fig. 12, (5)] of diameter from 1 to 1.5 mm and about 1 cm in length. The leads passed through the holes in the wall of the capillary.

Application of a new design of probe allows a slight simplification of the experimental procedure in that the shunting can be removed from the test section. In this case the experiments are carried out in the V = const regime, and a 20 μm dia wire can be used for the potential leads. But, in contrast to the previous experimental procedure, the temperature of the hot ends becomes dependent on the heat flux.

The results of the above experiments are given in Fig. 13 (curve 2), where the data on heat transfer obtained in the R = const regime (curve 1) are also presented for comparison. As is seen, the minimum heat flux amounted to about 18 W cm^{-2} (1.7×10^5 kcal m^{-2} h^{-1}), while the surface temperature was 205–207°C. Even at these magnitudes, the transition to the nucleate regime is realized in the form of a travelling wave initiated in the region of attachment of the potential leads. Based on this fact, one may conclude that in the experiments described the true values of the minimum heat fluxes have been approached but not obtained.

It is pertinent to note that by using the obtained values of $q_{cr\,2}$ (20 W cm^{-2}) and knowing the value of the

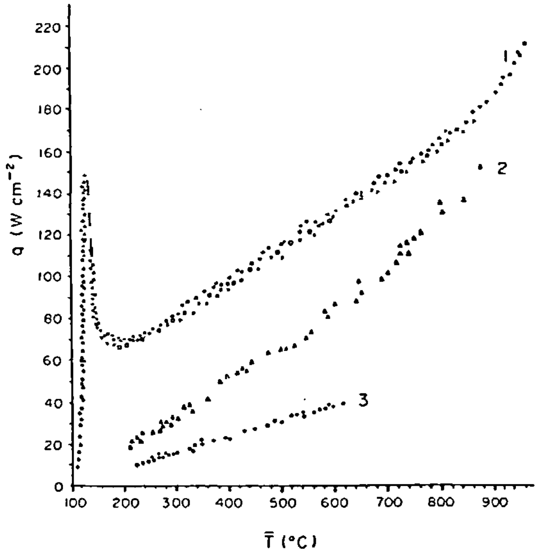

FIG. 13. Boiling curve (1) obtained in the R = const regime (d = 100 μm). The film boiling branch (2) obtained in the experiments with hot ends (d = 100 μm); (3) the same for the heater 0.5 mm in diameter.

heat flux at which a neutral equilibrium is realized ($\bar{q} \sim 50$ W cm^{-2}), one can obtain a lower estimate for the quantity $q_{\mathrm{cr}\,1}$. As was expected, the value determined in such a way markedly exceeds the experimental value and is equal to about 250–300 W cm^{-2}.

In order to elucidate the effect of heater diameter on the heat transfer intensity, some experiments were carried out in which the heating element was a platinum wire 0.5 mm in diameter. As has been remarked above, the use of heaters of a large enough diameter allows one to employ a much simpler technique, as described in ref. [9]. The results obtained are presented in Fig. 13 (curve 3). As can be seen in this figure, the value of the minimum flux was only 9 W cm^{-2} (7.4 × 10^4 kcal m^{-2} h^{-1}). However, this value too can hardly be the lowest one. The studies made by the present authors have shown that the experimental value of the critical flux depends substantially on the form of the heating element and the ratio between the lengths of the 'hot' and test sections of the vertical segment of the heater. Therefore, it is by no means certain that the optimal conditions have been achieved in the experiments. Moreover, the visual observations show that the nucleate regime wave is always initiated from the interface between the liquid and vapour phases. This seems to be associated with the buoyancy-effected rupture of the vapour film in the upper portion of the vertical segment of the heating element.

Though failing to give a final answer as to the magnitude of the minimum critical heat flux, the investigation carried out has confirmed the earlier conclusions. As can be concluded from the observations of the critical phenomena, the main perturbing factor on a horizontal filament is the presence of potential leads that act as local heat sinks. It is the present authors' conviction that by using certain techniques (in particular, the method of compensated heat losses) one can attain the true values of the critical fluxes. However, this problem would require a further improvement in the methods and a large number of experiments, and is a separate subject of investigation. The present discussion is limited to estimated values obtained on nichrome heaters 0.15 mm in diameter. The experiments were carried out on horizontal filaments, the ends of the test section of which were insulated with quartz capillaries.

The values of the minimum heat flux obtained (with the correction for the effects of hot ends) lie within the range 0.5–1.5 W cm^{-2} (4 × 10^3–1.2 × 10^4 kcal m^{-2} h^{-1}). If these are close to the true value and if the order of magnitude is coincident with the minimal fluxes for platinum heaters, then the results obtained mean that the boiling curve in the region $q_{\max} > q > q_{\min}$ is Z-like, i.e. it is unambiguous with respect to temperature. This means that even in isothermal conditions the transition from one boiling regime to the other should be accompanied by a jump in the heat transfer coefficient, while the branch of the transition boiling has a positive derivative.

The introduction of the discontinuous function $\alpha = f(T)$ does not contradict the basic laws of the physics of boiling and agrees well with the concepts of the hydrodynamic theory of crises [13–15]. It is evident that the verification of this conclusion is of principal importance for the physics of boiling and requires special investigation.

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ETATS STATIONNAIRES NON UNIFORME DE L'EBULLITION DANS LA REGION DE TRANSITION ENTRE LES REGIMES DE NUCLEATION ET DE FILM

Résumé—On étudie l'ébullition sur des fils fins métalliques dans la région de transition entre les régimes de nucléation et de film. On montre que, suivant le mode de chauffage (intensité constante, tension constante et résistance électrique constante), des états non uniformes différents (états d'ébullition mixte) apparaissent dans la région qui distord la forme de la courbe d'ébullition. On montre l'insuffisance des approches traditionnelles pour une mesure correcte des coefficients de transfert dans la région de transition et aussi des flux thermiques critiques. Des expériences excluant des états spatialement non uniformes sont décrites et on donne quelques estimations des flux critiques.

UNGLEICHFÖRMIGE STATIONÄRE ZUSTÄNDE IM ÜBERGANGSGEBIET ZWISCHEN BLASENSIEDEN UND FILMSIEDEN

Zusammenfassung—Es wird eine Untersuchung des Siedens an dünnen metallischen Drähten im Übergangsgebiet zwischen Blasensieden und Filmsieden durchgeführt. Es zeigt sich, daß abhängig von der Art der Leistungszufuhr (konstanter Strom, konstante Spannung und konstanter elektrischer Widerstand) unterschiedliche ungleichförmige Erscheinungsformen (der Zustand des "gemischten Siedens") in diesem Gebiet auftreten, welche die Form der Siedekurve signifikant verändern. Es wird gezeigt, daß die herkömmlichen Verfahren zu genauen Messungen des Wärmeübergangskoeffizienten und der kritischen Wärmestromdichten im Übergangsgebiet nicht geeignet sind. Experimentelle Verfahren, welche das Auftreten von räumlich ungleichförmigen Erscheinungen ausschließen, und einige Abschätzungen für die kritische Wärmestromdichte werden vorgeschlagen.

НЕОДНОРОДНЫЕ СТАЦИОНАРНЫЕ СОСТОЯНИЯ ПРОЦЕССА КИПЕНИЯ В ОБЛАСТИ ПЕРЕХОДА МЕЖДУ ПУЗЫРЬКОВЫМ И ПЛЕНОЧНЫМ РЕЖИМАМИ

Аннотация—Проведено изучение процесса кипения на тонких металлических нитях в области перехода между пузырьковым и пленочным режимами. Показано, что в этой области в зависимости от способа подачи тепловой нагрузки (режимы постоянного тока, постоянного напряжения, постоянного электросопротивления) реализуются различные неоднородные состояния (состояние «смешанного» кипения), существенно искажающие вид кривой кипения. Показана невозможность корректных измерений коэффициентов теплоотдачи в переходной области, а также критических тепловых потоков посредством традиционных методик. Описаны экспериментальные методики, позволяющие избежать возникновения пространственно-неоднородных состояний и приведены некоторые оценки критических тепловых потоков.