536. 423. 1 : 532. 5

Maximum Heat Fluxes for Pool Boiling on Partly Ill-Wettable Heating Surfaces*

(Part 1, On the Visual Observation of Boiling and the Temperature Profiles of Heating Surface)

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The current study presents some experimental results for examining the maximum heat fluxes in pool boiling of saturated water at atmospheric pressure on partly ill-wettable heating surfaces. The experiment was carried out on the electrically heated horizontal strip, at the center of which an artificially ill-wettable portion was installed. The boiling regime on the ill-wettable portion at very low heat fluxes is nucleate boiling whose behavior closely resembles a transition one. Alternatively stable vapour film is formed on this portion at comparatively low heat fluxes of 5×10^4 kcal/m²hr to 10^5 kcal/m²hr that depend on the geometrical dimension of ill-wettable area and thereafter the simultaneous nucleate-film boiling is realized.

Accordingly, in such a system, while the maximum heat fluxes are prescribed by the transition to film boiling for large sizes of ill-wettable part, the formation of stable vapour film is not clear for small sized ill-wettable part on account of drastic hydrodynamic interaction of nucleate boiling. Parallel to the experimental measurements of heating surface temperature at the center of ill-wettable portion for simultaneous nucleate-film boiling regime, simple analytical calculations were performed and, in consequence, favorable consistencies were obtained for the wide ranges of heat fluxes and ill-wettable dimensions of interest.

1. Introduction

For revealing the burnout mechanism many researchers have approached the problem by taking up pool boiling, which is a comparatively simple phenomenon, and by using some physical models provided for explaining burnout phenomenon it seems that this mechanism has been made clearer. In a more strict sense, however, those researches are not quite satisfactory where they treat of burnout mechanism. That is to say, putting aside Kutateladze's⁽¹⁾ method based on the dimensional analysis, as explained from the historic progress of development, the theory of Rohsenow-Griffith⁽²⁾, Zuber's instability theory and Chang's⁽³⁾ theories seem to lack propriety in the assumption they made before they carried out analysis or proposed theories.

According to the reports^{(4) (5)} lately published by Katto et al., they have derived a view, from the result of their high speed photography, that the essential phenomena which affect the burnout heat flux are confined to the part adjacent to the heating surface by making an interference plate bring close to the heating surface and that the eventual burnout mechanism is the equilibrium between the consumption time of the micro-layer of liquid which is formed on heated surface and the intermission of coalescent clouds of vapor. Also in the experiment⁽⁶⁾ carried out by one of the authors, burnout heat flux scarcely changed when the space configuration high above the heating surface was changed variously in conjunction of floodings of vapour and liquid. Accordingly it is empirically believed that burnout is a phenomenon which takes place near heating surface.

The authors therefore assumed that the properties of heating surface should have effect upon burnout phenomenon and carried out an experiment on the pool boiling of saturated water by rendering

* Received 14th May, 1968.

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the central part of the heating surface ill-wettable with a thin silastic adhesive coating over it. Similar experiment was executed by Torikai et al.⁽⁷⁾, who presented in their report that the boiling mode resembled transition boiling and that there was no micro-layer of liquid on heating surface at the part where bubbles were adhered, that is, dry. In case a heating surface has an ill-wettable area, the boiling mode on this part shifts easily to film at the low heat fluxes and thereafter the simultaneous nucleate and film boiling regime is realized, and there are some studies on the simultaneous nucleate and film boiling, for instance, Nishikawa et al.⁽⁸⁾ performed an experiment on the fine wire. In the present paper, the authors carried out the experiment and observed the boiling behavior on the part which had been made artificially less wettable, as mentioned before, by varying the area of ill-wettable part variously, and expressed some views on the critical heat flux of boiling as well as the temperature of heating surface when the simultaneous nucleate-film boiling was taking place.

Incidentally, the authors believe that the result of the present study will be useful as it will suggest the possibility of burnout to occur at the unexpectedly low heat flux in the practical problems and it will also contribute to the study of burnout mechanism.

2. Nomenclatures

a : ($2a$)=width of ill-wettable part m

b : width of heating surface m

d : thickness of heating plate m

q : heat flux kcal/m²hr

Q_1, Q_2 : heat transfer rate kcal/hr

T : temperature °C

ΔT : excess temperature above saturation °C

w : volumetric heat generation in heating plate kcal/m³hr

x : axis of coordinate (longitudinal direction of heating surface)

α : heat transfer coefficient kcal/m²hr°C

λ : thermal conductivity of heating plate kcal/mhr°C

$\kappa_1 = (\alpha_v / \lambda d)^{1/2}$ m⁻¹

$\kappa_2 = (\alpha_l / \lambda d)^{1/2}$ m⁻¹

$\phi = T - (T_v + wd / \alpha_v)$ °C

$\psi = T - (T_l + wd / \alpha_l)$ °C

suffixes

a : values at $x=a$

BO=burnout

l : liquid (saturated water)

0 : the value of heating surface center ($x=0$)

sat: at saturation

v : vapour (steam)

3. Experimental apparatus and procedure

The schematic view of experimental apparatus is shown in Fig. 1. The heating surface is an up-turned horizontal plate made of stainless steel, 20 mm wide, 100 mm long and 0.3 mm thick, which is electrically heated (alternating current) with its underside thermally insulated.

The heating plate is fixed on the plate of silicon glass layers with thermostable adhesive binding agent, and in order to prevent it from coming off and also from contacting water at the back side of plate when heated, it is covered with a layer of about 10 sheets of a tape which is adhesive on both sides. Further, the heating surface is pulled in the direction of the insulating plate using a welded fine wire. The pool, used for the experiment, is a large beaker whose diameter and height are 220 mm and 345 mm respectively. As shown in the figure, the whole pool is submerged in a water bath whose confronting two sides are made of glass for facilitating the visual observation and there are installed electric heater units in the pool and in the water bath respectively. Temperature of heating surface is measured by electromotive force of thermocouple welded to the underside of the plate with an auto-recorder, while the surface temperature is extrapolated by correcting for each heat flux. Heat flux

1 thermocouple	2 thermal insulator
3 heating plate	4 electrode
5 beaker	
6 200 W electric heater	
7 1000 W electric heater	
8 750 W electric heater	
9, 10, 11 electric power switch	
12 cold junction	13 auto-recording potentiometer
14 P.T.	15 C.T.
16 standard AC wattmeter	
17 transformer	18 voltage regulator
19 voltage stabilizer	20 condensor

Fig. 1 Schematic view of experimental apparatus

is evaluated from input electric power. Input electric power is introduced to the electrodes on both sides through a stabilizer, a slidac and a transformer while the slidac is driven by an electric motor with the reduction gearing.

In the present experiment, input power is gradually increased by the motor after the water in the pool and thermos bath has attained saturated temperature, and the motor is stopped as occasion demands for observations or measurements. The increase of input power is kept up until the heating plate is heated to red hot condition and burnt out. Incidentally, in order to let input power and temperature correspond to each other, some signal is recorded in the autorecorder for the temperature at the moment at which the wattmeter is read. The increased step of electric power at each heat flux is not large as shown in Fig. 4.

Alternatively, the heating surface is rendered ill-wettable by putting a thin layer of silastic adhesive (about $10 \sim 20 \mu$ thick) the width which is $2a(m)$ and the ill-wettable portion is situated at the central part of heating surface as schematically shown in Fig. 2. The temperatures of heating plate are measured at the center of ill-wettable part and also at the point located apart from the center. The experiment is repeated 5 to 20 times on each

● Position of thermocouple welded
Fig. 2 Schematic view of heating plate

width of $2a$, which is changed from $0.001(1 \text{ mm})$ to $0.02 (20 \text{ mm})$ and also includes 0.1 m , that is, the case of being fully covered with silastic adhesive. All the experiments are performed on saturation boiling of distilled water.

4. Experimental results and discussions

4.1 Visual observation of boiling

After boiling curve is evaluated on the heating surface without the layer of silastic adhesive in order to examine the experimental apparatus, the experiment is resumed on the heating surface with a thin film of silastic adhesive stuck in its center. By the way, the burnout heat flux q_{BO} of ordinary heating surface which is measured herein is $(0.9 \sim 1.3) \times 10^6 \text{ kcal/m}^2\text{hr}$.

When a silastic thin film is stuck on heating surface, main characteristics of boiling mode determined by means of visual observation and the analysis by movie (64 frames per second) are as follows;

(i) Initiation of boiling invariably occurs at the ill-wettable part with silastic adhesive, and even in the case of low heat fluxes where no bubbles are generated on the ordinary surface, there are found a pretty many boiling sites at the part with silastic adhesive.

(ii) The heating surface temperature in this case seems to show no great difference between the part applied with silastic adhesive and that without it.

(iii) The diameter of bubble on the departure from the surface is unusually large, being about 5 mm .

(iv) These large bubbles are arrayed rather regularly at nearly 5 mm pitch. That is, when the pasted width $2a$ is 5 mm , 10 mm , 15 mm and 20 mm , the number of bubble arrays will be 1, 2, 3 and 4 columns in turn, and in the case when pasted width is not a multiple of 5 mm , there are bubbles having the size of 5 mm in all places and also are bubbles of irregular sizes smaller than 5 mm among them.

(v) The configuration of the bubbles of such sizes is not constricted at the contact angle of bubbles.

(vi) Careful examination shows that these large bubbles are produced as a result of coalescence of small bubbles which are initially generated on the heating surface and the life of small bubble is considerably short compared with the bubble period, and except for the case of extremely low heat fluxes large bubbles appear to start growing from the beginning.

(vii) The boiling mode on the ill-wettable part closely resembles the transition boiling, and therein lots of small bubbles are crowded among the large bubbles. And these bubbles are seemingly absorbed

Fig. 3 Photographs of boiling adjacent to the heating surface

by large bubbles before they depart from the heating surface.

(viii) There is formed a stable vapour film at extremely small heat flux ($5 \times 10^4 \sim 10^5 \text{ kcal/m}^2\text{hr}$) on the pasted part, and the heat flux forming the vapour film is inversely proportional to the width of silastic adhesive in a manner shown in Fig. 5.

(ix) When the value of $2a$ is reduced to less than 5 mm, the configuration of large bubbles comes to get constricted at the apparent contact part of bubble, and the formation of a stable film is no clearer than in the case of $2a \geq 5 \text{ mm}$.

(x) The temperature of heating surface after a film has been formed naturally makes a sudden rise in the pasted part, and that temperature varies in accordance with the value of pasted width $2a$ and heat flux, the relevance of which will be explained in some details later.

(xi) When silastic is not pasted on, the burnout occurs at any position of the heating surface, whereas when silastic is pasted, it occurs invariably at the pasted part, even if the value of $2a$ is small. What has been mentioned so far can be partially understood from the photos showing the vicinity of heating surface given in Fig. 3.

4.2 On the critical heat fluxes

Some typical results obtained in the present experiment are shown in Fig. 4. The numerals in the figure are the value of the width $2a$ and the experimental points are plotted as relations of heat fluxes versus excess temperatures above saturation at the center of heating surface while the solid lines denote the calculated values of the temperature to be explained in the next section, whose numerals are marked with primes. The experiment is repeated on the 5~20 test pieces for

the same pasted width. The reproducibility of the experimental results is considerably good as shown in Fig. 4 for the case of $2a=10$ mm.

Figure 5 illustrates the relation between the minimum heat flux on which a stable vapour film is formed at the part pasted with silastic and the heating surface temperature before and after the formation of stable film and the pasted width. As already stated in Section 4.1, the heat flux at which a stable film is formed on the part pasted with silastic is approximately within the range of $5 \times 10^4 \sim 10^5$ kcal/m²hr, and the larger the width of pasted part, the lower the heat flux at which the film is formed. Contrarily when the pasted width is small ($2a \leq 3$ mm), a sudden rise of the heating surface temperature is not definite, when it is hard to confirm the existence of a stable film even by a close observation on the neighborhood of heating surface. The reason for this phenomenon is that the boiling

mode on the ill-wettable surface is apparently different from ordinary nucleate boiling within the range of small excess temperatures above saturation ΔT_{sat} and the boiling behavior closely resembles transition boiling, as pointed out by Torikai et al.⁽⁷⁾. Besides it is difficult if the pasted width is small, to discern nucleate boiling (say,

Fig. 5 Heat flux and temperature of heat surface versus pasted width of silastic adhesive

Fig. 4 Boiling characteristic curves on the partly ill-wettable heating surfaces

transition-like nucleate boiling) from film boiling. In the present paper, the authors have intentionally refrain from using such an expression as "transition from nucleate to film boiling." Instead, adopted a simple description "the formation of stable film."

A similar experiment is carried out by the authors using other apparatus which regulates the temperature of heating surface, consisting of the outer surface of 6 mm copper tube and fully pasted silastic adhesive. In this experiment the transition-like nucleate boiling with large bubbles is consecutively realized up to 100°C of ΔT_{sat} and it shifts to film boiling when ΔT_{sat} is raised further. The tangent of characteristic curve of boiling ($q \sim \Delta T_{\text{sat}}$) is positive in the whole range of ΔT_{sat} .

Meanwhile it is necessary to speculate the burnout heat flux of boiling and the relation between the burnout and critical heat fluxes in conjunction with appreciating the critical heat flux in such a system of pool boiling where there exists an ill-wettable part on heating surface. Let us make here discussions referring to the result of observation on boiling behaviour.

In the first place, boiling in the range of small excess temperatures is classified as nucleate boiling that has some resemblances to transition boiling, where heat flux of ordinary transition boiling decreases with the increase of ΔT_{sat} , whereas heat flux increases with the increase of ΔT_{sat} . The detailed observation of bubble formation reveals the fact that tiny bubbles are initially generated and they are immediately coalesced into larger bubbles of about 5 mm without any constriction on the heating surface before they depart the heating surface, and the time needed to coalesce smaller bubbles on the heating surface is very much shorter compared with the period of bubble frequency. Such a mechanism is apt to be overlooked even within a small range of heat flux and, in consequence, those large bubbles appear to be grown from the beginning. They are therefore considered to be different essentially from ordinary transition boiling, but they are substantially nucleate boiling, though boiling on the ill-wettable surface behaves like transition boiling. (For convenience, this will be called "transition-like nucleate boiling.")

Accordingly a phenomenon in which transition-like nucleate boiling, such as shown in Fig. 4, shifts to film boiling is the same as so-called burnout phenomenon, which may be explained structurally by adopting the view of Katto et al.⁽⁶⁾ That is, on the ill-wettable surface the micro-layer of liquid can hardly exist at the moment when the coalescent large bubbles with about 5 mm diameter have been generated because of the properties of heating surface, and even if there survived liquid,

they would scarcely exist, and the mean consumption time of liquid film on heating surface would be shortened. On the other hand, since the intermittent frequency of massive clouds of vapour does not change by heat flux, it is understandable that burnout can take place at a very low heat flux in such a system as given in the present experiment being founded on the view of Katto et al., who assert that burnout occurs when the mean consumption time of liquid film is balanced with the mean intermittent frequency of massive clouds of vapour.

Next consideration is about the critical value of heat flux of pool boiling in the case of an ill-wettable part existing on heating surface. As is illustrated from Fig. 4, it will be more reasonable to consider that the critical heat flux is not necessarily determined by the shift from transition-like nucleate to film boiling which corresponds to the usual burnout phenomenon. Namely, when the silastic pasted width is so small as 1~2 mm, neither the formation of stable vapour film is clearly distinguished even by a closer observation of boiling condition, nor the distinct temperature jump is depicted in the boiling characteristic curves. Furthermore, in spite of a rather large excess temperature of heating surface at the critical, the heating surface is durable at considerably high heat fluxes of $(80 \sim 90) \times 10^4 \text{ kcal/m}^2\text{hr}$. And with the increase of the silastic pasted width, the heat flux at the time when a stable film is formed becomes clearer, the temperature jump increases and the critical heat flux in the case when heating surface is burnt out decreases.

On the other hand, when the silastic pasted width is large, the temperature jump at the time of the generation of stable vapour film becomes large and this heat flux becomes the critical value. That is, when heat flux is increased a little even after the generation of stable film, the boiling mode of nucleate-film coexistence can be maintained, but when it is more increased, the heating surface is burnt out at an extremely small heat flux. In evaluating the width of silastic adhesive that governs the critical heat flux, it is necessary to take into account the thermal conductivity and heat capacity of heating plate. Accordingly, the evaluation will be fulfilled after the examination of temperature profiles of heating surfaces in the next section coupled with the visual observation results of boiling behavior.

4.3 Temperature profile of heating surface in the case of simultaneous nucleate-film boiling

Consider the situation of simultaneous nucleate-film boiling that the nucleate boiling occurs over a heating surface except the silastic pasted part on

which the stable film boiling is realized. For the analytical purpose some simplifications such as one dimensional temperature profile, constant thermal properties and constant volumetric heat generation of plate are introduced. It is further assumed that the back side of heating plate is thermally insulated and heat transfer coefficients, designated by α_v and α_i on the film and nucleate boiling respectively, are also constant. The coordinate system is schematically shown in Fig. 6 and putting the thickness of heating plate and conductivity as d and λ respectively the basic equations of one dimensional heat conduction with the boundary conditions will be

$$(i) \quad 0 \leq x \leq a \quad \frac{d^2 T}{dx^2} - \frac{\alpha_v}{\lambda d} (T - T_v) + \frac{w}{\lambda} = 0 \quad (1)$$

$$(ii) \quad a \leq x \quad \frac{d^2 T}{dx^2} - \frac{\alpha_i}{\lambda d} (T - T_i) + \frac{w}{\lambda} = 0 \quad \dots\dots (2)$$

$$\left. \begin{aligned} x=0 \quad dT/dx &= 0 \\ x=a \quad (dT/dx)_{x=a-0} &= (dT/dx)_{x=a+0} \\ x=\infty \quad dT/dx &= 0 \end{aligned} \right\} \quad \dots\dots (3)$$

provided that T_v , T_i are the temperature of vapour and water respectively. Transforming the dependent variable T to the following

$$\Phi = \{T - (T_v + wd/\alpha_v)\} \quad \dots\dots (4)$$

$$\Psi = \{T - (T_i + wd/\alpha_i)\} \quad \dots\dots (5)$$

Equations (1) and (2) will be written as follows respectively,

$$\frac{d^2 \Phi}{dx^2} - \kappa_1^2 \Phi = 0 \quad \dots\dots (6)$$

$$\frac{d^2 \Psi}{dx^2} - \kappa_2^2 \Psi = 0 \quad \dots\dots (7)$$

where κ_1 and κ_2 are

$$\kappa_1 = \sqrt{\alpha_v/\lambda d}, \quad \kappa_2 = \sqrt{\alpha_i/\lambda d}$$

Equations (6) and (7) will be easily solved as

$$\Phi = \left\{ T_a - \left(T_v + \frac{wd}{\alpha_v} \right) \right\} \frac{\cosh \kappa_1 x}{\cosh \kappa_1 a} \quad \dots\dots (8)$$

$$\Psi = \left\{ T_a - \left(T_i + \frac{wd}{\alpha_i} \right) \right\} \exp\{-\kappa_2(x-a)\} \quad \dots\dots (9)$$

Here T_a represents the temperature of heating surface at the position of nucleate-film boundary and is given by the following equation.

$$T_a = \left\{ \kappa_1 \frac{\sinh \kappa_1 a}{\cosh \kappa_1 a} \left(T_v + \frac{wd}{\alpha_v} \right) + \kappa_2 \left(T_i + \frac{wd}{\alpha_i} \right) \right\} / \left\{ \kappa_1 \frac{\sinh \kappa_1 a}{\cosh \kappa_1 a} + \kappa_2 \right\} \quad \dots\dots (10)$$

Fig. 6 Coordinate system

Also temperature T_0 in the central part ($x=0$) of film boiling can be evaluated from Eqs. (4) and (8).

$$T_0 = \left\{ T_a - \left(T_v + \frac{wd}{\alpha_v} \right) \right\} / \cosh \kappa_1 a + \left(T_v + \frac{wd}{\alpha_v} \right) \quad \dots\dots (11)$$

The temperature at this point is measured by using thermocouple. Heat transfer coefficients α_i , α_v of nucleate boiling and film boiling which are necessary for calculating temperature profile, temperature at nucleate-film boundary and central temperature from Eqs. (8) and (11) are evaluated from the result of experiment.

Namely, α_i is calculated from ordinary nucleate boiling curve and α_v from the boiling curve under the condition where stable film is formed all over the heating surface ($2a=100$ mm) by pasting silastic. Incidentally, since the measuring point is on the back side of the heating plate, the heating surface temperature T_w is corrected by using the heat flux in each case.

In Fig. 7 the lengthwise temperature profile of heating surface is shown, where (a), (b), (c) are given the silastic pasted width of 2 mm, 10 mm and 20 mm in their order.

Figure 8 illustrates the temperatures at $x=0$ and $x=a$ (nucleate-film boundary) of the heating surface, designated by T_0 and T_a , against the silastic pasted width. Reference to the figure reveals that T_a is generally small compared with T_0 and that the effect of heat conduction toward the part of nucleate boiling is extended to the central part of the heating surface when the silastic pasted width is small and or when even the width is large under the high heat flux. The temperature rise of unpasted part, however, is drastically confined to within a few millimeters from the edge of stable film ($x=a$). This fact might be simply explained by the large heat transfer coefficient of nucleate boiling, although any remarkable increase of boiling sites couldn't be observed in the immediate vicinity of the vapour film. Instead it appears that an array of extremely fine bubbles is found on the nucleate-film boundary line and that it holds the film. And these fine bubbles are considered to supply vapour to the stable film without departing from the heating surface independently, and the film boiling in the central part seems to be different from ordinary film boiling. Especially when the silastic pasted width is small, it might be considered that the boiling mode on the adhesive pasted part rather resembles transition boiling.

4.4 Discussions

Designating the amount of heat transferred to liquid by film boiling and that conducted to the direction of x across the film-nucleate boundary ($x=$

Fig. 7. Temperature profiles of heating surface

a) along the plate by Q_1 (kcal/hr) and Q_2 (kcal/hr) respectively, it is easy to calculate Q_1 and Q_2 from Eqs. (4), (8) and (9) which give temperature profile of the heating surface of pasted part:

$$Q_1 = \alpha_v b \int_0^a (T - T_v) dx = \alpha_v b \left[\frac{T_a - \left(T_v + \frac{wd}{\alpha_v} \right)}{e^{k_1 a} + e^{-k_1 a}} \right] \times \left\{ \frac{1}{k_1} (e^{k_1 a} - e^{-k_1 a}) + \frac{wd}{\alpha_v a} \right\} \quad (12)$$

$$Q_2 = -\lambda (bd) \left(\frac{dT}{dx} \right)_{x=a} = -\lambda bd \left\{ \frac{T_a - \left(T_v + \frac{wd}{\alpha_v} \right)}{e^{k_1 a} + e^{-k_1 a}} k_1 (e^{k_1 a} - e^{-k_1 a}) \right\} \quad (13)$$

where b in Eqs. (12) and (13) denotes the width of heating surface. Figure 9 gives the result of calculation of in which the ratio of Q_1 to Q_2 has been calculated versus the volumetric heat generation of the heating plate, w . For facilitating comparison the corresponding mean heat flux q is drawn in abscissa.

The parameter shown in this figure means the value of pasted width $2a$, according to which, the smaller the pasted width is, the more remarkable the effect of thermal conductivity, but the values of Q_1/Q_2 hardly change even if the amount of generated heat is increased. In other words, when the pasted width is small, the effect of thermal

Fig. 8. Temperatures of heating surface at center of stable film and nucleate-film boundary

conductivity is large even if the amount of generated heat is small. Also when the pasted width is large but the amount of heat generation is small, the value of Q_1/Q_2 is considerably large, but with the increase of the amount of heat generation the amount of heat transmitted to the part of nucleate boiling becomes large by conduction. In any case, the difference of heat transfer coefficient between the two parts of film boiling and nucleate boiling influences upon the temperature profile and, in consequence, determines the critical heat flux. In the practical equipments the heating walls are uniformly thick so that Q_2 becomes larger than Q_1 .

In Fig. 4 the calculated values of central temperature on the heating surface T_0 are given in solid lines when a stable film has been formed. Those values show good accord with experimental values in the case when the pasted width is large, but with the decrease of pasted width the discrepancy is going to increase, especially in the case of $2a=1\sim3$ mm. As a whole, however, there is fairly good correspondence between the experimental points and the calculated values. There are various reasons conceivable for the disagreement in the small range of pasted width as follows:

- (i) Calculation is simplified exceedingly.
- (ii) The thermal conductivity of heating plate is assumed to be constant.
- (iii) There is some uncertainty in the

estimations of α_v and α_l .

(iv) There is a tendency, as mentioned above, in which the heat flux in the part of stable film is actually smaller than q given in the figure because of the transfer of heat to the part of nucleate boiling due to heat conduction and this tendency is more conspicuous within the range of small pasted width.

(v) As the diameter of thermocouple welded to the center is 0.2 mm, the relative dimension of thermocouple to pasted width is large. Then the central temperature is measured as rather lower than it really is, with the decrease in the pasted width.

It is, however, the most important reason that for a small pasted width the boiling behaviour including the formation of stable vapour film is considerably different, as already mentioned. In the case of $2a=1\sim2$ mm, it is difficult to recognize whether a stable film has been actually formed at the silastic pasted part or not, and even if it is formed, it is controversial to presume such a condition of boiling as film boiling. That is, when the pasted width is small, the heat flux at which a film is supposed to be formed is also large, temperature rise of heating surface is checked by the interference of violent nucleate boiling on both sides of the silastic pasted part, and film boiling is likely to become unstable due to the hydrodynamic disturbance.

This fact is also related with the treatment of the critical heat flux, and when there is an ill-wettable part of a few millimeters on the heating surface, it will be justifiable to consider the critical heat flux as nearly equivalent to the former burnout heat flux, though we cannot overlook the shift from transition-like nucleate boiling to film boiling. It is, however, necessary to treat separately such a case when ill-wettable parts exist pretty densely and close to one another, even if they are small.

And when the size of ill-wettable part exceeds 5 mm, as plain from Fig. 4, the shift from transition-like nucleate boiling to film boiling provides the critical heat flux. This might be related with the fact that the diameter of large bubbles generated in transition-like nucleate boiling almost amounts to 5 mm.

Boiling condition on an ill-wettable heating surface presents quite unusual condition as mentioned previously, and the phenomenon corresponding to the burnout in this case occurs at an extremely low heat flux. Young et al.⁽⁹⁾ showed a significant decrease of surface temperature at a given heat flux when a number of spots on the heating surface were coated with

Fig. 9 Q_1/Q_2 versus volumetric heat generation

Teflon, and according to Costello's reports⁽¹⁰⁾, on the up-turned semi-cylindrical heating surface whose surface was subjected to some kind of treatment, burnout heat flux amounted to $3.2 \times 10 \text{ kcal/m}^2\text{hr}$, and it is obvious that the characteristics of heating surface have a great deal of effect upon the domain of nucleate boiling as well as burnout heat flux.

5. Conclusions

As the result of investigations carried out on pool boiling of saturated water when there was ill-wettable part on heating surface, the following conclusions were drawn.

(1) Boiling condition in an ill-wettable part apparently resembles transition boiling at low heat flux but it is essentially nucleate boiling.

(2) Transition to film takes place in an ill-wettable part at a comparatively low heat flux, for the larger the area of ill-wettable part is, the less heat flux at which the transition takes place, and with a decrease in the area of ill-wettable part the formation of stable film becomes less clear.

(3) The critical value of heat flux in such a system cannot be treated uniformly, for it is related with the area of ill-wettable parts, their population and the physical properties of the heating plate such as thermal conductivity and specific heat.

(4) There is steep slope centering around nucleate-film boundary on the heating surface where a stable film has been formed, and the calculated value of the temperature in the center of film boiling almost agreed with the measured value, even when heat flux and the width of silastic coating were changed.

Finally, the authors wish to express their deep gratitude to Professor Kaneyasu NISHIKAWA, Faculty of Engineering, Kyushu University, for his valuable advices in carrying out this study. They are also thankful to Messrs. Yoshio KITAJIMA (graduated in 1966) and Yoshiyuki SAKANAKA (graduated in 1967) who were the students of the Industrial Teachers' Training School of Kyushu University for their cooperation in executing experiment as well as to Mr. Toshiyuki TAKEGAWA, assistant of the Department of Nuclear Engineering, Kyushu University, who helped the authors in calculation and a part of compilation. In addition it would be noted that the research fund was partly subsidized by the Ministry of Education from the research grant for the fiscal years of 1966 and 1967 (Nos. 52523 and 52914 for individual researches) and one of authors (R. Echigo) express his appreciation to The Sakkokai Foundation for the scholarship.

References

- (1) S. S. Kutateladze: *AEC-tr-3770*, (1952).
- (2) W. M. Rohsenow and P. Griffith: *Chem. Engng. Progr. Symp. Ser.*, Vol. 52, No. 18 (1956), p. 47.
- (3) Y. P. Chang and N. Y. Snyder: *Chem. Engng. Progr. Symp. Ser.*, Vol. 56 (1960), p. 30; Y. P. Chang, *TID-14004*, (1961).
- (4) Y. Katto and S. Yokoya: *Proc. Third Intl. Heat Transfer Conf. (A.I.Ch.E.)*, No. 219 (1966).
- (5) Y. Katto and S. Yokoya: *Intl. Jour. Heat Mass Transfer*, Vol. 11, No. 6 (1968), p. 993.
- (6) S. Hasegawa: not yet published.
- (7) K. Torikai and T. Yamazaki: *Trans. Japan Soc. Mech. Engrs.*, Vol. 32, No. 242 (1966), p. 1557.
- (8) K. Nishikawa and R. Shimomura: *Trans. Japan Soc. Mech. Engrs.*, Vol. 29, No. 204 (1963), p. 1381.
- (9) R. K. Young and R. L. Hummel: *7th National Heat Transfer Conf., Cleveland, Ohio*, (1964).
- (10) C. P. Costello and W. J. Frea: *Chem. Engng. Progr. Symp. Ser.*, Vol. 61 (1965), p. 258.