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PRINCIPAL MECHANISM OF BOILING CRISIS IN POOL BOILING

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Abstract—High-speed photography has been employed to study the mechanism of the boiling crisis in pool boiling of saturated water at high heat fluxes. Three configurations have been examined: normal free boiling on a heated 10-mm dia. horizontal copper disc and the same system subjected to the interference of a flat plate and a short tube held above the heated disc.

The mechanism of pool boiling crisis is clarified both by the qualitative observations of the fluid behavior and by an analysis based on the experimental facts. It is concluded that the phenomenon of pool boiling crisis is related to the intermittent behavior of vapor masses and to the consumption of liquid film which builds up on the heated surface.

Previous theories of boiling crisis and transition boiling are discussed in relation to the mechanism revealed by the present study.

NOMENCLATURE

A_w, area of heated surface;
A'_w, total sectional area of vapor stems;
D, average diameter of vapor stems;
g, gravitational acceleration;
H_{fg}, latent heat of evaporation;
q, heat flux;
q_c, peak heat flux;
$\bar{q}$, average heat flux in transition boiling;
t, time;
t_c, life of liquid film at the point of peak heat flux.

Greek symbols
δ, height of vapor stem;
δ_0, initial thickness of liquid film;
ρ_l, density of liquid;
ρ_v, density of vapor;
σ, surface tension.

1. INTRODUCTION

As THE most fundamental boiling crisis, the boiling crisis in saturated pool boiling is studied in the present paper. As is well known, various theories have already been published on this subject. Roughly speaking, we have one group which considers the obstruction of heat transfer due to vapor masses anchored on the heated surface and another which postulates that the crisis is due to the existence of a limit in the state of the fluid system. The latter consists of two groups of theories, namely the geometrical theories of Rohsenow and Griffith [1], and Chang and Snyder [2] based on critical bubble spacing near the heated surface, and the hydrodynamic ones of Kutateladze [3], Chang and Snyder [4], Zuber, Tribus and Westwater [5], and Torikai [6] based on the instability of the interface between liquid and vapor.

However, quite a number of experimental observations on boiling and the boiling crisis cannot be explained by the above-mentioned theories. For example, according to Torikai and Yamazaki [7], and Kirby and Westwater [8] who studied the nucleate boiling on a glass plate coated with a transparent, heated film of metal oxide, in order to observe the state of fluid very close to the heated surface, a liquid film exists on the heated surface even in the vicinity of boiling crisis. Furthermore, Kirby and Westwater reported that dry spots sometimes appear in the liquid film at high heat fluxes near boiling crisis; that dry spots grow in size but they have a life after which liquid washes across the dry area and again wets the solid; and that dry spots presumably signal the boiling crisis. These observations are not in keeping with the models on which existing theories are based. In addition, it has been known that the properties of the heated surface, such as wettability, influence to some extent the critical heat flux as shown for example, by Costello and Frea [9]. This is also difficult to explain with the existing theories.

The above-mentioned observations would indicate that there are still important fundamental inadequacies in the existing theories. These theories try to explain the boiling crisis by an essentially static model, whereas boiling, especially in the nucleate and transition regions, is a phenomenon characterized by periodical or intermittent processes. If so, the principal mechanism of boiling crisis should be connected with such periodical aspects. In addition, the point of peak heat flux is a limit not only of the nucleate boiling but also of the transition boiling. Consequently, the phenomenon which gives a limit to one region should have a close relation to the mechanism of boiling in the other region.

With such a point of view in mind, observation and analysis of pool boiling at high heat fluxes are carried out in the present study using high-speed photography and adopting particular configurations of boiling which enable us to approach the essential nature of boiling crisis with ease.

2. EXPERIMENTAL APPARATUS

The boiler is illustrated schematically in Fig. 1. This is the same as that used in the authors' preceding study [10], so that description of its details will be omitted. Pure water at the atmospheric pressure is boiled on a horizontal copper disc of 10 mm in diameter facing upward. A vapor mass of comparatively simple shape is generated on the heated surface intermittently at high heat fluxes, and the peak heat flux is around $1{\cdot}6 \times 10^6$ kcal/m^{2}h.

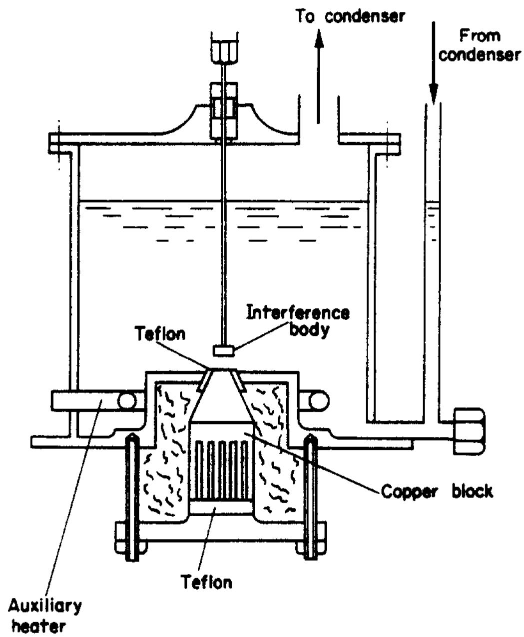

FIG. 1. Boiler and heater.

Experiments are carried out for three different configurations of boiling, namely the normal free boiling and the boilings subject to interference originated by holding either an optical assembly (Fig. 2) or a short tube (Fig. 3) vertically above the heated surface. The optical assembly, which is the same as that in the preceding study [10], is used not only to interfere with the behavior of vapor masses by placing the bottom glass-surface parallel to the heated surface, but also to observe the state of the fluid on the heated surface through a circular window. In the last configuration mentioned above, short tubes 3-, 10- and 20-mm long are used, all having outer diameter equal to the diameter of the heating disc. They are made of acrylic resin of good transparency so that the behavior of the fluid inside can be observed with ease.

When the spacing, s, between the bottom surface of each of the interference bodies aforementioned and the heated surface is varied, the peak heat flux, q_c, shows a characteristic

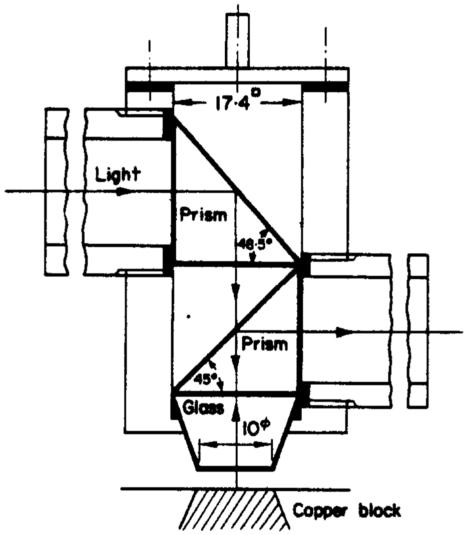

FIG. 2. Optical assembly.

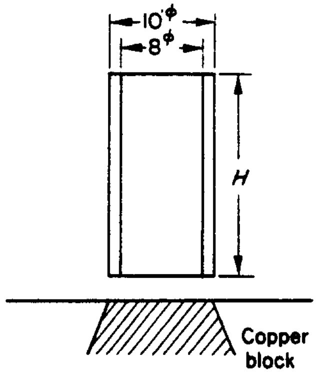

FIG. 3. Tube.

variation such as is shown in Fig. 4. It is particularly of interest to notice that in the case of the tubes there is a spacing range where q_c increases as s is decreased. Of course, if s is sufficiently increased, every curve in Fig. 4 tends to the magnitude of peak heat flux observed in the normal free boiling: $q_c \doteqdot 1{\cdot}6 \times 10^6$ kcal/m^{2}h. It should be noted that most published studies of pool boiling crisis have been made on the normal free boiling, and that they give no reliable explanation of such a variation of q_c as shown in Fig. 4.

3. NUCLEATE BOILING AT HIGH HEAT FLUXES

Before reporting the present results, some of the existing knowledge of nucleate boiling at high heat fluxes will be mentioned for convenience. A typical aspect of nucleate boiling on a heated surface at high heat fluxes is shown schematically in Fig. 5(a). There is a liquid film on the heated surface, and a lot of small vapor stems within the film are supplying vapor to an overlying vapor mass. Gaertner and Westwater [11] have measured the average diameter of the vapor stems, D, in the saturated boiling of water at the atmospheric pressure on a horizontal copper surface to give the solid curve in Fig. 6 showing the variation of D with heat flux q. As for the height of vapor stems, δ, Gaertner [12] has reported, in the discussion on his paper, that the following relation exists independently of q:

$$\delta = 0{\cdot}6\, D. \qquad (1)$$

This is the relation obtained from side-view photographs taken of the boiling of water on a horizontal copper surface at high heat fluxes.

On the other hand, it may be presumed that if an interference plate is pushed downward from above into a vapor mass as shown in Fig. 5(b), the characteristics of boiling heat transfer do not vary until the spacing, s, between the plate and the heated surface approaches the thickness of the liquid film, δ. The critical spacing, s_f, at which the variation of heat-transfer characteristics begins, has been measured by the authors [10]. The results are plotted in Fig. 6 showing the existence of a kind of mutual relation with the result of Gaertner and Westwater.

The authors have also measured the increase of volume of a vapor mass generated just above the 10 mm diameter horizontal copper surface with high-speed photography. According to the results, the rate of increase of vapor within a vapor mass is almost constant through the growth period of the vapor mass indicating

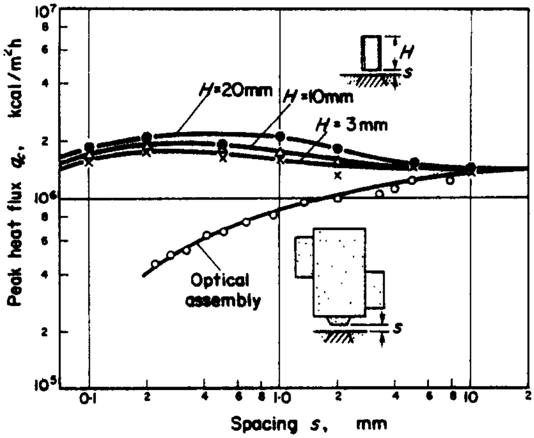

FIG. 4. Variation of peak heat flux with spacing.

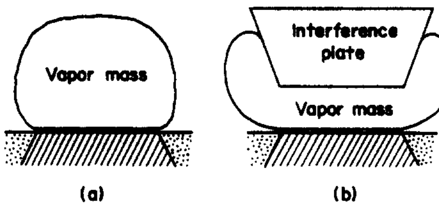

FIG. 5. (a) Nucleate boiling at high heat fluxes. (b) Nucleate boiling with an interference plate.

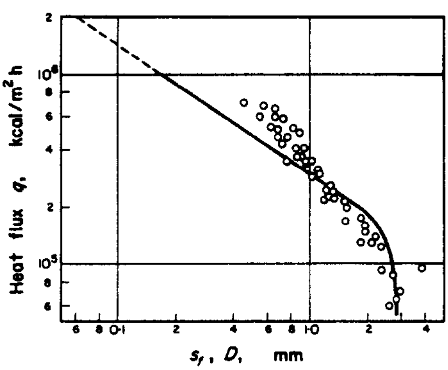

FIG. 6. Variation of critical spacing s_f (indicated by circles) and average diameter of vapor stems D (indicated by solid curve) with heat flux. Broken line is extension of experimental result.

that vapor is generated from the liquid film on the heated surface at a constant rate.

Summarizing the results which have been stated above, it may be concluded that nucleate boiling at high heat fluxes is characterized by nucleate boiling within a liquid film built up on the heated surface and its production of vapor. According to the solid curve in Fig. 6 and equation (1), the thickness of the liquid film decreases as the heat flux is increased, and it is surmized to be only 0·1 mm or so in the vicinity of the boiling crisis of water at atmospheric pressure.

4. GENERATION AND CONSUMPTION OF LIQUID FILM

How such a liquid film as described in the preceding section is built up on the heated surface is a problem of great importance. In order to clarify the mechanism, the behavior of the fluid has been carefully observed in the present study.

4.1. *Free boiling*

As a typical example, Fig. 7 shows successive states of vapor masses in the vicinity of the free heated surface at intervals of 0·84 msec, which were obtained at a heat flux of $1{\cdot}39 \times 10^6$ kcal/m²h. It is noticed that a perfect detachment of vapor mass from the heated surface occurs in frames 9–13 and a new vapor mass has already begun to grow in frame 14 pushing up the overlying liquid. The time elapsed in one detachment of vapor mass is found to be about 3 msec at the most, whereas the average period from one detachment to the next has been found to be around 60 msec in this case. It may be said, therefore, that the heated surface is always covered with a vapor mass except the extremely short period of detachment of vapor mass, occurring nearly at constant frequency.

When a vapor mass grows on the heated surface, it continues a very rapid expansion of volume forcing out the surrounding liquid with a constant rate of increase of vapor, so that the inside pressure should be somewhat higher than

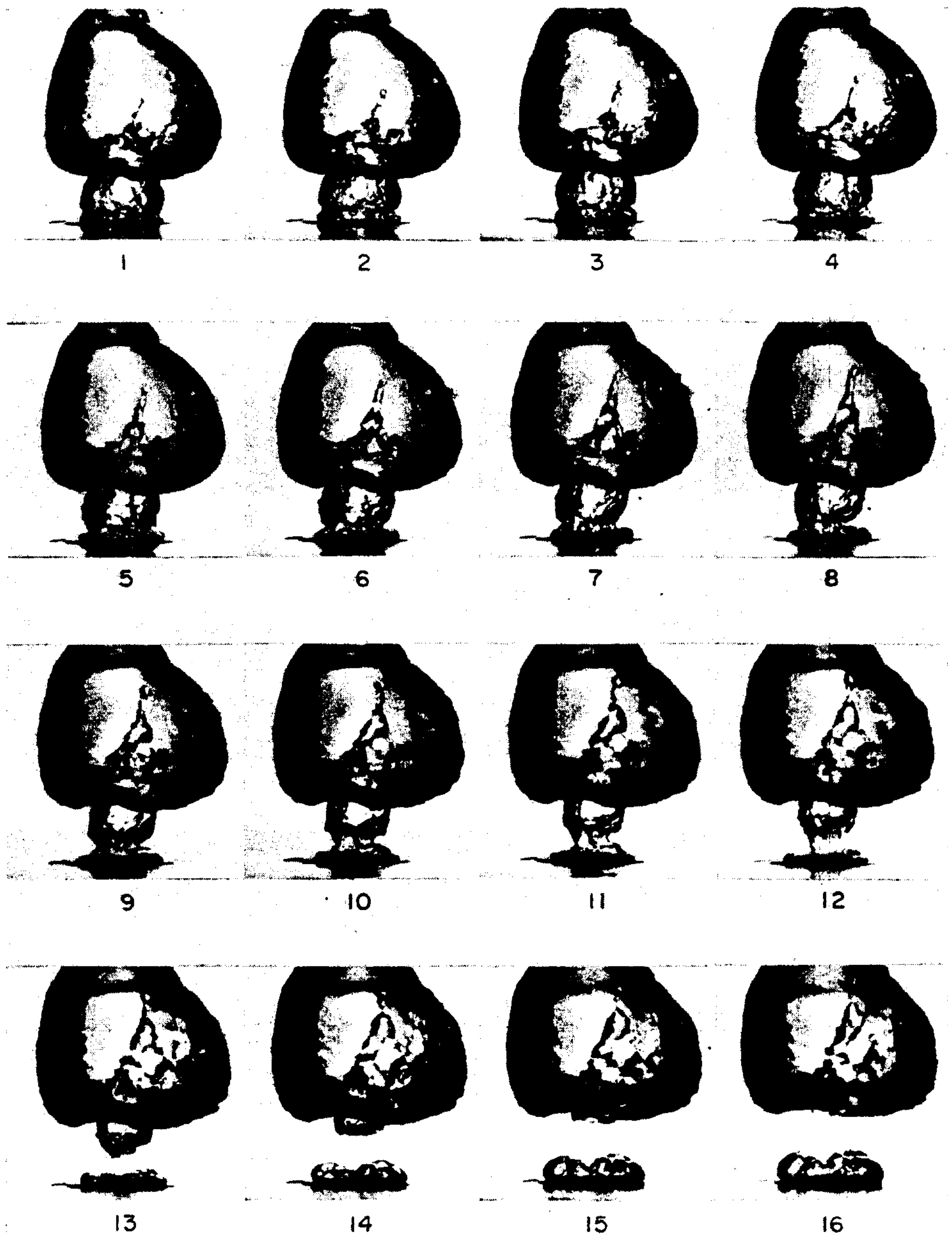

FIG. 7. Successive states of vapor mass in free nucleate boiling (q = 1·39 × 10^6 kcal/m^2h, interval = 0·84 msec).

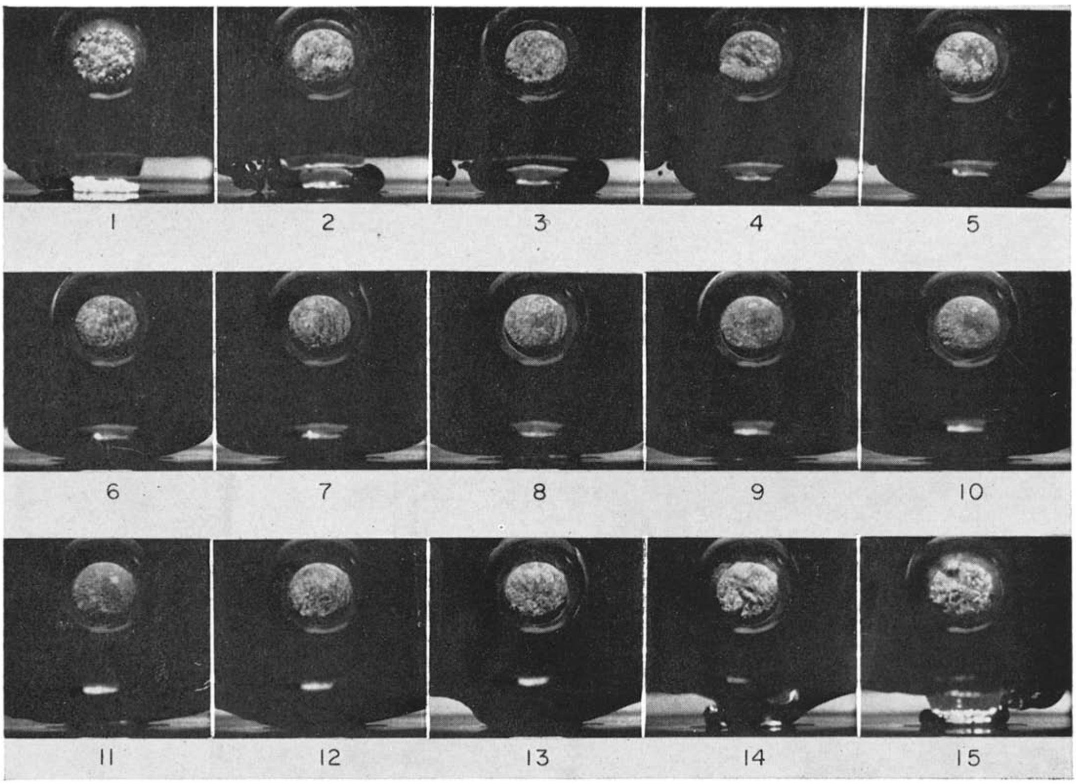

FIG. 8. Nucleate boiling with optical assembly at a heat flux lower than peak heat flux ($s = 2$ mm, interval $= 8{\cdot}6$ msec).

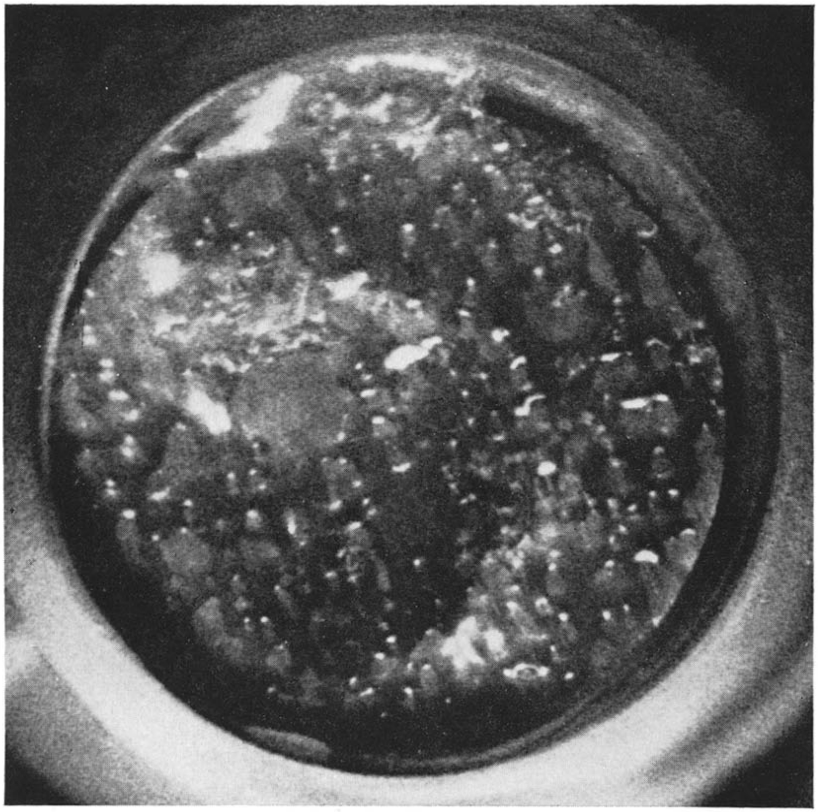

FIG. 9. Liquid film in the late period of a cycle of nucleate boiling with optical assembly very close to peak heat flux ($s = 2$ mm). Liquid is dark, and white points scattered are only reflection of light.

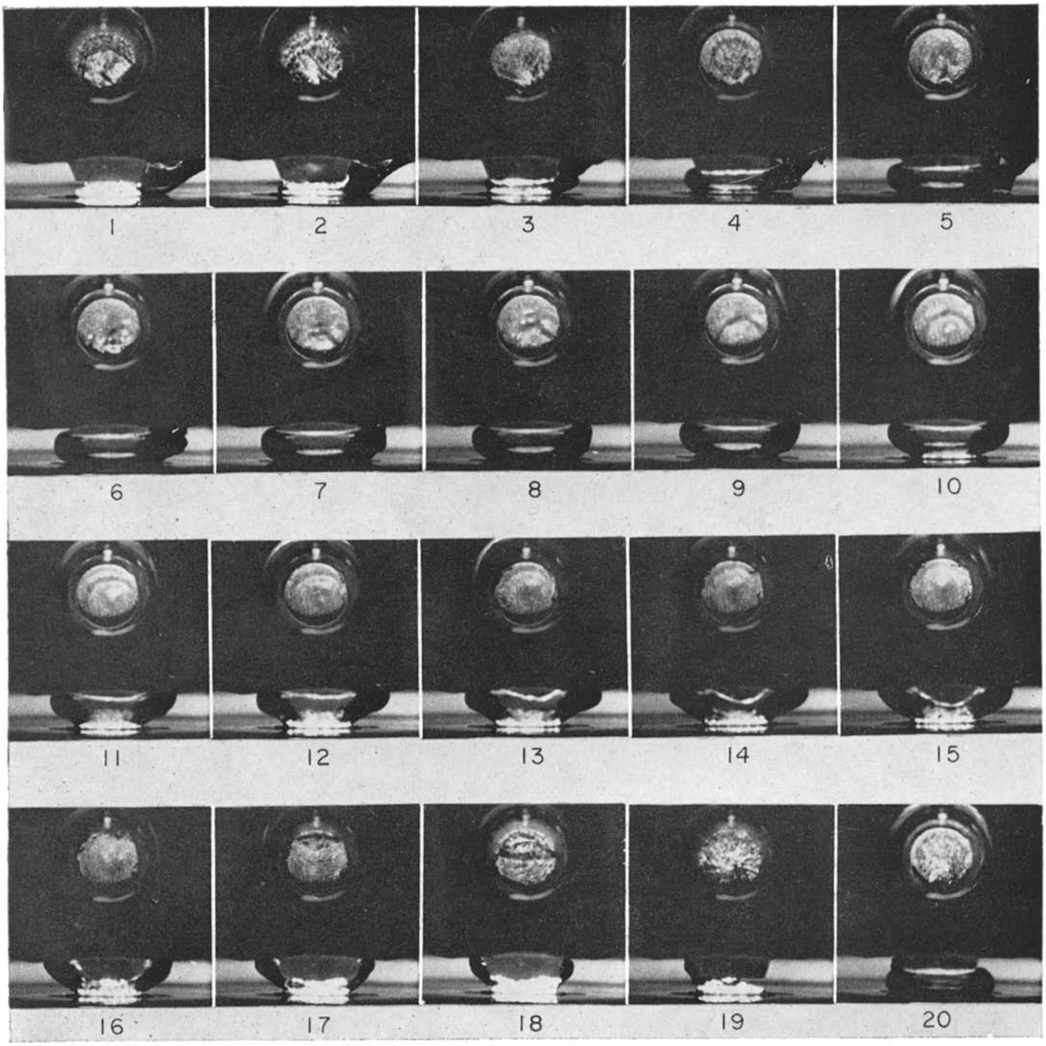

Fig. 10. Transition boiling with optical assembly (s = 2 mm, interval = 5·4 msec). Since a liquid film is built up on the lower surface of glass plate also, meaningless waves are sometimes observed. Due to heat capacity of copper block, quasi-steady transition boiling can be observed.

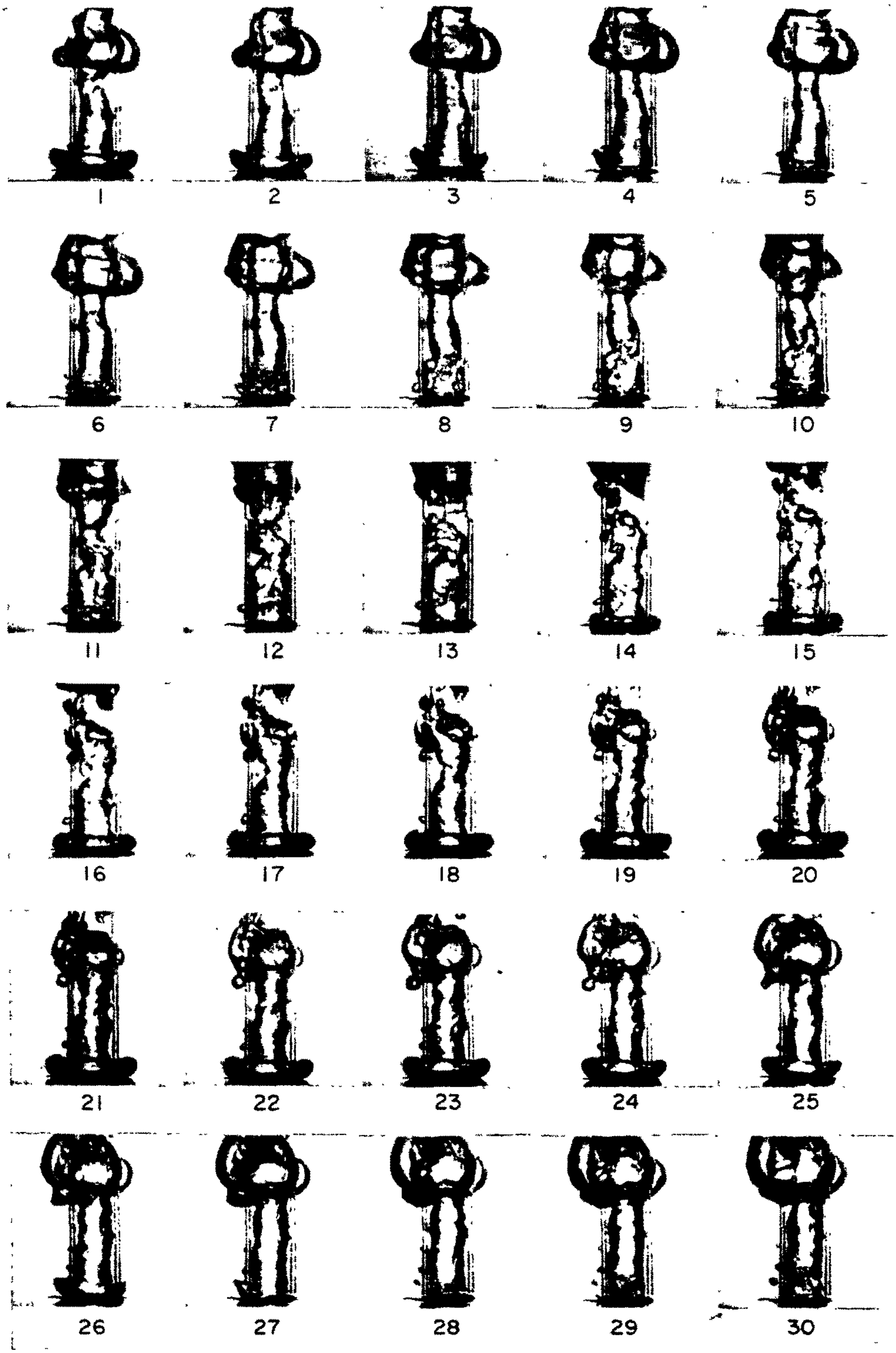

FIG. 11. Successive states of vapor mass in nucleate boiling with tube ($H = 20$ mm, $s = 2$ mm, $q = 1{\cdot}69 \times 10^6$ kcal/m^{2}h, interval $= 1{\cdot}9$ msec).

the surroundings. Since this pressure is exerted on the heated surface too, it is almost certain that during the growth period of a vapor mass, liquid cannot be supplied from the surroundings to the heated surface. If so, it is presumed that the supplying of liquid to the heated surface is performed only when the vapor mass detaches from the heated surface, and that thereafter a new vapor mass grows consuming the liquid film thus built up.

4.2. *Boiling subject to interference of optical assembly*

The boiling, subject to interference of the optical assembly with a spacing of $s = 2$ mm, has been studied; the configuration is useful to examine the presumption described in Section 4.1. In this case, photographs were taken simultaneously from the right-hand side of the optical assembly shown in Fig. 2 as well as through the optical assembly itself, thereby not only a side view of boiling near the heated surface but also a horizontal view of the heated surface are caught simultaneously on a film.

First, Fig. 8 shows a typical example of the successive states of the fluid in the case of a heat flux lower than the peak heat flux (interval: 8·6 msec). A circular image on the upper part of each frame is a horizontal view of the heated surface which is observed through the window of the optical assembly. It is noticed that a vapor mass begins to grow on the heated surface in frame 1, and after filling the space over the heated surface, the vapor mass is expanding radially in frame 2. Since the boiling within the liquid film on the heated surface continues ever after, the vapor mass continues to expand more and more until it covers the lower portion of the optical assembly as seen in the frames after frame 7. However, when time has elapsed up to frames 13 and 14, the vapor mass begins a very rapid escape originating an inflow of liquid into the space over the heated surface. Then, reproducing the initial state in frame 15, the same cyclic process as before is repeated.

In the case of Fig. 8, a liquid film remains on the heated surface during the whole period of a cycle. However, if the temperature of the heated surface becomes higher approaching the point of peak heat flux, dry spots sometimes appear and grow on the heated surface near the end of each cycle. This is the consequence of the consumption of liquid film. Since the initial thickness of a liquid film as well as the anchorage period of a vapor mass vary to some extent from cycle to cycle, dry spots appear inevitably near the end of those cycles which happen to have more severe conditions. As an example, Fig. 9, which was obtained at a heat flux close to the peak heat flux, shows several dry areas as well as many dry spots on the heated surface. It should be mentioned with respect to the situations described here that they are very similar to those described in the report of Kirby and Westwater referred to in Section 1.

If the temperature of the heated surface is further increased beyond the point of crisis, a situation arises such that every cycle includes a period during which the heated surface is perfectly dry as shown in Fig. 10. The interval of successive frames is now 5·4 msec and the surface temperature is 5 degC higher than that at the point of peak heat flux. Liquid is flowing into the space between the glass plate and the heated surface creating nucleate boiling in frame 1. Then the same processes as in Fig. 8 (boiling within liquid film and growth of vapor mass) are undergone up to frame 6 or its vicinity where the liquid film is consumed away. Disregarding waves which sometimes appear in a liquid film built up on the lower surface of the glass plate of the optical assembly, and which can be seen in some of the frames, it is noticed that perfect dryness of the heated surface as well as no growth of the vapor mass continue afterwards. In frames 13 to 17, however, an escape of the vapor mass occurs introducing liquid into the space above the heated surface, and the initial state is reproduced in frame 18. Comparing the growth of a vapor mass in Fig. 10 with that in Fig. 8, it may be noticed that the amount of vapor produced during one cycle is obviously less in Fig. 10 than in Fig. 8. This presumably suggests that the liquid film built up on the heated surface becomes thinner as the temperature of the heated surface is increased.

4.3. *Boiling subject to interference of short tube*

The situation in the case of boiling subject to the interference of a short tube is the same in principle as in the preceding cases. As an example, Fig. 11 shows a result obtained under conditions of $H = 20$ mm, $s = 0{\cdot}8$ mm and $q = 1{\cdot}69 \times 10^6$ kcal/m^{2}h (interval: 1·9 msec). It may be of interest to notice an unforeseen fact that a part of vapor mass protrudes radially through the circumferential narrow opening between the tube and the heated surface as shown in frames 14 to 24. The protrudent part of vapor mass is, however, inhaled finally into the tube when the vapor mass begins to escape and ascend as shown in frames 25 to 27. At the same time, liquid is supplied to the heated surface through the narrow opening following the rapid retreat of vapor. Notice the splash of liquid on the heated surface in frame 28.

5. MECHANISM OF POOL BOILING CRISIS

The observational results reported in the preceding section have already suggested that the point of peak heat flux is a point at which the average life of liquid films on the heated surface coincides with the average detachment period of vapor masses. According to Sections 3 and 4, it may be assumed that the rate of consumption of the liquid film is in proportion to the heat flux, and that the initial thickness of the liquid film decreases with the heat flux. On the other hand, the detachment period of vapor mass is generally finite. Particularly, it should be noted that the detachment period has been found to change very little with the heat flux for the region of nucleate boiling at high heat fluxes investigated in the present study. Consequently, as the heat flux is increased, a transition point must inevitably occur.

Now let us examine the mechanism of boiling crisis quantitatively. If a liquid film is formed with an initial thickness δ_0 on a heated surface of area A_w subject to a high heat flux q, the life of the film, t, is determined as follows:

$$t = \frac{\rho_l \delta_0 (A_w - A_w') H_{fg}}{q A_w} \tag{2}$$

where ρ_l is the density of liquid, A_w' the total sectional area of vapor stems within the film, and H_{fg} the latent heat of evaporation. A_w'/A_w and δ_0 in equation (2) should be known in order to estimate t. According to the experiments of Gaertner and Westwater [11] of water boiling on a copper surface, the following approximate relation holds independently of q at high heat fluxes:

$$A_w'/A_w = 1/9. \tag{3}$$

As to δ_0, it is reasonable to use equation (1) obtained from the side-view photographs of boiling. Since the circumference of the heated surface is always exposed to the surrounding liquid, δ in equation (1) gives a value rather close to the initial thickness of the liquid film.

Substituting equations (1) and (3) into equation (2) and determining D in equation (1) from the curve in Fig. 6, the life of the liquid film, t, is calculated as a function of q to give the thick solid curve in Fig. 12.

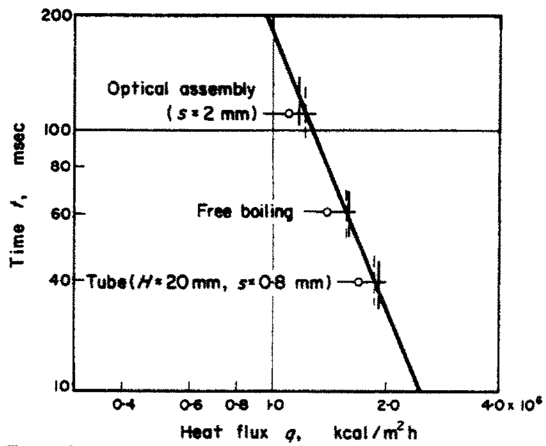

FIG. 12. Comparison of analytical peak heat flux data (indicated by broken vertical lines) with experimental results (indicated by solid vertical lines). Case of optical assembly has a detachment-period about three times greater than case of tube.

Experimental results of average detachment period, t, obtained at a heat flux, q, in the vicinity of boiling crisis are indicated by circles in Fig. 12 for three different kinds of boiling. Then the analytical peak heat fluxes which correspond to these detachment periods respectively should be determined at the positions of the vertical broken lines in Fig. 12. For comparison, the experimental heat fluxes obtained corresponding in the same experiments as above are also shown by the vertical solid lines in Fig. 12. It may be noticed that the agreement between the analytical and experimental results is rather good.

6. DISCUSSION

6.1. *Various features of pool boiling crisis*

The mechanism of boiling crisis which has been revealed in the present paper enable us to explain various features of pool boiling crisis in a unified manner.

Agitation of fluid increases the peak heat flux through the reduction of the period of vapor anchorage. If liquid is supplied by any means to the liquid film lying under a vapor mass, the peak heat flux is increased.

If the period of anchorage of vapor mass is increased, the peak heat flux is reduced. This has already been shown experimentally by a blocking surface attached to a heated surface facing downward in the study of Ishigai *et al.* [12] as well as by the optical assembly in the present study. When for some reason the supply of liquid to the heated surface is obstructed, stable formation of liquid film on the surface is disturbed, reducing the peak heat flux.

Due to scattering of the initial thickness of the liquid film, the detachment period of the vapor mass, and other causes, dry spots and areas sometimes appear on the heated surface in the neighborhood of boiling crisis. Consequently, the temperature of the heated surface fluctuates, to some extent, when the surface is heated at a constant heat flux.

6.2. *Relation to customary theories*

It is an unobjectionable fact that if normal systems of boiling alone are considered, current theories have succeeded considerably in correlating the experimental results of peak heat flux; Kutateladze's correlation, for example, is written as follows:

$$\frac{q_c}{H_{fg}\rho_v}\Bigg/\sqrt[4]{\left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right]} = \text{const.} \qquad (4)$$

where q_c is the peak heat flux, H_{fg} the latent heat of evaporation, σ the surface tension, g the gravitational acceleration, ρ_v the density of vapor, and ρ_l the density of the liquid. The constant value in the right-hand side of equation (4) is determined experimentally.

Time is not included in equation (4), whereas time has been introduced as an important factor in the present study. In spite of this discrepancy of quality, however, a result similar to equation (4) could be derived easily from the theory of the present paper at least for normal systems of boiling. The range of experiment, though, is so limited in the present study that a general, positive verification is impossible, but it may not be useless to mention the following analysis.

According to the present study, it seems likely that two kinds of vapor velocities play particularly important roles in the physics of boiling crisis, namely the ejection velocity and the escape velocity of vapor from the heated surface. The former is obviously $q/H_{fg}\rho_v$, and the latter is tentatively assumed to be in proportion to $\sqrt[4]{[\sigma g(\rho_l - \rho_v)/\rho_l^2]}$ from an analogy with the rising velocity of bubbles in a liquid. Then, taking account of dimensions, the initial thickness of liquid film, δ_0, and the detachment period of vapor mass, t, may be written respectively as follows:

$$\delta_0 = \text{const.} \times l \left\{\frac{\sqrt[4]{[\sigma g(\rho_l - \rho_v)/\rho_l^2]}}{q/H_{fg}\rho_v}\right\}^{1\cdot 5} \qquad (5)$$

$$t = \text{const.} \times \frac{l}{\sqrt[4]{[\sigma g(\rho_l - \rho_v)/\rho_l^2]}} \qquad (6)$$

where l represents a term which has the dimension of length. The index of 1·5 in the right-hand side of equation (5) has been determined so as to satisfy the relation between δ_0 and q given by equation (1) and the curve in Fig. 6. Substituting equations (5) and (6) into equation (2) and replacing q by q_c, yields

$$\frac{q_c}{H_{fg}\rho_v} \Bigg/ \sqrt[4]{\left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right]} = \text{const.} \left(1 - \frac{A'_w}{A_w}\right)^{0\cdot 4} \left(\frac{\rho_v}{\rho_l}\right)^{0\cdot 1}. \quad (7)$$

In the right-hand side of equation (7), $1 - (A'_w/A_w)$ may be regarded as almost unity, and the variation of $(\rho_v/\rho_l)^{0\cdot 1}$ is comparatively small; in other words, equation (7) is akin to equation (4).

6.3. *Transition boiling*

In connection with the mechanism of boiling crisis, the transition boiling will be touched. As stated in Section 4, if the temperature of the heated surface is increased beyond the point of boiling crisis, every cycle includes a period of perfectly dry surface. Consequently, the temperature of the heated surface fluctuates considerably in the transition boiling except in the case of surface temperature kept exactly constant. In addition, a very rapid growth of a vapor mass is followed by a period during which the vapor mass ceases to grow, making the explosive expansion of vapor in the initial stage conspicuous. Therefore, some aspects of the behavior of liquid and vapor presumably become different from those in the nucleate boiling region. Furthermore, the properties of the heated surface such as dirtiness and wettability may become particularly influential in the transition boiling because liquid must be supplied to the perfectly dry surface at the end of every cycle. It should be kept in mind that the heated surface is substantially wet in the nucleate boiling region.

In relation to the above observations, it may be worth while mentioning the following analysis of transition boiling. Figure 13 shows the experimental results of boiling of water at atmospheric pressure on a copper surface obtained by Ishigai *et al.* [13], and the thick solid line represents the region of nucleate boiling. Now, for simplicity, three assumptions will be adopted for the transition boiling region: (i) the detachment period of the vapor mass is kept at the same magnitude as that at the point of peak heat flux, (ii) the boiling within the liquid film has the same characteristics as in the region of nucleate boiling, and the extension of the nucleate boiling curve is permitted as shown by the broken line in Fig. 13, and (iii) the heat transfer during the period of perfectly dry surface is negligibly small. Then, if the heat flux to the liquid film is represented by q and the initial thickness of the liquid film by $\delta_0(q)$, equation (2) yields the life of the liquid film, t, as follows:

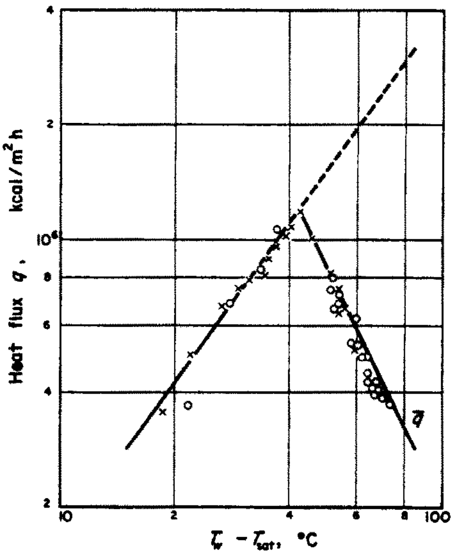

FIG. 13. Heat flux vs. temperature of heated surface in pool boiling of water. Data indicated by circles and crosses from Ishigai *et al.* [14].

$$t = \frac{\rho_l \delta_0(q)(A_w - A'_w) H_{fg}}{q A_w}. \quad (8)$$

Similarly, at the point of peak heat flux,

$$t_c = \frac{\rho_l \delta_0(q_c)(A_w - A'_w) H_{fg}}{q_c A_w} \quad (9)$$

where q_c is the peak heat flux. According to the assumption (i), t_c is equal to the detachment period of the vapor mass in transition boiling. Then, taking the assumption (iii) into account, the average heat flux, $\bar{q}$, for one cycle is deduced to be $\bar{q} = q \times (t/t_c)$; and the substitution of equations (8) and (9) immediately gives

$$\bar{q} = q_c \cdot \frac{\delta_0(q)}{\delta_0(q_c)}. \tag{10}$$

Now, q_c is determined at the point of peak heat flux, and q by the broken line in Fig. 13. $\delta_0(q)$ and $\delta_0(q_c)$ are determined by equation (1) and the curve in Fig. 6. The average heat flux, $\bar{q}$, thus calculated is shown in Fig. 13 as a function of the temperature of the heated surface, and it may be noticed that the agreement with the experimental results is rather good.

Of course, the present analysis has been made with bold simplifications of the phenomenon so that such a correspondence with the experimental results as aforementioned should not be regarded as universally obtainable. However, even if such ambiguities exist, the principal nature of the transition boiling described here is presumed not far from the truth. It may be of interest to mention that the mechanism of transition boiling presumed qualitatively by Ishigai and Kuno [15] from the fluctuation of the temperature of the heated surface agrees well with that in the present study.

7. CONCLUSIONS

(1) Experimental and analytical studies have been carried out in the present study adopting three special configurations of boiling presumed to be particularly effective to attack the mechanism of pool boiling crisis.

(2) Boiling crisis in pool boiling is a phenomenon connected with a balance between the consumption of the liquid film on the heated surface and the supplying of liquid through the intermittent removal of vapor masses.

(3) Physical models upon which existing theories of boiling crisis are based are questionable. However, so far as their final results are concerned, there is a possibility for them to be derived as special cases from the mechanism of boiling crisis revealed in the present paper.

(4) Transition from nucleate to transition boiling does not arise from a perfect metamorphosis of boiling. Roughly speaking, the main cause is only the appearance of a period of perfectly dry surface within every cycle. The nucleate boiling still remains intermittently in the vicinity of boiling crisis at least.

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REFERENCES

1. W. M. Rohsenow and P. Griffith, Correlation of maximum heat transfer data for boiling of saturated liquids, *Chem. Engng Prog. Symp. Ser.* **52**(18), 47 (1956).
2. Y. P. Chang and N. W. Snyder, Heat transfer in saturated boiling, *Chem. Engng Prog. Symp. Ser.* **56**(30), 25 (1960).
3. S. S. Kutateladze, A hydrodynamic model of the critical heat transfer in boiling liquids with free convection, *Zh. Tekh. Fiz.* **20**(11), 1389 (1950).
4. Y. P. Chang and N. W. Snyder, Heat transfer in saturated boiling, *Chem. Engng Prog. Symp. Ser.* **56** (30), 25 (1960).
5. N. Zuber, M. Tribus and J. W. Westwater, The hydrodynamic crisis in pool boiling of saturated and subcooled liquids, in *International Developments in Heat Transfer*, p. 230 Am. Soc. Mech. Engrs, New York (1961).
6. K. Torikai, Burnout in pool boiling, in *Boiling Heat Transfer*, p. 183. Japan Soc. Mech. Engrs, Tokyo (1965).
7. K. Torikai and T. Yamazaki, The contact area of boiling bubbles on the heating surface, *Bull.* J.S.M.E. **8**, 660 (1965).
8. D. B. Kirby and J. W. Westwater, Bubble and vapor behavior on a heated horizontal plate during pool boiling near burnout, *Chem. Engng Prog. Symp. Ser.* **61**(57), 238 (1965).
9. C. P. Costello and W. J. Frea, A salient nonhydrodynamic effect on pool boiling burnout of small semicylindrical heaters, *Chem. Engng Prog. Symp. Ser.* **61**(57), 258 (1965).
10. Y. Katto and S. Yokoya, Experimental study of nucleate pool boiling in case of making interference-plate approach to the heating surface, in *Proceedings of the Third International Heat Transfer Conference*, p. 219. Am. Inst. Chem. Engrs, New York (1966).
11. R. F. Gaertner and J. W. Westwater, Population of active sites in nucleate boiling heat transfer, *Chem. Engng Prog. Symp. Ser.* **46**(30), 39 (1960).
12. R. F. Gaertner, Photographic study of nucleate pool boiling on a horizontal surface, *J. Heat Transfer* **87**, 17 (1965).

13. S. Ishigai, K. Inoue, Z. Kiwaki and T. Inai, Boiling heat transfer from a flat surface facing downward, in *International Developments in Heat Transfer*, p. 224. Am. Soc. Mech. Engrs. New York (1961).
14. S. Ishigai, K. Inoue and T. Kuno, Transition boiling on the vertical wall in an open vessel, Paper No. 27, JSME Heat and Thermodynamics Conference (September 1963).
15. S. Ishigai and T. Kuno, An experimental study of transition boiling on the vertical wall in an open vessel, *Trans. Japan Soc. Mech. Engrs* **31**, 1251 (1965).

Résumé—On a effectué des expériences d'ébullition saturée en réservoir de l'eau à des flux de chaleur élevées et des observations des phénomènes qui s'y rapportent à l'aide de la photographie à grande vitesse afin de clarifier le mécanisme de la crise de l'ébullition en réservoir. Trois configurations de l'ébullition sur une surface de cuivre horizontale de 10 mm de diamètre sont étudiées, c'est-à-dire l'ébullition libre normale sur la surface chauffée et les cas soumis à l'interference d'une plaque plane ou d'un tube court tenu au-dessus de la surface chauffée.

Le mécanisme de la crise de l'ébullition en réservoir est alors claifié non seulement à travers l'observation qualitative des comportements de fluide mais aussi à travers l'analyse quantitative qui est basée seulement sur des faits expérimentaux. En résumant les résultats, on en conclut que la crise de l'ébullition en réservoir est un phénomène relié aux comportements intermittents de masses de vapeur aussi bien qu'à la disparition des films liquides qui se forment sur la surface chauffée.

De plus, les théories habituelles de la crise de l'ébullition et de l'ébullition de transition sont discutées également en relation avec le mécanisme de la crise de l'ébullition révélé dans l'étude actuelle.

Zusammenfassung—Es wurden Versuche über Behältersieden von Wasser bei Sättigung und hohen Wärmestromdichten durchgeführt und die zugehörigen Erscheinungen mit Hilfe von Hochgeschwindigkeitsphotographie beobachtet, um den Mechanismus der Krisis beim Behältersieden zu klären: Beim Sieden an einer horizontalen Kupferfläche von 10 mm Durchmesser wurden drei Anordnungen untersucht: gewöhnliches freies Sieden an der Heizfläche und die Fälle, dass Störungen dadurch auftraten, dass entweder eine ebene Platte oder ein kurzes Rohr über die Heizfläche gehalten wurden.

Der Mechanismus der Krisis von Behältersieden wird dann nicht nur durch qualitative Beobachtung des Flüssigkeitsverhaltens erklärt, sondern auch durch eine quantitative Analyse, die allein auf experimentellen Ergebnissen beruht. Aus den Ergebnissen wird geschlossen, dass die Krisis beim Behältersieden eine Erscheinung ist, die ebenso mit dem intermittierenden Verhalten der Dampfmassen zusammenhängt wie mit dem Verschwinden der Flüssigkeitsfilme, die sich an der Heizfläche aufbauen.

Аннотация—Проведено экспериментальное исслование кипения воды при температуре насыщения в большом объеме при больших тепловых потоках и связанных с ним явлений путем исиользования высокоскоростной съемки с целью объяснения механизма кризиса кипения в большом объеме. Изучались три конфигурации кипения на горизонтальной медной поверхности диаметром 10м, включая обычное свободное кипение на нагретой поверхности, а также случаи, отноящеся к интерференции или плоской пластины или короткой трубки, расположенной над нагретой поверхностью.

Механизм кризиса кипения в большом боъеме объясняется не только качественным наблюдением за поведением жидкости, но также с помощью количественного анализа, основанного только на экспериментальных фактах. Суммируя результаты можно сделать вывод, что кризис кипения в большом объеме представляет собои явление, связанное с неустойчивостью паровых образований и жидких пленок, возникающих на нагретой поверхности.

Далее, обсуждаются известные теории кризиса кипения и переходного кипения в связи с механизмом кризиса кипения, которыи выявлен в данном исследовании.