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WAVE PROCESSES ON HEAT GENERATING SURFACES IN POOL BOILING

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Abstract—The wave propagation of film or nucleate boiling over the surface of a heating element has been investigated theoretically and experimentally. In the linear approximation of the heat-transfer function, an analytical expression is obtained for the velocity of the wave and width of the front. An experimental verification has been carried out for water boiling from electrically heated thin metallic wires. In the case of subcooling, a region of neutral equilibrium is discovered in which steady co-existence of two regimes is possible. The results obtained allow the conclusion that there is a branch of unstable steady states on the curve between the regions of film and nucleate boiling.

The instability of steady-state heat transfer at temperatures close to the temperature of boiling is studied as a function of the types of heat flux supply. A phenomenological model is suggested which accounts for the effects described.

NOMENCLATURE

a,	thermal diffusivity;
c, d, ρ,	heat capacity, diameter and density of the heating element, respectively;
F,	source term in equation (1);
h_1, h_2,	heat-transfer coefficient in nucleate and film boiling regimes, respectively;
P,	auxiliary variable;
T_s,	saturation temperature;
T_1, T_2,	temperature of nucleate and film boiling regimes, respectively;
T_*,	Leidenfrost temperature;
T_+, T_-,	temperature of onset and disappearance of a stable nucleate boiling regime, respectively;
q_+,	heat power output in the wire;
q_-,	rate of heat transfer from the wire surface to the boiling liquid;
q_{max},	maximum heat flux in nucleate boiling;
q_{min},	minimum heat flux in film boiling;
u,	velocity of front;
x,	coordinate;
θ,	dimensionless temperature, $0 \leq \theta \leq 1$;
δ,	width of front;
λ,	thermal conductivity.

INTRODUCTION

IT IS known that pool boiling of liquid from solid heat-transfer surfaces can display two physically different modes of behaviour—nucleate and film boiling regimes—and that, the heat flux being a variable parameter, transitions between these two regimes occur in jumps (discontinuities of temperature of the heating surface) and are accompanied by the hysteresis effect [1, 2]. The study of this phenomenon on the heating elements (electrically heated wires and rods) has revealed [3] that the change-over from one regime to the other does not occur straightway over the entire surface, but originates locally over some portion of the surface with subsequent superseding of the old regime by the new one layer by layer or, in other words, the transition is due to the inception of a travelling temperature wave which spreads the new regime over the surface. The analytical and experimental investigation of this phenomenon is described in the first part of the present paper. The second part is concerned with the study of instability of the steady-state heat transfer in another temperature region, i.e. that which is close to the occurrence of nucleate boiling. Unlike the burnout phenomenon, this problem has received little attention in the literature on boiling. We can mention here the works [4, 5] which show the existence of oscillatory regimes preceding the development of a steady nucleate boiling, which are particularly pronounced in boiling of metal coolants. Some of the publications [6–10] point to the existence of the critical phenomena and the hysteresis effects in the above temperature region. Using the boiling of water as an example, the nature of this kind of instability originating in the process of heat transfer from the heated wire is studied in the second part of this paper as a function of the type of the heat flux supplied and a phenomenological model is suggested which explains the effects observed. The study has made it possible to predict and experimentally reproduce a new type of wave processes in pool boiling.

THE REGION OF TRANSITION FROM NUCLEATE TO FILM BOILING

Theoretical analysis

In order that the analysis be as clear as possible and the qualitative features of the process be revealed, we shall consider the simplest system consisting of a cylindrical heater (say, an electrically heated metallic wire) submerged in a pool of liquid. Let us assume the power of heat release, q_+, by the element to be the parameter independent of the wire surface temperature. The rate of heat transfer, q_-, from the wire surface to the boiling liquid is qualitatively governed by the familiar law [1] plotted in Fig. 1. Nucleate boiling is realized at the surface temperatures between the boiling temperature T_s and the critical temperature T_*. The nucleate boiling is characterized by the heat-transfer coefficient h_1 which is assumed here to be independent of temperature. At the critical temperature T_* the nucleate boiling is replaced jumpwise (and this is close to reality) by the film boiling with the heat-transfer coefficient h_2. The range of heat loads

$$q_{min} < q < q_{max}$$

is associated with the transition region and, as a rule, is extremely wide. This range covers both the nucleate and film boiling regimes.

The principal objective of the present investigation is to analyze the system stability to local disturbances when in the transition region. Can its spontaneous transition towards a new regime be prompted by a local disturbance? What laws will govern this transition in time?

Practically very much the same model was earlier studied in [11–13] which had been postulated to describe the exothermic heterogeneous catalytic process developing on the surface of a cylindrical heater. The only difference between the models is that in the case of boiling it is heat removal which is non-linear (whence the diversity of steady-state regimes), while in the above chemical analog the non-linearity is evidenced by the source. Acting on the conclusions drawn in [11] it is possible to state that a local disturbance in the range of diverse steady states (i.e. in the transition region) can initiate a thermal wave which propagates with a constant velocity and causes the change-over of the regimes on the heater. The equation governing this process (with no regard for the temperature distribution over the wire cross-section) in a coordinate

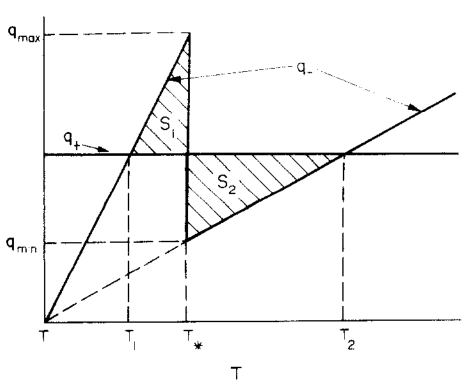

FIG. 1. Qualitative pattern of the boiling curve. T_1 and T_2, steady-state surface temperatures for nucleate and film boiling, respectively, at constant heat power output on the surface (q_+), T_s, saturation temperature.

system moving with the wave front is of the form

$$\lambda \frac{d^2T}{dx^2} - uc\rho \frac{dT}{dx} + \frac{4}{d}(q_+ - q_-) = 0, \qquad (1)$$

where λ, c, ρ are the thermal conductivity, heat capacity and density of the wire, respectively; T is the temperature in the given cross-section of the wire; x the coordinate; u the linear velocity of motion of the boiling regime; d the wire diameter (the source q_- is measured per unit surface of the wire).

The boundary conditions are

$$T = T_1 \quad \text{at} \quad x = -\infty; \qquad (2)$$
$$T = T_2 \quad \text{at} \quad x = +\infty,$$

where T_1 and T_2 are the steady-state temperatures of the wire surface which correspond to the nucleate and film boiling regime, respectively, and which are determined from the equation $q_+ - q_- = 0$ (see Fig. 1). These conditions comply with the situation when at the initial instant of time the nucleate boiling is deliberately produced on one end of the wire and the film boiling, on the other. The solution of the problem is reduced to determination of the quantity u which is an eigen-value of equations (1)–(2); its solubility will imply the existence of the steady-state wave processes during transition between the boiling regimes.

Changing from the variables T and x to $P = dT/dx$ and T and thus reducing the order of equation (1), we obtain the velocity expression in the following integral form

$$u = \frac{\int_{T_1}^{T_2} F(T)dT}{\int_{T_1}^{T_2} P(T)dT}, \qquad (3)$$

where $F(T) = 4/d(q_+ - q_-)$. Equation (3) describes the basic qualitative features of the phenomenon in question. When $J = \int_{T_1}^{T_2} F(T)dT > 0$, the wave propagation results in displacement of the nucleate boiling regime by the film one. In other words, if this condition is fulfilled, the nucleate boiling regime is unstable and an occasional local disturbance will lead to the change-over from the nucleate to the film boiling regime, with the transition occurring as a travelling wave of high temperature corresponding to the temperature of the film boiling regime.† When $J < 0$, the wave of the nucleate boiling regime will force the film boiling out (the velocity will acquire the opposite sign). The nucleate boiling in this case becomes stable and a chance zone of film boiling, originating on the heater, fails to spread over the element and, on the removal of the disturbing factor, disappears spontaneously.

The equality $J = 0$ is the critical condition for a change in the direction of the front propagation at which the velocity of the wave propagation becomes zero. In this case the regions of nucleate and film

† The amplitude of the disturbance required to initiate the wave process is not considered in the paper.

boiling can co-exist steadily side-by-side on the heating element not interacting with each other. This phenomenon has been described in the relevant literature and has been given special examination in [2]. The analysis of the data reported in this work reveals that a standing wave is realized at such a value of q_+ at which J becomes zero (the condition of equality of the surface areas, $S_1 = S_2$, see Fig. 1).

The adopted piecewise-linear approximation of the temperature function $q_- = q_-(T)$ makes it possible to derive an analytical expression for the velocity of the travelling thermal wave. Integration of equation (1) subject to condition (2) with the source term

$$F(T)|_{T_1 \leqslant T \leqslant T_*} = 4/d[h_1(T_1 - T)], \qquad F(T)|_{T_* < T \leqslant T_2} = 4/d[h_2(T_2 - T)] \tag{4}$$

yields the velocity expression of the form

$$u = \frac{a\sqrt{2}}{\sqrt{(\lambda d)}} \cdot \frac{h_2(1-\theta^2) - h_1\theta^2}{\sqrt{[h_2\theta(1-\theta)^2 + h_1\theta^2(1-\theta)]}}, \tag{5}$$

where $a = \lambda/c\rho$ is the thermal diffusivity of the wire; $\theta = (T_* - T_1)/(T_2 - T_1)$ is the dimensionless parameter varying within the limits $0 \leqslant \theta \leqslant 1$.

It is evident from (5) that θ is the parameter which governs the velocity sign. Its variation by adjustment of q_+ allows realization of the wave of either the nucleate, $\theta_{cr} < \theta \leqslant 1$, or film, $0 \leqslant \theta < \theta_{cr}$, boiling regime. The case of $\theta = \theta_{cr}$ corresponds to the vanishing velocity. The value of θ_{cr} is readily obtained from the velocity expression (5)

$$\theta_{cr} = n/(1+n), \qquad \text{where } n = \sqrt{(h_2/h_1)}.$$

Since $h_2 \ll h_1$ ($\theta_{cr} < 1/2$), the critical value of the heat flux q_+, at which the wave front changes its direction, is strongly shifted toward q_{min} (see Fig. 1). It is of interest to note that in the catalytic counterpart of this phenomenon [11, 12] θ_{cr} is exactly equal to 1/2. The velocity of the front, turning out to be infinite at $\theta = 0$ and $\theta = 1$, is a consequence of the limitation of the adopted approximation. An expression for the width of the travelling wave front, which can be represented as the ratio of the maximum temperature difference in the front to the maximum temperature gradient in it, i.e. $\delta = (T_2 - T_1)/P_{max}$, can be rewritten as

$$\delta = \frac{1}{\sqrt{2}} \cdot \frac{\sqrt{(d\lambda)}}{\sqrt{[h_2\theta(1-\theta)^2 + h_1\theta^2(1-\theta)]}}.$$

Although the analysis in the present paper was performed for a very simple model, the results obtained can be applied in practice to the processes when such heating elements are used the heat power of which is constant and independent of the coordinate of the heater and its surface temperature. A quantitative specification of the results will require consideration of such factors as the existence of the dependence of h_1 on the heat load (i.e. the surface temperature); absence of the jumplike discontinuity in the function $q_- = q_-(T)$ at $T = T_*$; temperature distribution over the wire cross-section; variety of the heater geometries. This specification can hardly run into basic difficulties and can be accomplished with the aid of computers.

It should be noted that the analysis performed enables an insight into the problem of a certain practical interest, viz., just how closely the critical heat flux, q_{max}, can be approached not taking the risk of a spontaneous transition from the nucleate to the film boiling regime, i.e. the problem of the stability limit of a technologically advantageous nucleate boiling.

Experimental results

In order to check the results of the above theoretical analysis, such a system has been selected which comprised a thin metallic wire placed horizontally in an open vessel with the working liquid, the temperature of which was independently controlled by a thermostatic device. In all the experiments the working liquid was distilled water. The wave of the film boiling regime was initiated with the aid of a capillary tube one of the ends of which was positioned in the immediate vicinity of the heater. When air was blown through the capillary, a narrow zone of film boiling was formed on the heated wire. Within a certain range of parameters this zone initiated the inception of the self-wave process of the film boiling regime propagation over the entire wire. The wave transition from the film to the nucleate boiling regime was initiated by cold patches of the wire adjacent to the massive brass rod electrodes. Since the wire temperature in film boiling rises to about 1000°C (as against ~100°C in nucleate boiling), motion-picture records of the travelling waves of boiling could be made. A picture taken of the travelling wave for the film boiling regime is displayed in Fig. 2. It can be seen that the wave process is very similar to propagation of the combustion front and to the earlier observed wave propagation in the heterogeneous catalytic reaction [11]. However, to measure the wave velocities, we used in our experiments a more simple and accurate ohmic technique developed in [12]. That this technique could be applied, the wire was made of platinum (the results given below are obtained for the wire 8 cm long and 100 μm in diameter). The wire also served as a temperature-sensitive probe. The time derivative of the wire resistance recorded during the wave process is the magnitude proportional to the wave velocity in boiling. In order to ensure the constant electric power output from the probe in the regions of nucleate and film boiling, constant current was supplied to the heater throughout the whole process of self-propagation via a special tracker device with current stabilization accurate to 10^{-2}% (the absolute error is 10^{-4} A).

Figure 2 presents the basic results as the curves of the wave velocity vs the strength of the current passed through the probe. The presence of two zones has been revealed in full qualitative conformity with the theory. In one of the zones, a local disturbance imposed on the wire operating in nucleate boiling regime initiates a

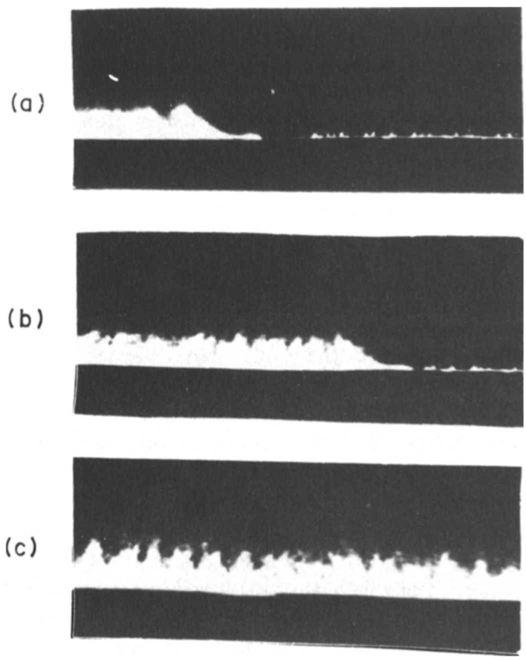

Fig. 2. Motion picture records of propagation of the film boiling wave (pool boiling of water on a platinum wire 100 μm in diameter and 8.6 cm in length). $T_w = 98°C$; $i = 2.96$ A; $u = 1.1$ cm s^{-1}.

wave of film boiling which forces out the nucleate boiling regime (positive velocities), while in the other zone, the film boiling is progressively forced out by nucleate boiling (negative velocities). These zones are separated by the region of neutral equilibrium (zero velocities of wave propagation) in which the two regimes can steadily co-exist not interacting with each other.

The wave velocity in film boiling can be estimated with the aid of equation (5). For the platinum wire used in our experiments $a = 0.2545$ cm^2 s^{-1}; $\lambda = 0.72$ W cm^{-1} K^{-1}; $h_2 = 0.3$ W cm^{-1} K^{-1}; $d = 0.01$ cm. Assuming that the heat transfer coefficients h for nucleate and film boiling differ by an order of magnitude, i.e. $h_1 = 10 h_2$, $\theta = 10^{-3}$ (the system is maintained close to the critical heat flux and the difference $T_{film} - T_{nuc}$ is about 1000°C) and disregarding the second-order quantity, we shall obtain

$$u \sim \frac{a}{\sqrt{(\lambda d)}} \cdot \frac{\sqrt{h_2}}{\sqrt{\left(\theta + \frac{h_1}{h_2} \cdot \theta^2\right)}} \sim 1 \text{ cm s}^{-1}$$

We can see that this estimate is in good agreement with the experimentally measured velocities (see Fig. 3). A more rigorous quantitative comparison can be made using the exact curve of boiling in each specific case.

The study of the wave behaviour in boiling with an increased subcooling of the working liquid below the saturation temperature has revealed a very important feature. It can be seen in Fig. 2 that farther away from the saturation temperature the branches of the positive wave velocities shift to the right along the X axis, while the branch of the negative velocities does not virtually change its position (Fig. 3). Thus, the states of neutral equilibrium (zero velocities) in a subcooled liquid can be realized not at one value of the parameter (as it follows from the theory), but over the whole finite region the width of which increases with subcooling (Fig. 4). As the temperature falls below 93°C, the wave propagation in film boiling becomes unstable: the wave velocity is no longer constant in time and acquires an oscillating character. A more detailed study of the wave process in the unstable region was hindered by considerable warming of the element during transition to the film boiling regime which often even damaged the heater.

The feature revealed appears to contain important information on the exact mechanism underlying the process of boiling. The dependence of the boiling heat

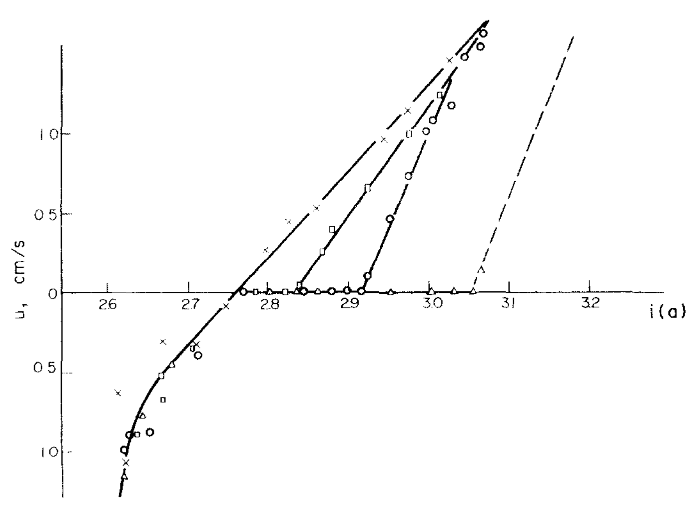

Fig. 3. Velocity of wave propagation in film ($u > 0$) and nucleate ($u < 0$) boiling as a function of the current strength in the wire. $T = 98°C$ (1); $T = 96.5°C$ (2); $T = 95°C$ (3); $T = 93°C$ (4).

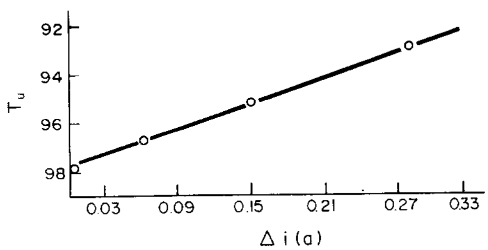

FIG. 4. Relationship between the water temperature and the width of the neutral equilibrium zone.

transfer on the surface temperature is usually represented as a temperature-unique function of the type of curve 1 in Fig. 5. The above theoretical ideas allow the assertion that such a single-valued function and the stepwise approximation (curve 2 in Fig. 5) cannot predict the appearance of the neutral equilibrium region with finite dimensions. The situation is realizable if we assume that the boiling curve is shaped as Z (like curve 3 in Fig. 5)—a phenomenologically similar phenomenon has been treated in detail in [12] for a heterogeneous catalytic process on a platinum wire. Here we shall not dwell in detail on this problem. It should be only noted that the appearance of the region of temperature nonuniqueness on the boiling curve of the subcooled liquid can be due to the effect of formation of nuclei on the heater surface and their collapse.† With higher subcooling, the region of nonuniqueness on the boiling curve extends along with

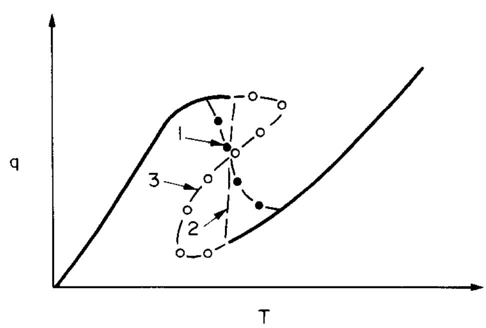

FIG. 5. Boiling curves.

† The appearance of oscillatory regimes in propagation of the front also speaks in favour of this assumption. As subcooling increases, these processes can become dominating and can compete with the thermal mechanism resulting in the occurrence of instability.

‡ It is the misunderstanding of just this phenomenon which has led the authors of [6] to incorrect conclusions as to the existence of critical phenomena and hysteresis in the post-dryout region. This is also the reason of the non-coincidence of the maximum heat fluxes at increasing and decreasing temperatures of the heater and of the overestimated values of the minimum critical heat fluxes as compared with [15].

the width of the zone of neutral equilibrium.

The boiling curves reported in literature are usually obtained by measuring heat transfer as a function of the surface temperature in the mode of mean integral temperature stabilization of the heater. This stabilization is usually effected by vapour heating. The above results enable a conclusion that the boiling heat transfer functions obtained in this way are strongly distorted qualitatively and quantitatively in the region of nonuniqueness of boiling regimes. This is accounted for by the fact that under such experimental conditions the uniformity of the heater temperature fields is not maintained—the fact revealed already in [14]. This and the electrical stabilization of the mean integral resistance [6] merely regulates the relationship between the dimensions of the zones of nucleate and film boiling, automatically reducing the process to the state of neutral equilibrium.‡

TRANSITION FROM CONVECTION TO BOILING

There is an extensive literature devoted to investigations of the stability of steady-state regimes of nucleate and film boiling on heating surfaces and of the conditions for the occurrence of spontaneous transitions between them (known as the 'crisis of boiling'). Instability of the steady-state heat transfer in boiling has also been observed in another temperature region which is situated close to the region of initiation of nucleate boiling. This, however, has been very little treated in literature. We can mention here references [4, 5] in which the existence of oscillatory regimes, that precede the development of the steady-state nucleate boiling, is described (the states which are especially pronounced in boiling of metallic coolants). Some of the works [6–10] point to the existence of the critical phenomena and the hysteresis effects in the above temperature region.

In the present work, using water pool boiling as an example, we have studied the instabilities originating during heat transfer from a heated wire depending on the type of the heat flux supplied, and suggested a phenomenological model to account for the effects observed.

The experimental procedure was that as described above. The heat load was supplied to the wire either in the mode of constant electric current (i = const) or of constant current resistance (R = const) with the aid of stabilizers which were earlier used in electrothermographic devices [16, 17]. The first mode nearly approximates the regime of constant heat load supplied to the heater, while the second, the regime of constant temperature of the heater surface. The accuracy of current stabilization was 10^{-4} A and of temperature stabilization, about 1°C.

The experimental data obtained under identical conditions (the same wire with the temperature of water 97°C) at constant current and resistance are plotted in the coordinates "specific electric power-wire temperature" in Figs. 6 and 7. It can be seen that the

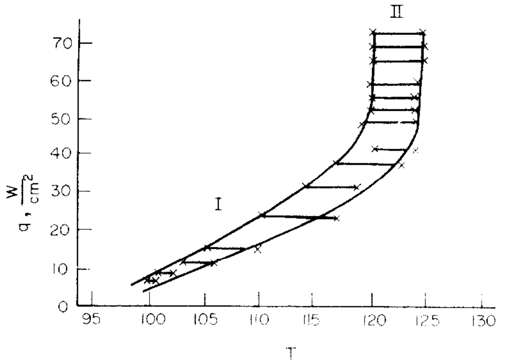

FIG. 6. The shape of the boiling curve obtained at the constant heat flux (q = const). $T_w = 97°C$ (1). I, region of convective heat transfer; II, region of unstable boiling.

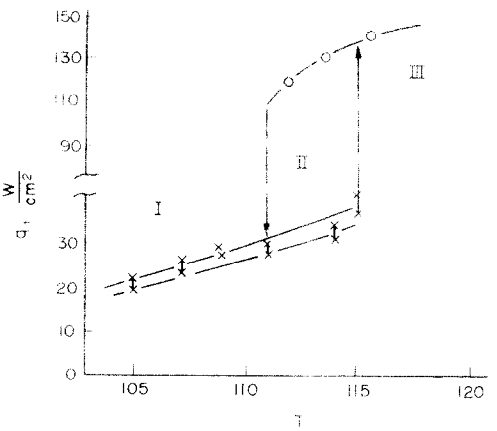

FIG. 7. The shape of the boiling curve obtained at the constant surface temperature (T_{surf} = const), $T_w = 97°C$. I, region of convective heat transfer; II, region of nonunique steady states; III, region of stable nucleate boiling. T_+ and T_-, critical temperatures of transition into the upper and lower steady states, respectively.

trends in the figures are completely different. In the mode of constant current, the zone of convective heat transfer in the absence of boiling (Fig. 6, I) is followed by the region of unstable boiling (Fig. 6, II), which is characterized by temperature fluctuations on the heater associated with the oscillatory process. The horizontal dimension of the cross-hatched region corresponds to the oscillation amplitude which is virtually independent of temperature in region II.† The mean heat-transfer coefficient in region II rises up steeply, almost vertically, as the heat load increases. Under these conditions the unstable nucleate boiling persists until the critical load is attained at which a spontaneous transition to film boiling occurs in the mode of a travelling wave. With higher subcooling of water, the boiling crisis is preceded by the appearance of the zone of stable nucleate boiling (Fig. 6, curve 2). Annealing of the platinum wire in oxygen at 1000°C to 1200°C does not affect the behaviour of graphs in Fig. 6. It leads, however, to a shift in the frequency of temperature fluctuations toward higher frequencies.

In the mode of the constant temperature of the heater, the type of instability during transition from convection to boiling changes basically (Fig. 7). Continuous motion along the branch of the steady-state regimes in the zone without boiling comes to a halt at a certain critical temperature T_+ and the process makes a jumpwise transition toward the steady-state regime of stable nucleate boiling, with the heat-transfer coefficient increasing more than by a factor of five. Cessation of boiling also occurs in a jumplike fashion, though at a different critical temperature $T_- < T_+$ (hysteresis effect). The interval $T_- < T < T_+$ corresponds approximately to the region in which the unstable boiling was observed in the first case, while the width of the hysteresis loop is close to the amplitude of temperature fluctuations (Figs. 6 and 7). It should be noted that the critical heat flux at which the change-over to film boiling occurs at R = const is higher than its counterpart at i = const by more than two times.‡

In the mode of heater resistance stabilization, the transition from the nucleate to film boiling proceeds first as local occurrence of the new regime in the zone the size of which continuously increases with the preassigned resistance.

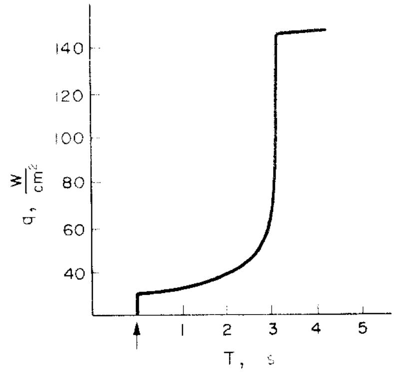

FIG. 8. Dynamics of transition into the upper steady state at T_{surf} = const. The arrow shows the onset of the prescribed temperature; τ, induction period.

† Temperature fluctuations are also observed in region I. These, however, are due to hydrodynamic instability (turbulence) of free convective liquid flow near the wire and, consequently, are of different nature.

‡ We think that the increase of this quantity in the case of subcooling does not show the true rise in the critical heat flux. The conclusions drawn in the first part of the paper make it possible to assume that with increase of subcooling the hydrodynamic situation in the vicinity of the wire improves, i.e. the flow becomes less turbulent, whence a decrease in temperature fluctuations the effect of which leads to the system change-over into a new regime well before the true critical flux is attained. On the ground of the above reasoning it seems more than likely that the true value of the critical heat flux is substantially in excess of the values reported in literature.

A distinctive attribute of the dynamic picture of the process is the presence of the period with slow changes (induction period) which precedes a violent avalanche development of the transition from convection to boiling and the other way round. Thus, the time dependence of the heat transfer coefficient obtained with a rapid heating of wire to the temperature above T_+ is distinctly S-shaped (Fig. 8), i.e. a spontaneous transition to boiling encompasses the induction period which is replaced by the period of progressive growth of the coefficient. The duration of the induction period is rapidly reduced as the temperature rises high above the critical temperature T_+.

The study of the regularities in the change of the induction period has revealed the effect which can be identified as the 'memory effect', which basically is as follows. If the spontaneous transition from convection to boiling is interrupted at the end of the induction period by a rapid cooling of the heater to the temperature of water (by switching off the current), then with subsequent heating of the wire the change-over to boiling will occur without the induction period, i.e. as though the wire 'remembered' these earlier changes. When the wire is then held in the convection regime, the memory 'fades', i.e. the induction periods are restored, with 'fading' proceeding more rapidly the closer the temperature of the heater to that of water.

Numerous experimental studies of the critical effects have shown that these phenomena are observed in the system irrespective of the purity of water (whether it is distilled or commercial), water saturation with air, liquid subcooling, pre-treatment of the platinum wire (preliminary annealing of the heater in air at high temperatures). All these factors have only a quantitative effect on the change in the critical temperatures, the width of the hysteresis loop and dynamics of critical transitions.

The above data on the critical phenomena, the hysteresis effect and on the dynamics of spontaneous transitions from convection to boiling and the other way round allow the assertion that the full curve of heat transfer in the transition region has a characteristic S shape distinguished by the branch of unstable steady-state regimes (Fig. 9, branch bc). This form of the heat transfer curve, physically stemming, in all likelihood, from certain aspects of the processes of boiling nuclei formation and collapse (the processes which are very much in keeping with the branched-chain ones) makes it possible to furnish an explanation to all the above phenomena within the framework of the phenomenological analysis. If the study is carried out at constant temperature, then as soon as point b (upward motion with respect to temperature) and point c (downward motion with respect to temperature) are reached, the steady-state regime loses its stability and the system changes over jumpwise into the steady-state regime of stable boiling (the process bb') or into the regime of stable convective heat transfer in the absence of boiling (the process cc'). It can be easily shown that the dynamic picture of these

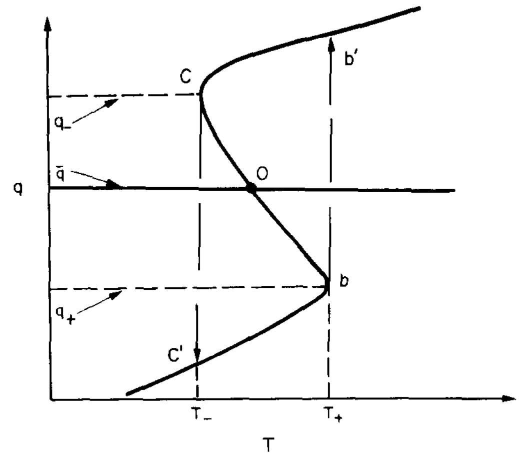

FIG. 9. Qualitative pattern of the boiling curve in the region of transition to boiling (for details see the text).

transitions is characterized by the presence of the induction stage which passes into the stage of rapid changes of the parameter measured (similarly to Fig. 8). The "memory effect" observed in the experiment seems to be associated with this process of accumulation of some new quality during the induction period (say, generation of vaporization centers).

A completely different picture should be observed if the experiments are carried out in the mode of constant rate of heat release. As is seen from Fig. 9, the steady-state regime in this case is always unique (a single point of intersection of the line $q = \text{const}$ with the heat transfer curve). However, within the range of heat loads $q_+ < q < q_-$ the steady-state points lie on the unstable branch (e.g. point o at $q = \bar{q}$). As is known from the theory of stability, this unstable point should be circumferenced by a stable limiting cycle (this kind of an oscillatory process has been treated in the classical monograph [22] for a neon-filled lamp). The oscillation period consists of the convective states c'bb'cc', with the oscillations having a relaxation character. It is this type of instability which is experimentally observed during transition from the region without boiling to that with nucleate boiling, while the amplitude of temperature oscillations, as it follows from the above analysis, nearly approximates the width of the hysteresis loop (Figs. 6 and 7).

It has been shown in the first part of the paper that whenever a local disturbance is introduced in the region, the nonuniqueness of the steady-state heat transfer regimes leads to the appearance of a travelling wave which brings about the change-over from one regime to the other. In the process considered the effect of nonuniqueness is encountered again. Taking as a basis the analogy of the wave phenomena in the transitions between the nucleate and film boiling, we can assert that under the conditions of constant temperature of the heater within $T_- < T < T_+$ the local disturbance must produce a travelling wave which either initiates the nucleate boiling or suppresses it. But despite the phenomenological generality, these processes are physically quite different. While in the first case the self-propagation is due to the thermal mechanism (heat transfer between the zones of nucleate and film boiling), then in the second case the mechanism is in no way associated with heat transfer over the wire (the process is realized under isothermal conditions). It may be presumed that in the second case the travelling wave is due to the processes of initiation and transfer of vaporization centers. The predicted phenomenon has been checked experimentally. In keeping with the theory, the travelling wave has been detected in the narrow range of nonuniqueness $T_- < T < T_+$. Local superheating of the wire was employed as a perturbing factor to initiate the wave of boiling which forces the regime of convective heat transfer out. The locally excited boiling, accompanied by intensive nucleation and a characteristic cracking sound, spreads very rapidly over the entire elements. It has not been possible as yet to make an accurate quantitative recording of the wave process, but the estimates show that the values of the velocities are of the orders of meters and tens of meters per second (c.f., cm s^{-1} for a thermal case). It is clear that at the present time there is a lack of information on the physical nature of this process. We can only say that the cavitational mechanism for the transfer of vaporization centers seems to be quite plausible, i.e. formation of boiling centers on the wire surface in the zone of convection by mechanistic action transmitted into this zone from that of boiling through the layer of liquid.

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APPENDIX

It was when our papers [18, 19] had been published that we came across the paper of Overkerk [20] devoted to the study of transitions between the nucleate and film boiling in response to a local superheat or cooling of the heater surface. The paper contains correct conclusions about the existence, on each side of a certain critical heat load q_0, of metastable regions a local disturbance in which can lead to the transition from the nucleate to the film boiling ($q > q_0$) and vice versa at $q < q_0$. However, the steady-state approach used by the author has not allowed him to obtain the correct value of the critical heat flux q_0. The analysis of this problem on the basis of our study of the self-wave processes in boiling (see Part I) has established a rigorous condition for obtaining of q_0, i.e. the satisfaction of the equality $\int_{T_1}^{T_2} F(T)\mathrm{d}T = 0$ (this corresponds to the equality between heat release and heat transfer, on average, over the width of the wave front). The expression for q_0 derived from this condition is of the form

$$q_0 = \frac{h_2[1 + \sqrt{(h_2/h_1)}]}{\sqrt{(h_2/h_1)} - 1}(T_* - T_s).$$

This expression differs greatly from that used in [20], viz.

$$q_0 = (h_1 \cdot h_2)^{1/2}(T_* - T_s).$$

Thus, the mathematical apparatus of the combustion theory has allowed us not only to describe the unsteady phenomena of the travelling waves in boiling, but to specify strict boundaries of the regions with metastable boiling.

Further development of the analogy with the combustion theory shows that the problem posed by the author of [20] is in line with that of ignition of a solid fuel (see, for example, [21]). The ignition problem is essentially unsteady and, as the experience accumulated in the combustion theory has shown, it requires the analysis of an unsteady-state equation of heat balance and, besides the effect of the perturbation center width, it also involves the study of the effect of perturbation amplitude and its duration as well as the regularities in the dynamics of the steady-state onset in the system. All these points, which are to be considered in the analysis of the processes of transition between various modes of boiling initiated by a disturbance center, have been overlooked by the author of [20]. The above reasoning allows the conclusion that the steady-state approach used by Overkerk does not seem to be justified. It should also be noted that the paper does not contain the analysis of the stability of the steady-state solution. The absence of stability is regarded as a criterion for the onset of transition between the regimes. Taking the results obtained in [23] as a basis, it can be assumed that a non-uniform steady-state solution with the boundary condition $T = T_*$ is unstable, i.e. it cannot exist.

MECANISMES D'ONDE DANS L'EBULLITION EN RESERVOIR SUR DES SURFACES CHAUFFEES

Résumé—On étudie théoriquement et expérimentalement la propagation d'onde de l'ébullition en film ou nucléée à la surface d'un élément chauffé. Dans l'approximation linéaire de la fonction de transfert thermique, on obtient une expression analytique pour la vitesse de l'onde et pour la largeur du front. Une vérification expérimentale est faite pour l'eau bouillante sur des fils fins métalliques. Dans le cas du sous-refroidissement, on décèle une région d'équilibre neutre dans laquelle est possible la coexistence de deux régimes. Les résultats obtenus conduisent à la conclusion qu'il y a un embranchement d'états permanents instables sur la courbe entre les régions d'ébullition en film et nucléée. L'instabilité du transfert thermique en régime stationnaire à des températures proches de la température d'ébullition est étudiée en fonction des types de flux thermiques apportés. Un modèle phénoménologique est suggéré pour rendre compte des effets constatés.

WELLENFÖRMIGE AUSBREITUNG DER VERDAMPFUNGSFRONT AN EINER HEIZFLÄCHE BEIM BEHÄLTERSIEDEN

Zusammenfassung—Die wellenförmige Ausbreitung des Film- oder Blasensiedens an einer Heizfläche wird theoretisch und experimentell untersucht. Aus der linearen Näherung der Wärmeübergangsgleichung erhält man einen Ausdruck zur Bestimmung der Geschwindigkeit und der Breite der Ausbreitungsfront. Zur experimentellen Bestätigung wurde das Sieden von Wasser an elektrisch beheizten dünnen Drähten untersucht. Beim unterkühlten Sieden wurde ein Bereich indifferenten Gleichgewichts beobachtet, bei dem gleichzeitig zwei Zustände möglich sind. Die Ergebnisse lassen den Schluß zu, daß es zwischen dem Film- und Blasensieden einen Teilbereich neutralen Gleichgewichts gibt, in welchem zwei Zustände nebeneinander stetig vorhanden sind.

ВОЛНОВЫЕ ПРОЦЕССЫ НА ТЕПЛОВЫДЕЛЯЮЩИХ ПОВЕРХНОСТЯХ ПРИ КИПЕНИИ ЖИДКОСТИ

Аннотация — Теоретически и экспериментально исследован волновой процесс распространения пленочного режима кипения по поверхности нагревательного элемента. В линейном приближении функции теплоотдачи получено аналитическое выражение для скорости и ширины фронта. Экспериментальная проверка проведена на примере кипения воды на тонких металлических нитях, обогреваемых электрическим током. В случае недогрева обнаружено существование области безразличного равновесия, в которой возможно устойчивое сосуществование двух режимов. На основании полученных результатов сделан вывод о наличии ветви неустойчивых стационарных состояний в области между пузырьковым и пленочным режимами.

Исследовано явление неустойчивости стационарной теплоотдачи в области вблизи температур возникновения кипения в зависимости от способов подачи тепловой нагрузки. Предложена феноменологическая модель, объясняющая описываемые эффекты.