Study on Contact Area of Pool Boiling Bubbles on a Heating Surface* (Observation of Bubbles in Transition Boiling)

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The contact area of boiling bubbles on the horizontal heating surface of transparent glass was observed from the back side of the heating surface through a transparent fused salt in transition boiling. The boiling liquid was Freon R-113, and the experiment was performed under the saturation condition at atmospheric pressure. The behavior of bubbles and liquid on the heating surface was observed in transition boiling by means of photography. As a result, the ratio of the area of the microlayer in contact bubbles on the heating surface to the total area of the heating surface decreased and the ratio of the dry contact area of the bubbles on the heating surface increased with increasing of the superheat of the heating surface.

Key Words: Pool Boiling, Transition Boiling, Behavior of Boiling Bubbles, Microlayer of Liquid, Dry Area of Heating Surface

1. Introduction

Details of the contact state of boiling bubbles on the heating surface in nucleate boiling were reported in the investigation by one of the authors and a colleague⁽¹⁾. In the experiment, an electroconductive glass was employed as a heating surface to observe the contact surface of bubbles from behind a heating surface by means of photography. The practice was performed below the near critical heat flux point, because the electroconductive layer broke in the higher superheat region. However, a lot of new interesting information was obtained through earlier investigations^{(2),(3)}. For example, very thin microlayers of liquid existed between the contact bubbles and the heating surface, and the microlayer exhibited very high heat transfer performance. These facts evidently proved that nucleate boiling had a much better heat transfer coefficient than that of single-phase flow.

Some investigators reported without use of the visual observation method that the boiling liquid maintained contact with the heating surface in transition boiling^{(4)~(6)}. Nevertheless, in fact, the details of the contact state of liquid on the heating surface in

transition boiling are still unknown.

In the present research, a specific experimental arrangement was designed to observe visually the contact surface of liquid and bubbles on the heating surface in boiling heat transfer. A thin transparent quartz glass plate was employed as a heating surface, and the quartz glass plate was heated by hot transparent fused salts. This arrangement enables the examination of a boiling heat transfer in the region from nucleate boiling to the beginning of film boiling. The present experiment was performed using Freon R-113 for boiling liquid to research the details of the contact state of bubbles and liquid on the heating surface in the wide range of the boiling region by means of a direct visual observation method.

2. Nomenclature

- A_0 : Total area of heating surface, m^2
- A_c : Area of dry part in the single contact bubble on the heating surface, m^2
- A_f : Area of vapor film in the single contact bubble on the heating surface, m^2
- A_l : Area of microlayer in the single contact bubble on the heating surface, m^2
- A_v : Area of single contact bubble on the heating surface, m^2
- q : Heat flux, W/m^2
- q_{cr} : Critical heat flux, W/m^2

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- T : Temperature, K
 T_0 : Temperature of heating liquid, K
 $T'_{0\text{ exp}}$: Measured temperature of opposite surface of heating surface, K
 $T'_{0\text{ ext}}$: Estimated temperature of bottom surface of aluminum column by extrapolation of axial temperature distribution, K
 T_{sat} : Saturation temperature, K
 ΔT_{sat} : Superheat of heating surface, K
 ΔT_{sub} : Subcooling of boiling liquid, K
 T_w : Temperature of heating surface, K
 Δx : Thickness of heating plate, K
 λ_G : Thermal conductivity of heating plate, W/mK

3. Experimental Arrangement

The outline of the experimental arrangement is shown in Fig. 1 and the details of the heating surface are shown in Fig. 2. The quartz glass cylinder bottle 3 is supported by the stainless steel case 2 and thermal insulating materials 15, 16. The diameter of the outer case 2 is 105 mm, and the thickness is 1.5 mm. The bottom surface of the cylinder bottle 3 is used as a heating surface, and the diameter is 35 mm and the thickness is 0.8 mm, respectively, as shown in Fig. 2. The insulation 15 is glass wool sheets, and the insulation 16 is a siliglass plate which is a kind of ceramic material and has very good heat resistance. The bottle 3 and the support case 2 are assembled on the heating vessel 1, which is made of a Pyrex glass.

A fused salt is employed as a heating liquid and

Fig. 1 Experimental arrangement

poured into vessel 1. The heating liquid is heated by an electric heater (SiC) 6. The temperature of the heating liquid is controlled and maintained uniformly by a power controller 14, a watt meter 13, a thermometer (thermocouple-K) 8 and a stirrer 7.

The reference temperature of the opposite side of the heating surface is measured by a sheet thermocouple (K type) 9 which is fixed 8 mm from the center of the heating plate by a silver paste, as shown in Fig. 2. The sheet thermocouple is standardized as grade 0.75 in JIS (Japan Industrial Standard), and the time constant is 0.13 s.

4. Experimental

4.1 Heating liquid and boiling liquid

Good thermal conductivity, good transparency and high resistivity against corrosion are strongly required for a heating surface material in the present experiment. A thin quartz glass plate satisfies the above requirements. A quartz glass cylinder is welded into the quartz glass plate because of the strength and difficulty of sealing against boiling liquid, and the bottom surface of the cylinder bottle forms a heating surface.

It is required for a heating liquid in the present experiment that the transparency be superior in a wide range of liquid temperature, that the thermal conductivity be not much lower than the critical heat flux point of liquid, and that the melting point be about 373 K or below. A fused salt (HTS) is effective in the experiment. The fused salt HTS is composed of NaNO_3 in 7 mol %, KNO_3 in 44 mol % and NaNO_2 in 49 mol %. The melting point of HTS is 415.2 K, and the maximum usable temperature is 673.2 K.

Then, it is required for a boiling liquid to give some temperature difference between both sides of the heating plate, that the saturation temperature be lower than 373 K at atmospheric pressure and that the

Fig. 2 Details of heating surface

latent heat be not so large. If the saturation temperature of boiling liquid is extremely low, the fused salt which is touching the heating plate will be congealed and turn opaque. Freon R-113 was employed as a boiling liquid which satisfied the above requirements. The saturation temperature of R-113 is 320.8 K, and the latent heat is 1.45×10^5 kJ/kg.

4.2 Measurement of temperature of heating surface and heat flux

In the present experiment, it is impossible to measure directly the temperature distribution of a heating plate or to determine the temperature of a heating surface and the heat flux by the temperature distribution because the heating plate is made of a thin piece of quartz glass. If a small thermometer were fixed on the heating surface, the surface condition of the measuring area would be different from the other areas of the heating surface, and boiling bubbles would be easy to generate from the measuring area. Therefore, a supplemental experiment for the estimation of temperature of heating surface and heat flux was provided before the experiment was conducted.

Figure 3 shows a schematic diagram of the supplemental experiment. An aluminum column is used in the place of a quartz glass plate. The diameter is 35 mm and the length is 110 mm. Four thermocouples (K type) are inserted in the center axis of the column with intervals of 15 mm. The thermocouples are grade 0.75 in JIS and the wire diameter is 0.35 mm. An aluminum vessel is assembled on the top of the column, and the vessel is filled with boiling liquid. The top surface of the column is the heating surface. A sheet thermocouple is fixed at the bottom surface of the column in the same manner as for the quartz glass plate. The side surface of the column is enveloped with thermal insulating materials which are silicon rubber and glass wool. Heat loss from the side surface of the column is estimated below about 2% of the axial heat flow rate by a temperature distribution of thermal insulations.

Heat flux q is calculated by the axial temperature distribution in the column and the popular equation of one-dimensional thermal conduction.

The temperature of heating surface T_w can be estimated by the temperature of the opposite side of the heating surface $T'_{0 \text{ exp}}$, heat flux q , thickness of heating plate Δx and thermal conductivity of heating plate λ_G as given by Eq. (1).

$$T'_{0 \text{ exp}} - T_w = q \Delta x / \lambda_G \quad (1)$$

Figure 4 shows a relation of measured values $T'_{0 \text{ exp}}$ by sheet thermocouple and extrapolated values $T'_{0 \text{ exp}}$ of temperature distribution for the surface temperature of the bottom of the aluminum column. No differences are found between the two temperatures. According

to the result of Fig. 4, the measured temperature is used for the reference temperature of the opposite side of the heating surface. Figure 5 shows an experimental result on heat flux q , and the temperature difference between the heating liquid T_0 and the opposite side of the heating surface for R-113 and water. Specific relations of heat flux q , temperature of the heating liquid T_0 and the surface temperature of the opposite side of the heating surface $T'_{0 \text{ exp}}$ are given by the result of Fig. 5 and the temperature of heating surface T_w can be determined by Eq. (1).

The critical heat flux of R-113 is about 1.5×10^5 W/m², and the superheat of the heating surface is about 50 K. The difference in temperature between the

Fig. 3 Supplemental apparatus for estimation of heat flux and temperature of heating surface

Fig. 4 Relation of surface temperature between measured values $T'_{0 \text{ exp}}$ and estimated values $T'_{0 \text{ exp}}$

two sides of the quartz glass plate is about 87 K and the temperature of the opposite side of the heating surface is about 460 K. Referring to these data, the present experimental arrangement shown in Fig. 1 is considered to be effective for the experimental research on the boiling heat transfer in the wide range of the transition region.

4.3 Experimental procedure

A strobo flashing beam is applied to the heating surface through the heating vessel 1 and the heating liquid HTS, and the image of boiling bubbles and liquid on the heating surface is focused into photocamera 19 in Fig. 1. In the present research, the heat transfer of R-113 is evaluated at atmospheric pressure and saturated condition. The heating surface has been finished with 5 mm of fine roughness so that a microlayer of the liquid and the dry part of the contact bubble on the heating surface is displayed brightly. A strobo beam is completely reflected at a microlayer of liquid and partially reflected at a dry part of the bubble, as shown in Fig. 6. The former reflection focuses into clear image on the monochromatic photofilm, and the latter one forms a gray image. No reflection is made without bubbles on the heating surface. By reading out the image of bubbles

Fig. 5 Relation between heat flux q and temperature difference of heating liquid T_0 and back side of heating surface $T'_0 \text{ exp}$

and calculating the area of the dry parts and the microlayer, it can be known quantitatively the microlayer which has a very high heat transfer coefficient⁽⁷⁾ and the dry parts which have a low heat transfer coefficient.

5. Results

The experimental result on transition boiling of R-113 is shown in Fig. 7. The experiment was performed under the condition of saturation and atmospheric pressure, and the result is coincident with the boiling curve which is calculated by Kutateladze's equation⁽⁸⁾. According to the result, it is considered that the estimation method of surface temperature and heat flux in the present experiment is reasonable and effective in practice. Every point indicated in Fig. 7 is plotted as an average value for time, and the variation is shown in Fig. 8.

The contact state of bubbles with the heating surface changed instantaneously. Therefore, about 10 photographs were taken continuously at the same superheat of heating surface and average values of the contact area of bubbles on the heating surface were computed by reading out all of the photographs with a digitizer. A typical example of the photographs of contact state of bubbles for R-113 at the near critical heat flux point is shown in Fig. 9. The estimated heat flux is $1.18 \times 10^5 \text{ W/m}^2$, and the superheat of the heating surface is 42 K. As seen from the pictures, the contact state of the bubbles changes gradually within a very short period. In the photographic observations, no dry area is found on the heating surface, or even if dry parts existed, they are observed in the contact area of coalesced bubbles on the heating surface even under the same condition of heat flux and superheat. Figure 9(d) shows an enlarged picture of Fig. 9(c). In the present research, vapor film is defined as coalesced bubbles including the dry area on the heating

Fig. 6 Illustration of light beam path and contact bubbles on the heating surface

surface.

Figure 10 show the contact state of bubbles at 48 K in superheat and $1.2 \times 10^5 \text{ W/m}^2$ in heat flux. Comparing Fig. 10 with Fig. 9, larger dry areas are observed in coalesced bubbles. Figure 11 shows the contact state of bubbles at 52 K in superheat and $1.19 \times 10^5 \text{ W/m}^2$ in heat flux. A larger dry area is observed on the heating surface, but this dry area is very unstable and alternates the growth and the decay within a short period.

The progressive change of the dry area on the heating surface with superheat in the region from transition boiling to the beginning of film boiling is shown in Fig. 12 to Fig. 15. While the superheat rises gradually from 79 K to 223 K, the dry area continues to increase, and the vapor film covers the entire heating surface at about 223 K in superheat.

The contact area of bubbles on the heating sur-

Fig. 7 Boiling curve of R-113 (q - ΔT_{sat})

Fig. 8 Change of superheat ΔT_{sat} and heat flux q for time

face is computed from the series of pictures by a digitizer, and the ratio of area of contact bubbles to the area of heating surface is given with respect to the superheat of the heating surface. The ratio of the total area of contact bubbles to the area of heating surface $\Sigma A_b/A_0$ with respect to the superheat is shown in Fig. 16. The ratio of the microlayer of contact bubbles to the area of the heating surface $\Sigma A_i/A_0$ is shown in Fig. 17. The ratio of the total dry area of contact bubbles to the area of the heating surface $\Sigma A_c/A_0$ and $(\Sigma A_f + \Sigma A_c)/A_0$ are shown in Fig. 18.

6. Discussion

It is widely known that boiling liquid maintains contact with the heating surface in transition boiling.

Fig. 9 Photographs of contact state of bubbles in the higher heat flux region of nucleate boiling

Fig. 10 Photographs of contact state of bubbles in the beginning of transition boiling at $\Delta T_{\text{sat}} = 48 \text{ K}$

Fig. 11 Photographs of contact state of bubbles in the beginning of transition boiling at $\Delta T_{\text{sat}} = 52 \text{ K}$

Fig. 12 Contact state of bubbles in transition boiling at $\Delta T_{\text{sat}} = 79 \text{ K}$

Fig. 13 Contact state of bubbles in transition boiling at $\Delta T_{\text{sat}} = 115 \text{ K}$

Fig. 14 Contact state of bubbles in transition boiling at $\Delta T_{\text{sat}} = 162 \text{ K}$

Fig. 15 Contact state of bubbles at $\Delta T_{\text{sat}} = 223 \text{ K}$

Nevertheless, no one has directly observed the contact state and no one has dealt with the contact state of liquid or bubbles on the heating surface with quantitative expressions. Figures 16, 17 and 18 show that the contact state of boiling bubbles on the heating surface in transition boiling is indicated as a ratio of the contact area of bubbles to the total area of the heating surface. The ratio $\Sigma A_c/A_0$ is approximately 0.55 at the near critical heat flux point ($\Delta T_{\text{sat}} = 40 \text{ K}$) and decreases to about 0.05 (10 % of the former ratio) at 200 K in superheat, as shown in Fig. 17.

$$\Sigma A_v/A_0 \approx -0.50 \left(\frac{\Delta T_{\text{sat}} - \Delta T_{\text{max}}}{\Delta T_{\text{min}} - \Delta T_{\text{max}}} \right)^{0.355} + 0.55 \quad (2)$$

where ΔT_{max} means ΔT_{sat} at which the maximum heat flux or critical heat flux is given, and ΔT_{min} means ΔT_{sat} at which the minimum heat flux is given.

On the other hand, the dry area of the heating surface increases gradually along the nucleate boiling curve with increasing of superheat, as shown in Fig. 18. The ratio of the increase of the dry area becomes smaller above about 50 K in superheat (about 10 K over the critical heat flux point), and the vapor film and the dry part cover the entire heating surface ($(\Sigma A_c + \Sigma A_f)/A_0 = 1.0$) at a little over 200 K in superheat. The total area of the dry part in contact area of single bubble ΣA_c decreases rapidly above superheat of the critical heat flux point, and then the bubbles almost coalesce with each other, and finally the vapor film is formed. Over the entire transition region, the total area of dry part $\Sigma A_c/A_0$ takes the value of 0.02 ~ 0.03.

As shown in Fig. 16, the total area of contact bubbles on the heating surface does not increase as rapidly with the increasing of superheat compared with the case of nucleate boiling above the critical heat flux point, and the dry area increases remarkably

Fig. 16 Ratio of contact area of boiling bubbles to area of heating surface with respect to superheat of heating surface

Fig. 17 Area of microlayer of bubbles and superheat

because of large bubbles coalesced on the heating surface. On the other hand, the number of single bubbles which contact the heating surface decreases with the increasing of superheat and the boiling state continues to proceed to the minimum heat flux point. Film boiling seems to begin from the minimum heat flux point.

7. Conclusions

Boiling heat transfer was investigated by means of a visual observation method using a thin transparent quartz glass plate for a heating surface, Freon R-113 for boiling liquid and a transparent fused salt for a heating medium. The contact state of liquid, bubbles or vapor film on the heating surface was observed directly from the opposite side of the heating surface. According to the experimental research, the following conclusions were obtained.

(1) In transition boiling, boiling liquid maintains contact with the heating surface and bubbles are observed as the case of nucleate boiling. The dry part and microlayer of liquid are observed in the contact surface of bubbles.

(2) In transition boiling, bubbles on the heating surface alternate to coalesce with each other with increasing of superheat of the heating surface, and the dry area which is displayed as spotted pictures in the photographs increases in the contact surface of bubbles.

(3) When the superheat further rises continuously in transition boiling, coalesced bubbles grow larger and the dry area appears near the heating surface. However, the dry surface is very unstable and some dry parts become small and finally disappear.

(4) Dry area covers almost all of the heating

Fig. 18 Dry area of heating surface and superheat

surface near the minimum heat flux point.

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References

- (1) Torikai, K. and Yamazaki, T., Contact Area of Boiling Bubbles on the Heating Surface, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 31, No. 223, (1965), p. 440.
- (2) Torikai, K. and Yamazaki, T., Dry State in Contact Surface of Boiling Bubbles on the Heating Surface, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 92, No. 240, (1966), p. 1275.
- (3) Torikai, K. and Yamazaki, T., On Boiling Heat Transfer on the Unwetttable Heating Surface, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 32, No. 242, (1966), p. 1557.
- (4) Ishitani, K. and Hisano, T., Experimental Research on Transition Boiling Heat Transfer from Vertical Heating Surface in the Water Pool at Atmospheric Pressure, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 31, No. 228, (1965), p. 1251.
- (5) Dhuga, D.S. and Winterton, R.H.S., Measurement of Surface Contact in Transition Boiling, *Int. J. Heat Mass Transfer*, Vol. 28, No. 10, (1985), p. 1868.
- (6) Witte, L.C. and Lienhard, J.H., On the Existence of Two 'Transition' Boiling Curves, *Int. J. Heat Mass Transfer*, Vol. 25, No. 6, (1982), p. 771.
- (7) Torikai, K., Heat Transfer in the Contact Surface of Boiling Bubbles, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 32, No. 240, (1966), p. 1265.
- (8) Kutateladze, S.S., Heat transfer in Consideration and Boiling, *AEC Trans. 3370*, U.S.AEC Tech. Info. Service., p. 340.