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AN INVESTIGATION OF MINIMUM HEAT FLUXES IN POOL BOILING OF WATER

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Аннотация—Измерены минимальные тепловые потоки при кипении воды в условиях свободной конвекции на горизонтальных проволочках при давлениях от 1 до 100 ата. Обнаружено, что окисление поверхности образца приводит к возрастанию величины $q_{\min}$. Показано, что охлаждение концов образца токоподводами приводит к завышенным значениям величины $q_{\min}$. В интервале тепловых потоков от $q_{\min}$ до $q_{\max}$ существует равновесный тепловой поток (q_{eq}), при котором пузырчатый и пленочный режимы кипения одинаково устойчивы. Показано, что пузырчатый режим кипения устойчив к колебаниям температуры поверхности нагрева только при тепловых потоках меньших равновесного. Проведены измерения равновесного теплового потока при атмосферном давлении на горизонтальных цилиндрах и предложен метод расчета q_{eq}.

NOMENCLATURE

q,	specific heat flux [kcal/m^{2}h];
$q_{\max}$,	maximum heat flux in nucleate boiling [kcal/m^{2}h];
$q_{\min}$,	minimum heat flux in film boiling [kcal/m^{2}h];
q_{eq},	equilibrium heat flux [kcal/m^{2}h];
t,	temperature [°C];
t_s,	saturation temperature [°C];
θ,	$= t - t_s$, difference between test section temperature (in a given cross-section) and liquid temperature [degC];
θ_1, θ_3,	differences between test section temperature and liquid temperature in nucleate and film boiling [degC];
$\theta_{m_1}, \theta_{m_2}$,	differences between test section temperature and liquid temperature in case of $q_{\max}$ and $q_{\min}$ [degC];
T,	absolute temperature [°K];
r,	latent heat of evaporation [kcal/kg];
γ', γ'',	specific weight of liquid and vapour [kg/m^3];
σ,	surface tension [kg/m];
d, u, f,	diameter [m], perimeter [m] and area of a cross-section of a sample [m^2];
λ,	heat conductivity [kcal/m h degC];
I,	electric current [A];
R,	resistance of a sample per metre of length [Ω/m];
α,	heat-transfer coefficient [kcal/m^2 h degC];
p,	pressure [atm];
g,	gravity acceleration [m/s];
x,	distance along the sample axis [m];
v,	specific volume [m^3/kg].

INTRODUCTION

THE REPLACEMENT of a nucleate boiling regime by film boiling leads to a sharp decrease in the heat-transfer coefficient, as a result of which the heating surface is usually burnt-out. At present there is a large number of experimental works on measurement of the maximum heat fluxes ($q_{\max}$). The heat fluxes $q_{\min}$, at which the transition from a film to a nucleate regime occurs, has been studied very little. It should be noted that the transition from nucleate boiling to film boiling is possible at mean heat fluxes considerably smaller than $q_{\max}$. Since the replacement of nucleate boiling by film boiling at heat fluxes less than $q_{\min}$ is impossible, it is of practical interest to know the value of $q_{\min}$.

MINIMUM HEAT FLUXES

Minimum heat fluxes were obtained in pool boiling of water on a surface of a horizontal cylinder. A test section was located in a tank (Fig. 1). The test section was heated by electric current. To avoid the premature vanishing of the vapour film from the ends of the test section cooled by the current leads, the test section was made U-shaped (Fig. 1), and its ends were in the vapour phase [1]. The height of the ends projecting from the liquid was chosen such that the vertical ends of the test section were slightly superheated. In this case the vanishing of the vapour film always started at an arbitrary point of a horizontal section of the test section.

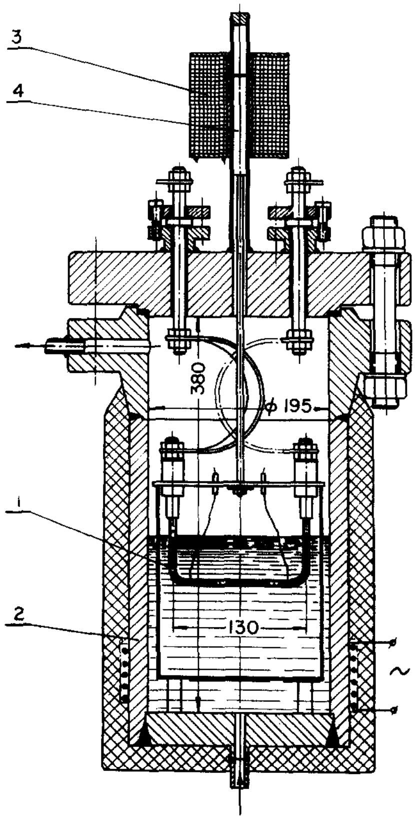

FIG. 1. Boiling apparatus.
1.—test section; 2.—tank; 3.—electric magnet; 4.—core of electric magnet.

The experiments were carried out in the following order. The test section was lifted into the vapour phase with an electric magnet and was heated there. The heated test section was submerged into boiling liquid and film boiling occurred on its surface. After the boiling process was stabilized, the heat flux was gradually decreased. The heat flux decreased up to the moment when film boiling ceased. The minimum heat flux was considered to be obtained when the disruption of the vapour film started on the horizontal part of the test section. One experiment was carried out for 10–12 min. For verification the special runs were carried out in which film boiling was maintained for 30 min and more at heat fluxes slightly greater than $q_{\min}$. The relative error of the measurements of a minimum heat flux was -7 per cent to $+4$ per cent.

The dependence of the value of a minimum heat flux upon a pressure was studied using nichrome wires of 2–2·5 mm diameter. Before the experiment the surface of the test section was polished or rubbed with fine emery paper and was washed by distilled water and alcohol. Two series of runs were carried out. At first $q_{\min}$ were measured on one and the same wire successively at different pressures. However, it was found that during runs the test section surface oxidized, and this led to the increase in $q_{\min}$. The second series of runs was therefore carried out. A number of successive measurements of $q_{\min}$ was carried out on the test section at a given pressure; on one wire were made one after another for 15–20 runs and more. This allowed measurements of $q_{\min}$ on a pure surface as well as under the stabilized conditions on the test section surface. The runs were performed at pressures of 1, 2, 5, 10, 20, 50 and 95–98 atm. The results of these runs are presented in Fig. 2.

With the procedure of successive experiments on one and the same wire at a fixed pressure the quantity $q_{\min}$ increases gradually. The

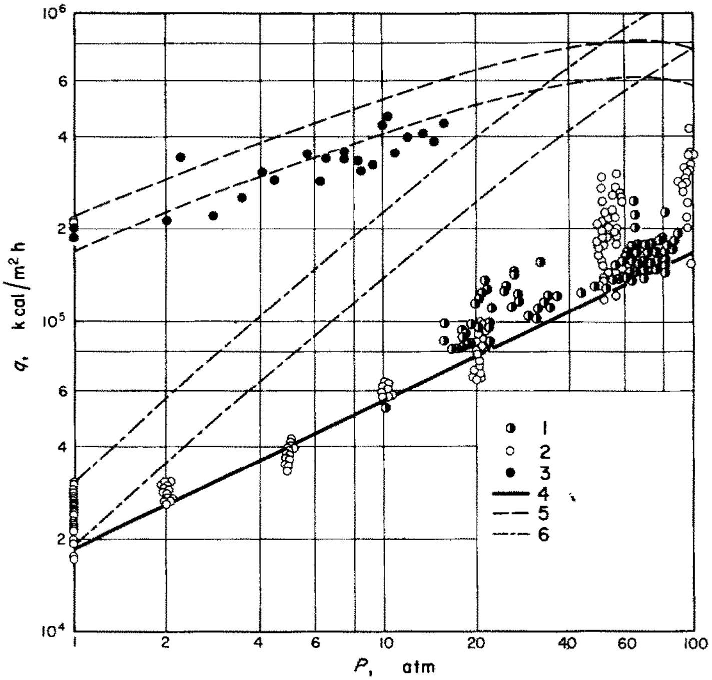

FIG. 2. Dependence of $q_{\min}$ on pressure. 1.—author's data, series I; 2.—author's data, series II; 3.—data from reference [7]; 4.—equation (1); 5.—equation (2) from reference [8]; 6.—equation (3) from reference [9].

experimental points given in Fig. 3 illustrate a change in $q_{\min}$ in the case of the procedure of successive experiments on one and the same test section. As it is seen from Fig. 3, a great increase in $q_{\min}$ is observed at pressures of 50–100 atm from run to run. This is due to the fact that at high pressures the surface of the test section is subjected to a more rapid oxidation.

The increase in the value of the minimum heat fluxes with oxidation of the surface may be explained as follows. In nucleate boiling the liquid in contact with a heating surface is superheated, i.e. above the saturation temperature and is in a metastable state. The maximum theoretical superheating of the liquid (t_m) is limited by the following thermodynamic condition: $(\partial p/\partial v)_T = 0$ (after the liquid has achieved the temperature t_m spontaneous boiling occurs). In transition boiling there exists a direct contact between the liquid and the heating surface, and the surface temperature should be less than t_m. For a minimum heat flux the heating surface temperature is close or equal to t_m [2]. However, in the case of low wetting of the heating surface by the liquid the onset of boiling of the liquid and the formation of the vapour film on the surface will occur at temperatures lower than t_m [3]. This means that the temperature difference between the wall and liquid for a minimum heat flux and also the quantity $q_{\min}$ itself decrease with bad wettability. The oxidation of the surface leads to a decrease in the wetting angle [4] and, consequently, also to an increase in $q_{\min}$.

Thermal resistance of a layer of oxides may be another possible reason leading to an increase in $q_{\min}$. The vapour film, surrounding the test section, is subjected to the oscillatory motion and the liquid periodically approaches the heating surface. In places where the vapour film becomes thinner, heat transfer to a liquid

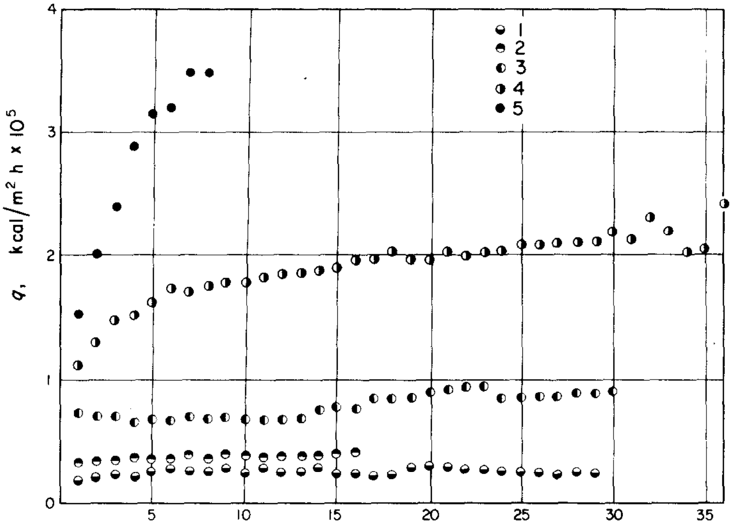

FIG. 3. Dependence of q_{min} on the number of the measurements (N). 1.—p = 1 atm (24 January 1964); 2.—p = 5 atm (31 January 1964); 3.—p = 20 atm (4 February 1964); 4.—p = 50 atm (24 April 1964); 5.—p = 95 atm (9 April 1964).

should increase. Film oscillations occur with a relatively low frequency (20–30 cps), therefore at individual points the temperature of the oxidized layer surface may essentially decrease. A local temporary decrease in the temperature of the oxidized surface may lead to a contact between the liquid and surface at a mean surface temperature considerably greater than t_m.

Thus, if the test section is covered with a film of oxides with low heat conductivity, a periodic contact of a liquid with a heating surface may start at mean values of a heat flux higher than those on a pure surface.

The visual investigations carried out on the test sections at atmospheric pressure have shown that the transition from film boiling to nucleate boiling is somewhat different on pure and oxidized surfaces. On the test lengths with a pure non-oxidized surface when the heat flux decreases down to q_{min} and with the onset of transition boiling there occurs a rapid cooling of a sample and the replacement of a transition by a nucleate regime. (The transition boiling regime may be easily found visually since in transition boiling the vapour film undergoes intense oscillations.)

If initially q_{min} was measured on a test section at high pressures, and the sample surface is oxidized, then in the case of a decrease in the heat flux transition boiling occurs on discrete portions of the sample. After some time transition boiling changes into film boiling. Such successive changes of regimes may occur for a very long time. In the case of a further decrease in heat flux, transition boiling persists for a longer period. After some heat flux is reached, film boiling is finally replaced by transition boiling, and later by nucleate boiling.

As is seen from Fig. 2, over a pressure range of 1–100 atm the quantity q_{min} increases with pressure. As a first approximation it is possible to assume that on a pure surface made of nichrome q_{min} increases with pressure as follows:

$$q_{min} = 18{\cdot}5 \times 10^3 \times p^{0{\cdot}48}. \qquad (1)$$

The measurements of the minimum heat fluxes made in the course of the present work have shown that the relation q_{max}/q_{min} somewhat decreases with an increase in the pressure. For a pure surface this relation is equal to ~50 at atmospheric pressure and decreases up to ~22 at a pressure of 100 atm. The obtained relation q_{max}/q_{min} agrees with the available relations for other liquids. Thus, in the experiments [5] for CCl_4 $q_{max}/q_{min} = 22$–28 and for *n*-pentane ~16–33. In reference [6] for methanol $q_{max}/q_{min} = 31$.

The data [7] are presented in Fig. 2. In that study the quantities q_{min} were measured on a horizontal graphite rod 2·2 mm in diameter. The ends of the rod were fastened to copper current leads which were immersed in the boiling liquid and were at the temperature of the liquid. Film boiling began to vanish at the ends of the test section cooled by the current leads for heat fluxes higher than q_{min}. As seen in Fig. 2 the data [7] are 5–8 times higher than the real values of q_{min}.

The comparison of the obtained results with the equations proposed in references [8] and [9] is also given in Fig. 2. In the formula [8]

$$q_{min} = k_1 \,.\, k_2 \,.\, r \sqrt{(g\gamma'')}\, \sqrt[4]{[\sigma(\gamma' - \gamma'')]}; \qquad k_1 = 0{\cdot}14 \qquad (2)$$

the value of the constant $k_2 = 0{\cdot}17$–$0{\cdot}22$ is chosen to fit the results of the measurements of q_{min} obtained for some liquids. These runs are made on the test section, whose ends are cooled by the current leads. As is seen from Fig. 2, the values of q_{min} calculated by formula (2) are 5–8 times higher than the real values.

The formula by N. Zuber [9]

$$q_{min} = k \,.\, r\gamma'' \sqrt[4]{\left[\frac{\sigma g^2(\gamma' - \gamma'')}{\gamma'^2}\right]} \qquad (3)$$

$(k = 0{\cdot}176 \sqrt{[\gamma'/(\gamma' + \gamma'')]}$ or $k = 0{\cdot}109$–$0{\cdot}144)$

gives satisfactory agreement with the runs at atmospheric pressure but essentially overestimates the value of q_{min} at high pressures. Probably such a considerable divergence is explained by the fact that the treatment of the changes of boiling regimes as hydrodynamic crisis is inadequate. In such an approach the cessation of film boiling is treated as a result of a loss of stability of the vapour phase motion. Since it is supposed that there is no contact of the liquid with the heating surface before the stability of the boundary layer is disrupted, the replacement of the boiling regimes is completely unrelated to the conditions on the heating surface. However, our experiments show that the state of the heating surface, especially, the contact angle of wetting is essential. It is natural to suppose that for the poorly wetted surfaces q_{min} may be quite small. Therefore, a conclusion suggests itself that, in general, the hydrodynamic stability of a boundary layer in a case of boiling on ordinary surfaces with good wettability does not limit the value of the minimum heat flux.

EQUILIBRIUM HEAT FLUXES

Consider a temperature distribution over the length of a metallic rod of infinite length. Electric current I flows through the rod. This means that in the body of the rod there are uniformly distributed heat sources. The heat flux density, averaged over the length of the rod surface, will be: $q = 0{\cdot}86\ I^2R/\pi d$. The experimental studies show that at the rod surface simultaneous nucleate and film boiling may exist. Changing the current intensity it is possible to choose such a heat flux, averaged over the length $q_{eq}(q_{min} < q_{eq} < q_{max})$, at which the interface of the boiling regimes will be in equilibrium [1]. If the heat flux on the rod surface q is increased $(q_{eq} < q < q_{max})$, the interface of the boiling regimes starts moving to nucleate boiling, and film boiling spreads over the whole surface. If the heat flux $(q_{min} < q < q_{eq})$ is decreased, the gradual movement of the interface of the boiling regimes leads to the cessation of film boiling over the whole surface of the rod. For each liquid at a given pressure and the prescribed conditions on the test section surface, the equilibrium heat flux (q_{eq}) will be unique.

With simultaneous film and nucleate boiling on a surface the surface temperature over the rod length differs by hundreds of degrees. At the interface of the regimes there will be considerable transport of heat through the body of the rod. The simultaneous stable existence of boiling regimes is possible only if heat balance is gained for all the portions of a sample. (The amount of heat released by the sources distributed over the rod body and supplied through the rod by heat conduction should be equal to that released by a boiling liquid from a surface [10]. Since the dependence of the heat-transfer coefficient on the temperature difference is known, it is possible to find the heat flux (q_{eq}), at which for any element of the surface of an infinitely long rod the heat balance is satisfied. Assume that the temperature over the cross-section of a rod is constant. For the element of the rod with the length dx the heat balance equation will be:

$$\frac{d^2}{dx^2} - \frac{\alpha\theta u}{f\lambda} - q\frac{u}{f\lambda} = 0. \tag{4}$$

Here $q = (0{\cdot}86\, I^2R/\pi d)$ is the heat flux averaged over the length. The heat-transfer coefficient (α) has a very complex dependence on a temperature difference. To a first approximation the boiling process may be divided into three regimes: nucleate (α_1), transition (α_2) and film (α_3). For nucleate boiling ($\theta < \theta_{m_1}$) it is possible to assume: $\alpha_1 = Aq^n$, for transition boiling ($\theta_{m_1} \leqslant \theta < \theta_{m_2}$) we assume: $\alpha_2 = B\theta^m$ and for film boiling ($\theta > \theta_{m_2}$) we assume $\alpha_3 = \text{const}$. Since each boiling regime is described by its own dependence $\alpha = f(\theta)$, then for each boiling regime the temperature field over the rod length will be described by its own equation. From equation (4) it is not difficult to obtain:

$$\frac{d\theta}{dx}_i = \pm\sqrt{\left[\frac{2u}{f\lambda}\int(\alpha_i\theta - q)\,d\theta\right]} \tag{5}$$

where

$i = 1, 2, 3$ α_1 is nucleate boiling,
α_2 is transition boiling,
α_3 is film boiling.

Assume that one end of the rod is occupied by nucleate boiling; another, by film boiling and between them there is a region of transition boiling. Far away from the transition region, where there is no transport of heat through the rod ($d\theta/dx = d^2\theta/dx^2 = 0$), the temperature in the regions of nucleate and film boiling respectively will be equal to:

$$\theta_1 = \frac{q}{\alpha_1} \qquad \theta = \frac{q}{\alpha_3}. \tag{6}$$

It we take into account that at the boundaries of the regimes at the points where the temperatures are θ_{m_1} and θ_{m_2}, the derivatives on the left and on the right are equal, then the system of equations (5) and (6) leads to the equation:

$$q^2 - \frac{q^{2-n}\alpha_3}{A(2-n)} = \frac{2\alpha_3(1-n)}{2-n}A^{\frac{1}{1-n}}\theta_{m_1}^{\frac{2-n}{1-n}} + \frac{2\beta\alpha_3}{m-2} \times (\theta_{m_1}^{2-m} - \theta_{m_2}^{2-m}) - \alpha_3^2\theta_{m_2}^2. \tag{7}$$

For water boiling at atmospheric pressure on the surface of a horizontal cylinder 5–15 mm in diameter it is possible to assume:

$q_{\max} = 1{\cdot}1 \times 10^6$ kcal/m^{2}h; $A = 2{\cdot}6$; $n = 0{\cdot}7$
$q_{\min} = 3 \times 10^4$ kcal/m^{2}h; $B = 10^9$; $m = 3{\cdot}12$
$\alpha_3 = 220$ kcal/m^{2}h degC.

In this case the solution of equation (7) for an equilibrium heat flux gives a quantity $107{\cdot}2 \times 10^3$ kcal/m^{2}h.

Note that when deriving equation (7) we used the dependence $\alpha = f(\theta)$ which is observed in the experiments on isothermal heating surfaces. Therefore, the solution obtained will be satisfied the better, the smaller the temperature gradients over the length, i.e. the greater the product $f\lambda$ of this rod.

Equilibrium heat fluxes were measured with pool water boiling on the surface of a horizontal cylinder at atmospheric pressure. Wires located horizontally and the tube made of nichrome 12 mm in diameter served as the test sections. The test sections were fully submerged into boiling water. The test section was 300 mm in length. It was heated by electric current. The current intensity was chosen so that the interface of the boiling regimes may remain stable for a long period of time (for one hour). The heat flux was calculated from the current intensity and the electric resistance of the test section. The resistance of the test section was found as the arithmetic mean of the resistances with film and nucleate boiling. The error of the measurements of an equilibrium heat flux did not exceed ±4 per cent.

The results of the measurements are presented in Fig. 4. With an increase in the test section diameter from 0·5 to 12 mm the quantity q_{eq} decreases approximately three times. Some scatter in the quantities of the equilibrium heat fluxes (for a given diameter) is explained by the fact that the equilibrium heat flux is somewhat greater on the oxided surface of a sample. It should be noted that the quantity q_{eq} calculated by equation (7) fairly agrees with the results of the measurements on the tube 12 mm in diameter.

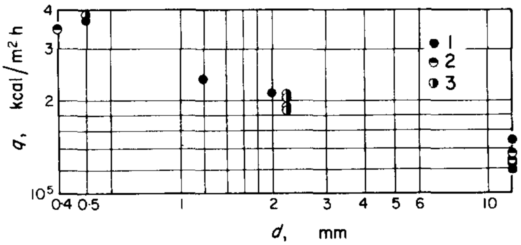

FIG. 4. Dependence of q_{eq} on a sample diameter. 1.—author's data; 2.—data from reference [11]; 3.—data from reference [7].

In Fig. 4 are presented the results of the measurements of q_{min} obtained at atmospheric pressure [7]. As has been mentioned, in these experiments the ends of the test sections were cooled by the current leads. The slipping off of the vapour film from the ends of the test section started at the heat fluxes considerably greater than q_{min}. It is possible to assume that from the central part of the test section the vapour film slipped off at the mean heat fluxes similar to q_{eq}. As is seen from Fig. 4 the results of the measurements [7] satisfactorily agree with our measurements of q_{eq} obtained on the wire 2 mm in diameter.

In Fig. 4 is also presented the heat flux [11] for which film boiling ceased on a horizontal nichrome wire. The ends of a wire were submerged in the boiling liquid and were cooled by the current leads. The quantity obtained as a result of this measurement satisfactorily agrees with q_{eq} obtained on the wire 0·5 mm in diameter.

Note that the equilibrium heat flux cannot be identified with q_{min}. It is not correct to consider it to be equal to q_{max} either. Let us assume that nucleate boiling is maintained on the rod surface. Also assume that apart from the heat released by the sources uniformly distributed over the length, a certain amount of heat is supplied to some element of a surface. For example, heat may be transferred by conduction through the rod from an adjacent section of the surface thermally insulated from a liquid. If the heat flux is gradually increased, then at the boundary with a thermally insulated section film boiling will appear for very small mean values of the heat flux. As soon as the heat flux exceeds q_{eq}, film boiling will spread over the whole surface. Undoubtedly, the equilibrium heat flux measured in such a way cannot be identified either with q_{max} or with q_{min}.

It is necessary to consider the practical application of the concept of the equilibrium heat flux. When calculating industrial installations cooled by a boiling liquid it is necessary to choose a safe heat flux. In the industrial installations the heat fluxes similar to q_{max} are not allowed. This is due to the fact that in operation some fluctuations of the parameters of a process (pressure, local heat fluxes quality of a boundary layer, etc.) are observed. Such variations of the parameters may cause a transition to film boiling at the mean values of the heat flux considerably smaller than q_{max}.

It is therefore necessary to know at which heat fluxes nucleate boiling is stable. The equilibrium heat flux appears to divide the interval $q_{\min}$ to $q_{\max}$ into regions of stable nucleate and film boiling. This can be illustrated by some examples.

Let nucleate boiling with heat flux q be maintained over the whole surface of a sufficiently long horizontal rod. Assume that on some section as a result of fluctuations of any parameter the rod temperature increased temporarily and transition to film boiling occurred. If $q > q_{eq}$, then the sections of the surfaces near the boundary of film boiling will be heated, and after some time film boiling will spread over the whole surface. If $q < q_{eq}$, then the hotter section of the surface will be cooled due to the heat outflows through the rod, and nucleate boiling will be restored. This means that nucleate boiling is stable only for heat fluxes smaller than the equilibrium ones. It may be also shown that for $q > q_{eq}$ film boiling is stable to considerable random local falls of surface temperature.

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Abstract—Minimum heat fluxes in pool boiling of water on horizontal wires at pressures from 1 to 100 atm were measured. It was found that the oxidation of the test section surface leads to an increase in $q_{\min}$. It was shown that cooling of the ends of a sample by current supplies leads to the overestimated values of $q_{\min}$. Within the range of the heat fluxes from $q_{\min}$ to $q_{\max}$ there exists an equilibrium heat flux (q_{eq}), for which nucleate and film boiling regimes are equally stable. It was shown that nucleate boiling is stable to temperature oscillations of a heating surface only at heat fluxes smaller than the equilibrium one. The measurements of an equilibrium heat flux at atmospheric pressure on horizontal cylinders are carried out, and the method for calculating q_{eq} is proposed.

Résumé—Les flux de chaleur minimaux dans l'ébullition en réservoir d'eau sur des fils horizontaux à des pressions de 1 à 100 atm ont été mesurés. On a trouvé que l'oxydation de la surface de la section d'essai conduit à une augmentation de $q_{\min}$. On a montré que le refroidissement des extrémités d'un échantillon par les amenées de courant conduit à des valeurs surestimées de $q_{\min}$. Dans la gamme des flux de chaleur de $q_{\min}$ à $q_{\max}$, il existe un flux de chaleur d'équilibre (q_{eq}), pour lequel les régimes d'ébullition nucléée et par film sont également stables. On a montré que l'ébullition nucléée n'est stable par rapport aux oscillations de température d'une surface chauffante seulement à des flux de chaleur inférieurs au flux d'équilibre. On a mesuré le flux de chaleur d'équilibre à la pression atmosphérique sur des cylindres horizontaux, et l'on propose une méthode pour calculer q_{eq}.

Zusammenfassung—Für Drucke von 1 bis 1000 atm wurde die minimale Wärmestromdichte an Drähten bei freiem Konvektions Sieden in Wasser gemessen. Es ergab sich, dass das Oxydieren der Drahtoberfläche zu einem Anstieg von $q_{\min}$ und dass das Abkühlen der Drahtenden durch die Stromzuführungen zu zu hoch bestimmten Werten von $q_{\min}$ führten. Innerhalb des Wärmestromdichtebereiches von $q_{\min}$ und $q_{\max}$ gibt es eine Gleichgewichts wärmestromdichte (q_{eq}), bei welcher Blasen- und Filmsieden nebeneinander stabil sind. Es konnte gezeigt werden, dass Blassensieden gegen Temperaturschwankungen der Heizoberfläche nur bei Wärmestromdichten keliner als q_{eq} stabil bleibt. An horizontalen Zylindern wurden Messungen der Gleichgewichts wärmestromdichte bei Atmosphärendruck durchgeführt und eine Berechnungsmethode für q_{eq} vorgeschlagen.