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BURNOUT IN POOL BOILING THE STABILITY OF BOILING MECHANISMS

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Abstract—In pool boiling, when the burnout heat flux is approached, a large number of areas are observed where the heating surface is dry for short intervals. The mechanism of formation of these dry areas is different for atmosphere and low-pressure conditions. The majority of dry areas do not lead to burnout. but the odd one is suddenly fatal when it grows to cover the entire heating surface. This suddenly different behaviour can be explained qualitatively by considering the conduction of heat along the heating surface, for which a modified interpretation of the boiling curve must be used. A critical size is found beyond which dry areas keep growing. The stability properties of both nucleate and film boiling are found to depend on the imposed heat flux and explain the familiar form of the boiling curve.

NOMENCLATURE

A, strength of heat source [W];
q, heat generation per unit surface area [$W m^{-2}$];
q_0, q_1, q_2, special values explained in text [$W m^{-2}$];
T_0, saturation temperature [K];
T, local wire temperature [K];
$\bar{T}$, average wire temperature [K];
T_c, maximum liquid contact temperature [K];
T_c^*, Leidenfrost temperature [K];
a, heat diffusivity [$m^2 s^{-1}$];
x, coordinate [m];
t, time [s];
r, wire radius [m];
h, heat transfer coefficient [$W m^{-2} K^{-1}$];
s_f, half length of dry area [m];
s_n, half length of wetted area [m];
d, plate thickness [m];
Φ, local heat flux [$W m^{-2}$];
$\bar{\Phi}$, average heat flux [$W m^{-2}$];
$\bar{\Phi}_b$, burnout heat flux [$W m^{-2}$];
λ, heat conductivity [$W m^{-1} K^{-1}$];
ρ, density [$kg m^{-3}$];
c, specific heat [$J kg^{-1} K^{-1}$].

Subscripts n and f relate to nucleate and film boiling, s and l to solid and liquid.

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1. INTRODUCTION

THE HEAT flux from a solid surface to a liquid is limited by a phenomenon called burnout. Above a certain heat flux a vapour film is formed which covers the heating surface and acts as an insulating layer. As a result burnout may occur: the temperature of the heating surface then increases to excessive values, giving rise to damage to the heating surface.

A connection between burnout and the occurrence locally of dry areas on the heating surface has been observed by Kirby and Westwater [1] and by Gaertner [2]. Further information on dry area behaviour has now been obtained in a series of experiments which are described in this paper. It turns out that whereas some dry areas disappear some time after their creation, others will grow and thereby cause burnout.

During the growth of individual vapour bubbles dry areas of a different type occur on the heated surface. The liquid microlayer which is present under each bubble, as the experiments of Moore and Mesler [3] indicated, will evaporate completely near the centre of the bubble. Experimental evidence of this, supplementary to our own observations [4], has been advanced by Sharp [5], Torikai [6] and by Cooper and and Lloyd [7]. The connection between these dry areas and those leading to burnout will be indicated.

Dry area behaviour has been analysed in connection with burnout by Semeria and Martinet [8]. They considered the motion of a point of transition between film and nucleate boiling. Although they paid some attention to the stability of an isolated region of film boiling, they did not describe such a situation systematically and gave no explicit solution. Their interpretation of the boiling curve is essentially different from the one which is presented in section 4, even though one of their approximations to the boiling curve corresponds to our simplified mathematical model for heat transfer by two different mechanisms simultaneously. From this model we will ultimately derive the shape of the boiling curve. A relation exists between their arguments concerning dry area behaviour and some remarks on the stability of boiling regimes by Kovalev [9], which has remained unnoticed. In his paper Kovalev concludes that nucleate boiling would be unstable above an equilibrium value of the heat generation, corresponding to q_0 in this paper, while film boiling would be unstable below this value. With our different interpretation of the boiling curve to describe the heat transfer to a boiling liquid a different conclusion will be drawn here.

The boiling curve represents the relationship between average heat flux and the average superheat of the heating surface. It can be divided into three parts or regimes, nucleate boiling, transition boiling and film boiling, in the order of increasing superheat. In experiments using an imposed heat flux hysteresis between the transitions from nucleate to film boiling and back occurs, transition boiling being unstable.

Stephan [10] has succeeded in determining heat flux versus temperature curves for the part corresponding to transition boiling, but does not give a visual description of the boiling process under these conditions.

In the following, after a description of the observed behaviour of dry areas, a simple model will be developed to explain this behaviour. The arguments can then be extended to serve in a determination of the stability of boiling and the occurrence of hysteresis.

2. EXPERIMENTAL

To study experimentally the occurrence of dry areas we used a round plate. Pyrex or fused quartz, of 20 mm thickness as the bottom plate for an experimental vessel. This plate, which had a diameter of 0·2 m, carried on the surface in contact with the liquid a transparent electroconductive layer in the form of a square with sides of 90 mm, which could be heated by passing through an electric current. The conductive layer itself was a layer of gold having a thickness of 10 nm, sandwiched between two layers of bismuth oxide of 45 nm each by means of evaporation under vacuum.

The surface of the plate was finely ground with amaryl 302 before the layer was applied to allow the detection of dry areas on the surface of the plate during boiling. As the refractive indices of the plate and the liquids under investigation are practically equal, the grain on the surface is invisible at places where the liquid is in contact with it, but shows where the surface is dry.

A glass prism was placed against the outer surface of the glass plate; see Fig. 1. The presence of some glycerol ensured optical contact between plate and prism.

A thin film of liquid, which is present on the surface of the plate covered by the electroconductive layer and extends over an areas with dimensions large compared with its thickness, has its vapour–liquid interface practically parallel to that surface. Diffuse light which enters this film from the vapour is confined to a cone by the "reversed" effect of total reflection. As the refractive indices of liquid, plate and prism are practically equal, the light is confined to the same cone in the prism. When in the case of visual or photographic observation through a slanted face of the prism, the line of observation is outside this cone, the area on the glass plate covered by the liquid film will be observed as a dark area. Fig. 1 illustrates this situation.

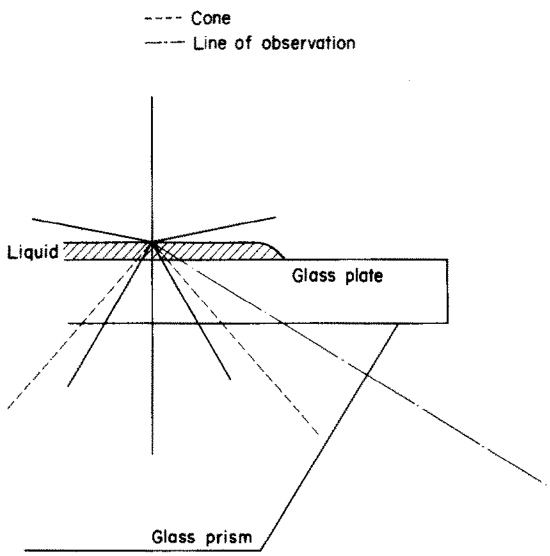

FIG. 1. Reversed effect of total reflection.

This effect, together with the use of a ground surface, enabled us to observe the liquid microlayer and the dry area at its centre under a vapour bubble growing at low pressure. In the study of the burnout phenomenon the presence of large vapour masses near the heated surface and the occurrence of dry areas on it could thus also be detected.

Torikai *et al.* [11] reported a similar experimental arrangement. Although the two experiments were set up independently, the basic ideas behind them are clearly the same, differences appearing in details only, such as the light path chosen and the technique of preparation of the electroconductive layer. Kirby and Westwater [1] also used a glass heating surface, but without optical refinements.

For observation we used a Hitachi high-speed camera, in most cases running at a speed of 4000 frames per s. Timing marks at 0·02 s intervals were made on the edge of the films by a stroboscopic lamp inside the camera synchronized to 50 Hz electricity mains frequency. The optical technique used for the observations made interpretation of the films quite simple.

The three layers, bismuth oxide, gold, bismuth oxide, were also deposited on polished glass surfaces. Their uniform colour in reflected light indicated that the total film thickness was constant within 5 nm. The evaporation technique results in the gold film thickness being a constant fraction of the total, and therefore constant within 0·6 nm. The position where dry areas occurred was governed entirely by the geometry of the flow set up in the liquid by the rising vapour bubbles. Only when a film had been in use for several weeks did we observe that burnout occurred more frequently at some preferred locations. The heating surface was then replaced·

3. OBSERVATION OF DRY AREAS AND BURNOUT

With the equipment described above we have determined the maximum or burnout heat flux of n-heptane boiling at various pressures. The boiling vessel always contained an amount of liquid corresponding to a clear liquid depth of 50 mm. The electrical heat input was increased slowly until a stationary dry area on the heating surface was detected visually, and then switched off again. The maximum heat input was read from a recorder. At each pressure five values were obtained and averaged. A spread of about 10 per cent between the individual values was normal.

The average values have been plotted against pressure in Fig. 2. A change in the slope of the resulting curve occurs at a pressure of 33·3 kN/m^2.

High-speed films made through the transparent heating surface at 20 kN/m^2 and at atmospheric pressure show a markedly different behaviour of the boiling liquid at the two pressures; see Figs. 3a and 3b. In both cases dry areas are observed at heat flux values as low as approximately 20 per cent below the burnout value.

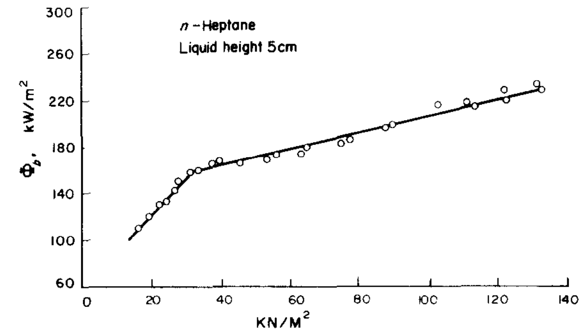

FIG. 2. Burnout heat flux as a function of pressure.

At atmospheric pressure the dry areas are created by a rather complicated sequence of events. When large numbers of vapour bubbles coalesce near the heating surface at some point they form a large cloud of vapour hovering near the surface. In a thin layer of liquid which is present on the heating surface under the cloud new bubbles nucleate and coalesce with it. From the small dry area which occurs under each of these bubbles a tiny dry spot remains in the liquid film under the cloud of vapour. Evaporation of the liquid film causes these dry spots to grow and to merge with neighbouring ones to form much larger dry areas. Normally the solid is wetted again when the increase in buoyancy with size removes the vapour cloud from the vicinity of the heating surface and liquid rushes in. When the heat flux is sufficiently large, suddenly at some point on the heating surface a dry area is not wetted and starts growing, leading to burnout. Even while this occurs the process of formation and disappearance of dry areas continues at other points on the heating surface.

At 20 kN/m^2 the creation of dry areas follows a simpler pattern. Individual bubbles grow to immense sizes, and so do the dry areas in their microlayer. Sometimes the size of such a dry area is further increased when it merges with that of a second bubble growing from the microlayer within the first. The large dry areas disappear when the bubbles rise from the heated surface. Again, when the heat flux is large enough, suddenly some dry area will not disappear and start growing.

Figure 3a shows some regions where the thin layer of liquid under a vapour cloud is present, at atmospheric pressure, with the small dry areas growing and merging. The black dots form a square grid at 10 mm intervals. Figure 3b shows the large dry areas under individual bubbles, typical of the low-pressure case. Both forms can be observed in Fig. 3c, at a pressure of 33·3 kN/m^2. At this pressure the slope of the burnout heat flux vs. pressure curve of Fig. 2 changes. Unavoidably, still pictures only partly convey the information afforded by the high-speed films.

Surprisingly we found upon analysis of the high-speed films that the maximum size and lifetime of dry areas did not change significantly when the heat flux was varied from 80 to 100 per cent of the burnout value. The frequency of their occurrence did change, however.

Both the direct observation of the onset of burnout and the fact that the change in slope of the curve of Fig. 2 can be closely related to the change in mechanism of dry area formation prove that the dry areas are of vital importance for the occurrence of burnout. On the other hand, the occurrence of dry areas of a certain size and lifetime is not sufficient in itself to cause burnout, this only being brought about by some dry area satisfying as yet unknown conditions. In the following it will be shown that there is a critical condition which governs dry area behaviour and is also the cause of the familiar hysteresis between nucleate and film boiling.

4. DRY AREAS ON A WIRE

Before returning to the phenomena observed on a flat plate we will first discuss the slightly simpler situation of boiling on a long wire, heated electrically.

When such a wire is partly removed from the

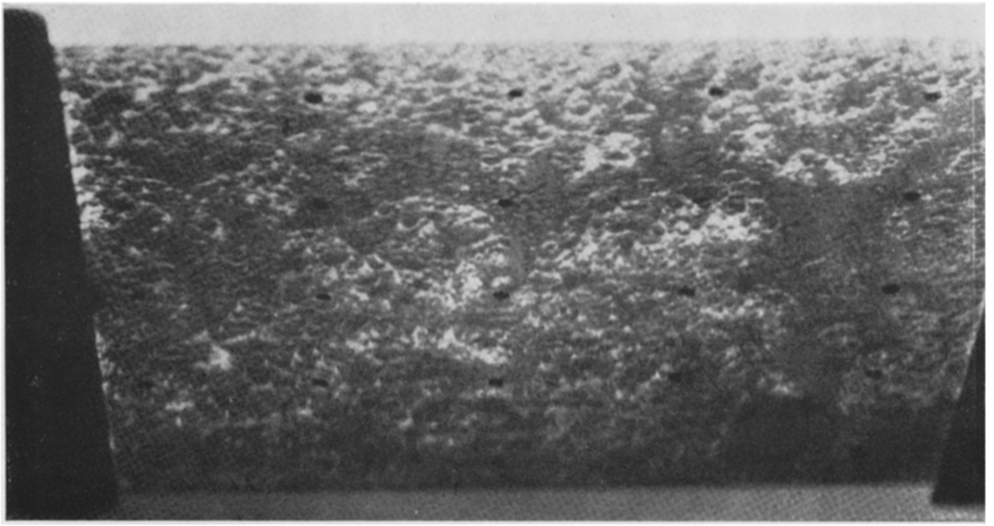

FIG. 3a. Dry areas on the heated surface. Atmospheric pressure: 101·2 kN/m^2.

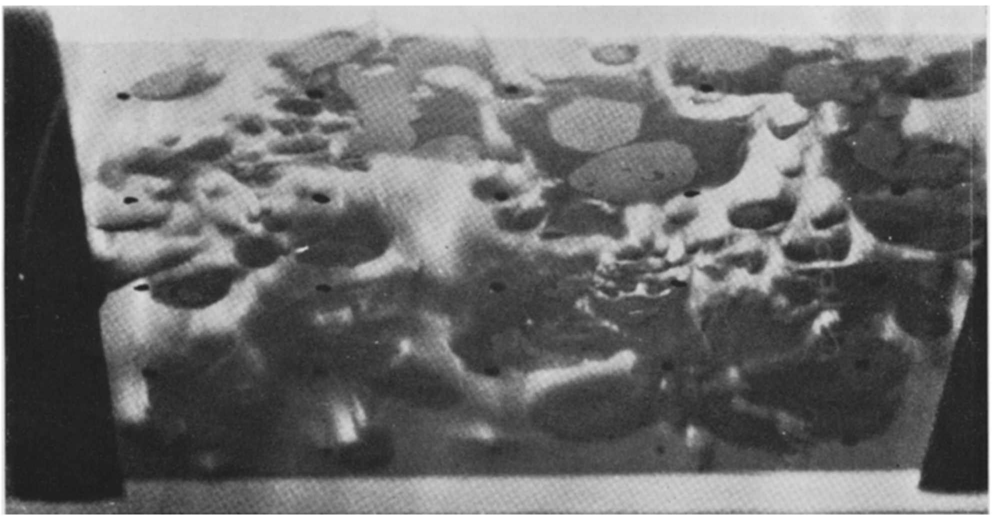

FIG. 3b. Dry areas on the heated surface. Low pressure: 20 kN/m^2.

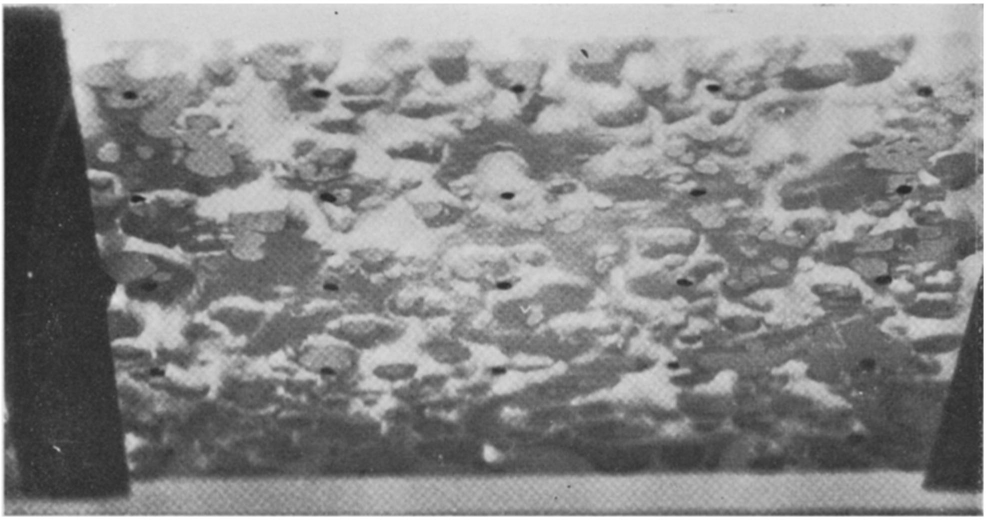

FIG. 3c. Dry areas on the heated surface. Intermediate pressure: 33·3 kN/m².

liquid for a few seconds, the non-immersed part will heat up. When it is entirely submerged again, two different kinds of boiling can be observed, nucleate and film boiling, the second form being introduced by the manipulation described. The point of transition between the regions of nucleate and film boiling either moves at a constant velocity or is stationary. There is no rapid motion back and forth, as was shown by a high-speed film. Similar results were obtained by Semeria and Martinet [8]. They interpreted this situation by assuming that the wire temperature T_c at the point of transition is constant under given experimental conditions. The function describing heat transfer is assumed to be as shown in Fig. 4 (for simplicity the heat transfer coefficients h_n and h_f have been taken constant). We want to emphasize that this relationship for both boiling mechanisms is between heat flux Φ and wire temperature T, each averaged over an area and time interval larger than bubble dimensions and lifetimes in order to smooth out fluctuations. On the other hand the familiar boiling curve is defined as the relationship between $\overline{\Phi}$ and $\overline{T}$, both averaged over the entire heat transfer surface for stationary conditions. This curve has a negative slope for certain values of the temperature.

The temperature T_c is by definition the maximum solid temperature at which nucleate boiling can occur, that is the maximum temperature at which contact can exist between hot solid and liquid. This temperature can be tentatively related to the Leidenfrost temperature T_c^*, by requiring that a solid at temperature T_c^* is cooled to T_c instantaneously upon contact with the liquid at the saturation temperature T_0. Then T_c^* is the maximum temperature at which such contact can be established.

$$(T_c^* - T_0)/(T_c - T_0) = 1 + (\lambda_l \rho_l c_l / \lambda_s \rho_s c_s)^{\frac{1}{2}}. \quad (1)$$

Butler *et al.* [12] also consider such a relationship between T_c and T_c^* as a realistic approximation.

Assuming T_c to be constant and heat transfer as in Fig. 4 Semeria and Martinet [8] calculated the constant velocity of the transition point and compared this with experiment. For the transition point to be at rest they found that the heat generation q per unit surface area must be:

$$q = q_0 = (h_f h_n)^{\frac{1}{2}}(T_c - T_0). \quad (2)$$

When film boiling occurs over a short length of wire $2s_f$ only, two points of transition are

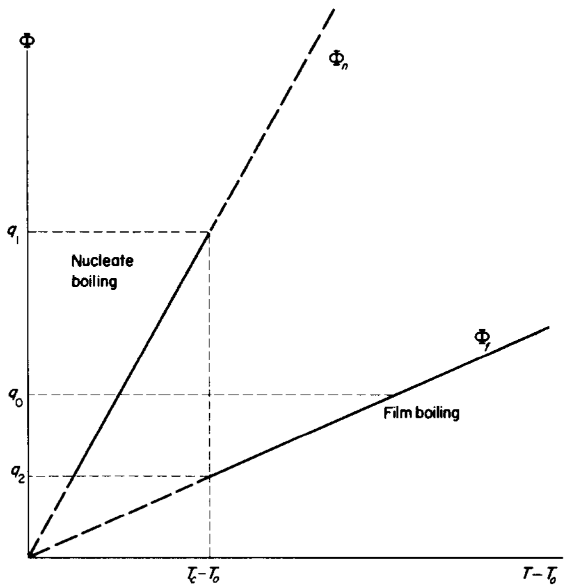

FIG. 4. Local rate of heat transfer as a function of local superheat for both nucleate and film boiling.

present. For such a dry region a critical size $2s_f^*$ can be found at which it is in equilibrium for a given q larger than q_0. As shown in the appendix q and s_f^* are related by:

$$\frac{h_f^{\frac{1}{2}}(T_c - T_0 - q/h_f)}{h_n^{\frac{1}{2}}(T_c - T_0 - q/h_n)} = -\left[\tanh\{(2h_f/\lambda_s r)^{\frac{1}{2}} s_f^*\}\right]^{-1}. \quad (3)$$

This equilibrium is unstable, a dry region larger than $2s_f^*$ will grow, a smaller one disappear. Heat generated in the region of film boiling cannot entirely be given off to the liquid directly, but must be conducted to the regions of nucleate boiling. The amount of heat which should be removed increases with increasing dry area size, the amount which can be removed is constant. The excess heats the wire, extending the dry region. The instability of the equilibrium is demonstrated in a more formal way in the appendix.

Note that the length of a dry region corresponding to unstable equilibrium decreases with increasing q.

$$s_f^* = \infty \quad \text{when} \quad q = q_0$$

$$s_f^* = 0 \quad \text{when} \quad q = q_1 = h_n(T_c - T_0)$$

Only when $q_0 < q < q_1$ can an equilibrium size be found for an isolated dry region. For a circular dry area of radius s_f^* on a thin plate of thickness d, insulated on one side, the expression corresponding to (3) is

$$\frac{h_f^{\frac{1}{2}}(T_c - T_0 - q/h_f)}{h_n^{\frac{1}{2}}(T_c - T_0 - q/h_n)} = \frac{I_0\{(h_f/\lambda_s d)^{\frac{1}{2}} s_f^*\}\, K_1\{(h_n/\lambda_s d)^{\frac{1}{2}} s_f^*\}}{I_1\{(h_f/\lambda_s d)^{\frac{1}{2}} s_f^*\}\, K_0\{(h_n/\lambda_s d)^{\frac{1}{2}} s_f^*\}} \tag{4}$$

I_n and K_n denote modified Bessel functions of the first and second kind of order n.

Our experiments showed that dry areas on the heating surface are created during boiling, by one of two mechanisms of which we can give a "verbal" description but which we do not yet understand entirely. The average sizes and lifetimes of these dry areas depend hardly on the heat flux applied. When the vapour cloud shielding a dry area leaves the heating surface, this will be wetted where its temperature is below T_c^*. The remaining dry area will be smaller than the critical size s_f^* at low heat inputs, and therefore disappear. When the heat input is increased, however, s_f^* is reduced until it is less than the size of the largest remaining dry areas. The first dry area at which s_f^* is exceeded in this way will be the one to grow and cause transition. This confirms our experimental result that the occurrence of dry areas in itself is not sufficient to cause transition, this being brought about only by some dry area satisfying an additional requirement. For our experiment, at the observed "burnout" heat flux, equation (4) predicts $s_f^* = 6{\cdot}8$ mm. We estimated $T_c^* - T_0$ to be approximately 45 K (from dry area lifetime and the value of q), therefore $T_c - T_0$ is about 35 K. Observed values for dry area radius at burnout are approximately 2·5 mm.

Dry area formation at low pressures offers the best hope for description in view of the extensive knowledge about single bubbles [4, 6, 7], whereas the high pressure mechanism of formation is more complex since it involves coalescence. If dry area formation could be described, we should be in a position, with an improved analysis of dry area behaviour developed along the lines indicated in this section, to describe the transition to film boiling on the basis of observed phenomena. The thermal properties of the heating surface would then be taken into account, which is not the case with the Zuber hydrodynamic model [13].

5. HYSTERESIS BETWEEN NUCLEATE AND FILM BOILING

The discussion of dry area behaviour can serve to explain the hysteresis between nucleate and film boiling. In the case of a narrow region of nucleate boiling between regions of film boiling, by the same analysis, we find that this wetted area is in unstable equilibrium when its size $2s_n$ is equal to $2s_n^*$, related to q by

$$\frac{h_n^{\frac{1}{2}}(T_c - T_0 - q/h_n)}{h_f^{\frac{1}{2}}(T_c - T_0 - q/h_f)} = -\left[\tanh\{(2h_n/\lambda_s r)^{\frac{1}{2}} s_n^*\}\right]^{-1} \tag{5}$$

s_n^* increases with increasing q

$$s_n^* = \infty \quad \text{when} \quad q = q_0$$

$$s_n^* = 0 \quad \text{when} \quad q = q_2 = h_f(T_c - T_0).$$

Note that such an equilibrium exists for $q_2 < q < q_0$ only. Wetted regions larger than $2s_n^*$ will grow, those smaller than $2s_n^*$ will decrease in size and disappear.

These findings can be used to determine under what conditions nucleate and film boiling are stable. When $q < q_0$ nucleate boiling is stable, any dry area which is created, no matter how large, will disappear and nucleate boiling be restored. When $q_0 < q < q_1$, small dry areas will disappear, but one which is larger than the critical size will grow, spreading film boiling over the entire wire area. Nucleate boiling is metastable under these conditions, stable with respect to small perturbations but unstable to large ones. When $q > q_1$ nucleate boiling is unstable and will not occur. At $q = q_1$ already the critical size for dry areas is zero. In the same way it is found that film boiling is stable when $q > q_0$, metastable when $q_2 < q < q_0$ and unstable when $q < q_2$. This behaviour has been indicated in Fig. 5.

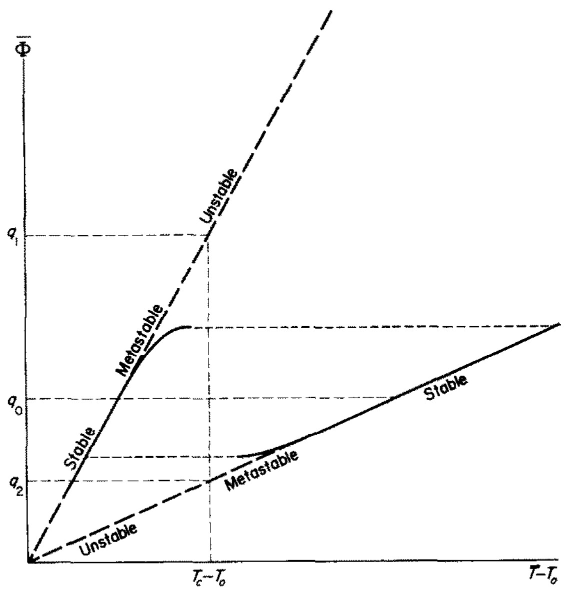

FIG. 5. Construction of boiling curve. Stability of boiling mechanisms.

Nucleate boiling occurring over the entire area of a heating surface will persist as a metastable situation when the heat flux is increased above q_0. A further increase will cause the formation of dry areas on the heated surface, according to one of the mechanisms described in section 3, to begin and become more and more prominent. At the same time it decreases the critical size $s_f{}^*$ for a dry area. Before q reaches the value q_1 some dry area will exceed the critical size and cause transition to film boiling. From the curve $\Phi_n = h_n(T - T_0)$ one branch of the boiling curve can now be constructed. The average heating surface temperature will rise slightly above the value $T = q/h_n + T_0$ owing to the intermittent presence of dry areas, before transition occurs. The branch of the boiling curve representing nucleate boiling will therefore have the form shown in Fig. 5.

When film boiling has been fully established, decreasing the heat generation q will ultimately bring about transition from film boiling to nucleate boiling, at the latest when the value q_2 is reached below which film boiling is unstable (thermally, in the sense used above). Clearly we have hysteresis between the transitions, which agrees with experience. Isolated wetted areas can come into existence intermittently at wire temperatures below T_c^*. Using similar arguments as above, now involving $s_n{}^*$, q_0 and q_2, we can now also construct the second branch of the boiling curve, indicated qualitatively in Fig. 5. (for clarity the two branches have been drawn with slopes less extreme than would be realistic). A curve having the familiar form of the boiling curve results from these arguments.

Using special arrangements where the heat flux which must be transferred to the boiling liquid can sharply decrease locally when superheat increases and vice versa, the transition cannot develop completely. A mixed form of nucleate and film boiling will occur and a curve connecting the two branches of Fig. 5 will be found. That such a curve is found is the result of the definition of the boiling curve as the relationship between the averages $\bar{\Phi}$ and $\bar{T}$.

6. CONCLUDING REMARKS

The influence of the heat conductivity of the solid surface on the value of the burnout heat flux is difficult to predict. When a highly conducting solid is compared with one of lower conductivity for a given value of q we see that:

(a) Heat accumulated in the superheated solid enhances the growth of dry areas under a a vapour cloud. This influence is stronger as the value of $(\lambda_s \rho_s c_s)^{\frac{1}{2}}$ is larger.

(b) The rise in temperature at a dry area still under a vapour cloud is less rapid.

(c) Only a small part of a dry area can be directly wetted when the vapour cloud rises because T_c* is less in view of (1).

(d) The critical size is larger in view of (3) or (4), and therefore less readily exceeded.

These are conflicting influences, (a) and (c) promoting burnout, (b) and (d) counteracting its occurrence.

The influence of the heat conductivity on the minimum film boiling heat flux can be indicated. For a highly conducting solid the value of T_c* is smaller than for a solid of lower conductivity, and for equal q the critical size of a wetted area which can grow is larger. For the transition to nucleate boiling to occur the surface temperature of the solid must be lowered to allow the liquid to come into contact with the solid, and the critical size below which wetted areas will not grow must be reduced. This can be effected by decreasing q. On a solid with a high conductivity a larger decrease will be required, and the minimum film boiling heat flux is therefore less than for a solid of lower conductivity. The results of Butler *et al.* [12] show that the minimum film boiling heat flux is higher on surfaces covered by a layer of material of low conductivity.

A further comparison with results in the literature is virtually impossible because experiments under similar hydrodynamic conditions offer the only basis for comparison, in view of the important influence of such effects. No contradictory results are known to us.

Clearly, the present treatment can only be considered as a first step towards a better understanding of the "burnout" phenomenon. We hope that the observations of the creation and behaviour of dry areas and the discussion of their role in the transition from nucleate to film boiling may provide a basis for further work.

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APPENDIX

Critical Size and Stability of a Dry Area

Consider a local dry region of film boiling on a long thin wire, heated electrically, supporting nucleate boiling. We choose the origin of the x-coordinate along the wire at the centre of the dry region and neglect temperature dfferences over the cross-section of the wire. The unstable equilibrium which we are looking for can be analysed as a stationary condition. For future use we assume the presence of hypothetical continuous point sources of heat, strength A, at the transition points. The equations and conditions are:

$$0 = \pi r^2 \lambda_s \frac{d^2T}{dx^2} + 2\pi r\{q - h_n(T - T_0)\}, \quad x > s_f \qquad (A.1)$$

$$0 = \pi r^2 \lambda_s \frac{d^2T}{dx^2} + 2\pi r\{q - h_f(T - T_0)\}, \quad 0 < x < s_f \qquad (A.2)$$

$$\frac{dT}{dx} = 0 \quad \begin{cases} \text{at } x = 0 & (A.3) \\ \text{at } x = \infty & (A.4) \end{cases}$$

$$T = T_c \quad \text{at } x = s_f \qquad (A.5)$$

$$\lambda_s\left(\frac{dT}{dx}\right) - \lambda_s\left(\frac{dT}{dx}\right) = \frac{A}{\pi r^2} \quad \text{at } x = s_f. \qquad (A.6)$$

These differential equations can also be found in the paper by Semeria and Martinet [8] but their solution is not presented there.

In actual practice $A = 0$ and the last condition then requires the temperature grandient to be continuous at the transition points, $x = s_f$. Equations (A.1)–(A.5) have the solution:

$$\frac{T - T_0 - (q/h_f)}{T_c - T_0 - (q/h_f)} = \cosh\left\{\left(\frac{2h_f}{\lambda_s r}\right)^{\frac{1}{2}} x\right\} \cosh^{-1}\left\{\left(\frac{2h_f}{\lambda_s r}\right)^{\frac{1}{2}} s_f\right\},$$
$$0 \leqslant x \leqslant s_f \qquad (A.7)$$

$$\frac{T - T_0 - /q/h_n)}{T_c - T_0 - (q/h_n)} = \exp\left\{\left(\frac{2h_n}{\lambda_s r}\right)^{\frac{1}{2}} (s_f - x)\right\}, x \geqslant s_f. \qquad (A.8)$$

From (A.6) we find that s_f must satisfy

$$\left(\frac{2h_f}{\lambda_s r}\right)^{\frac{1}{2}} \left(T_c - T_0 - \frac{q}{h_f}\right) \tanh\left\{\left(\frac{2h_f}{\lambda_s r}\right)^{\frac{1}{2}} s_f\right\} + \left(\frac{2h_n}{\lambda_s r}\right)^{\frac{1}{2}} \left(T_c - T_0 - \frac{q}{h_n}\right) = \frac{A}{\pi r^2}. \qquad (A.9)$$

Actually we have $A = 0$, then $s_f = s_f^*$, equation (A.9) reducing to (3) presented in the text.

It is easily verified that A decreases monotonously with increasing $s_f - s_f^*$. Hence $s_f - s_f^* > 0$ would require the presence of sources of negative strength to make the situation a stationary one. Actually no sources are present to take up heat, which is used instead to increase the wire temperature near the transition points, increasing s_f. Thus a dry region larger than s_f^* will grow, and similarly one smaller than s_f^* will decrease in size. The equilibrium situation $s_f = s_f^*$ is unstable with respect to changes in length of the dry region. Semeria and Martinet [8] have demonstrated instability of the equilibrium with respect to changes in q.

CALÉFACTION DANS L'ÉBULLITION EN RÉSERVOIR. LA STABILITÉ DES MÉCANISMES DE L'ÉBULLITION

Résumé—Quand le flux thermique de caléfaction est approché dans l'ébullition en réservoir un grand nombre de sites sont observés pour lesquels la surface chauffante est sèche pendant de courts intervalles de temps. Le mécanisme de formation de ces aires sèches est différent suivant que les conditions sont atmosphériques ou à basse pression. Les aires sèches ne conduisent pas toutes à la caléfaction mais l'une d'elles est soudainement fatale lorsqu'elle croît pour couvrir entièrement la surface chauffante. Ce comportement subitement différent peut être expliqué quantitativement en considérant la conduction thermique le long de la surface chauffante pour laquelle on peut utiliser une interprétation modifiée de la courbe d'ébullition. On trouve une taille critique au-delà de laquelle les aires sèches s'étendent. Les propriétés de stabilité de l'ébullition nucléée et en film sont dépendantes du flux thermique imposé et expliquent la forme classique de la courbe d'ébullition.

KRITISCHE WÄRMESTROMDICHTE BEIM BEHÄLTERSIEDEN. DIE STABILITÄT VON SIEDEVORGÄNGEN

Zusammenfassung—Beim Behältersieden ist eine grosse Zahl von trockenen Stellen auf der Heizfläche zu beobachten, wenn die kritische Wärmestromdichte erreicht wird. Der Vorgang der Bildung von Trockenstellen ist unterschiedlich bei atmosphärischem Druck und bei niedrigem Druckniveau. Der grösste Teil von Trockenstellen führt nicht zum "burn-out", doch kann eine einzige Stelle verhängnisvoll werden, wenn sie sich über die ganze Heizfläche ausdehnt. Dieses plötzlich geänderte Verhalten lässt sich bei Betrachtung der Wärmeleitung längs der Heizfläche qualitativ erklären, wobei eine modifizierte Auslegung der Siedekurve anzuwenden ist. Es gibt eine kritische Grösse, oberhalb welcher Trockenstellen weiterwachsen.

Die Stabilitätseigenschaften von Blasen- und Filmsieden zeigten sich als abhängig vom aufgeprägten Wärmestrom und erklären die vertraute Form der Siedekurve.

КРИТИЧЕСКИЙ ТЕПЛОВОМ ПОТОК ПРИ КИПЕНИИ В БОЛЬШОМ ОБЪЕМЕ. УСТОЙЧИВОСТЬ МЕХАНИЗМОВ КИПЕНИЯ

Аннотация—При кипении в большом объёме рпи приближении к критическому тепловому потоку наблюдается большое число участков, на которых поверхность нагрева остаётся сухой в течение коротких промежутков времени. Механизм образования этих сухих участков различен для атмосферных условий и при низком давлении. Большинство сухих участков не приводит к критическому тепловому потоку, но некоторые иногда внезапно становятся критическими, когда они увеличиваются, покрывая всю поверхность нагрева. Это поведение можно качественно объяснить при рассмотрении теплопроводности вдоль поверхности нагрева, для которой необходимо использовать модифицированную кривую кипения. Найдено, что свойства устойчивости при пузырьковом и пленочном кипении зависят от наложенного теплового потока и объясняют хорошо известный вид кривой кипения.