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A Fundamental Study on High Heat Flux Cooling using Subcooled Flow Boiling with Microbubble Emission

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ABSTRACT

In the cooling technology using boiling heat transfer, the maximum cooling heat flux is limited by the critical heat flux and there is a high risk of burning out of cooling surface due to dry-out. So, there have been difficulties to use boiling heat transfer for cooling technology in electronic devices, for an example.

Subcooled flow boiling of water was performed in the horizontal rectangular channel with small heating surface of 10 mm × 10 mm on the bottom surface. The channel is 17 mm in height, 12 mm width and 160 mm length. Microbubble emission boiling occurred in transition boiling and many microbubbles were emitted from coalesced bubbles on the heating surface. Stable microbubble emission boiling, MEB, was observed in transition boiling at 0.5 m/s of liquid velocity and above 40 K of liquid subcooling. The heat flux increased significantly higher than the ordinary critical heat flux and the maximum heat flux reached 10 MW/m^2. The microbubble emission boiling was categorized into two types that were violent and silent ones according to the observation of bubble behaviors and pressure fluctuations in the channel. In the violent MEB, a periodic MEB was observed in many cases.

In the periodic MEB, the cycle of bubble collapse on the heating surface was well correspondent with the frequency of the pressure fluctuation. The heat fluxes increased in proportion to the pressure frequency.

In the terminal stage of microbubble emission boiling, the heating surface was covered with thin vapor film and the surface temperature rose up rapidly, then the boiling turned to film boiling.

INTRODUCTION

It has been well known that the high heat flux is indicated in the beginning of transition region in highly subcooled boiling. The details of the phenomenon were reported in the series of experimental researches on subcooled pool boiling carried out by Inada and his co-workers (1981). Microbubbles were emitted from coalesced bubbles formed on the heating surface and temperature of the heating surface fluctuated. It was observed frequently that the heat flux increased higher than the ordinary critical heat flux.

In subcooled convection boiling performed by Fujibayashi, A.,et al.(1985), Kubo, R. and Kumagai, S. (1992) and Kubo, R., et al. (1993), microbubble emission was significantly observed and the heat flux increased higher than the ordinary critical heat flux. The boiling has been called Microbubble Emission Boiling, MEB. They categorized MEB into two types which were a stormy and a calm one. Then, the maximum heat flux reported was more than 10 MW/m^2 (Kumagai, S. ,2004) in the subcooled flow boiling with parallel jet to the small heating surface.

In the authors' experiments on subcooled flow boiling of water in a small scale rectangular channel with heating surface of 10 mm × 10 mm, MEB occurred and the maximum heat flux obtained was about 10 MW/m^2 (Torikai, K. and Suzuki, K., 1999). The liquid subcooling and the liquid velocity in the channel are the most important factors for MEB generation.

For recent ten years, electronics technology has been surprisingly developed such as personal computers, audio visual systems and many kind of electronic devices. Mobile phone is a typical example of the splendid results.

In near future, the energy density of electronic devices used for electric power regulating systems, electric vehicles and fuel cell systems for example will be high and the thermal emission delivered from the electronic elements and components will be increased considerably. For the future high power electronic systems, it is essential to develop the higher heat flux cooling technology than the conventional ones.

As mentioned above, MEB occurs in transition boiling and the maximum heat flux is considerably higher than the ordinary critical heat flux. So, MEB is strongly expected for the high heat flux cooling technology, however, the details of MEB have been still unknown.

In the present study, microbubble emission boiling occurred in a horizontal rectangular channel with small square heating surface are investigated for fundamental study on high heat flux cooling using subcooled flow boiling.

EXPERIMENT

Experimental setup

An experimental setup is shown in Fig.1. Distilled water is heated in a water tank and circulated between a test section and the tank through a flow meter, a filter and a supplemental heater. The tested subcoolings were 20 ~ 50K and maintained within ±0.5K of predetermined temperature at the entry of test section. The tested liquid velocities were 0.1 ~ 0.5m/s given by measured volume flow rate and the cross sectional area of rectangular channel. The mean pressure in the channel was maintained atmospheric pressure by the adjusting exit valve of the channel.

Test section

Test section is composed of rectangular channel with 17 mm height and 12 mm width and copper heating block shown in Fig.2. The top surface of heating block is placed at the bottom surface of the channel for a heating surface of 10 mm square. The heating block consists of a rectangular straight part and a trapezoidal part. Cartridge heaters are assembled parallel to the heating surface in the trapezoidal section as shown in Fig.2.

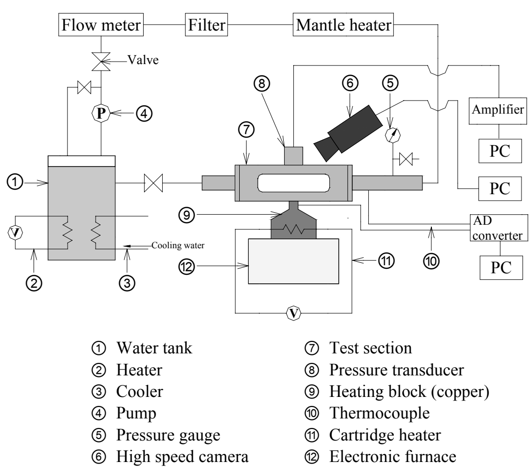

Fig. 1 Experimental setup

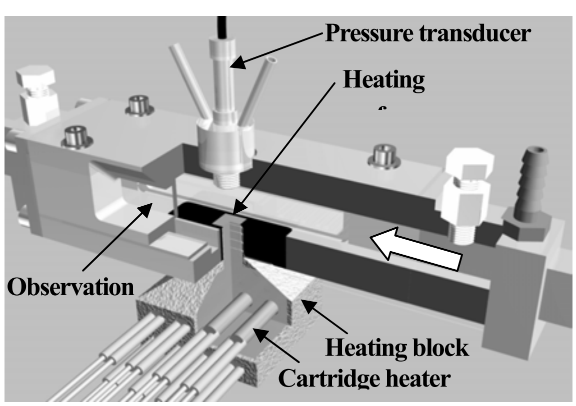

Fig. 2 Cutting view of test section

The heating block is set on an electric furnace and heated by the furnace and cartridge heaters. Four K-type sheathed thermocouples with 0.5mm diameter are fitted on the axis of the straight portion of the heating block with 1mm, 4mm, 8mm and 12mm apart from the heating surface. Temperature of heating surface is determined by extrapolating the measured temperature distribution to the surface and the heat flux is calculated by the temperature gradient. Heating surface was polished with emery paper of # 500 and cleaned with acetone and water prior to experiment. The heating block is enveloped with thermal insulations and the heat loss from the side surface is estimated within 3 percent of axial heat flow of straight portion.

An electronic pressure sensor is assembled at the overhead of the heating surface to measure pressure fluctuation in the channel. Bubble behaviors on the heating surface are visually observed through a transparent glass window assembled on the side panel of the channel and recorded by a high speed video camera.

RESULTS AND DISCUSSION

Effect of liquid subcooling on boiling with MEB

An effect of liquid subcooling on boiling with MEB is shown in Fig.3 as an example of experimental results. The liquid subcooling is 0.5 m/s. In the nucleate boiling region, the boiling curves are almost same track and reach to the each critical heat flux. Then, the boiling turns to transition region and MEB occurs. Instantaneous change in heat flux and surface temperature is observed between the critical heat fluxes and MEBs in Fig.3. So, the experimental data are unable to be indicated in the beginning of transition boiling as shown in Fig.3. Once MEB occurs, the heat fluxes increase stably higher than the CHFs, however, it is unstable and easy to turn to film boiling region at 20 K of liquid subcooling. The terminal stage of MEB will be described in the final chapter. As shown the experimental results, liquid subcooling gives a strong effect on MEB generation and needs more than 20 K for stable MEB.

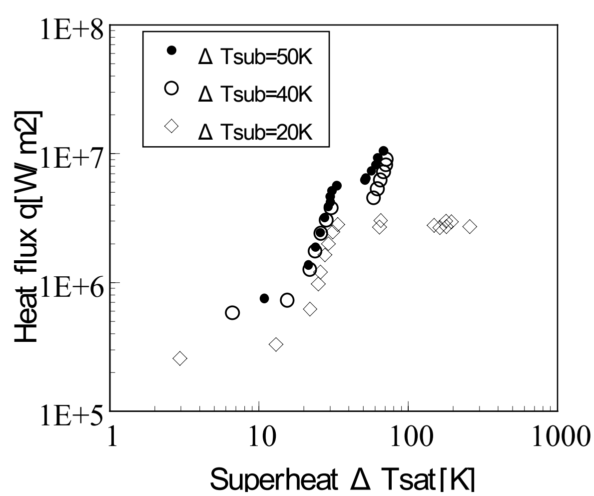

Fig. 3 Effect of liquid subcooling at 0.5 m/s of liquid velocity on boiling

Effect of liquid velocity on boiling with MEB

An effect of liquid velocity on boiling with MEB is shown in Fig.4 as an example of experimental result. Liquid subcooling is 40 K. In the experiment, no large differences in the boiling between both liquid velocities are observed. As a result, the effect of liquid subcooling on boiling is considerably strong than the liquid velocity.

Bubble behaviors of MEB and pressure fluctuations

Microbubble emission boiling is categorized into silent and violent ones in the experiment. They are considered to be correspondent to the MEBs reported by Kubo and Kumagai (1992). Both MEBs have been observed all MEBs and, especially, a periodic MEB occurs in many cases of violent MEB. Typical examples of pressure fluctuation and bubble behavior are shown in figures 5 and 7 for silent MEB at 50 K of liquid subcooling and in figures 6 and 8 for periodic MEB at 40 K of liquid subcooling. The liquid velocity is 0.5 m/s for both experiments.

In silent MEB, the pressure fluctuation is low and the wave pattern is irregular. Many microbubbles are emitted continuously from coalesced bubbles on the heating surface and the heating surface is covered continuously with boiling bubbles as shown in Fig.7.

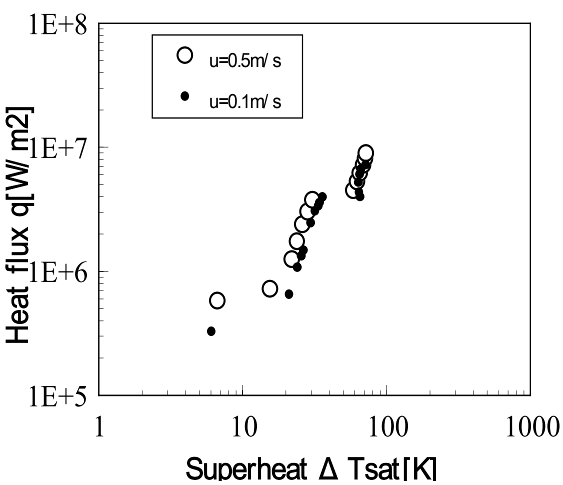

Fig. 4 Effect of liquid velocity at 40K of liquid subcooling on boiling

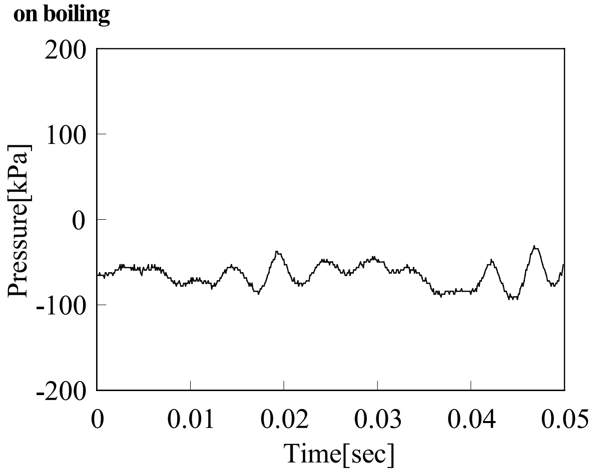

Fig. 5 An example of pressure fluctuation of silent MEB ΔT_{sub}=50K, u=0.5m/s (ΔT_{sat}=51.0K, q=6.76MW/m^2)

In periodic MEB, the pressure fluctuation indicates a completely periodic wave pattern shown in Fig.6. The bubbles on the heating surface also show periodic motion as shown in Fig.8. Where, liquid supply, bubble growth, bubble coalescence and bubble collapse are repeated periodically. In Fig.8, no boiling bubbles were observed on the heating surface at the start of photograph (t = 0). Boiling bubbles begin to generate at t = 3.24 msec and grow gradually (t = 5.67 msec). Large coalesced bubbles cover the whole of heating surface (t = 5.67 ~ 10.3 msec). Then, they brake into many microbubbles (t = 13.0 msec). No bubbles are on the heating surface again at t = 14.3 msec and liquid is supplied into the heating surface. The pressure wave pattern is correspondent to the bubble motions on the heating surface (Suzuki and Inagaki, 2004) and the maximum pressure is indicated at bubble collapse like cavitation phenomena.

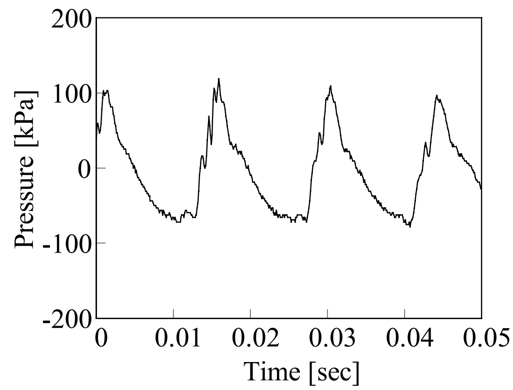

Fig. 6 An example of pressure fluctuation of periodic MEB ΔT_{sub}=40K, u=0.5m/s (ΔT_{sat}=50.0K, q=6.5MW/m^2)

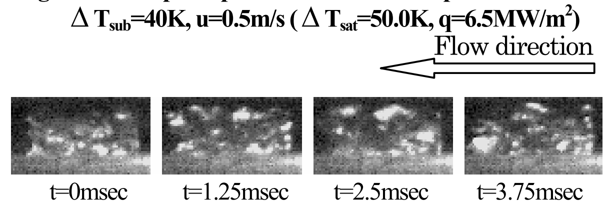

Fig. 7 Bubble behavior on the heating surface in silent MEB ΔT_{sub}=40K, u=0.5m/s

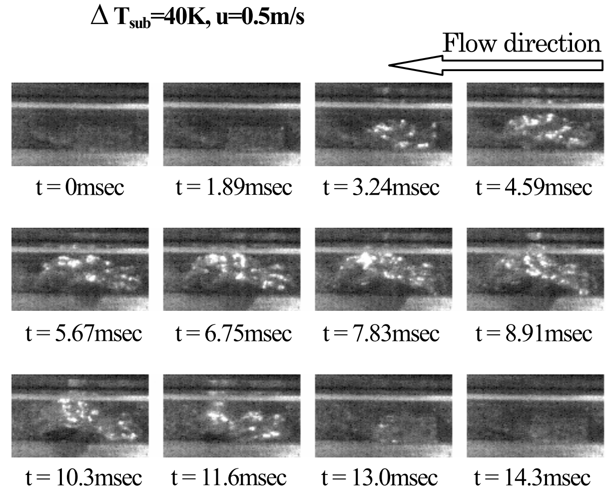

Fig. .8 An example of bubble behavior on the heating surface in periodic MEB
ΔT_{sub}=40K, u=0.5m/s (ΔT_{sat}=50.0K, q=6.5MW/m^2)

In the analysis of pressure fluctuation of periodic MEB, the band of peak frequency is indicated about 30 ~ 90 Hz. Heat fluxes in periodic MEB increase approximately proportionally to the peak frequency as shown in Fig. 9. The peak frequency is considered to be frequency of liquid supply and bubble collapse. As seen from Fig. 9, it is roughly shown that the higher liquid subcooling introduces the higher frequency and the higher heat flux. However, it is indicated lower heat fluxes and frequency for the grooving surface or rough surface. The problems of such surface condition have been now under investigation.

According to the experimental results shown in Fig.9, the heat flux q in periodic MEB could be indicated as following relation assuming that the mass of liquid is almost same for one liquid-vapor exchange.

$$q \propto \frac{m(C_P \Delta T_{sub} + \Delta h)}{A} f$$

where, q denotes heat flux (W/m^2), A area of heating surface (m^2), C_p specific heat (kJ/kgK), f peak frequency of pressure fluctuation (Hz), Δh latent heat of liquid (kJ/kg), m mass of liquid supplied into heating surface (kg), ΔT_{sub} liquid subcooling (K).

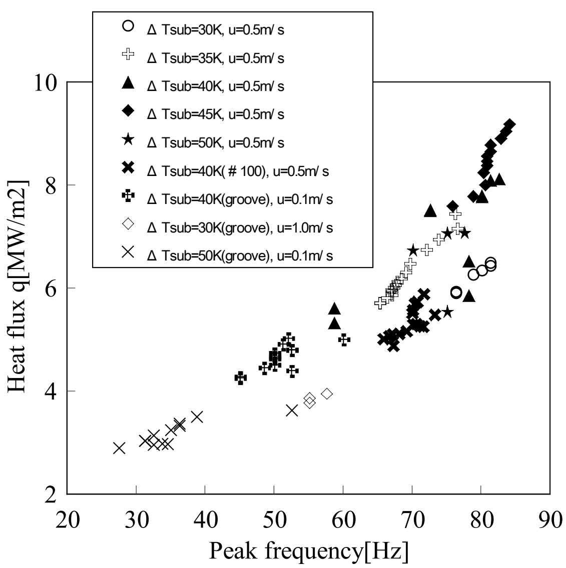

Fig. 9 Peak frequency vs. Heat flux in Periodic MEB

Termination of MEB

At low liquid subcooling such as 20 K as shown in Fig.3, MEB is unstable and turns easily to film boiling as shown in Fig.10 for an example. As MEB is going to high superheat or high heat flux, the temperature of heating surface rises up rapidly and the heat flux begins to fall down with temperature rise as popular transition boiling. We named the state "Terminal stage of MEB".

At the terminal stage of MEB, the heating surface is covered with many cloudy microbubbles as shown in Fig. 11, and then a thin vapor film covers the heating surface without microbubble emission as shown in Fig.12. The boiling turns instantaneously to film boiling. Here, the pressure fluctuation is very small as shown in Fig.13. Finally, the heating surface begins to dry out.

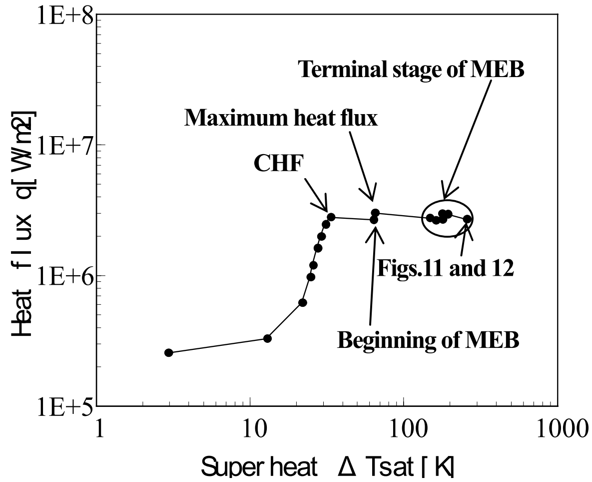

Fig. 10 Boiling curve (ΔT_{sub}=20K, u=0.5m/s)

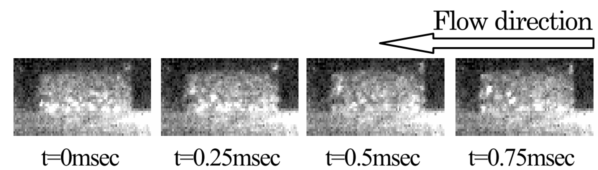

Fig. 11 Cloudy microbubbles on the heating surface at terminal stage of MEB

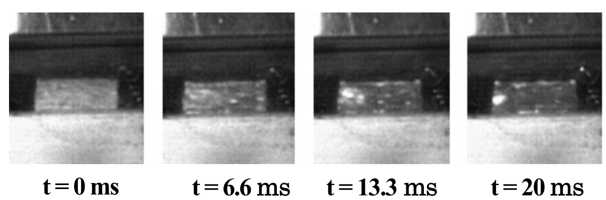

Fig. 12 A thin vapor film on the heating surface at terminal stage of MEB

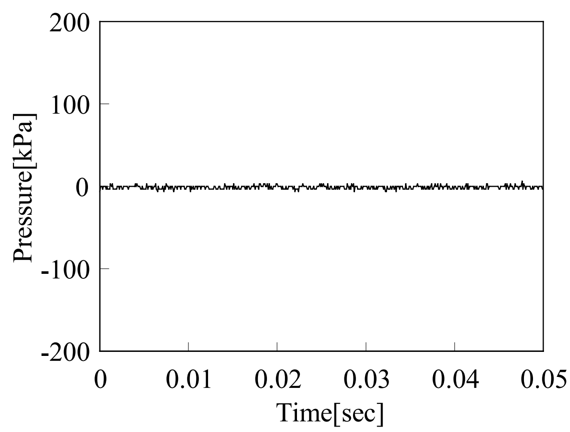

Fig. 13 Pressure fluctuation at terminal stage of MEB

CONCLUSIONS

Subcooled flow boiling of water was performed in a small horizontal rectangular channel with small square heating surface of 10 mm × 10 mm. Stable microbubble emission boiling occurred at 0.5 m/s of liquid velocity and above 20 K of liquid subcooling and the heat flux increased higher than the ordinary critical heat flux. Silent and violen MEBs were observed and a periodic type of MEB occurred in many cases of violent MEB.

In the periodic MEB, a series of bubble generation, bubble growth, bubble collapse and liquid supply is repeated periodically. The frequency of periodic motion of bubbles is well agreed with the frequency of pressure fluctuation in the channel. The heat flux increases proportionally to the frequency.

In the silent MEB, the pressure fluctuation is considerably lower than the periodic MEB and microbubbles are emitted continuously from coalesced bubbles on the heating surface.

In the terminal stage of MEB, the heating surface is covered with cloudy microbubbles and the surface temperature rises rapidly, then the surface covered with a transparent thin vapor film without microbubbles. The heating surface begins to dry out as same as popular transition boiling.

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