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Time Variation of Nucleate Boiling Heat Transfer of Water*

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Boiling heat transfer is greatly affected by ease of bubble formation conditioned by surface quality and contamination of the heating surface. This tendency is represented quantitatively as the proportionality constant

$$\zeta = \alpha R / \Delta\theta^2$$

where α =coefficient of heat transfer, R =radius of heating surface and $\Delta\theta$ =temperature difference between heating surface and boiling liquid. ζ decreases with time from the initial value ζ_0 to the final value ζ_∞ corresponding to the steady state of boiling. This process can be written

$$\zeta/\zeta_\infty = 1 + \{(\zeta_0 - \zeta_\infty)/\zeta_\infty\} e^{-kt}, \quad k = 1.5 \text{ 1/h}$$

It is shown that k is independent of the applied heat flux, surface quality of the heating surface and presence of solute, unless it deposits scale on the heating surface. The cause of the variation of ζ is desorption of adsorbed gas during exposure of the freshly polished heating surface to the atmosphere.

Introduction

The coefficient of heat transfer in the region of nucleate boiling decreases with time and reaches to a stationary value, as M. Jakob⁽¹⁾ has already pointed out. Regarding this subject, Nishikawa⁽²⁾, one of the authors of this paper, suggested from the results which he had obtained by experimenting with a roughened surface showing a large time variation of the coefficient of heat transfer that this variation was due to the effect of the air adsorbed to the heating surface. No quantitative relation, however, was obtained at that time. Later, the authors carried out for other purpose a series of experiments with a heating surface coated with thin films of saturated fatty acids and found that there was quite a regular relation in the time variation of the coefficient of heat transfer. Then, after re-examining the data of their previous experiments, the authors could also find the same relation valid generally. This conclusion was confirmed by the complementary experiments recently carried out. This report gives an account of the progress and the results of the research.

1. Method of experiments

The construction of the heater is shown in Fig. 1. The heating surface was a brass plate 100 mm in diameter and 5 mm thick. The side wall and the bottom surface were made of German silver plates. The heat loss from the bottom was prevented by an air chamber installed near it.

l ; Heater	m ; Lid of inner beaker
n ; Inner beaker	o ; Outer beaker
p ; Steam pipe	q ; Hole for feed water
r ; Thermocouple	s ; glass wool

Fig. 1 Test apparatus

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Table 1 Conditions and results of experiments

Test no.	ζ_0	ζ_∞	Heat input, W	Heating surface	Boiling liquid	Year
A	2.95	1.16	120 (constant)	with concentric grooves, 0.2×1.2*	distilled water	1953
B	900	3	**120, (80-120-160)	with orthogonal grooves, 0.25×1.0	"	1954
C	1 330	13	"	"	"	"
D	34.1	14.8	"	"	"	"
E	44.9	12.0	***160, (80-120-160)	"	"	"
F	22.1	13.4	(80-120-160)	"	"	"
G	14.8	11.5	240 (constant)	with orthogonal grooves, 0.2×2.0	"	1957
H	11.7	8.65	120 (constant)	"	"	"
I	13.6	10.3	200 (constant)	"	"	"
J	6.87	3.72	(80-120-160)	smooth, gold-plated	Na oleate solution, 50ppm	1956
K	4.22	3.32	"	"	"	"
L	4.51	3.05	"	with concentric grooves, 0.3×0.6	Na oleate solution, 600ppm	"
M	2.24	1.76	"	smooth, gold-plated	10% saccharose solution	"

* Depth×pitch of grooves. The section of every groove represents an equilateral triangle.

** Constant heat input for the first three points. Cyclic heating for other points.

*** The same as * except that the data are the mean values for each half cycle.

(a) with concentric grooves (depth 0.2 mm × pitch 1.2 mm)
(b) with orthogonal grooves (depth 0.25 mm × pitch 1.0 mm)

Fig. 2 Grooved heating surfaces

Fig. 3 Methods of heating

The varieties of the heating surface were as follows:

- rough surfaces with concentric grooves,
- rough surfaces with orthogonal grooves and
- a gold-plated smooth surface (Table 1).

Fig. 2 shows the grooved surfaces. They were cleaned before experiments by rinsing with benzene and distilled water.

The heater was placed in a beaker 150 mm in diameter. Then the beaker was filled with the liquid, which was to be boiled, so that its level might rise up to 60 mm above the heating surface. In order to prevent heat loss from the side wall,

the beaker was put in a larger one after covering it tightly with a lid, leaving an outlet of steam, and the space between the inner and outer beaker was filled with boiling water to let it serve as a heat insulator.

A thermocouple was inserted into a hole of small diameter drilled radially up to the center of the heating surface, half as deep as the plate thickness. By correcting the reading of the thermocouple, the surface temperature was estimated. The temperature of boiling liquid was also measured. These were measured at the prescribed intervals from the moment the temperature of liquid rose to 100°C. Heat was supplied by means

of an electric heater beneath the heating surface. Fig. 3 shows the magnitude of the heat flux and its change. The heat flux was either kept constant or changed cyclically as $q_1 \rightarrow q_2 \rightarrow q_3 \rightarrow q_2 \rightarrow q_1 \rightarrow$. The cyclic heating was carried out, in order to confirm the validity of the relation (1) in the next section.

2. Representation of bubble formation ability

Some years ago the authors carried out a research on the boiling of water containing calcium sulphate⁽³⁾. The results were as follows: The amount of deposited scale or contamination on the heating surface was considered to be nearly constant during a cycle of heating. The corresponding coefficient of heat transfer could be written

$$\alpha = q / \Delta\theta \propto \Delta\theta^2$$

where

α = coefficient of heat transfer in kcal/m²hr°C,

$\Delta\theta$ = temperature difference between the heating surface and the boiling liquid in °C,

and

q = heat flux in kcal/m²hr.

When the cycles of heating were repeated there was a considerable change of the scale deposition or the contamination, which affected the bubble formation ability or the nucleation, causing α to vary. The proportionality constant defined by

$$\zeta = \alpha R / \Delta\theta^2 = (\alpha R)^3 / (qR)^2 \dots\dots\dots (1)$$

which was constant during each cycle showed different values for different cycles. Here, R denotes the radius of the heating surface in m which was introduced in order to consider its effect on the boiling heat transfer. As the difference of ζ was caused by the change of the bubble formation ability, the latter could be expressed by ζ .

This was also justified in other cases. It was found from the results of many experiments that another expression for the bubble formation ability i.e. the number of vapor columns on the heating surface n was connected with ζ as follows:

$$n = (\zeta q R / 298)^2 \dots\dots\dots (2)$$

The fact that ζ is constant for definite surface condition can be verified also by analysing the data of Jakob's experiments. Strictly speaking, ζ is not the parameter purely representing the bubble formation ability. However, when the physical properties of boiling liquid are definite, as in the case of boiling water under the atmospheric pressure, the bubble formation ability can be relatively represented by using ζ . Therefore, in the following description, the authors will consistently use ζ and trace its time variation.

3. Results of experiments

(a) Experiments with heating surface coated with film of saturated fatty acid

It was through the experiments with a heating surface coated with a thin film of saturated fatty acid that the authors found for the first time the fact that the nucleate boiling heat transfer varied in a quite regular manner with time. These experiments were carried out primarily in order to find the dependence of the boiling heat transfer upon greasy contamination on the heating surface. The quantitative representation of the contamination was obtained by measuring the contact potential difference between the heating surface and a standard electrode of gold-plated brass plate with Zisman's method of vibrating electrode. The value of the contact potential difference was connected with the value of ζ obtained by the boiling experiments. A very small amount of saturated fatty acid $C_nH_{2n}O_2$ with different values of n was rubbed onto the heating surface and its thin film was formed. As the surface tension of the boiling water did not change practically, there was no change of the physical properties. Consequently, the authors could compare the bubble formation ability of the coated films by using ζ .

The results are shown in Table 2 in which the number of carbon atoms is given by $C_6 \dots C_{18}$. It will be rather safe, however, to consider it as denoting merely the sample number, the purity of the sample being doubtful and the thickness of the coated films not always equal according to circumstances. Now, calculating the mean value of ζ for each half cycle, denoting by ζ_0 , ζ_1 , ζ_2 and ζ_3 respectively, and plotting these against the corresponding time, the time variation of ζ will be found to be expressed by an exponentially decreasing curve. Moreover, the curves corresponding to different values of n are similar to each other, as shown in Fig. 4. Neglecting the slight deviation from the specified time for each half cycle and plotting these values of ζ against ζ_3 , the values of ζ_0 , ζ_1 and ζ_2 will be clearly shown as proportional to ζ_3 , as in Fig. 5. From the values of ζ/ζ_3 in Table 3 the asymptotic value ζ_∞/ζ_3 is estimated as 0.97. Then, analysing the data in the Table, the authors obtain finally the relation

$$\zeta/\zeta_\infty = 1 + 0.48e^{-1.5t} \dots\dots\dots (3)$$

The power of the exponential function takes a common coefficient 1.5 to all the samples. This relation is also shown in Fig. 8. The contact potential difference $\Delta\varphi$ mV measured simultaneously when the temperature of water rose to 100°C and the bubbles reached to the free surface with-

Table 2 The change of ζ for the heating surface coated with thin films of saturated fatty acids

Sample no.	Main constituent	No. of cycle							
		1/2		1		1 1/2		2	
		t_0	ζ_0	t_1	ζ_1	t_2	ζ_2	t_3	ζ_3
C ₆	Caproic acid	0	4.17	35	3.77	75	3.66	110	3.49
C ₈	Caprylic acid	0	3.42	40	2.90	75	2.46	110	2.47
C ₁₀	Capric acid	0	2.83	35	2.21	75	2.04	110	2.04
C ₁₂	Lauric acid	0	5.11	40	4.00	75	3.78	110	3.67
C ₁₄	Myristic acid	0	5.86	40	4.80	75	4.58	110	4.10
C ₁₆	Palmitic acid	0	9.39	35	7.72	75	6.78	120	6.48
C ₁₈	Stearic acid	0	11.49	35	8.67	75	7.73	110	7.43
Average time, min		0		37.14		75.00		111.7

Fig. 4 Experimental results with heating surface coated with thin films of fatty acids

Fig. 5 Relation between ζ in each half cycle

out condensing is plotted in Fig. 6 against ζ_0 corresponding to the boiling experiment that succeeded it. Although it may have only an indirect significance to the subject of the present report, what is noteworthy here is a close dependence existing between the two.

Table 3 Results and conclusion of the experiment with the heating surface coated with thin films of saturated fatty acids

	ζ_0	ζ_1	ζ_2	ζ_3	ζ
t , min	0	37.14	75.00	111.7	∞
t , hr	0	0.619	1.25	1.86	∞
ζ/ζ_3	1.44	1.16	1.04	1.00	0.97
ζ/ζ_∞	1.48	1.19	1.07	1.03	1.00
$(\zeta - \zeta_\infty)/\zeta_\infty$	0.48	0.19	0.07	0.03	0
$\log_e(\frac{\zeta - \zeta_\infty}{\zeta_\infty})$	-0.734	-1.655	-2.66	-3.5	$-\infty$
$\log_e(\frac{\zeta_0 - \zeta_\infty}{\zeta_\infty})$	0	0.921	1.93	2.8	—
$\log_e(\frac{\zeta_0 - \zeta_\infty}{\zeta_\infty})/t$	—	1.49	1.54	1.5	—

Fig. 6 Relation between ζ and contact potential difference of heating surface coated with thin films of fatty acids

(b) Experiments with rough surface in distilled water

In order to verify the exponential decrease of ζ , checking the results of the experiments carried out several years ago, the authors found rough surfaces to show large time variation of ζ generally. Especially, the variation was largest with the orthogonally grooved surface. When Nishikawa treated the change of the boiling phenomena with rough

heating surfaces qualitatively in the previous report, he pointed out that the appearance of boiling changed considerably with the time variation of ζ . The lines A–F in Table 1 show the results of the re-examination, where ζ_0 is the value of ζ at the time when the temperature of water rose to 100°C. Fig. 7 is the plot of $\log_{10}(\zeta - \zeta_\infty)$ against time t . It decreases linearly with t , and the slope of every straight line has an equal value in the wide range of ζ i.e. 0.1–10³. Analytically, we can write

$$\frac{\zeta}{\zeta_\infty} = 1 + \left(\frac{\zeta_0 - \zeta_\infty}{\zeta_\infty} \right) e^{-kt} \quad (4)$$

where

$$k = 1.5 \quad 1/h \quad (5)$$

It is noted that these relations hold independently of the procedure of heating such as A–F in Fig. 3. Moreover, the relation (3) was obtained from the experiments with the mean flux of 21 860 kcal/m²hr (200 W), while in the present case it was 13 130 kcal/m²hr (120 W). The value of k is equal independently of the heat flux. In order to ascertain this conclusion, we carried out additional experiments with steady heat flux 120, 200 or 240 W. The authors' view was confirmed by the results shown in Fig. 7 as the lines H, I and G. The coefficient 0.48 in Eq. (3) was obtained in a particular case. For general cases, it is advisable to adopt the Eq. (4), since the coefficient is

different according to surface condition, as will be shown in the following paragraph.

(c) Experiments with soap solution

When the solution of sodium oleate was used in place of distilled water, the bubble formation ability was generally improved and ζ increased. Here, the surface tension of water decreased, but the relations (4) and (5) held equally, the evidence of which is shown in Fig. 8. The lines J and K are corresponding to the gold-plated heating surface, while L is the result with concentrically grooved surface. Therefore, it is also verified that the difference in the heating surface has no influence on the value of k .

The result of the experiment with 10 % saccharose solution with the gold-plated surface was summarized as a straight line close to the line of $(\zeta - \zeta_\infty)/\zeta_\infty$ in Fig. 8. However, such solution as CaSO₄ that deposited scale on the heating surface gave less value of k than other cases. The scale deposition often caused an increase in the bubble formation ability or ζ in extreme cases.

4. Discussion and conclusions

As mentioned above, the relations (4) and (5) held independently of the procedure of heating, the roughness and the plating of the heating surface, the presence of thin film of fatty acid, and the kind and concentration of the solute. In the case of a smooth brass plate, the time variation

Fig. 7 Experimental results with distilled water (Symbols are shown in Table 1)

Fig. 8 Experimental results with solution of sodium oleate and time variation of $(\zeta - \zeta_\infty)/\zeta_\infty$ with heating surface coated with films of fatty acids

Table 4 Effect of condition of heating surface on change of ζ

Boiling liquid	Condition of heating Surface	Newly polished		After Boiling	
		laid in air	laid in water	laid in air	laid in water
Water containing gas	$*T_1 \times T_2$, hr	0×20	***0×0	—	3×19
	ζ_0/ζ_∞	**11.7/8.65 10.4/8.15	7.29/6.89	—	5.57/5.28
Degassed water	$T_1 \times T_2$, hr	0×19.5	—	2×25	3×20
	ζ_0/ζ_∞	13.6/10.3	—	3.77/3.61	1.69/1.58
$(\zeta_0 - \zeta_\infty)/\zeta_\infty$, %		32	6	4	6

Note: Heating surface: with orthogonal grooves, depth×pitch=0.2 mm×2.0 mm

*) T_1 : Time of boiling after polishing

T_2 : Time of lying in air or in water after T_1

The change of ζ is corresponding to the experiment after the time T_2 .

**) The value with the heating surface lying in air for 200 hr was 14.8/11.5. The change was 29%.

**) After polishing the heating surface was submerged in water and heat input was applied immediately.

of ζ was so small that it was often covered by experimental errors. The same relations, however, may hold in this case, too. Concerning the cause of the time variation of boiling, Jakob concluded that it was due to the adsorption of air to the heating surface. Nishikawa also obtained the same conclusion in the previous report. The authors could confirm this by analysing the rate of change of ζ during the boiling experiments. Table 4 shows the results.

There was no appreciable difference between the values of $(\zeta - \zeta_\infty)/\zeta_\infty$ with distilled water from which dissolved gas had been purged by boiling in advance and those with water containing dissolved air. Thus, it was made clear that the time variation was not caused by the effect of the dissolved air. Next, the experiment with the heating surface laid about 20 hr in the air after the polishing of it showed the value of $(\zeta - \zeta_\infty)/\zeta_\infty$ as much as 32 %, whereas it was merely 6 % when the heating surface had been submerged in water immediately after the polishing but without the exposing of it to the air. On the other hand, in the case of the surface colored dark by boiling in advance, the value of $(\zeta - \zeta_\infty)/\zeta_\infty$ was 4 % even after the exposing of it to the air for 25 hr and it was 6 % after its submersion in water for 20 hr.

From the foregoing experimental evidence it is concluded that the regular time variation of ζ is caused by the desorption of air adsorbed to the heating surface or to the thin film on it. The authors could further confirm the conclusion of the previous report that the dark-colored surface covered with an oxide film hardly caused the variation of ζ , since its surface had lost the ability to adsorb air.

Beside the experiments under the atmospheric pressure, the authors are now carrying out those under reduced pressure. They further intend to undertake various experiments with liquids other than water and with adsorbed gases other than air.

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