Microbubble Emission Boiling on a Horizontal Upward-Facing Rectangular Surface in Subcooled Flow*

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It is known that there exists a boiling condition of subcooled liquid at which many microbubbles are emitted from a heated surface in the transition boiling regime. We call this phenomenon "microbubble emission boiling" (MEB). MEB occurs easily in systems where the subcooled liquid removes the bubbles naturally, and not against their own motion from the surface soon after their generation. Consequently the subcooling and the velocity of the liquid should be very important factors concerning the occurrence of MEB. In this study, our purpose was to clarify the effects of the degree of liquid subcooling and its approaching velocity to the surface on the occurrence of MEB and the intensity of microbubble emission by measuring temperature fluctuations of the surface and pressure fluctuations in the liquid above the surface.

Key Words: Phase Change, Microbubble Emission Boiling, Subcooled Flow Boiling, Liquid Subcooling, Liquid Velocity, Temperature Fluctuation, Pressure Fluctuation

1. Introduction

It is known that there exists a boiling state of highly subcooled liquid in which many microbubbles are emitted from a heated surface in the transition boiling regime. In the following, we call this phenomenon "microbubble emission boiling" (MEB). In comparison with the characteristics of heat transfer in ordinary saturated pool boiling, a very high heat flux is transferred in this MEB region against a relatively lower wall superheat. The typical boiling curve involving MEB is shown in Fig.1. Exceeding the DNB point, the boiling regime changes not to the film boiling with a large, sudden temperature increase of the surface, but to the state which is the so called residual nucleate boiling (RNB) state⁽¹⁾, where the boiling curve has a gentle positive slope. As the heat flux is further increased, microbubbles begin to emit from the surface, and then, the inclination of the boiling curve becomes steep again.

Fig. 1 Regimes in boiling heat transfer

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The microbubble emission phenomenon in the transition boiling regime has already been reported by Nishikawa et al.,⁽²⁾ Inada et al.⁽³⁾ and Tsuchiya⁽⁴⁾ in subcooled pool-boiling systems, and by Fujibayashi et al.⁽¹⁾ and Saito et al.⁽⁵⁾ in subcooled flow-boiling systems.

According to Inada et al.⁽⁶⁾ and Saito et al.,⁽⁵⁾ the microbubble emission phenomenon occurs when a sufficient amount of scale having hydrophilic properties is deposited on the surface during solid-liquid contact in the high heat flux region of boiling, and subcooled liquid is introduced to the surface through it. It is well-known that by selecting the materials of the heated surface and the loop, and controlling carefully the purity of liquid, it is possible to avoid the pollution of the test liquid, and hence, the deposition of scale. In fact, when the experiment was stopped in the RNB regime just before the onset of MEB, no scale could be observed on the surface. When the experiment was stopped in the MEB regime, carbon-like black scale was deposited on the surface, even after selecting the materials of the heated surface and the loop and controlling the liquid purity. Therefore, it can be concluded that scale is produced during MEB, and that the scale is not a main factor affecting on the occurrence of MEB.

Fujibayashi et al.⁽¹⁾ have shown that MEB can easily occur in systems where such subcooled liquid is sucked normally to a horizontal and upward-facing heated surface, and is difficult to occur in systems containing a horizontal and downward-facing heated surface. Saito et al.⁽⁵⁾ confirmed that MEB can be realized in the system where subcooled liquid flows parallel to a horizontal and upward-facing heated surface, as shown in Fig. 2. Judging from the aforementioned facts, MEB occurs easily in the system where the subcooled liquid removes the bubbles naturally and not against their own motion from the surface soon after their generation. Hence, the subcooling and the velocity of the liquid should be the most important factors affecting the occurrence of MEB.

Now, in this study, in consideration of the fact that MEB easily occurs in the systems of horizontal

Fig. 2 Systems in which MEB occurs

upward-facing surfaces, experiments of subcooled flow boiling were performed in a system under the following conditions: the orientation and the shape of the surface were selected to be horizontal upward-facing and rectangular; the area of the surface was relatively large; and subcooled liquid flowed along the surface in the longitudinal direction. Our purpose was to clarify the effects of the degree of liquid subcooling and its approaching velocity to the surface on the occurrence of MEB and the intensity of microbubble emission, by measuring temperature fluctuations of the surface and pressure fluctuations in the liquid above the surface.

2. Nomenclature

q : heat flux, W/m^2

u : velocity, m/s

ΔT_{sat} : temperature difference between the surface and the saturation of liquid

ΔT_{sub} : temperature difference between the saturation of liquid and the liquid supplied

DNB: departure from nucleate boiling

RNB: residual nucleate boiling

MEB: microbubble emission boiling

3. Experimental Apparatus and Procedure

The experimental apparatus is shown schematically in Fig. 3-A. Figure 3-B shows the geometric relationship between the heated surface and the nozzle.

Fig. 3

zle. The heated surface was the upper end of a copper block ③ 10mm wide and 20mm long. The subcooled liquid was supplied to the heated surface horizontally from the nozzle ② (cross-sectional area, $2 \times 20\text{mm}$) and was allowed to flow along it. There was some finesse involved in suspending the copper block at its shoulder, so as not to get a large displacement in the arrangement between the heated surface and the nozzle as a result of thermal expansion of the copper block (as shown in Fig. 3-C). Brass foil was soldered around the heated surface for watertight sealing and thermal insulation, and was fitted to the test chamber ① by a flange. Si-C electric heaters ④ were inserted into the copper block for heating purposes. Heat flux and surface temperature were calculated from the temperature distribution on the axis of the copper block, which was measured with thermocouples ⑤, and their accuracy was evaluated in the saturated pool boiling experiment.

Stainless steel pipes were used for the loop to avoid contamination of the liquid and the deposition of scale on the surface. Test liquid was pure water. Fluid delivery rate was regulated by a needle valve ⑫, and flow velocity was determined by the delivery rate and the cross-sectional area of the nozzle.

Experiments were performed in steady-state conditions by increasing or decreasing gradually the power input to the Si-C electric heaters after regulating the liquid subcooling with a cooler ⑭ and a heater ⑮ in a storage tank ⑬ and the fluid delivery rate.

Before each experiment, the test liquid was renewed and the heated surface was polished with waterproof abrasive paper (#1000) and washed clean with ethanol and pure water.

4. Aspects of MEB

Photographs in Fig. 4 show a series of boiling aspects of nucleate boiling, RNB and MEB under the conditions of $\Delta T_{sub} = 80\text{K}$ and $u = 0.5\text{m/s}$. The letters (a), (b), (c), (d) under the pictures correspond to the positions on the curve in Fig. 5, and the white line in the picture indicates the position of the heated surface.

Figure 4(a) is the photograph near the DNB point which is, judging from the shape of the boiling curve, showing a coalescent bubble trailing at the end of the heated surface of the downstream side, where subcooled liquid is flowing to the right. Increasing the heat flux, the coalescent bubbles begin to form bubble-clouds just above the heated surface in such a way as to adhere to it on the end of the heated surface of the downstream side, which is the onset of the RNB region. The gradient of the boiling curve in RNB becomes gentler than that in nucleate boiling. This situation of boiling spreads on the surface toward the upstream direction with increasing the power input. In Fig. 4(b) the bubble-clouds have progressed to the middle part of the surface (indicated by an arrow), but nucleate boiling remains on the half of the surface of the upstream side. The bubble-clouds have spread

Fig. 4 Aspects of boiling

over the whole surface in Fig. 4(c). When the surface temperature is increased somewhat from this state, a cluster of microbubbles blows out through the bubble-clouds at some points on the surface. The emission of microbubbles becomes continuous and violent with increasing the power input. The heated surface appears indistinct on account of the crowding of microbubbles in the surroundings, as shown in Fig. 4(d). In MEB, microbubbles emit mostly from the middle part of the surface, but rarely from the upstream-side or downstream-side of the surface. Black scale-like carbon was observed on the heated surface after working in the MEB region.

Decreasing the heat flux in MEB, the data retraces the boiling curve which is obtained in increasing the heat flux.

5. Two Possible Factors on the Mechanism of Occurrence of MEB

5.1 Effect of subcooling

Figure 5 shows the effect of subcooling on the boiling curve, by changing ΔT_{sub} from 30 to 80 K for $u = 0.5 \text{ m/s}$. The shapes of the boiling curves can be classified into 3 groups for the subcooling of the liquid.

5.1.1 $\Delta T_{sub} = 30$ and 40 K. Under these conditions, MEB does not occur. If heat input is increased over the DNB point, the surface temperature rises up slowly but unstably to a point near the minimum point of the boiling curve. As this surface temperature behavior is very sensitive to the power input, it is impossible to sustain a steady state between DNB and the minimum point. Above the minimum point, both ΔT_{sat} and q increase with

Fig. 5 Effect of subcooling on boiling curve

increasing of the power input. In the case of $\Delta T_{sub} = 30 \text{ K}$, the boiling state suddenly shifts again to film boiling for the heat flux comparable to the DNB point.

5.1.2 $\Delta T_{sub} = 50 \text{ K}$. In this case, the RNB and MEB regions appear. In the RNB region, the sound peculiar to transition boiling can be heard, and data can be measured in steady state which are different from the cases of $\Delta T_{sub} = 30$ and 40 K. q and ΔT_{sat} increase gradually against the increase of the power input. At a heat flux exceeding about 10^7 W/m^2 , the boiling curve comes to have steep acclivity because of MEB. The boiling sound is higher in tone than that of RNB. Maximum heat flux of MEB is recognized.

5.1.3 $\Delta T_{sub} = 70$ and 80 K. In these cases, MEB is firmly established. In comparison with the case of $\Delta T_{sub} = 50 \text{ K}$, the range of the surface superheat in the RNB region is narrower and the boiling sound in MEB is higher and louder. After the completion of a run, very small holes can be seen on the heated surface, as if they were picked with needles.

In consequence, the liquid subcooling has a great influence on the occurrence of MEB.

5.2 Effect of Velocity

Figures 6 and 7 show the effect of the liquid velocity on the boiling curve, by changing u from 0.1 to 1.0 m/s for $\Delta T_{sub} = 80 \text{ K}$, and from 0.5 to 2.0 m/s for $\Delta T_{sub} = 50 \text{ K}$ respectively.

In the case of $\Delta T_{sub} = 80 \text{ K}$ and $u = 0.1 \text{ m/s}$, MEB does not occur, and the boiling regime changes suddenly to film boiling after DNB. MEB is observed in all other cases except this. Therefore, it can be seen that the velocity of the subcooled liquid is also a necessary

Fig. 6 Effect of velocity on boiling curve at $\Delta T_{sub} = 80 \text{ K}$

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condition for MEB to occur. In each case of $\Delta T_{sub} = 80\text{K}$ and 50K , the RNB range in ΔT_{sat} becomes narrower and the occurrence location of MEB shifts to a higher heat flux region with increasing flow velocity, and the position of DNB and the starting point of MEB on the boiling curve become distinct. Especially in the case of $\Delta T_{sub} = 50\text{K}$ and $u = 2.0\text{m/s}$ (Fig. 7), the boiling curve continues to rise up smoothly from nucleate boiling to MEB. However, the RNB region in which the bubble-clouds covers the surface exists also in this case, and the datum which belongs to that region in the figure is the point of " $q = 1.57 \times 10^7 \text{W/m}^2$ for $\Delta T_{sat} = 82.5\text{K}$." That is, increasing of the flow velocity is effective in increasing the heat transfer coefficient of MEB, as the boiling curves shift leftward with velocity.

6. Temperature Fluctuation on the Heated Surface and Pressure Fluctuation in the Boiling Liquid above the Surface

6.1 Temperature fluctuation

In general, the transition from nucleate boiling depends on the area of the nucleate boiling liquid layer on the heated surface which is diminishing above the DNB point, or on the area of dry patches on the surface which come to appear in that region. The temperature fluctuation on the heated surface is very small in nucleate boiling because the whole heated surface is wetted. In the post-DNB region, however, the temperature fluctuation on the heated surface becomes large as the liquid comes in contact with some dry patches on the heated surface. A sound peculiar to transition boiling is heard, which is made

Fig. 7 Effect of velocity on boiling curve at $\Delta T_{sub} = 50\text{K}$

by explosive evaporations at the instant of such solid-liquid contacts⁽⁷⁾. It is conceivable that the above-mentioned is applicable to the subcooled boiling or the flow boiling. Therefore, it should be possible to guess when the liquid is supplied to the heated surface by measuring temperature fluctuations.

Figure 8 shows examples of the temperature fluctuation at the center and 3mm below the heated surface, where $\Delta T_{sub} = 80\text{K}$ and $u = 0.5\text{m/s}$. The temperature fluctuation, which is extremely small in the nucleate boiling region, becomes somewhat larger as the heat flux approaches that of the DNB point. The temperature fluctuation is about 3 degrees in the amplitude of the oscillation in the RNB region, as shown in Fig. 8(a). Figure 8(b) shows that the temperature oscillates fractionally and regularly in MEB, and the amplitude of the oscillation is about 1.5 degrees. A comparison between Fig. 8(a) of RNB and Fig. 8(b) of MEB reveals that the liquid supply to the heated surface is stabler and more regular in MEB than in RNB. The cause of this can be explained as follows: the more forcefully microbubbles are emitted from the heated surface, the more powerful the reaction of liquid induced above the surface becomes, and the liquid can reach the surface, even in this high heat flux region. Consequently, MEB can enhance the heat transfer because a violent emission of microbubbles supplies the subcooled liquid very close to the heated surface. As the heat flux is increased further, the temperature fluctuation becomes irregular again (as shown in Fig. 8(c)) and no enhancement of heat transfer due to microbubble emission is created.

6.2 Pressure fluctuation

As described in section 5.1, the boiling sound of MEB and the intensity of the emitting forces of microbubbles depend on the liquid subcooling, and the heated surface suffers damage by microbubbles in a certain subcooling as if picked with needles. The

Fig. 8 Examples of temperature fluctuation on heated surface

Fig. 9 Examples of pressure fluctuation in boiling liquid

pressure fluctuation in the boiling liquid is obtained with the aid of the pressure transducer set 5mm above the heated surface. The pressure oscillation is measured through a low-pass filter (10Hz) because it can be recognized that the peak of a waveform after passing the filter corresponds with the emission of a cluster of microbubbles visually observed from the surface.

Figure 9-B shows the pressure fluctuation in each region of a boiling curve in the case of $\Delta T_{sub}=80$ K and $u=0.5$ m/s, where the letters (a), (b), (c) and (d) conform to the symbols in Fig. 9-A.

Figure 9-B (a) shows the pressure fluctuation in a nucleate boiling region. The fluctuation appears at the moment when an isolated bubble departs from the surface. Figure 9-B (b) shows that near the DNB point. The pressure begins to oscillate in a manner similar to the case of the temperature fluctuation. Figure 9-B (c) shows that in the RNB region, where the bubble-clouds are seen above the heated surface. The pressure shows irregular fluctuations corresponding to a complicated behavior of bubble-clouds. Figure 9-B (d) shows that in the MEB region. The amplitude of the oscillation becomes large and the waveform at the peak becomes sharp.

Figure 9-C shows the pressure fluctuation for the case of $\Delta T_{sub}=50$ K and $u=0.5$ m/s. The tendency of the change of the pressure fluctuation with heat flux is

similar to the case of $\Delta T_{sub}=80$ K. However, it appears by making a comparison between Fig. 9-B (d) and Fig. 9-C (c) that the amplitude of the pressure fluctuation in the MEB region depends on the subcooling.

8. Conclusions

Experiments on boiling heat transfer from a horizontal upward-facing rectangular surface to a subcooled liquid flowing along it were performed to obtain information on the MEB phenomena, mainly the conditions of its occurrence, and the following conclusions were drawn.

1. The subcooling and the velocity of the liquid have a great influence on the occurrence of MEB, and the microbubble emission phenomenon occurs after the whole heated surface is covered with bubble-clouds in the RNB region.
2. In MEB, liquid is supplied stably to the surface, which is confirmed from the temperature fluctuation in the heated surface. This is different from the usual transition boiling.
3. The pressure fluctuation indicates that the intensity of bubble emission from the surface and the liquid attacking to it in MEB depend on the liquid subcooling. The amplitude and frequency of the fluctuation increase with increasing the subcooling, and the surface is occasionally damaged.

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