Application of Boiling Heat Transfer to High-Heat-Flux Cooling Technology in Power Electronics

Koichi Suzuki*, Kazuhisa Yuki*, and Masataka Mochizuki**

*Tokyo University of Science, Yamaguchi, 1-1-1, Daigaku-dori, Sanyo-Onoda-shi, Yamaguchi 756-0884, Japan  
**Thermal Tech. Div., Fujikura Corp., 1-5-1, Kiba, Koto-ku, Tokyo 135-8512, Japan

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Abstract

Boiling heat transfer is a superior heat transfer technology using the latent heat transport with phase-change. However, it has been difficult to employ as a cooling technology for electronics because the unstable transition boiling and film boiling with excessive high temperature are impossible to control. In highly subcooled boiling, the coalescing bubbles formed on the heating surface collapse to many fine bubbles at the beginning of transition boiling and the heat flux exceeds the critical heat flux. This boiling regime has been called Microbubble Emission Boiling (MEB). Two models of cooling device are introduced using subcooled flow boiling with MEB for power electronics, where the maximum heat flux is 500 W/cm² (5 MW/m²).

Keywords: MEB (Microbubble Emission Boiling), High Heat Flux, Cooling Technology, Power Electronics

Nomenclature

\( h_B \); Heat transfer coefficient in boiling, kJ/m²K  
\( h_{MEB} \); Heat transfer coefficient in MEB, kJ/m²K  
\( q \); Heat flux, W/m²  
\( T_l \); Bulk temperature of liquid, K  
\( T_{sat} \); Saturation temperature of liquid, K  
\( T_w \); Temperature of heating surface, K  
\( \Delta T_{sub} \); Liquid subcooling, K  
\( \Delta T_{sat} \); Superheat of heating surface, K

1. Introduction

Since the end of the last century, we have serious problems with the natural environment, energy resources, and global warming. In particular, the reduction of CO₂ emissions is an important problem to be resolved urgently.

In order to reduce CO₂ emission and save fossil fuels, the development of electric vehicles (EVs) has recently been accelerated. In the near future, automobiles driven by petrol or oil will be replaced by EVs or fuel cell vehicles (FCVs). In the EV power control system, an IC package is employed for electronic power equipment such as an inverter. These IC inverters produce large amount of heat and the maximum heat flux has been predicted at higher than 300 W/cm².

Recently, Silicon Carbide, SiC, has attracted interest as a new power semiconductor material in place of the conventional Silicon. The maximum operating temperature of SiC is said to be 400~450°C. However, the actual operating temperature should be lower than 200°C in order to decrease power loss and to protect circuit parts from high temperatures. Of course, it is impossible to remove such high heat flux from the new power IC devices by conventional cooling technologies, namely air cooling or liquid cooling.

Boiling heat transfer is well known as a superior heat transfer technology to remove large amounts of heat from a hot body using the transport of latent heat with a phase-change. However, there are some difficulties with applying this cooling method to electronics. The heating surface becomes covered with coalescing bubbles at the critical heat flux (CHF), the maximum of nucleate boiling where the liquid is not fully in contact with the heating surface. The remaining liquid layer or microlayer below the coalescing bubbles evaporates rapidly and the surface begins to dry. The boiling then turns rapidly to film boiling with the instantaneous temperatures rising through transition boiling. Finally, the surface is seriously damaged by the high temperature burnout. Generally, it is impossible
In highly subcooled boiling, many microbubbles are emitted from coalescing bubbles formed on the heating surface at the beginning of transition boiling and the heat flux exceeds CHF considerably, as CHF shown in Fig. 1 and 2.[1] This boiling regime has been called Microbubble Emission Boiling (MEB). The investigation of MEB was started by Shigeaki Inada, Professor of Gunma National University, in 1981.[2–5] More recently, MEB research has been conducted by a group led by Satoshi Kumagai, Professor of Tohoku National University, for subcooled flow boiling[6–8] and by Kin-ichi Torikai and Koichi Suzuki for channel flow boiling.[9, 10] For example, the maximum heat flux is higher than 1000 W/cm² in subcooled flow boiling of water with microbubble emissions under atmospheric conditions. The present paper introduces Microbubble Emission Boiling and its application to cooling technology in power electronics.

2. Outline of Microbubble Emission Boiling (MEB)

Bubble behaviors in subcooled pool boiling are shown in Fig. 2 as a typical example of MEB.[1] A copper heating surface 10 mm in diameter is placed facing upward on the bottom of the boiling vessel. The surface is polished with #500 sand-paper. The boiling liquid is a mixture of water, an aqueous solution of 10 wt% Ethanol and an aqueous solution of 7.5 wt% Propanol. The boiling is performed in subcooled quasi-pool boiling under atmospheric conditions. Large coalescing bubbles formed on the heating surface at CHF collapse to many fine bubbles at the beginning of transition boiling. The liquid is supplied to the heating surface as the bubbles collapse. The supplied liquid then evaporates and the boiling bubbles again expand to large coalescing bubbles at CHF. The process is repeated rapidly and the heat flux exceeds the critical heat flux.[9, 10]

Microbubble emission boiling occurs significantly in highly subcooled flow boiling. Boiling curves with MEB are shown in Fig. 3 as an example of subcooled flow boiling in a horizontal rectangular channel.[10] As an example, a test section for channel flow boiling is shown in Fig. 4. The channel is 17 mm in height, 12 mm in width and 150 mm in length and is set horizontally. The 10 mm × 10 mm heating surface is the upper surface of a copper heating block placed at the bottom of the horizontal rectangular channel. The heating block consists of a straight section and a base block. A number of cartridge heaters are
Subcooled boiling was tested for liquid subcooling at 20 K, 30 K, 40 K, 50 K and 60 K.[10] At the beginning of transition boiling, MEB occurs and the heat fluxes exceed the CHFs, as shown in Fig. 3. The maximum heat flux reaches 10 MW/m² at the higher liquid subcooling of 40 K. However, no MEB occurs at the 20 K liquid subcooling or the boiling turns instantaneously to transition boiling without increasing heat flux even if MEB occurs. Therefore, the liquid subcooling is an important factor for MEB generation.

The liquid subcooling $\Delta T_{\text{sub}}$ is defined as the difference between the saturation temperature of the liquid $T_{\text{sat}}$ and the bulk liquid temperature, $T_l$, as indicated in equation (1). The superheating of the heating surface, $\Delta T_{\text{sat}}$, is defined as the difference between the temperature of the heating surface, $T_w$, and the saturation temperature of the liquid, $T_{\text{sat}}$, as indicated in equation (2).

$$\Delta T_{\text{sub}} = T_{\text{sat}} - T_l$$  
$$\Delta T_{\text{sat}} = T_w - T_{\text{sat}}$$  

The heat transfer coefficient is given by the boiling curves shown in Fig. 3. The heat transfer coefficient in boiling is based on the superheating of the heating surface as in equation (3).

$$h_{B}, h_{\text{MEB}} = \frac{q}{\Delta T_{\text{sat}}}$$  

For example, the heat transfer coefficient $h_B$ in nucleate boiling is about 80,000 W/m²K and $h_{\text{MEB}}$ in MEB is 140,000–200,000 W/m²K given by the experimental result shown in Fig. 3. Those heat transfer coefficients are considerably higher than those in single phase flow heat transfer.

3. Applications of MEB for Cooling Technology

Generally, an inverter used for an EV is composed of IC packages and the cooling surface is considered large, 10 cm $\times$ 20 cm for example. The thermal emission rate is predicted to be higher than 100 W/cm² (1 MW/m²), because the thermal emission issued from an inverter is generally estimated to be at least 20 percent of the maximum power output of an electric vehicle, which is assumed to be 100 kW. For cooling an inverter with a single channel, it is difficult to remove the heat from the down-stream section of cooling surface as shown in Fig. 5. The maximum heat flux and CHF are indicated for the length of the surface in Fig. 6 in our experimental results on the subcooled flow boiling of water in a horizontal rectangular channel. The heating surfaces are placed at the bottom of a horizontal...
rectangular channel 5 mm in height. The temperature of the distilled water is 40 K of liquid subcooling at the inlet of the channel and the mean flow velocity is 0.5 m/s (500 kg/m²s). The maximum heat flux and CHF decrease with the length of the heating surface. The critical heat flux agrees roughly with the correlation proposed by Haramura-Katto[12] and Ivey-Morris.[13] For a long heating surface, the maximum heat flux decreases as shown in Fig. 6. The experimental data indicate that the limit of cooling length in MEB is less than 50 mm.

According to the experimental results on subcooled flow boiling of water in a horizontal rectangular channel, the authors have proposed two models of high-heat-flux cooling device for power electronics.

3.1 Compact High-Heat-Flux Cooling Device (CHCD) [11, 14, 15]

Subcooled flow boiling was conducted for a horizontal rectangular channel with a flat heating surface placed at the bottom of the channel.[14] The channel is 5 mm in height, 24 mm in width, and 300 mm in length for a single unit. The heating surface is made of copper and is 20 mm in width and 50 mm in length. The boiling curves at liquid subcooling of 40 K and liquid velocity of 0.5 m/s (500 kg/m²s) are shown in Fig. 7.[14] Significant microbubble emission boiling occurs and the heat flux exceeds the CHF. The maximum heat flux obtained is 500 W/cm² (5 MW/m²²) and the maximum heat removal is 5 kW.

The test section is useful for a high-heat-flux cooling device where the length of the cooling surface is shorter than 50 mm. The proposed simple cooling device is named CHCD (Compact High-Heat-Flux Cooling Device).

A concept of the composite type of CHCD is shown in Fig. 8.[11] The maximum heat removed from the power component is 120 kW. However, high pressure fluctuations are generated in MEB as shown in Fig. 9.[14] MEB is extremely vigorous reaching a maximum pressure of 700~800 kPa.

In order to reduce the excessive instantaneous pressure fluctuations, many needle rods 0.5 mm in diameter and 4~4.5 mm in length are assembled in a lattice with 3~5 mm separation just above the heating surface from the upper housing of the rectangular channel, as shown in Fig. 10.[14, 15]
In microbubble emission boiling, large coalescing bubbles divide into small ones. The pressure fluctuations decrease dramatically and the peak pressures are lower than 200 kPa, as shown in Fig. 11. According to the experiment, a low noise and high-heat-flux cooling device can be produced by the pressure reduction needles.

### 3.2 Passive-Active High-Heat-Flux Cooling Device (PHCD) [11, 16, 17]

For a heating surface longer than 50 mm, it is difficult to remove the high heat flux from a high-powered electronics device with a single cooling channel. The liquid subcooling decreases as it flows along the heating surface and large coalescing bubbles form on the down-stream section as shown in Fig. 5. Microbubble emission boiling is generated on the up-stream section but dry-out can easily occur in the down-stream section.

An inverter with an IC package is employed for an electric vehicle. The size of the cooling surface will be 20 cm × 20 cm for more than 100 kW of power output. In order to prevent the long heating surface from dry-out, a model of cooling device with two channels and multi-needle nozzles is proposed and shown in Fig. 12. [11, 16, 17]

The subcooled liquid is separated into the main channel and the sub-channel assembled over the head of the main channel. The subcooled fluid in the sub-channel flows counter to the main channel flow. The tips of the nozzles have four small slits and are placed within 1 mm of the heating surface.

The performance of the cooling device is shown in Fig. 13. In the experiments, the cooling device was tested for a single unit with a heating surface 100 mm in length × 10 mm in width. The main channel is 5 mm high and the sub-channel is 10 mm high. Nine nozzles, each 1 mm in diameter and 4.5 mm in length, are aligned on the centerline of heating surface at 10 mm intervals.

Distilled water is used and the liquid subcooling is 40 K under atmospheric conditions. With a low thermal load, the cooling is performed in Passive Mode, where the mean velocity of the liquid is 0.03–0.05 m/s (30–50 kg/m²s) in the main channel, as shown in Fig. 13. The maximum cooling heat flux is 500 kW/m² (50 W/cm²) in the passive mode. With increasing thermal emission, the flow rate of...
the subcooled liquid in the main channel is increased to 0.5 m/s (500 kg/m²s) and the cooling is performed mainly by the main channel flow until the thermal emission reaches 2 MW/m² (200 W/cm²).

In the higher thermal emission region, the subcooled liquid is supplied into the heating surface directly from the sub-channel through the multi-needle nozzle. The strong subcooled jet removes the thin vapor film from the surface. This is Active Cooling Mode. The active mode removes up to 5 MW/m² (500 W/cm²). So the dual channel cooling device was named PHCD (Passive-Active High-Heat-Flux Cooling Device). The maximum heat flux of 500 W/cm² is sufficient to cover the cooling limit of future power electronics for motor vehicles. PHCD is flexible in terms of the size of cooling surface using multiple-units or multiple-channels and can adapt to cool variable thermal loads by continuously changing the cooling mode.

4. Conclusion

In subcooled boiling of water, microbubble emission boiling (MEB) is generated at liquid subcooling above 20 K under atmospheric conditions and the heat flux exceeds critical heat flux (CHF). The maximum heat flux is 10 MW/m² (1 kW/cm²) at liquid subcooling higher than 40 K and liquid velocity of 0.5 m/s (a mass flow flux of 500 kg/m²s) for a small heating surface of 10 mm × 10 mm with a cm-sized rectangular channel. The cooling heat flux decreases with the length of the heating surface. For a long heating surface with a single flow channel, it is difficult to remove high heat flux in the down-stream section of the heating surface.

Two models of compact high-heat-flux cooling devices using MEB have been proposed for high thermal-emission electronic devices such as IC packaged inverters used for electric vehicles or power electronics. They are a CHCD (Compact High-Heat-Flux Cooling Device) with a single rectangular channel and a PHCD (Passive-Active High-Heat-Flux Cooling Device) with two channels and a multi-needle nozzle.

The maximum length of the heating surface is 50 mm for CHCD. The maximum cooling heat flux is 5 MW/cm² (500 W/cm²) at liquid subcooling of 40 K and 0.5 m/s (500 kg/m²s), however, considerable high pressure fluctuation is induced at the collapse of large coalescing bubbles in MEB. The strong pressure fluctuations are successfully reduced by a multi-needle rod placed in lattice-wise above the heating surface.

PHCD has been proposed for heating surfaces longer than 50 mm. In the experiments, the test was conducted for a device with a heating surface 100 mm in length and 10 mm in width. The maximum cooling heat flux of 5 MW/m² (500 W/cm²) was obtained in active mode with impinging jets in addition to the main channel flow. The maximum heat flux is sufficiently higher than the predicted heat flux of 3 MW/m² (300 W/cm²) emitted from the power IC package used for electric vehicles or a compact electric power generator.

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