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SIMULTANEOUS MEASUREMENT OF BUBBLE GROWTH RATE AND THERMAL FLUX FROM THE HEATING WALL TO THE BOILING FLUID NEAR THE NUCLEATION SITE

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Abstract—An experimental study was performed to evaluate the thermal flux which in each moment is transmitted from the hot surface to the boiling fluid, in the surroundings of a single site of nucleation. It has also verified how the thermal flux is localized in space. The results obtained allow the inference that a quantity of heat equal to 60–70 per cent of the heat necessary to produce the vapour contained in the bubble at the moment of detachment is transmitted directly from the hot surface to the bubble during its growth, through part of the hot surface corresponding approximately to the largest contact area of the bubble itself.

A quantity of heat equal to about the remaining 30–40 per cent is transmitted, during the waiting time, through the same area, from the hot wall to the liquid replacing the bubble after its detachment.

The nucleation also strengthens the thermal exchanges as far as distances from the active site of the order of some diameters of the bubble itself, producing, in the test conditions, approximately a doubling of the convection coefficient.

NOMENCLATURE

- a, radius of heat-fluxmeter device (Figs. 2 and 3);
- c, specific heat;
- C, amount of heat;
- Q, heat flux;
- r, radial coordinate;
- S, largest apparent contact area of the bubble;
- t, temperature;
- t_b, bulk temperature of the water;
- t_p, temperature of the copper plate (4, Fig. 2);
- V, volume of the bubble;
- V_d, volume of the bubble at the detachment;
- z, axial coordinate.

Greek symbols

- α, thermal diffusivity;
- θ, average value of $(t - t_b)$ in the area $0 \leqslant r \leqslant a$;
- κ, thermal conductivity;
- λ, heat of vaporization;
- ρ, density;
- τ_c, growing time (between the birth and the detachment of the bubble);
- τ_a, waiting time (between the detachment and the birth of the bubble);
- τ_b, bubble period (between two successive births).

Superscripts

- $\bar{\ }$, time-average value in the bubble period.

INTRODUCTION

SEVERAL mechanisms have been proposed to explain the high values observed for thermal fluxes and exchange coefficients during boiling.

All mechanisms imply three basic assumptions: (i) Heat transmission is essentially due to convection phenomena, enhanced by the bubble formations, through agitation produced in the fluid [1–3] (ii) The growing bubble displaces the boundary layer from the surface; when the bubble detaches, a returning of relatively cold liquid takes place, subtracting heat from the heating wall; evaporization for bubble growing occurs at the liquid–vapour interface and the required heat comes from the cooling of the superheated liquid layer, pushed by the growing bubble [4–10] (iii) The growing bubble leaves a liquid microlayer adhering to the wall: because of the rapid evaporization of such microlayer into the bubble, removal of high quantities of heat occurs directly from the heating surface while the bubble grows [11–19].

Many experimental works [1–22] have indicated that all three mechanisms can be present. The aim of the present paper is to obtain a further understanding of the quantitative trend (in space and time) of the thermal flux as transmitted from the heating surface to the liquid in the neighborhood of the growing bubble and in relation to its evolution. In this way the boiling phenomenon should be clarified, indicating the relative importance of the proposed mechanisms, which surely contribute in characterizing it.

EXPERIMENTAL APPARATUS

The apparatus is shown in Figs. 1–3. It consists of a vessel containing distilled and deaerated water, and kept at T_{sat} by an independent heater.

The vessel is equipped with windows for the cinematographic observation of the test section. The vessel contains the boiling surface and its heater, together with the measuring probes. The part of the apparatus producing bubble (Figs. 2 and 3) is made of a copper rod 1, heated by a resistor thermocoax 2, supplied by an adjustable, direct current I_p; a coaxial disk of constantan 3 is soldered to the terminal section of the rod; and a thin copper sheet, 0·02 mm thick, of circular form, is soldered to the disk: the upper face of the sheet is the boiling surface. The soldering has been made using an alloy with a thermoelectric power negligible in regards

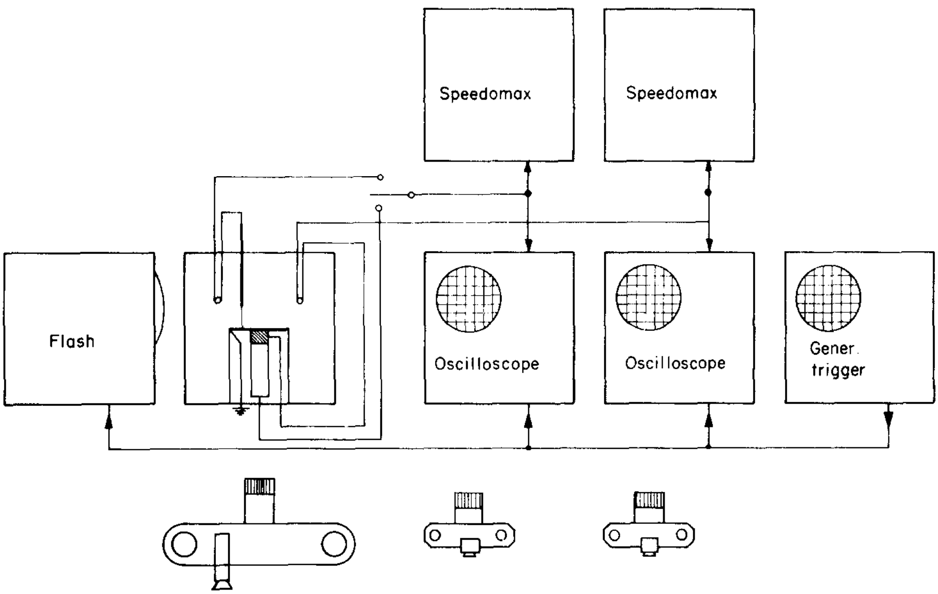

FIG. 1. Sketch of apparatus.

to copper. A wire, 0·05 mm dia. 5, is attached to the lateral surface of the constantan disk. Using appropriate values of current I_p, a stable and regular column of bubble is obtained exactly upon the disk 3. The heat transmitted from the boiling surface arrives completely through the constantan. However, the disk can also operate as a heat-fluxmeter since its geometry and thermal properties are known; furthermore, the e.m.f.'s present at the connection between the disk and the cylinder, and the disk and the copper sheet, give with a good approximation the average temperature on the two faces.

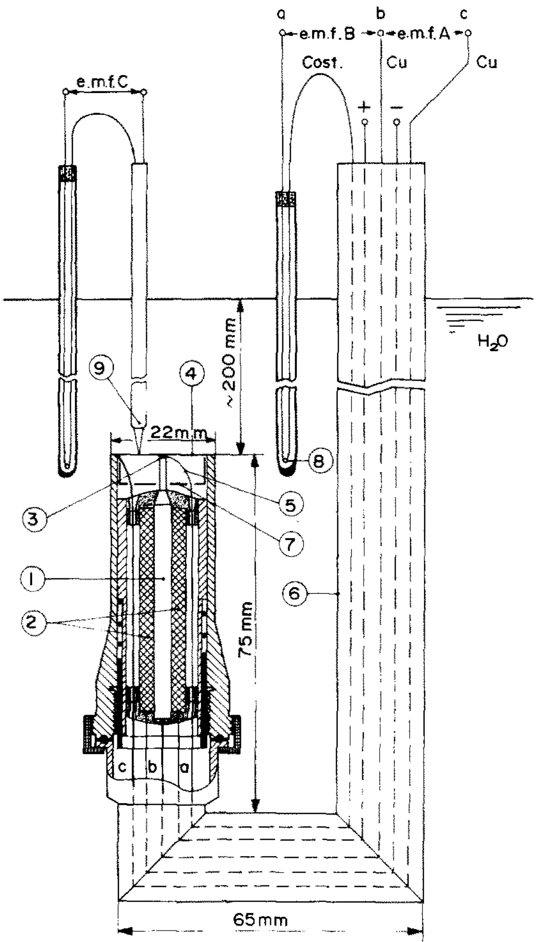

FIG. 2. Test section 1—Copper rod; 2—Heating resistor; 3—Constantan disk; 4—Copper sheet; 5—Constantan wire; 6—Container; 7—Aluminium diaphragm; 8—Cold junction; 9—Thermocouple T_c. (All lengths in mm.)

Another device described in detail in [10], containing a thermocouple T_c, 9, made of wires 0·02 mm dia., allows measurement of the temperature of the boiling surface, as a function of the position. The e.m.f.'s are recorded with oscilloscopes Hewlett Packard 140 A equipped with 1403 A differential amplifiers, and potentiometers Leeds & Northrup Speedomax, and the bubbles are simultaneously monitored with a movie camera Fastax XF2, equipped with an electronic timer. The synchronization between the camera and the oscilloscopes has been obtained using a pulse generator for the triggering of both the oscilloscopes and an electronic flash, which produces on the film a completely black frame. Of course, the precision of timing is controlled by the duration of frame exposure (about 150 μs). The synchronization allows us to relate the variation in temperature to the growing of the bubble.

EXPERIMENTAL PROCEDURE

In each experimental run the current I_p has been setted in such way as to obtain a regular and stable nucleation. Then the cinematography of the test section and the recording of the e.m.f. between the copper sheet 4 and the cylinder 1 (e.m.f. A) and between the disk 3 and the cylinder 1 (e.m.f. B) have been performed. Immediately afterwards (and without cinematography), simultaneous determination of the e.m.f.'s B and that from thermocouple T_c 9 (e.m.f. C) have been obtained at various distances from the axis of the column of bubbles. A total of ten runs has been performed; in each of these runs, the data relative to three or four bubbles have been recorded. In each test, the bulk fluid was at saturation temperature at atmospheric pressure.

PROCESSING OF THE EXPERIMENTAL RESULTS

The thermal fluxes considered are represented in Fig 4. The symbols in the figure indicate:

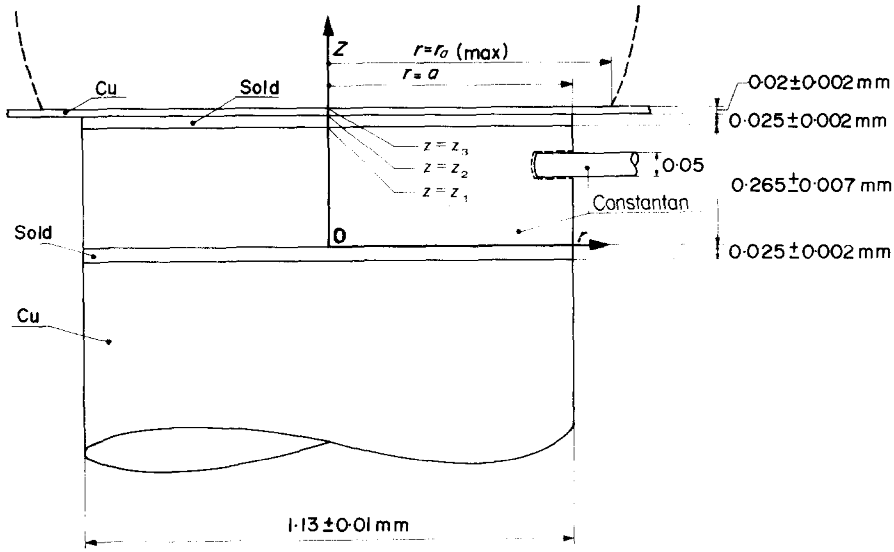

FIG. 3. Detail of the test section (All lengths in mm).

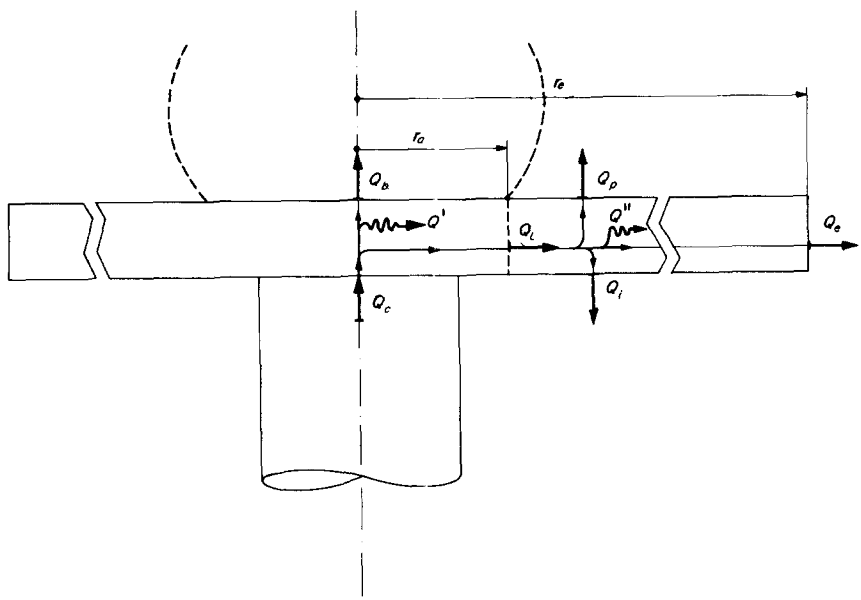

FIG. 4. Sketch of heat fluxes considered.

r_a = maximum radius of the contact area of the bubble.

r_e = radius of the ebullition surface.

Q_c = thermal flux passing through the welding surface between the constantan disk and the copper plate (Fig. 2).

Q_b, Q_p = thermal fluxes passing through the ebullition surface in the areas $0 \leqslant r \leqslant r_a$ and $r_a \leqslant r \leqslant r_e$, respectively.

$Q_t = Q_b + Q_p$ = thermal flux passing through the ebullition surface $r \leqslant r_e$.

Q_l = radial thermal flux inside the plate through the cylindrical surface of radius $r = r_a$.

Q', Q'' = thermal powers which can be accumulated in or released from the plate in the area $0 \leqslant r \leqslant r_a$ or $r_a \leqslant r \leqslant r_e$, respectively.

Q_i, Q_e = thermal fluxes through the lower surface or the perimetral surface of the plate, respectively; these quantities are completely negligible in regards to the others above mentioned.

The measurements performed allow the determination of Q_c, Q_l, Q' and Q''.

Therefore, Q_t, Q_p and Q_b can also be obtained as the relations are;

$$Q_t = Q_c + Q' + Q'' = Q_b + Q_p$$

$$Q_b = Q_c + Q' - Q_l$$

$$Q_p = Q_l + Q''$$

(i) *Calculation of* Q_c

Let us assume that (see Fig. 3), inside the constantan disk (or the solder sheet)

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial t}{\partial r}\right) + \frac{\partial^2 t}{\partial z^2} = \frac{1}{\alpha}\frac{\partial t}{\partial \tau}. \tag{1}$$

Considering the structure of the sample and the fact that the perimetral surface of the disk can be supposed insulated, from (1) follows that:

$$\frac{\partial^2 \theta}{\partial z^2} = \frac{1}{\alpha}\frac{\partial \theta}{\partial \tau}$$

where

$$\theta = \frac{1}{\pi a^2}\int_0^a 2\pi r(t - t_b)\,\mathrm{d}r \tag{2}$$

and a = radius of the constantan disk.

The boundary conditions are:

$$\begin{aligned} z &= 0 \qquad \theta = \phi_0(\tau) \\ z &= z_1 \qquad \theta = \phi_1(\tau) \end{aligned} \tag{3}$$

in which the average temperatures on the two faces of the disk as a function of time $\phi_0(\tau)$ and $\phi_1(\tau)$ can be obtained from the oscillograms of the e.m.f.'s A and B. The regularity of the oscillation of such temperatures (see Fig. 8) allows us to assume the hypothesis of steady periodic regime. In the solder sheet we have:

$$\begin{gathered} z = z_1 \qquad \theta = \phi_1(\tau) \\ \left(\kappa\frac{\partial \theta}{\partial z}\right)_{z=z_1-} = \left(\kappa\frac{\partial \theta}{\partial z}\right)_{z=z_1+} \end{gathered} \tag{3a}$$

ϕ_0 and ϕ_1 have expanded in Fourier series; the solutions of (2) and (3), (3a) have been obtained with an IBM 1130 computer. Lastly we have:

$$Q_c = -\pi a^2\left(\kappa\frac{\partial \theta}{\partial z}\right)_{z=z_2}. \tag{4}$$

The influence on Q_c of the experimental uncertainty due to the temperatures and the geometric and physical properties of the materials has been analysed with the same computer: the error for Q_c can be assumed to be of less than 10 per cent.

(ii) *Evaluation of* Q_l

Considering the small thickness of the copper plate and its high conductivity, we can assume that within the obtained experimental conditions, the temperature inside the plate is independent from z. We have then:

$$Q_l = -2\pi t_p(z_3 - z_2)\left(\kappa\frac{\partial r_a}{\partial r}\right)_{r=r_a}. \tag{5}$$

From the measurement made after each recording, it results that, with a good approximation, for $a < r < I, 5a$

$$t_p - t_b = \psi(r)\bar{\theta}(z_1) + \varphi(r)\left[\theta(z_1, \tau) - \bar{\theta}(z_1)\right] \tag{6}$$

in what the function $\psi(r)$ and $\varphi(r)$ are experimentally determined. Furthermore, these functions changed very little in all tested cases; each of them can then be represented, with a good

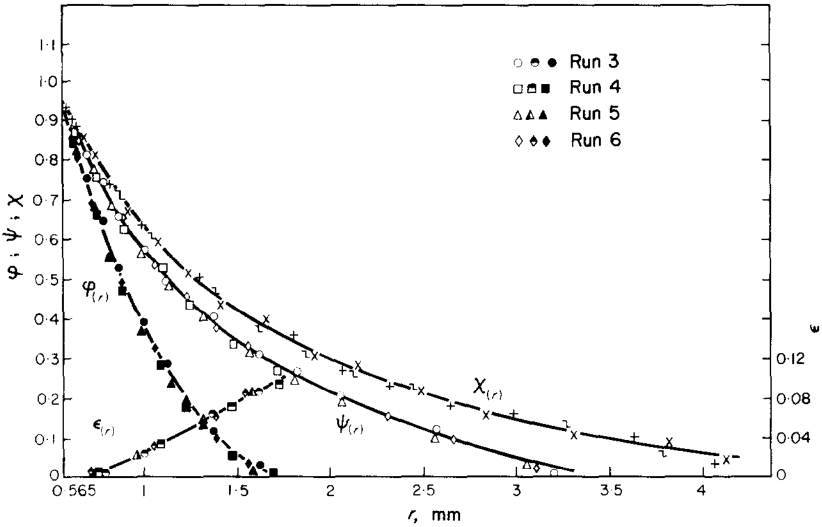

FIG. 5. Plot of ψ, φ, χ, ε vs. r.

approximation, by a single law (Fig. 5). However, it must be noted that, in all cases, there was also a small difference observed among the values of I_p, V_d, r_a, f, τ_a, τ_c.

Considering that, in the cases tested, it results $r_a = 1 \div 1{\cdot}3a$, we can use (6) for calculating (5).

(iii) *Evaluation of* Q'

Assuming Q' and Q'' positive if heat is released from the plate, we have

$$Q' = -\rho c \int_{z_2}^{z_3} \int_0^{r_a} 2\pi r \frac{\partial t}{\partial \tau} \, dr \, dz;$$

$$Q'' = -\rho c \int_{z_2}^{z_3} \int_{r_a}^{r_e} 2\pi r \frac{\partial t}{\partial \tau} \, dr \, dz. \quad (7)$$

Considering that the temperature in the plate is quite independent of z, for $r \leqslant a$ can be assumed

$$\int_0^a \frac{\partial t}{\partial \tau} 2\pi r \, dr = \pi a^2 \frac{\partial \theta(z_2, \tau)}{\partial \tau}$$

and for $a \leqslant r \leqslant r_a$, we can still consider valid (5), we have:

$$Q' = -\rho c(z_3 - z_2) \left[\pi a^2 \frac{\partial \theta(z_2, \tau)}{\partial \tau} + 2\pi \int_a^{r_a} \varphi(r) r \frac{\partial \theta(z_1, \tau)}{\partial \tau} \, dr \right] \quad (7a)$$

with r_a, $\varphi(r)$, $\theta(z_1, \tau)$ experimentally known.

(iv) *Evaluation of* Q''

We have:

$$Q'' = -\rho c(z_3 - z_2) \int_{r_a}^{r_e} 2\pi r \frac{\partial t_p}{\partial \tau} \, dr. \quad (8)$$

The evaluation of Q'' is of minor importance as Q'' is small in regards to the other quantities considered and does not affect the evaluation of the quantity which is of more interest, Q_b. In fact, for values of radius very different from $r = a$, relation (6) becomes little approximated and, at least, a lag of phase in regards to $\theta(z_1, \tau)$ must be taken into account. Thus we assume:

$$t_p - t_b = \psi(r)\bar{\theta}(z_1) + \varphi(r) \{\theta[z_1, (\tau - \varepsilon(r)\tau_b)] - \bar{\theta}(z_1)\} \quad (6a)$$

in which the function $\varepsilon(r)$ is experimentally determined. However, as the radius increases, the amplitudes of the oscillations reduce rapidly: so the areas where (6a) is less verified give less contribution to the value of Q''. Q'' has been then evaluated from (6a). However, the error involved must be considered higher than the one on Q'.

RESULTS

The values of $\varphi(r)$, $\psi(r)$, $\varepsilon(r)$, and those of

$$\chi(r) = \frac{t_p - t_b}{\theta(z_1)}$$

(in absence of ebullition) are presented in Fig. 5. Figures 6–9 indicate, for some of the bubbles examined, the courses of $Q_b(\tau)$; $Q_p(\tau)$; the apparent area of constant S; and $\theta(z_2, \tau)$ which, as already mentioned, is tangibly equal to the average value $\theta_s(\tau)$, inside the area $0 \leqslant r \leqslant a$, of the difference $t_p - t_b$. Furthermore, the average values in time of $\overline{Q}_t$; $\overline{\theta}(z_2)$; are also given.

Figures 6–9 present also the quantity:

$$Q^*(\tau) = \rho\lambda \frac{dV}{d\tau}$$

where ρ is the vapour density and λ the heat of evaporization, both for saturated vapour atmospheric pressure, and V the volume of the bubble. Evidently, Q^* represents the thermic power which should be necessary to produce the vapor contained in the bubble if its increase in volume is due only to evaporization, being pressure, temperature and density uniform and equal to those in equilibrium.

At this stage, it is interesting to point out that some authors [24–26] have demonstrated that the forces of inertia and those due to the surface tension are already negligible when the bubble is not very small anymore (of the order of 0·1 mm); therefore, the vapour contained in it can be considered approximately as saturated vapour at liquid pressure.

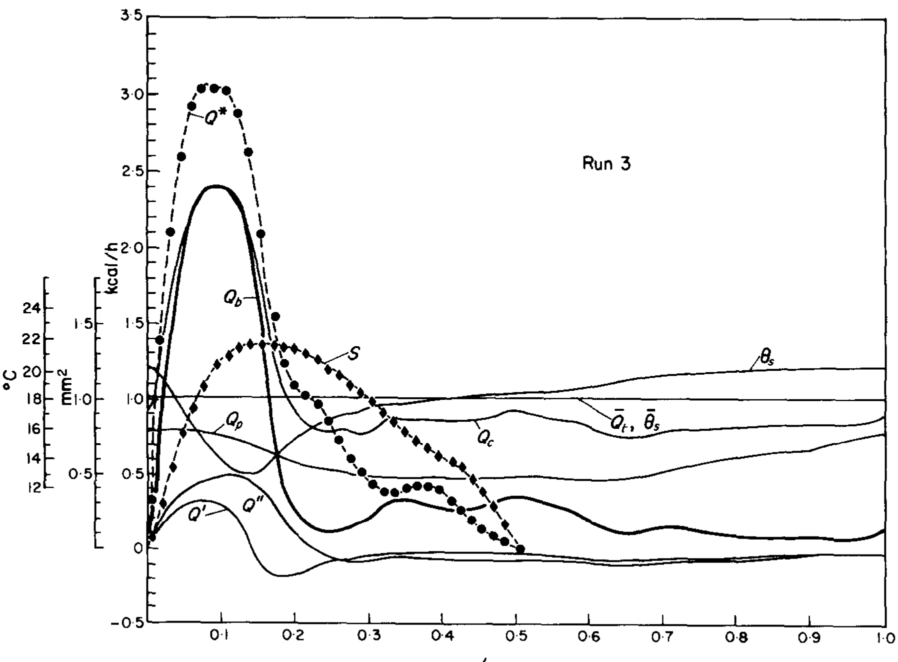

FIG. 6. Plot of Q_b, Q_c, Q^*, Q_p, Q', Q'', S, θ_s vs. time
$\tau_b = 16{\cdot}7$ ms.

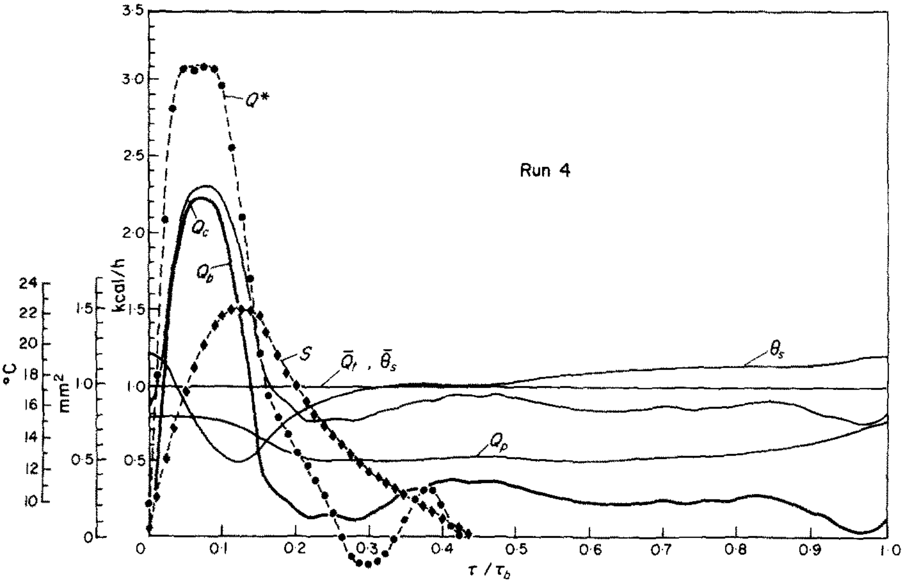

FIG. 7. Plot of Q_b, Q_c, Q^*, Q_p, S, θ_s vs. time $\tau_b = 20$ ms.

The volumes of the bubbles have been obtained from the photograms by numerical integration, assuming that the bubbles themselves are solids of revolution. In the diagrams, the origin of the times corresponds with the average instant of exposure of the first photogram in which the bubble is visible.

The trends of Q' and Q'' are also reported, as an example, in Fig. 6. In all tested cases, the trends of various quantities were strictly similar to those reported in Figs. 6–9. The photographic records (some typical photograms and photographies of the oscillograms) are also reported as an example (Fig. 8). Lastly, Fig. 10 indicate the relation between $\bar{\theta}_s$ and $\bar{Q}_p$ or the thermal flux Q_{conv} which, in absence of ebullition, is transmitted from the plate to the fluid.

DISCUSSION

The aim of the analysis of the results is to obtain some indications about the mechanism of formation of the bubble, the mode of supply of the necessary heat, and the influence of the nucleation on the thermal convection exchanges in the vicinity of the active site. These indications can be obtained by examination of the trends of Q_b, Q^* and Q_p.

The thermal flux Q_b transmitted from the hot wall in the area $r \leqslant r_a$ indicates a very remarkable maximum in the first part of the time of growth, just when the velocity of growth reaches the maximum values and in correspondence with the maximum for the thermal flux Q^* related to the evaporization. Moreover, Q_b and Q^* show very similar trends (Figs. 6–9). This indicated that in the first part of the time of growth, the thermal flux necessary for the bubble to grow is actually related to the formation of the vapour contained in the bubble; and that the thermic power required is given mostly to the growing bubble from the hot surface. It must be noted that the thermal flux Q_p, exchanged by the plate in the area $r \geqslant r_a$, is a much smaller one in comparison to Q_b, and does not follow the same typical trend; on the contrary, while Q_b reaches a maximum, Q_p has (in the initial part of the time of growth) a decreasing course. Such observation permits us

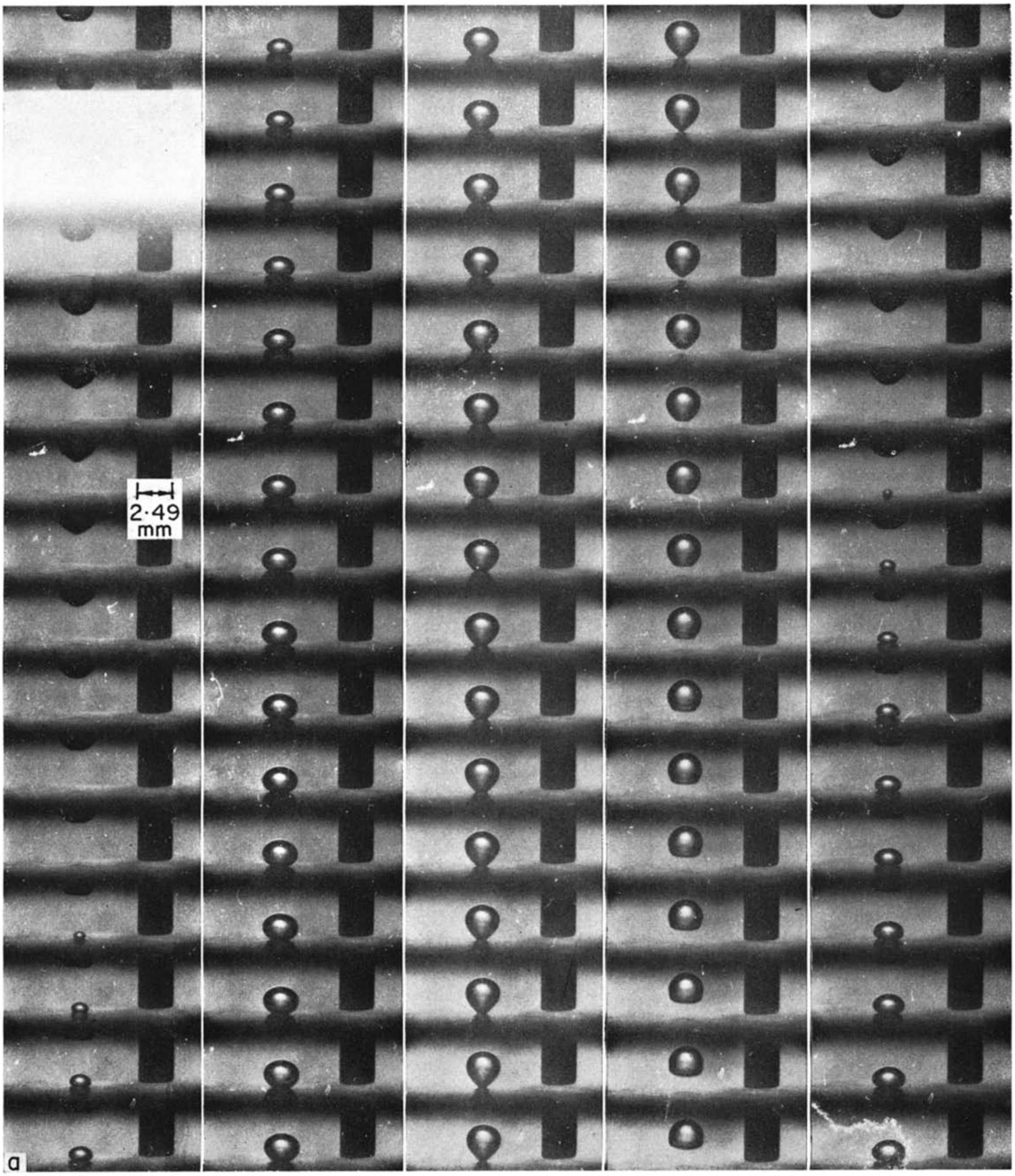

FIG. 8a. Cinematography of the bubble.

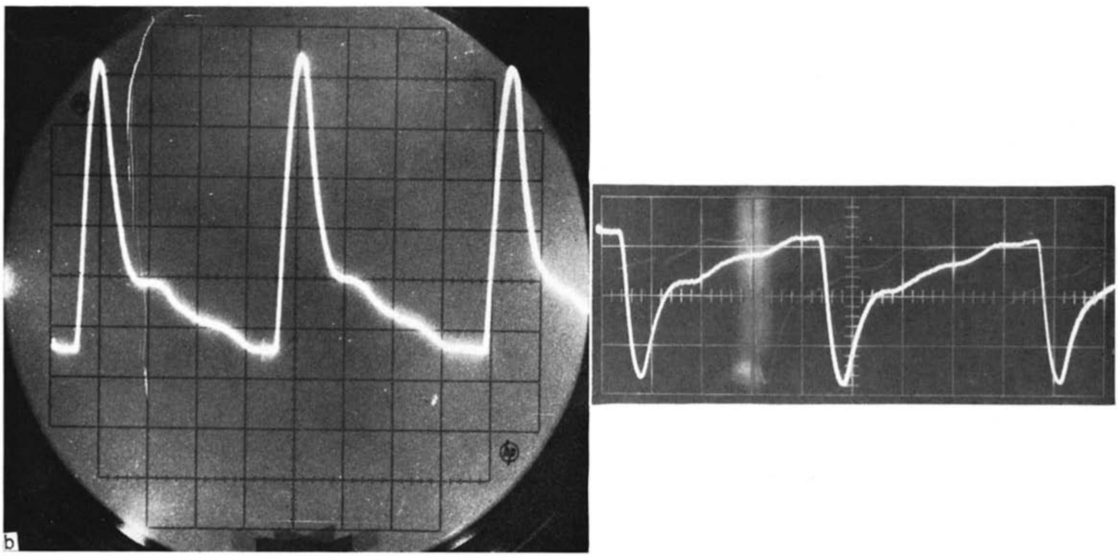

FIG. 8b (No 1). e.m.f. A: 0·05 mV/cm; time base: 5ms/cm; mean value: 0·485mV.

FIG. 8b (No 2). e.m.f. B: 0·1 mV/cm; time base : 5ms/cm; mean value 0·790 mV.

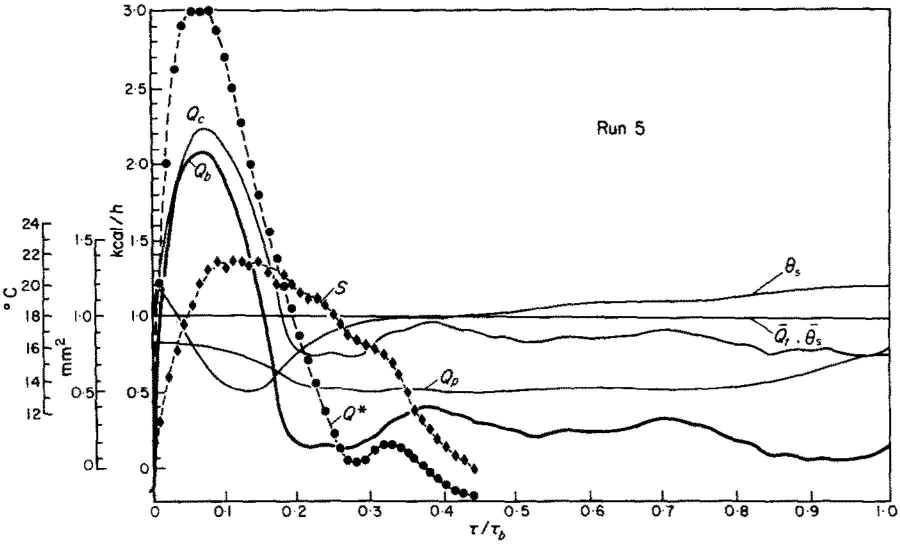

FIG. 8c. Plot of Q_b, Q_c, Q^*, Q_p, S, θ_s vs. time $\tau_b = 20{\cdot}4$ ms.

to conclude that the thermic exchange between the wall and the bubble occurs in the immediate vicinity of nucleation site, through a part of the surface of the same order of contact area of the bubble itself. Moreover, at least under the present experimental circumstances, the growth of the bubble produces such a request of thermic power (in area $r \leqslant r_a$) to cause a decrease in the thermal flux exchanged by the plate outside this area.

The direct relation between Q_b and Q^* lasts until Q_b reaches an accentuated minimum; afterwards, Q_b presents again a modest increase and remains slightly variable during the remaining life of the bubble, around values of about 0·2 kcal/h (even if with one or more not very

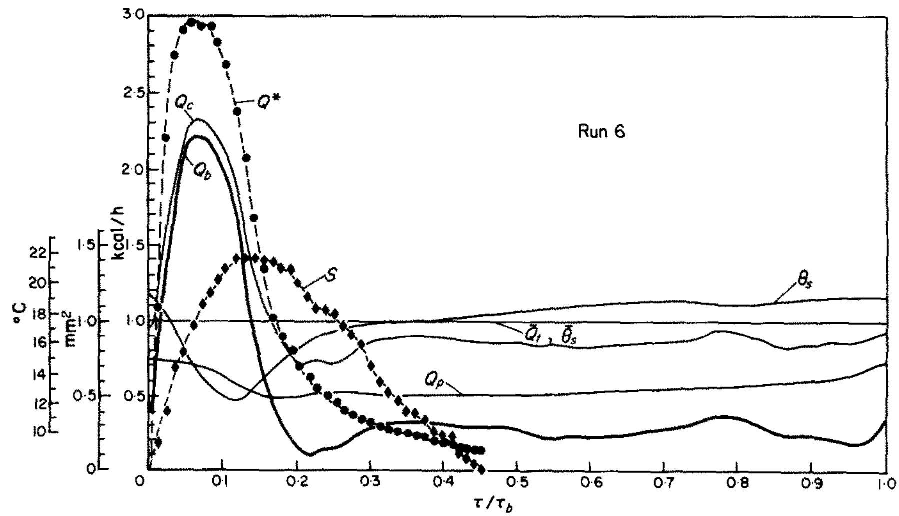

FIG. 9. Plot of Q_b, Q_c, Q^*, Q_p, S, θ_s vs. time. $\tau_b = 18{\cdot}9$ ms.

remarkable maxima). On the contrary, Q^* continues to decrease until the detachment, and, in some cases, undergoes some fluctuations corresponding with the similar fluctuations observed for the volume of the bubble. Neither Q_b nor Q_p seem to show traces of the same fluctuations, therefore, the corresponding quantities of heat are not transferred directly from the hot surface. This could be explained by

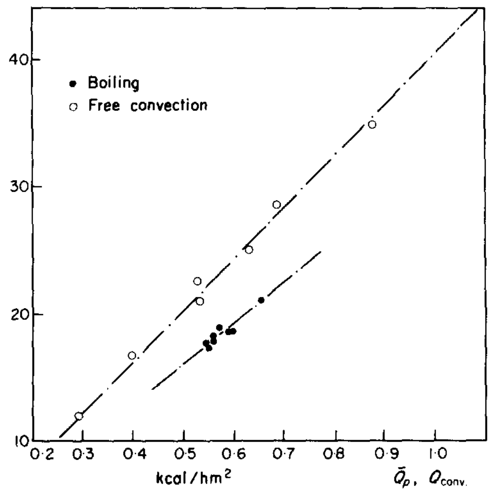

FIG. 10. Plot of $\overline{Q}_p$, Q_{conv} vs. θ_s.

assuming that the vapour fluctuations are due to compression of the vapour with small exchanges of mass and heat, or that these exchanges occur in conditions such that they do not influence directly on the thermic field of the solid wall; for example, by taking place in correspondence of the upper part of the bubble. Furthermore, it is necessary to consider that the upper observed fluctuations may be due to errors in the volume measurement. In fact, the assumption that the bubble is a solid of revolution is highly verified in the first part of the time of growth, but less verified in the moments preceding the detachment.

Finally, the available results permit us to estimate the quantity of heat, C_b, which is released directly from the wall to the growing bubble. In fact, as indicated above, we can assume, with good approximation, that such heat is exchanged in the area $r \leqslant r_a$. The thermal flux transmitted in the area under examination is given by Q_b. Moreover, as far as the interval of time between the birth of the bubble and approximately the reaching of the first minimum of Q_b is concerned, we can assume that the heat is completely exchanged with the bubble. In fact in this period, it covers a large part of the area under examination; and moreover the values of Q_b taking place when the bubble is absent or its velocity of growth not very important (Q^* small or zero) are very small in comparison to those observed in the period, where the maximum of Q^* occurs.

Therefore, C_b can be calculated, with a good approximation through the relation:

$$C_b = \int_0^{\tau^*} Q_b \, d\tau$$

where τ^* indicates the instant in which the minimum of Q_b takes place. For the various cases tested, both the values of C_b and of the ratio

$$\frac{C_b}{\rho \lambda V_d} \tag{10}$$

have been calculated. This ratio results between 0·63 and 0·70.

The following quantities:

$$C_b' = \int_0^{\tau_c} Q_b \, d\tau$$

and the ratio:

$$\frac{C_b'}{\rho \lambda V_d} \tag{11}$$

have been also evaluated. This one differs less than 10 per cent from the values of (10) confirming that the quantities of heat Q_b, transmitted in the area $r \leqslant r_a$, become relatively small as soon as the velocity of growth of the bubble together with the evaporation rate become of negligible importance. Therefore, it is necessary to admit that 60–70 per cent of the heat necessary for bubble formation comes directly from the hot surface to the growing bubble; the remaining part comes probably from the liquid and is exchanged through the liquid–vapour interface.

The examination of the trend of Q_b permits us, then, to evaluate the effects of nucleation upon the convection exchange in the area $0 \leqslant r \leqslant r_a$, after the first minimum of Q_b and until the end of the bubble. In this regard, it can also be useful to refer to a local coefficient of convection h^*, defined by the relation:

$$h^* = \frac{Q_b}{\pi r_a^2 \theta_s}. \qquad (12)$$

When Q_b reaches its first minimum, considering the values shown at the same time by θ_s, we obtain values of h^* of the order of 3000–5000 kcal/hm^2°C (Figs. 6–9). This is the minimum value of h^* during the whole period of time. Afterwards, Q_b increases and undergoes some fluctuations, related to a similar trend in time of h^*, with one or more maxima. At such maxima, h^* can reach values of the order of 15 000 kcal/hm^2°C. These values are very much higher than those obtained, under similar conditions, for natural convection without ebullition.

Figures 6–9 indicate also that the first of the maxima considered (always present and the more important) takes place in a time interval (of few ms) close to the detachment of the bubble. This circumstance, together with the fact that the relative increase in thermal flux concerns mainly the central part of the plate, seems to indicate that the increase of h^* has to be related to the hypothesis expressed in (ii) of the introduction. However, the presence of other maxima and of an increase of the convection coefficient even at certain distance from the active site indicates how the effect of an agitation characterized by a smaller localization in space and time, and induced in the fluid from the evolution of the bubble—birth, growth, and detachment—is superimposed to the mechanism described in (ii).

Furthermore, it has to be noted that the heat C_b'', given by the wall to the fluid in the area under consideration, in the interval of time included between the first minimum of Q_b and the end of the bubble, that is:

$$C_b'' = \int_{\tau^*}^{\tau_b} Q_b \, d\tau$$

is equivalent, in all the observed cases, to 30–40 per cent of $\rho \lambda V_d$. Therefore, in the area $0 \leqslant r \leqslant r_a$ during the whole period, the wall gives to the liquid an overall quantity of heat nearly equal to that necessary to produce the vapour contained in the bubble at the moment of detachment.

It must be noted that the exchange coefficients occurring when the evaporization phenomenon is of importance, are of very high order of magnitude. In particular, if we maintain for h^* the meaning of an "equivalent" coefficient of convection (in the moments in which the bubble is present and evaporization important) in the area $0 \leqslant r \leqslant r_a$, we found, in relation to the main maximum of Q_b, values of specific flux of 2 000 000 kcal/m^{2}h and values of h^* of the order of 150 000 ÷ 200 000 kcal/hm^2°C.

Lastly, the experimental results permit us to obtain some indications on the effect of ebullition on the convection exchanges in the area $r > r_a$.

Figures 10 and 5 indicate respectively that, for equal $\bar{\theta}_s$, $\bar{Q}_p > Q_{\text{conv}}$ and in the area $r > r_a$ the surface temperatures of the plate are lower in presence than in absence of nucleation. Therefore, even in this area, nucleation produces an increase in the coefficients of thermal exchange. If we refer, then, to the average values of temperature of the plate we can calculate the orders of magnitude of the average coefficients of convection with and without ebullition. It results, in the two cases, $h \cong 3000$ kcal/hm^2°C and $h \cong 1500$ kcal/hm^2°C, respectively.

CONCLUSION

In the present work, the thermal flux which in each moment is transmitted from the hot surface to the boiling fluid in the surroundings of a single site of nucleation, in saturated ebullition, in natural convection at atmospheric pressure has been measured. It has been also verified how the thermal flux is localized in space, evaluating separately the trends of it inside and outside the largest contact area of the bubble.

The results obtained allow us to infer that:

(i) In regards to the mechanism of formation of the bubble and the modalities with which it obtains the necessary heat, the direct heat transmission from the hot surface to the bubble has a determining role during the bubble growth. In fact, under experimental conditions, it provides 60–70 per cent of the heat necessary to produce the vapour contained in the bubble; this heat is exchanged through a part of the hot surface corresponding approximately to the largest contact area of the bubble itself. The remaining part of the heat is probably provided by the superheated fluid at the liquid–vapour interface. The volume fluctuations often observed at the last moments of the bubble life do not coincide with the quantities of heat exchanged at the same time by the hot surface.

(ii) Values of local coefficients of thermal exchange of the order of $150000 + 200000$ kcal/hm^2°C occur at the base area of the bubble, during its growth. In the moments nearer to the detachment (when the importance of evaporization is negligible) and after it, fluctuating trends in the thermal fluxes and the coefficient of exchange (which reaches highest values of $10000 \div 15000$ kcal/hm^2°C, much higher than those obtained in similar condition without ebullition) can be observed. The trends in time and the values of the thermal flux and of the local coefficient of exchange are in a good agreement with the hypothesis that the bubble, at the detachment, produces a return of relatively cold water.

(iii) Under these particular experimental conditions, the nucleation strengthens the thermal exchanges even outside the above-mentioned area of contact (and as far as distances from the active site of the order of some diameters of the bubble itself) producing, approximately, a doubling of the convection coefficients in comparison to the values obtained in absence of ebullition.

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GLEICHZEITIGE MESSUNG DER BLASENWACHSTUMSRATE UND DES WÄRMEFLUSSES VON DER HEIZFLÄCHE AN DIE SIEDENDE FLÜSSIGKEIT NAHE DER KEIMSTELLE

Zusammenfassung—Es handelt sich um die experimentelle Untersuchung zur Abschätzung des Wärmestromes, der in der Umgebung einer einzelnen Keimstelle in jedem Augenblick von der Heizfläche an die siedende Flüssigkeit übergeht. Auch die räumliche Verteilung des Wärmeflusses wurde untersucht. Die Ergebnisse zeigen, dass 60 bis 70% der Wärme, die zur Erzeugung einer Dampfblase notwendig ist, bis zum Moment ihres Ablösens, direkt von der Heizfläche an die Blase übergeht, während ihres Wachstums. Sie geht durch den Teil der Heizfläche, welcher der grössten Berührungsfläche der Blase entspricht.

Eine Wärmemenge, die den übrigen 30–40% entspricht, wird während der Warteperiode nach Ablösung der Blase, durch die gleiche Fläche, von der heissen Wand an die Flüssigkeit übertragen.

Die Blasenbildung erhöht auch den Wärmeübergang im Umkreis mehrerer Blasendurchmesser von der Keimstelle, in dem sie, bei den Versuchsbedingungen, etwa eine Verdoppelung des konvektiven Wärmeüberganges bewirkt.

MESURE SIMULTANÉE PRÈS DU SITE DE NUCLÉATION, DE LA VITESSE DE CROISSANCE D'UNE BULLE ET DU FLUX THERMIQUE PARIÉTAL VERS LE FLUIDE EN ÉBULLITION

Résumé—On a mené une étude expérimentale afin d'évaluer le flux thermique qui à chaque instant est transmis depuis la surface chaude au fluide bouillant, au voisinage d'un site unique de nucléation. On a aussi observé la localisation du flux thermique dans l'espace. Les résultats obtenus permettent de déduire que la quantité de chaleur égale à 60 ou 70% de la chaleur nécessaire à la production de la vapeur contenue dans la bulle au moment du détachement est transmise directement de la surface chaude à la bulle pendant sa croissance, à travers une partie de la surface chaude correspondant à la plus grande aire de contact de la bulle.

La quantité de chaleur complémentaire à peu près égale à 30 ou 40% est transmise, pendant le temps d'attente, à travers la même surface depuis la paroi chaude au liquide qui remplace la bulle après son détachement.

La nucléation renforce les échanges thermiques tant que les distances du site actif à la bulle sont de l'ordre de quelques diamètres de la bulle elle-même et, dans les conditions du test, double approximativement le coefficient de convection.

СОВМЕСТНЫЕ ИЗМЕРЕНИЯ СКОРОСТИ РОСТА ПУЗЫРЕЙ И ТЕПЛОВОГО ПОТОКА ОТ НАГРЕВАЕМОЙ СТЕНКИ К КИПЯЩЕЙ ЖИДКОСТИ ВБЛИЗИ МЕСТА ОБРАЗОВАНИЯ ПУЗЫРЯ

Аннотация—Проведено экспериментальное исследование для оценки теплового потока, который в каждый момент времени переносится от нагретой поверхности к кипящей жидкости вблизи места образования единичного пузыря. Проверяется также, каким образом поток локализуется в пространстве. Полученные результаты позволяют сделать вывод о том, что количество теплоты, равное 60–70% тепла, необходимого для образования пара, содержащегося в пузыре в момент отрыва, переносится непосредственно от нагретой поверхности к пузырю при его росте через участок нагретой поверхности, приблизительно соответствующий наибольшей площади контактной поверхности самого пузыря.

Примерно 30–40% оставшегося тепла переносится за время задержки через ту же площадь поверхности от нагретой стенки к жидкости, занявшей место пузыря после его отрыва.

Образование пузыря также интенсифицирует теплообмен, когда активный центр находится на расстоянии порядка нескольких диаметров пузыря, что дает в условиях эксперимента примерно удвоенный коэффициент конвекции.