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Experimental Studies of Burnout under Boiling*

(2nd Report, On the Effects of Subcooling, Tube Diameter and Air Content)

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Continued from the 1st Report, this paper deals with the effects of subcooling, tube diameter and air content under the transient boiling caused by step heat input. The experiments were carried out under the condition of a natural circulation of the water under atmospheric pressure.

The results obtained are as follows:

- 1) Until a burnout occurs, the surface temperature of heat generator (nichrome wire) is independent of subcooling, the tube diameter or the air content, and the characteristics of heat transfer are similar to those under steady boiling.
- 2) The time lag to the burnout caused, which increases with the decreasing of the power input, is proportional to the subcooling or the tube diameter, but it has no relation to the air content.
- 3) When the value of subcooling, the tube diameter or the power input is large, a burnout is caused by the partial film boiling, while it is caused by the bubble blocking when that value is small. In the case of the subcooling of 0°C, especially, a burnout occurs owing to the film boiling without being affected by the tube diameter.
- 4) The critical heat flux, which does not cause a burnout, depends on the subcooling or the tube diameter, but it is independent of the air content.

1. Introduction

In the 1st Report⁽¹⁾, the natural circulation boiling caused by step heat input to the heat generator in a vertical circular tube was treated, and the transient phenomena to meltdown were made clear. In those experiments, the inlet subcooling and the air content of water were only one kind. By the way, McAdams et al⁽²⁾ and Forster et al⁽³⁾ concluded that in the steady nucleate boiling the degree of subcooling had not an effect on the characteristics of heat transfer if the heat flux was correlated with the superheating of wall surface. It is, however, supposed that the degree of subcooling being varied with position and time has some effects on bubble generating, bubble gathering, bubble blocking, etc. under transient boiling due to high heat flux in a channel flow. According to the studies by McAdams et al⁽²⁾ and Gunther⁽⁴⁾, it is clear that the degree of subcooling has an effect on

the burnout heat flux.

Jens and Lottes⁽⁵⁾ found from their experiments of steady boiling under high pressure that the air content had a negligible effect on the characteristics of heat transfer, but McAdams et al⁽²⁾ reported that the effect could not be neglected.

This paper deals with the effects of subcooling, tube diameter and air content on the burnout phenomena, under the condition of a natural circulation of water under atmospheric pressure due to step heat input to the heat generator supported in vertical tubes of various diameters.

2. Apparatus and experimental procedures

The heat generator was a nichrome wire of 200 mm length and 0.2 mm diameter and a copper wire of the same diameter was butt-welded at both ends. The surface treatment and the method of supporting the wire were similar to those in the 1st Report. In order to investigate the effects of subcooling and air content, a double water tank was used. The inlet subcoolings treated in the experiments are 0°C, 15°C, 25°C, 35°C, 50°C, 65°C and

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80°C. The temperature of the water was measured with thermocouples of copper-constantan, or mercury thermometers, and it was regulated within the range of $\pm 0.5^\circ\text{C}$ of the required value.

The experiments were carried out to investigate the effects of air content by using a degassed and a non-degassed water under the condition of the inlet subcooling of 80°C. The air content of the two kinds of water was measured with the Winkler method. The degassed water had 1.2 ppm O_2 , and the non-degassed 13 ppm O_2 . Counting the existent Nitrogen, the air contents were about three times of these values.

The diameters of tubes treated in the experiments were 2, 3, 4, 6, 8 and 10 mm. Moreover, the experiments were also carried out without a tube to investigate the burnout in a case of pool boiling.

The experimental procedures were similar to those in the 1st Report.

3. Results and discussions

(1) Temperature change of the heat generator

The temperature change of the heat generator recorded on the oscillogram varies according to the subcooling, tube diameter and heat input. The temperature rises abruptly soon after the heating, and the overshoot of about 20°C is caused at the maximum. Afterwards, the nucleate boiling begins

Fig. 1 Examples of oscillogram

and it continues until a burnout occurs. This process is shown in Fig. 1 (a) and (b), for example. In Fig. 1 (a), the inlet subcooling was 80°C, air content 1.2 ppm and tube diameter 3 mm. In Fig. 1 (b), the inlet subcooling was 0°C, air content 1.2 ppm and tube diameter 6 mm.

In each figure, the amplitude Z_g of oscillators of electromagnetic oscillograph corresponding to the change in the temperature of the nichrome wire is shown and the heat input is used as a parameter. Z_g is proportional to the products of temperature rise from the initial temperature and square root of heat input.

In Fig. 1 (a), small temperature change is observed within the transient boiling region. This is caused owing to a partial congregation of bubbles, but it is not so large as to cause a burnout. As shown in Fig. 1 (b), the transient boiling region is narrow, and the burnout occurs after a smooth change in the temperature of the heat generator. The burnout point is such as defined in the 1st Report, that is, the point where the temperature of the heat generator rises abruptly after the transient boiling region. Therefore, the burnout point is defined clearly when the subcooling is high, but it is rather difficult to define when the subcooling is near 0°C or the heat input is high. So, the experimental data are scattered. Generally speaking, however, the time interval of the region of transient nucleate boiling until a burnout occurs is longer, as the inlet subcooling increases or the heat input decreases.

After it passes the burnout point, the temperature of the heat generator rises abruptly and the heat generator is melted down in A, B, C or D type as defined in the 1st Report.

The details of the overshoot of temperature at the beginning of step change could not be observed satisfactorily, because the oscillator was braked excessively in the experiments. But a remarkable overshoot was observed, even when the subcooling was lower. This fact is different from the results by Rosenthal⁽⁶⁾.

(2) Surface temperature of the heat generator within the transient boiling region

The correlations between the temperature difference $\Delta T_{\text{sub}2}$ and the heat flux q_2 at the point where the transient boiling begins after the overshoot point are shown in Fig. 2, using the inlet subcooling as a parameter. The inlet subcoolings are 0°C , 25°C , 50°C and 80°C .

From this figure, it is shown that the degree of subcooling has a large effect on the correlation between $\Delta T_{\text{sub}2}$ and q_2 . But, the tube diameter has no effects on that correlation when the inlet subcooling is kept constant.

Fig. 2 Correlation between temperature difference ΔT_{sub2} and heat flux q_2

Fig. 3 Correlation between surface excess temperature ΔT_{sat2} and heat flux q_2

Fig. 4 Relation between burnout time and heat flux (inlet subcooling 80°C)

Fig. 5 Relation between burnout time and heat flux (inlet subcooling 50°C)

Fig. 6 Relation between burnout time and heat flux (inlet subcooling 25°C)

Fig. 7 Relation between burnout time and heat flux (inlet subcooling 0°C)

In the case where the inlet subcooling is 80°C, the correlation both for degassed water and for non-degassed are shown. The air content has no remarkable effects on the correlation.

In order to simplify a diagram of the results of experiments which were done with combinations of variables, namely, tube diameter, inlet subcooling and air content, the correlation between the surface excess temperature at the point 2, $\Delta T_{\text{sat}2}$ (the difference between surface temperature of the heat generator and the saturated temperature) and the heat flux q_2 is shown in Fig. 3, using the same key for the same subcooling. Although the data are rather scattered, it may be concluded that the inlet subcooling has scarcely any effect on the relation between $\Delta T_{\text{sat}2}$ and q_2 . From Fig. 3, the following equation is obtained for the experimental data;

$$q_2 = 4.68 \Delta T_{\text{sat}2}^{1.71} \times 10^3 \quad \text{..... (1)}$$

where $\Delta T_{\text{sat}2}$ is in °C and heat flux in kcal/m²hr.

(3) Burnout time and critical heat flux

The relation between burnout time τ_B (time interval from the beginning point of boiling till the burnout point) and the heat flux q_B is shown in Figs. 4, 5, 6 and 7 of log-log scale. Especially in Fig. 4, the data for the degassed water are compared with those for the non-degassed. The other figures show the data for the degassed water.

From these figures, the following facts are obtained:

i) When the relation between burnout time τ_B and heat flux q_B is shown in log-log scale, the curves have a constant gradient, independent of inlet subcooling, air content and tube diameter. The gradient is about -1.7.

ii) The burnout time, under the condition of constant heat flux, becomes longer as the tube diameter increases, although it is almost independent

of tube diameter under the inlet subcooling of 0°C.

iii) The burnout time becomes longer as the inlet subcooling increases, when the tube diameter and the heat flux are constant.

iv) The air content has scarcely any effect within the region of experiments.

v) The critical heat flux, the maximum heat flux which does not cause a burnout ($\tau_B = \infty$), is shown by arrow mark at the right part in each figure. This value is dependent on the inlet subcooling and tube diameter, but independent of the air content.

The critical heat flux is plotted in Fig. 8 of semi-log scale. The curves drawn in the figure are evaluated by the following equation:

$$q_c/10^7 = 4.5 D_e^{1.3} \Delta t^{0.824} \text{ kcal/m}^2\text{hr} \quad \text{..... (2)}$$

where D_e = tube diameter—diameter of heat generator, m

Δt = inlet subcooling, °C

This equation, however, is not satisfied for the inlet subcooling of 0°C and pool boiling.

vi) The empirical equation of burnout time τ_B when the heat flux is higher than the critical value is given by

$$\tau_B = C (q_B/10^6)^{-1.7} \text{ sec} \quad \text{..... (3)}$$

where C is a constant which is referred to the tube diameter as shown in Table 1.

When the inlet subcooling is 0°C and the heat flux is higher than the critical value which is related to the tube diameter, a burnout is caused by the film boiling all over the heat generator in a very short time (nearly 0.1 sec). So the effect of tube diameter can not be recognized and C is independent of the diameter.

(4) Behaviors of bubbles and its effects on burnout

Several investigators have already tried to analyse theoretically⁽⁸⁾⁽⁹⁾ the burnout, but a few have treated the burnout in a channel flow⁽¹⁰⁾⁽¹¹⁾. In order to provide a basis for theoretical analysis of burnout phenomena and consider the results of these experiments, the observation of the phenomena was made simultaneously with the measurement. In the following paragraph, the observation concerns the case where the heat input is near or over the

Fig. 8 Relation between inlet subcooling and critical heat flux

Table 1

Inlet subcooling Δt	Pipe diameter mm			
	2	3	4	5
80 (1.2 ppm O ₂) 13 ppm O ₂)	2.95	3.90	6.20	6.20
50 (1.2 ppm O ₂)	1.00	1.85	5.00	—
25 (")	0.30	0.52	0.95	—
0 (")	0.023	—	0.023	0.023

critical heat flux.

i) The case of the inlet subcooling of 80°C and non-degassed water.

The behavior of bubbles varies greatly until a burnout occurs corresponding to the heat input. Namely, in the case of comparatively low heat input and small tube diameter, the bubbles generated at the heat generator grow to about 1 mm of diameter as the mean temperature of water within the tube increases with time. These bubbles leave the heat generator and go up the tube. At the same time, powder-like-bubbles are ejected radially between the large bubbles generated at the surface of the heat generator.

In the case of comparatively high heat input or large tube diameter, large bubbles are not generated but small bubbles are ejected violently with a loud vibratory sound and they fill the tube.

The natural circulation of water in the tube owing to the generation of bubbles and the cause of burnout vary according to the tube diameter or the heat input. When the tube diameter is small (2, 3 or 4 mm) and the heat input is comparatively low (lower than 1×10^6 kcal/m²hr), large bubbles gather together as they go up in the tube and they fill the tube at the upper part of the tube and a steam blocking occurs. At that time, the blocking bubbles go up the tube, move reciprocatingly like a piston, or stand still at the same point. In these cases, the temperature of wall covered by bubbles rises, but a burnout does not always occur, when this part is comparatively small or the piston motion of bubbles appears. However, when the tube diameter is large and the heat input is not so high, comparatively small bubbles are mainly generated. As these bubbles go up, the subcooling at the upper part of the tube decreases and the bubble density increases, and then a burnout occurs. When the heat input is very high, a burnout is caused by the film boiling before the flow of water is fully developed in the tube.

ii) The case of the inlet subcooling larger than 0°C and degassed water.

The bubbles generated before a burnout occurs have various dimensions. But, comparatively small bubbles fill a large part of the tube, when the inlet subcooling and the heat input are comparatively high. For example, there exist mostly small bubbles in the tubes when the inlet subcooling is 80°C and the heat input is high (higher than 1.4×10^6 kcal/m²hr). On the other hand, large bubbles fill a large part of the tube, when the inlet subcooling is 15°C or 25°C and the heat input is low. Of course, there are large bubbles when the tube diameter is small and the heat input is low, even if the inlet subcool-

ing is high.

A burnout may be caused by a steam blocking when many large bubbles are generated, and by the film boiling when there are many small bubbles. It is difficult to observe the details of the burnout phenomena when it occurs rapidly, but it is recognized that the burnout is caused instantaneously by the film boiling when the subcooling is low and the heat flux is very high.

iii) The case of the inlet subcooling of 0°C and degassed water.

In this case, only large bubbles are generated. For comparatively low heat flux, large bubbles go up in the tube and a burnout is caused by a steam blocking near the tube exit. As the heat input increases, a burnout is caused by the film boiling before the flow in the tube is fully developed, and the film boiling is caused all along the heat generator at last. When the inlet subcooling is 0°C, the burnout process depends only on the heat input, unlike the other cases.

4. Conclusion

Using a nichrome wire of 200 mm length and 0.2 mm diameter as heat generator, the effects of the inlet subcooling, tube diameter and air content on the transient boiling within the vertical tube were investigated. The experiments were carried out under the condition of a natural circulation of water under atmospheric pressure.

The conclusions are as follows:

(1) Within the transient boiling region, the surface temperature of the heat generator is almost independent of the inlet subcooling, tube diameter and air content, and it is uniquely given by the heat flux as shown in Eq. (1).

(2) Two kinds of bubbles are observed. Large bubbles are mostly generated when the inlet subcooling and the heat flux are low, and small bubbles are mostly generated when those are high.

(3) A burnout is caused by the local film boiling when the inlet subcooling, heat input and tube diameter are large. On the other hand, a burnout is due to a steam blocking when the inlet subcooling, heat input and tube diameter are small. But it is caused by the film boiling in a wide region, independently of tube diameter, when the inlet subcooling is 0°C.

(4) The critical heat flux varies according to the inlet subcooling and tube diameter, but it is independent of the air content. The values are shown in Fig. 8.

(5) The time interval from the beginning point of boiling until the burnout point becomes longer, as the inlet subcooling and tube diameter

increase and the heat input decreases, but it is independent of the air content. This relation is indicated in Eq. (3), Figs. 4, 5, 6 and 7.

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Eddy Diffusions of a Fuel Gas from a Cylindrical Fuel Burner*

By Atsushi SAIMA**

It is easy to determine the mechanism of time average eddy diffusion of fuel gas in a flame. But it is very difficult to determine the instantaneous movements of fuel gas in the flame. In the experiment described in this paper the fuel jet was ignited at various positions in the fuel jet by electric sparks, and the spreading of the flame was observed.

Ignition probability was measured at various positions of the fuel jet, being determined by the mixture ratio and mean velocity of fuel jet and the velocity of secondary air.

It seems that the ignition probability chiefly depends upon the fluctuation of the fuel concentration.

It was found that, for an ignition for obtaining a steady flame, a spark must be provided immediately behind the burner tube wall.

1. Introduction

It is thought to be important for the industrial purposes to know the mechanism of eddy diffusions of a fuel gas from a burner tube to the surrounding air in the case of a cylindrical burner.

It is easy to determine the mechanism of time average eddy diffusion of fuel gas in a burner flame. For instance, the time average eddy diffusion in a flame has been determined by several researchers, using gas sampling methods, etc. But it is very difficult to determine the instantaneous movement of fuel gas in the flame. Optical methods would appear to be one of the methods available for this purpose, in the experiment described in this paper the fuel jet was ignited at various positions in the fuel jet by electric sparks, and the spreading of the flame was observed.

Ignition probability was measured at various positions of the fuel jet, being determined by the mixture ratio and mean velocity of fuel jet and the velocity of the secondary air.

It seems that the ignition probability chiefly depends upon the fluctuation of the fuel concentration that is in the inflammable limits.

2. Experimental apparatus

(a) Burner⁽¹⁾

Fuel gas and primary air were mixed at the bottom of a burner tube with 10 mm inner diameter and 600 mm length.

For the fuel, the commercial propane gas was used. The experiment was carried out on a fuel jet in which the fuel-air ratio $M = G_a/G_f$ of the mixture of primary air and fuel was varied.

G_a kg/sec and G_f kg/sec are rates of flows per unit time of primary air and fuel, respectively.

The mixture ratio M is outside of the inflammable limit, and it becomes an inflammable mixture

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