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Boiling Heat Transfer at the Coexistence of Nucleate and Film Regions*

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E. Zielinski discovered experimentally a comparatively easy method to reproduce film boiling. According to his method, if a wire which is making nucleate boiling with heating current adjusted to a rather low heat flux is pulled out of water for a short time, the surface of the wire dries up and its temperature rises because of the contact of the wire and air, even when heat flux is kept constant. If the wire is dipped in water later on, for the second time, it heats red-hot in a few seconds, followed by the appearance of film boiling. Film boiling is to be reproduced with comparative easiness by breaking temporarily the contact of heating surface with water. The authors who paid attention to Zielinski's method followed it with the result in which nucleate boiling and film boiling are made to coexist stably on the same heating surface by heating them with a given heat flux. This is considered to be a kind of transition boiling, and the present paper deals with the boiling phenomena at the coexistence of nucleate and film regions in saturated water, subcooled water and sodium oleate solution as well as their relation with boiling characteristic curve. In this region the coefficient of heat transfer decreases with the increase of temperature difference, while heat flux increases with the increase of temperature difference.

1. Introduction

E. Zielinski⁽¹⁾ discovered experimentally the following method that enables us to realize film boiling comparatively easily. That is, when a wire on which nucleate boiling has occurred with heating current adjusted to a rather low heat flux is pulled out of water for a short time, the surface of the wire dries up and its temperature rises, even if heat flux is kept constant, since the wire is brought to contact with air. If the wire is sunk again in water afterward, it will be heated red-hot after a few seconds and film boiling appears. He asserts that film boiling is to be realized thus with comparative easiness by cutting off temporarily the contact between heating surface and water. The authors who were interested in the experimental process of this paper carried out a similar experiment and succeeded in realizing a condition where nucleate and film boiling coexist stably on the same heating surface by heating with a given heat flux. This is considered to be a kind of transition boiling and the present paper deals with the boiling phenomena at

the coexistence of nucleate and film regions in saturated water, subcooled water and sodium oleate solution as well as their relation with boiling characteristic curve.

2. Method of experiment

The platinum wire of 0.5 mm in diameter and 90 mm long was used as the heating surface, which was heated by direct current. This heating wire was sunk horizontally in a beaker, 15 cm in diameter and 20 cm high, which was filled with the test fluid. The top of the beaker was covered tightly with a rubber lid. To fix the temperature of test liquid at boiling point or at a given value, the beaker was put in a thermostat with glass-windows on both the counter sides for interior observation. The water in the thermostat is controlled at a given temperature by cast-in heaters and stirrers.

Fig. 1 shows a systematic view of the experimental apparatus. The heat flux was obtained by measuring the voltage and current in the heating wire. The temperature of the heating wire was measured by using a platinum wire itself as a resistance thermometer. The Wheatstone bridge was constituted with heating wire R_x , variable resistance R_b , manganese wire resistance R_c and fixed resistance R_A as shown in Fig. 1. The temperature of the test

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liquid was measured by the copper-constantan thermocouple set at the point of 4 cm above the heating surface.

For the heating process of wire the following two methods were tested. (1) E. Zielinski's method. A platinum wire which is making nucleate boiling with the fixed heat flux is pulled out of water and immersed again into water immediately after the wire surface has dried up. Then the measurement is started when the condition of boiling has settled. (2) A. Farber-R. L. Scoria's⁽²⁾ method. The heat flux is increased gradually up to the burn-out point and then reduced before the wire burns out. At this point the heat flux is fixed to start measurement. When boiling in the regions where nucleate boiling and film boiling coexist have been attained through the above-mentioned two methods, data are recorded by the proper adjustment of heat flux. On the other hand, a perfect film boiling is worked out by covering both the sides of platinum wire with small insulating porcelain bushing.

The ranges of the experiment are as follows :
 test liquid : distilled water, sodium oleate solution ;
 concentration of sodium oleate solution : $C=10, 50, 150$ ppm (surface tension= $52.7, 38.3, 34.3$

dyn/cm) ;

degree of subcooling : $\Delta\theta_c=0, 3, 5, 7, 10^\circ\text{C}$;

heat flux : $q=(2\sim100)\times10^4\text{ kcal/m}^2\text{hr}$.

M : Motor, G : Generator, H₁ : Platinum-wire heater, H₂ : Base heater, H₃ : Cast-in heater, R_x : Heating wire, R_B : Variable resistance, R_C : Manganese-wire resistance, R_A : Fixed resistance, g : Galvanometer, R_g : Variable resistance, A : Ammeter, V : Voltmeter, CA : 35 mm camera, l : Condenser lens, L : Light source, T₁, T₂, T₃ : Thermometer.

Fig. 1 Experimental apparatus

Fig. 2 Appearance of local film boiling of saturated water

3. Results of experiment

3.1 Aspect of boiling Fig. 2 shows several examples of the photographs of boiling at the coexistence of nucleate and film regions. (We call this region hereafter as the local film boiling temporarily.) Fig. 2(a) corresponds to the lowest heat flux of local film boiling and Fig. 2(d) corresponds to the heat flux at which the condition was just changed to a perfect film boiling. In these photographs, while the part of film boiling in the wire is heated red-hot, the part of nucleate boiling remains dark. The end of vapor film is shaped like a funnel by the effect

of surface tension and is fixed at a definite position and kept in a stable state of given heat flux.

The lowest heat flux in which the local film boiling was to be attained with saturated water was about 2.0×10^5 kcal/m²hr and the heat flux where the heating surface was gradually covered up by the vapor film was 5.0×10^5 kcal/m²hr. When the aspect of boiling in this lowest heat flux is carefully observed, we are led to a conclusion that three vapor columns are at least necessary for the attainment of local film boiling. In the case of the columns less than three, the part of film boiling disappears finally with the lapse of time, leaving behind only

Fig. 3 Appearance of local film boiling of subcooled water

Fig. 4 Appearance of local film boiling of sodium oleate solution

the nucleate boiling on the heating surface. The cause of this phenomenon is considered to be as follows. It is presumable that, since the part of film boiling is higher in temperature, there is heat transfer from the conduction through the wire from the film region to the nucleate region beside that by conduction and radiation through the vapor film from the heating surface to boiling liquid, and the heat removal of these two is likely to exceed the heat input in the film region.

Fig. 3 shows the photographs of the aspect of local film boiling of the subcooled water. Figs. 3 (a), (b) and (c) correspond to nearly the same heat flux. It is clear from these photographs that the higher the degree of subcooling increases, the shorter the film boiling region becomes. Fig. 3 (d) is the photograph of a state where heat flux is increased from the state of (a).

The photographs of Fig. 4 show the aspect of local film boiling of sodium oleate solution at a saturated temperature. It is seen from these photographs that the difference in the concentration of sodium oleate exerts the similar effect on the degree of subcooling. In the nucleate region the number of vapor columns increases while the bubble diameter decreases with the increase of the additive quantities of sodium oleate.

3.2 Vapor film coverage In Fig. 5, there is plotted the relation between the rate of the region of film boiling which is L_f in length to L in the total length of platinum wire and heat flux q with the degree of subcooling $\Delta\theta_0$ of water as parameter.

Fig. 5 Vapor film coverage (water)

In Fig. 6, the similar relation for sodium oleate solution is given. The relation of L_f/L - q of Fig. 5 varies according to the degree of subcooling, the cause of which seems to be in the operation of a low temperature liquid surrounding the platinum in the region of nucleate boiling which prevents the vapor from emerging forth in filmy state with the increase of the degree of subcooling, though the temperature of the platinum wire remains the same. In Fig. 6, we can see how the number of vapor columns increases with the decrease of surface tension while the temperature of liquid maintains that of saturation, lowering thereby the temperature of the platinum wire in the region of nucleate boiling more or less and ultimately checking the advance of vapor film with the increase of the additive quantities of sodium oleate.

3.3 Boiling characteristic curve In Fig. 7, these is plotted on the case of saturated water the relation of heat flux q and heat transfer coefficient α with the temperature difference $\Delta\theta$ between heating surface and liquid. As seen from the figure, while the curve of q - $\Delta\theta$ shows the tendency of monotonous increase under local film boiling, α - $\Delta\theta$ tends to show the monotonous decrease. Furthermore, the heat flux in which α begins to increase with the increase of $\Delta\theta$ is almost equivalent to the burnout heat flux, and in this heat flux the heating surface is completely covered with vapor film. The broken lines of Fig. 7 show the result of experiment made on the perfect film boiling by the author before this⁽³⁾, which is different from the average lines in

Fig. 6 Vapor film coverage (sodium oleate solution)

the present experiment at the temperature below $\Delta\theta \approx 900^\circ\text{C}$. Since the former experiment was made with insulating porcelain bushing fixed at both ends of heating wire, there was not seen any trace of nucleate-film coexisting; even at low heat flux, film boiling over-running the whole part. It seems that the above-mentioned difference resulted, since the insulating porcelain bushings were not used in the present experiment of local film boiling. That is to say, if the insulating porcelain bushings are put at both ends of the heating wire, those parts are apt to be heated to high temperature, creating motive power for film boiling at the insulating porcelain bushings, and in such heat flux as generating film boiling the average temperature of the whole heating wire becomes higher than in the case of local film boiling under the same heat flux. For the above-mentioned reasons, the insulating porcelain bushings were fixed at both ends in the present experiment in order to realize a perfect film boiling.

In Figs. 8 and 9, there is plotted the relation between heat flux q and the temperature difference $\Delta\theta$ of heating surface and liquid with the degree of subcooling and the additive quantities of sodium oleate as parameters respectively. In Fig. 8 there is observed the effect of subcooling in the regions of nucleate boiling, perfect film boiling and local film boiling respectively. That is, in the region of nucleate boiling, the more the degree of subcooling increases, the worse heat transfer becomes, whereas the better heat transfer is seen in both the regions of local film boiling and perfect film boiling. It may be because while in the region of nucleate boiling, the more the degree of subcooling increases, the less the removal of the heat due to bubbles is expected, in the region of film boiling the lowering of liquid

Fig. 7 Coefficient of heat transfer and heat flux in the saturated water

temperature has the greater effect for the removal of heat. Then in Fig. 9, whereas heat transfer is improved with the increase of the additive quantities of sodium oleate in both the region of nucleate boiling and local film boiling, there is seen hardly any effect in the region of perfect film boiling. Since addition of sodium oleate means the reduction of only surface tension without changing other property values, the effect of nucleate and film boiling is to be estimated from the former experiments. It is therefore considered that the change of heat transfer due to the addition of sodium oleate in the region of local film boiling depends only on the effect from the region of nucleate boiling.

4. Considerations on the result of experiment

First consideration will be made on the case of the boiling of saturated water. Fig. 7 shows the region of perfect film boiling which has been produced by putting insulating porcelain bushings at both ends of wire as shown by the broken lines, where ABC represents the region of nucleate boiling, EGF that of local film boiling and GH that of perfect film

Fig. 8 Boiling characteristic curve (water)

Fig. 9 Boiling characteristic curve (sodium oleate solution)

boiling. When this figure is compared with the lines of saturated water of Fig. 5, there is noticed a relation as follows.

$$BF/BJ = L_f/L \quad \dots\dots\dots (1)$$

Now, in the case of local film boiling the region of film boiling looks red and that of nucleate boiling dark, which proves that the temperature at each region is obviously different. Assuming therefore the temperature distribution of wire as that of Fig. 10 with due regard to that the relation of Eq. (1) approximately holds, there will be induced the following equation about the heat quantity generated from the heated wire.

$$IR_0(1+\kappa\Delta\theta)L = IR_0(1+\kappa_f\Delta\theta_f)L_f + IR_0(1+\kappa_n\Delta\theta_n)L_n$$

Assuming now that the temperature coefficient of electric resistance of the platinum wire is equal in either region of nucleate boiling and film boiling, the above equation will be written as follows.

$$\Delta\theta = \Delta\theta_f(L_f/L) + \Delta\theta_n(L_n/L) \quad \dots\dots\dots (2)$$

Here, I : electric current flowing through platinum wire, R_0 : electric resistance per unit length of platinum wire at 100°C , κ : temperature coefficient of electric resistance of platinum wire, $\Delta\theta$: mean value of the temperature difference between heating surface and liquid over the whole length of wire, $\Delta\theta_n$ and $\Delta\theta_f$: temperature difference between heating surface and liquid in either region of nucleate boiling and film boiling, L : total length of wire, L_n and L_f : length of wire in the regions of nucleate and film boiling.

The relation of Eq. (2) shows the same relation with Eq. (1). The points marked with crosses on the q - $\Delta\theta$ curve in Fig. 7 are the values evaluated from Eq. (2) by letting the temperature differences of nucleate boiling and perfect film boiling on the equivalent heat flux lines in this picture be $\Delta\theta_n$ and $\Delta\theta_f$ respectively and using the value of L_f/L for this heat flux from Fig. 5.

In the next place, the average coefficient α of heat transfer of the whole wire will be written as follows by using Eq. (2).

$$\alpha = \frac{q}{\Delta\theta} = \frac{q}{\Delta\theta_f \frac{L_f}{L} + \Delta\theta_n \frac{L_n}{L}} \quad \dots\dots\dots (3)$$

$$\frac{1}{\alpha} = \frac{1}{\alpha_f} \frac{L_f}{L} + \frac{1}{\alpha_n} \frac{L_n}{L}$$

provided that

$$\alpha_f = q/\Delta\theta_f \quad \dots\dots\dots (4)$$

$$\alpha_n = q/\Delta\theta_n \quad \dots\dots\dots (5)$$

The points of cross marks on α - $\Delta\theta$ of Fig. 7 are the values of α calculated using Eq. (3). Eq. (3) corresponds to the equation of thermal resistance

Fig. 10 Assumption of temperature distribution along the heating wire

in which the thermal resistance in the nucleate region and that in the film region exist in parallel, which seems to explain qualitatively the mechanism of heat transfer at the coexistence of nucleate and film regions. What is noticeable here is that α_f and α_n correspond to Eqs. (4) and (5). That is, there are used the apparent heat transfer coefficients in which both the regions of nucleate and film boiling are considered to be of the same heat flux as α_n and α_f . As a matter of fact, however, the values of electric resistance and therefore heat flux are different due to the difference in the temperature of the nucleate and film regions. Accordingly, Eq. (3) bears no great significance physically, and it may be appropriate to consider it as an equation valid merely in form. At any rate, however, the value calculated by using Eqs. (2) and (3) corresponds to the result of experiment very well, as seen in Fig. 7.

The idea mentioned above will be tentatively applied to the liquids with different degrees of subcooling or surface tension. For the coefficients of heat transfer of nucleate and film boiling the following equations generally hold.

Nishikawa's equation⁽⁴⁾:

$$\alpha_n = 8.0 \left[\frac{1}{M^2 P} \frac{c_p \gamma'^2 \lambda^2}{\sigma r \gamma''} \right]^{1/3} q^{2/3} \quad \dots\dots\dots (6)$$

Bromley's equation⁽⁵⁾:

$$\alpha_f = 0.53 \left[\frac{\lambda'^2 \gamma'' (\gamma' - \gamma'') r}{R q \mu''} \right]^{1/3} \quad \dots\dots\dots (7)$$

Here, c_p : specific heat of liquid, λ and λ' : thermal conductivities of liquid and vapor, σ : surface tension of liquid, r : latent heat of evaporation, γ' and γ'' : specific weights of liquid and vapor, q : heat flux, R : characteristic dimension of heating surface, μ'' : viscosity of vapor, $M=900 \text{ m}^{-1}$, $P=1.699 \text{ kcal/hr}$. In order to represent the experimental results of liquid with various degrees of subcooling or surface tension by a single curve, it may be advisable to apply the values obtained by transforming α_n and α_f to the case of saturated water using Eqs. (6) and (7) respectively to Eq. (3). Evaluating these transformed values by putting $q=\text{constant}$, the result will be as follows.

In the case of surface boiling,

$$\alpha_{n0} = \alpha_n \left[\frac{c_{p0} \gamma_0'^2 \lambda_0'^2}{c_p \gamma'^2 \lambda^2} \right] \left[\frac{\sigma \gamma \gamma''}{\sigma_0 \gamma_0' \gamma_0''} \right]^{1/3} \left(\frac{\Delta\theta}{\Delta\theta_s} \right) \dots (8)$$

$$\alpha_{f0} = \alpha_f \left[\frac{\lambda'^3 \gamma_0'' (\gamma_0' - \gamma_0'') r_0}{\lambda'^3 \gamma'' (\gamma' - \gamma'') r} \right]^{1/3} \left(\frac{\mu''}{\mu_0''} \right)^{1/3} \dots (9)$$

In the case of different surface tension,

$$\alpha_{n0} = \alpha_n (\sigma / \sigma_0)^{1/3} \dots (10)$$

$$\alpha_{f0} = \alpha_f \dots (11)$$

Here, the suffix "0" is the value for saturated water and $\Delta\theta$ and $\Delta\theta_s$ are the temperature difference between the heating surface and liquid and the difference between the temperature of the heating surface and the saturation temperature. $(\Delta\theta_s / \Delta\theta)$ in Eq. (8) is the supplementary term of the motive force of convection current in surface boiling⁽⁶⁾. Accordingly, evaluating the coefficient of heat transfer α_0 which is transformed to the case of saturated water using Eqs. (8), (9) and (3) or Eqs. (10), (11) and (3) (where the one of saturated water is used for L_f/L) and plotting the relation between this α_0 and $\Delta\theta$ (measured value), the result will be as shown in Fig. 11, in which the experimental points of all the local film boilings are brought together into a single curve. As a result, it may be admitted that the explanation of the mechanism in the local film boiling stated already in connection with saturated water is generally applicable.

5. Conclusion

The authors experimented on boiling using a platinum wire and succeeded in realizing the condition where nucleate and film boiling coexist stably and also in grasping the aspect of boiling in that case. On the other hand, they found out about this region that while heat flux increases with the increase of temperature difference, the coefficient of heat transfer decreases with the increase of temperature difference. Such boiling phenomena of both nucleate and film regions as this are to be easily reproduced by temporarily breaking the contact of heating

Fig. 11 Correlation of heat transfer at the coexistence of nucleate and film regions

surface and liquid, generation of which is well conceivable, as a matter of fact, either in the case of piston flow of vapor and water in the evaporating tube or in the case when the scale has come off from the wall of the boiler tube.

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