Proceedings of the 3rd IASME/WSEAS Int. Conf. on HEAT TRANSFER, THERMAL ENGINEERING AND ENVIRONMENT, Corfu, Greece, August 20-22, 2005 (pp91-96)

Microbubble Emission Boiling of Alcohol-Water Mixtures

KOICHI SUZUKI
Department of Mechanical Engineering
Tokyo University of Science
2541 Yamazaki, Noda, Chiba, 278-8510
JAPAN

Abstract: - Subcooled boiling is performed for alcohol-water mixtures and compared with the boiling characteristics of water. In subcooled quasi-pool boiling, the critical heat fluxes of the mixtures are strongly depended by the alcohol mass concentration. The maximum critical heat flux (CHF) is obtained at 10 percent for Ethanol and 7.5 percent for Propanol and 2 percent for Butanol. They are higher than CHF of water. In subcooled flow boiling, microbubble emission boiling (MEB) occurs in horizontal rectangular and circular channels. The heat fluxes of the mixtures are higher than that of water in MEB. The pressure fluctuations in MEB are smaller than water. Alcohol-water mixtures accelerate MEB generation and increase the heat fluxes by Marangoni effect generated by concentration difference in the interface of vapor and liquid .

Key-Words: - Alcohol-water mixture, Subcooled boiling, Alcohol concentration, MEB, Transition boiling, High heat flux, Low boiling vibration

1 Introduction

In highly subcooled boiling, micobubbles are emitted from coalesced bubbles on the heating surface in transition boiling and the heat flux increases higher than the ordinary critical heat flux. The phenomenon has been called Microbubble Emission Boiling (MEB) [1~3]. Especially, MEB occurs remarkably in highly subcooled flow boiling and the maximum heat flux is higher than $10MW/m^2$ at atmospheric pressure [4~6]. Microbubble emission boiling occurs in a narrow horizontal rectangular channel with flat surface placed on the bottom and a small horizontal circular channel [6~7]. The higher heat flux has been obtained for both channels.

In near future, an automobile driven by internal combustion engine will be replaced by an electric power plant or a fuel-cell power plant. An electronic device will be assembled in the high power regulating system or management system. The thermal emission from the power electronic package or power IC package will be $300W/cm^2$ or more. The high heat flux is unable to be removed from the high power IC package by the conventional cooling technology such as air or liquid cooling, because the cooling limit of the today is about $100W/cm^2$. Boiling heat transfer is one of the high efficient heat transfer technology to remove heat from a hot solid, however there are critical heat flux as upper limit of the heat transfer rate, unstable transition boiling and high temperature film boiling in boiling phenomenon. Once the boiling reaches to the critical heat flux, it turns rapidly to film boiling trough transition boiling with rising surface temperature. The surface is burned out due to the extreme high temperature. Of course electronic chips have permanent damages. This is the reason why the boiling heat transfer has not been used in the cooling technology for electronic devices. Therefore, MEB is strongly expected as one of the high heat flux cooling technology for power electronics.

In boiling of volatile mixtures such as alcohol-water mixtures, the critical heat flux is depended by the volatile concentration and the maximum heat flux is higher than that of water [8]. The mixture is expected to increase the heat transfer efficiency by MEB. In the present study, MEB has been investigated for alcohol-water mixtures of Ethanol, Propanol and Butanol.

2 Experiments

2.1 Subcooled quasi-pool boiling

The subcooled boiling of alcohol-water mixture is investigated for quasi-pool boiling and flow boiling in rectangular and circular channels.

In subcooled quasi-pool boiling, a heating surface of 10mm in diameter is placed at the bottom of the boiling vessel shown in Fig.1. A heating surface with 10mm in diameter is placed on the bottom surface of a boiling vessel. The heating surface is a top of copper heating block which consists of cylindrical straight part with 15mm length and trapezoidal base. It is placed on an electric furnace for heating. Three K-type sheathed thermocouples with 0.5 mm in diameter are fitted on the axis of the cylindrical part at 1 mm, 5 mm and 9 mm apart from the surface. The surface temperature is estimated by extrapolating the temperature distribution and the heat flux is determined by the temperature gradient. The heating block is enveloped with thermal insulations and the heat loss from the side surface of the cyndrical part is estimated within 5 percent of the axial heat flow.

It is very difficult to perform the perfect subcooled pool boiling, so, the liquid subcooling is maintained in the quasi-pool condition with weak circulation made by a stirrer, a cooling coil and an auxiliary heater. Bubble behavior on the heating surface is visually observed by a high-speed video camera. Mass concentration of the alcohols is measured by a precision electronic balance meter.

The critical heat flux was tested for mass concentration of alcohol in the mixtures. Then, subcooled flow boiling was performed for the mixtures with the concentration at which the maximum critical heat flux was indicated.

2.2 Rectangular channel used in subcooled flow boiling

An example of test section used in flow boiling experiment is shown in Fig.2. The test section is composed of a rectangular channel with 5 mm in height, 22 mm in width and 200 mm in length and a heating block.

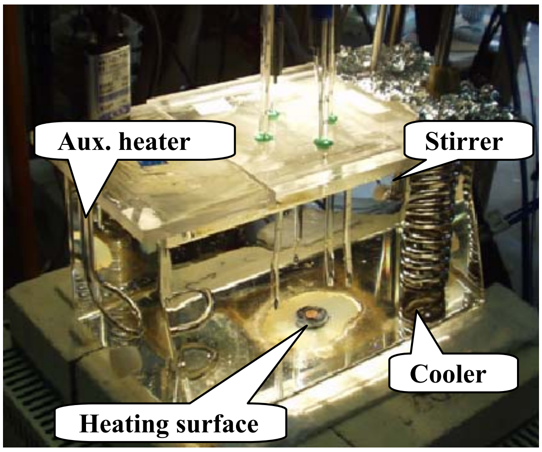


Fig.1 Experimental arrangement for subcooled quasi-pool boiling of alcohol-water mixture

The channel is arranged horizontally and the heating surface with 20 mm in length and 10 mm width is placed on the bottom surface of the channel. The heating block used in the flow boiling consists of straight part and trapezoidal base. Twenty cartridge heaters of 300 W in maximum power are inserted in the trapezoidal section parallel to the heating surface for high power heating. Three axes are referred at the heating surface to measure local surface temperature and heat flux. The axes are determined at 5 mm, 10 mm and 15 mm apart from the one side edge of the surface and three K-type sheathed thermocouples with 0.5mm in diameter are fitted at 2 mm, 6 mm and 10 mm apart from the surface on the each axis. The local surface temperature and the heat flux are obtained by the measured temperature distribution. The heating block is enveloped by thermal insulations and placed on an electric furnace. Bubble behavior on the heating surface is observed through the transparent glass window assembled on the upper housing of the channel. Pressure fluctuation in the channel is measured by an electronic pressure sensor fitted on the upper housing of the channel.

2.3 Circular channel used in subcooled flow boiling

The test section of circular channel is shown in Fig.3. The diameter of the channel in the copper heating block is 5mm and the heating section is 10mm length. Thirty cartridge heaters of 40W each in maximum power are inserted in the heating block parallel to the channel. Three K-type sheathed thermocouples with 0.5mm in diameter are fitted at the center of heating section with 4mm, 8mm and 12mm in radial distance from the heating surface to estimate the surface temperature and the heat flux. An electronic pressure sensor is fitted at 85mm downstream from the heating surface.

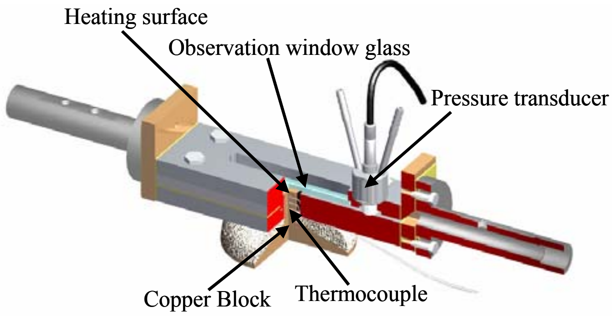


Fig.2 An example of test section for subcooled flow boiling

2.4 Experimental arrangement for subcooled flow boiling

The experimental arrangement used in subcooled flow boiling is shown in Fig.4. It consists of fluid loop, heating section and data recording section. Distilled water is circulated in the fluid loop. The fluid temperature is maintained within 3K of predetermined value at the entry of the channel. The mean pressure in the channel is maintained atmospheric condition by adjusting regulating valve in the fluid loop. The mean velocity is calculated by the measured volume flow rate and the cross sectional area of channel.

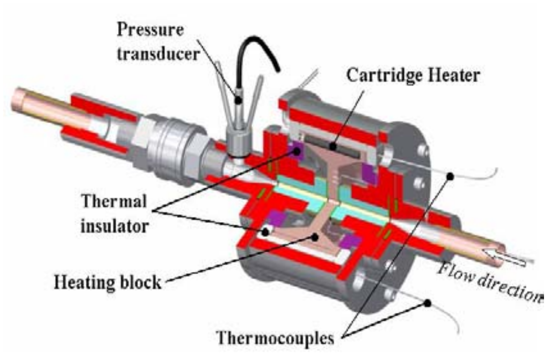
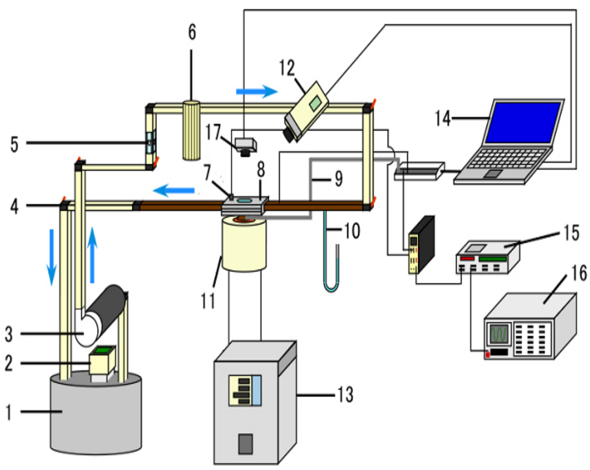


Fig.3 Test section of circular channel



1. Heating bath 2. Temperature controller
3. Pump 4. Regulating valve 5. Flow meter
6. Filter 7. Pressure sensor 8. Test section
9. Thermocouple 10. Manometer
11. Electric furnace 12. High speed video camera
13. Power regulator 14. PC 15 Recorder
16. FFT analyzer 17. Video camera

Fig.4 Experimental arrangement for subcooled flow boiling

3 Results and Discussion

3.1 Subcooled quasi-pool boiling

Relation of critical heat flux and alcohol concentration at 30K of liquid subcooling is shown in Fig.5. The maximum critical heat flux is obtained at 10 percent of mass concentration for Ethanol, 7.5 percent for Propanol and 2 percent for Butanol [9]. The same concentration at the maximum CHFs was obtained at 40K of liquid subcooling [10]. Mixtures with alcohol concentration at the maximum critical heat flux were used in boiling fluid in the experiments.

Boiling curves at 40K of liquid subcooling is shown in Fig.6. The experimental results show that the heat fluxes increase higher than CHFs in the beginning of transition boiling. The maximum heat fluxes of the mixtures are little higher than that of water. High speed video pictures of bubble behaviors in the beginning of transition boiling are shown in Fig.7. Large coalesced bubble on the heating surface is observed at CHF point. Then it is broken to many fine bubbles and the heat flux increases high as shown in Fig.6 and Fig.7. The collapse of coalesced bubbles introduces liquid supply into heating surface. The bubble collapse is repeated in high frequency and the heat flux is increased. According to the higher heat flux observed in the beginning of transition boiling and the bubble behaviors, the boiling is considered microbubble emission boiling.

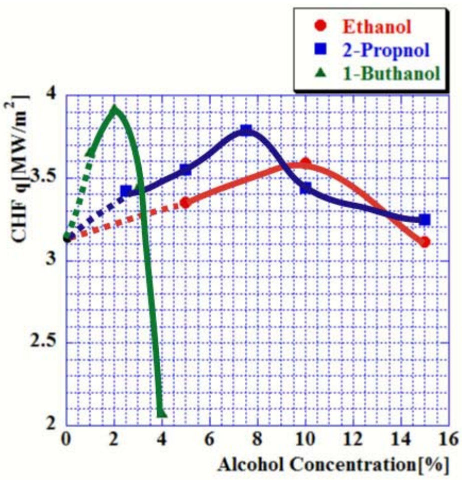


Fig.5 Mass concentration dependence of alcohol on critical heat flux in subcooled quasi-pool boiling of alcohol-water mixtures at 30K of liquid subcooling. (Suzuki, K., et al, 2005 [9])

At lower liquid subcooling of 20K, stable MEB is not observed and the heat fluxes decreases with rapid rising surface temperature.

In the binary mixtures, the difference of alcohol concentration are in the interface of liquid and boiling bubble between the bulk liquid and the contact line with the heating surface due to the temperature difference. The difference of concentration introduces the difference of surface tension in the interface and Marangoni convection is generated. The surface tension of the mixtures is smaller than that of water and the mixture is water rich near the hot heating surface. It is considered that the Marangoni convection in the interface and the low surface tension of the mixtures are considered to give strong effects on the accelerating MEB generation and promotion of the high heat flux.

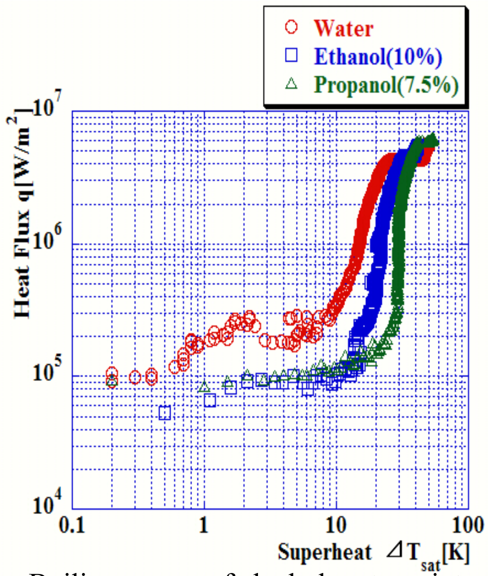


Fig.6 Boiling curves of alcohol-water mixtures in subooled quasi-pool boiling at 40K of liquid subcooling (Suzuki, K.,2005 [9])

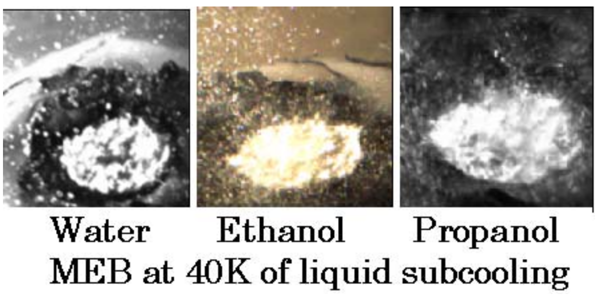


Fig.7 High speed video pictures of bubble collapse in subcooled quasi-pool boiling of alcohol-water mixtures with MEB at 40K of liquid subcooling. 300 Frames/s (Suzuki, K.,2005 [9])

3.2 Subcooled flow boiling in a rectangular channel

Boiling curves at 40K of liquid subcooling and 0.5m/s of liquid velocity are shown in Fig.8. They are the data on the center of heating surface. Microbubble emission boiling occurs and the heat fluxes increase higher than CHFs in the beginning of transition boiling. The heat flux of the mixtures is higher than that of water in MEB as shown in Fig.8. In flow boiling, Marangoni effect is considered small compared with the inertia of fluid flow, however, they give the enhancement of bubble detachment and bubble collapse.

Periodic MEB is observed as the authors' previous works have shown in subcooled flow boiling with MEB as shown in Fig.9. In the experimental results, the maximum pressure in the alcohol-water mixture is considerably lower than that of water. The low surface tension of the binary mixture might be concerned with the lower pressure fluctuations than that of water.

.

2.3 Subcooled flow boiling in a circular channel

Microbubble emission boiling occurs in subcooled flow boiling of Ethanol-water mixture in a horizontal circular channel of 5mm diameter as case of rectangular channel. Only Ethanol-water mixture is tested in the present stage.

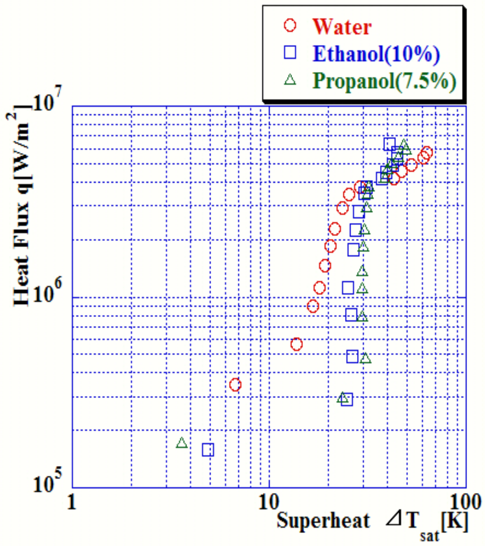


Fig.8 Boiling curves of alcohol-water mixtures in subcooled flow boiling at 40K of liquid subcooling and 0.5 m/s of liquid velocity (Suzuki, K.,2005 [9])

An effect of liquid subcooling on the boiling at 0.5m/s of liquid velocity is shown in Fig.10 for example. The higher heat flux is given by the higher liquid subcooling. An effect of liquid velocity on the boiling at 30K of liquid subcooling is shown in Fig.11. The higher heat flux is given by the higher liquid velocity. The subcooling and velocity of the liquid in the channel give a strong effect on the boiling with MEB according to the experimental results. However, the boiling curves are shifted high temperature side in different from the case of rectangular channel and the heat fluxes are not so higher than CHF.

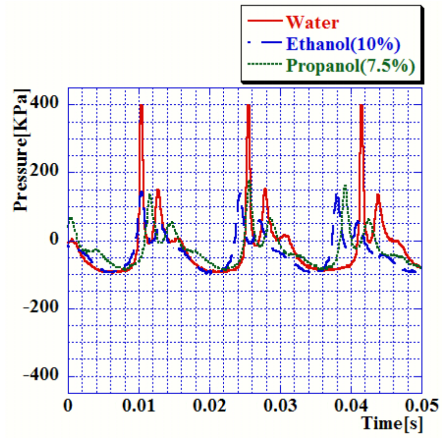


Fig.9 Pressure fluctuations of binary mixtures in a rectangular channel at 40K of liquid subcooling and 0.5m/s of liquid velocity (Suzuki, K.,2005 [9])

In case of circular channel used in the experiment, the heating section is a part of the channel with 10mm length. Boiling bubbles are generated whole surface of the circular channel. The actual cross section of channel decreases resultantly due to the bubbling. For the larger circular channel, 10mm in diameter for example, it has been observed that the heat flux increases higher than CHF in the experiments. So, it may be difficult to generate MEB and obtain high heat flux in smaller circular channel than 5mm in diameter.

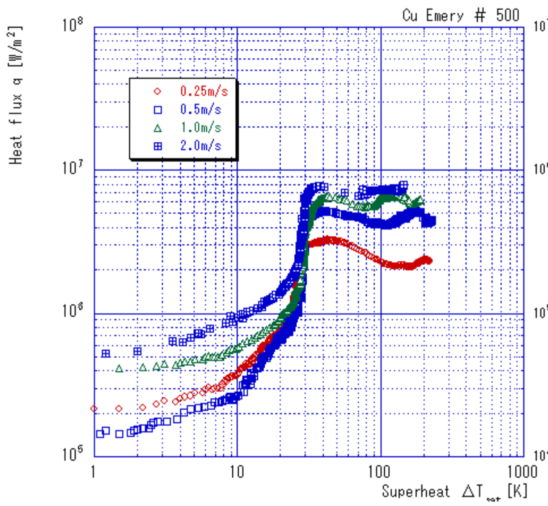


Fig.11 Effect of liquid velocity of Ethanol-water mixture on subcooled flow boiling with MEB in a horizontal circular channel at 30K of liquid subcooling

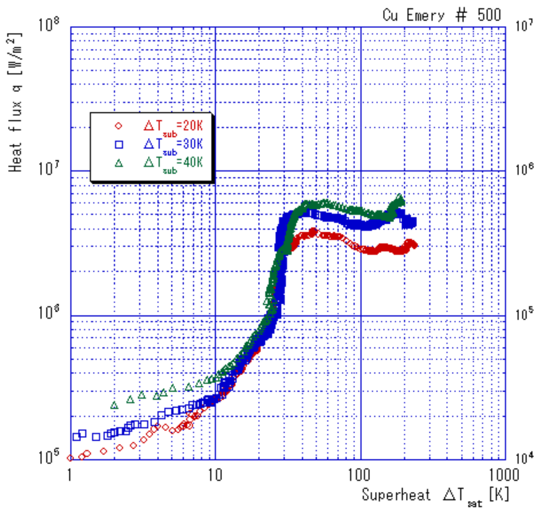


Fig.10 Effect of liquid subcooling of Ethanol-water mixture on subcooled flow boiling with MEB in a horizontal circular channel at 30K of liquid subcooling and 0.5m/s of liquid velocity

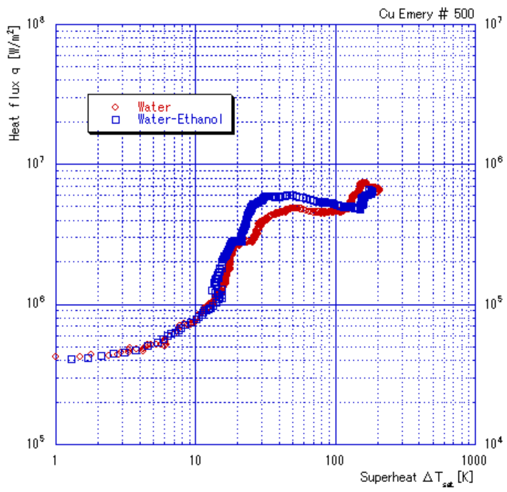


Fig.12 Comparison of boiling of Ethanol-water mixture with water in subcooled flow boiling with MEB in a horizontal circular channel at 30K of liquid subcooling and 0.5m/s of liquid velocity

Boiling curves of Ethanol-water mixtures and water at 30K of liquid subcooling and 0.5m/s of liquid velocity are shown in Fig.12. Compared with the boiling curves of both fluids, the heat flux of Ethanol-water mixture is little higher than that of water in transition boiling except the high temperature region above 200ºC of the heating surface.

4 Conclusion

Subcooled boiling is investigated for alcohol-water mixtures in the experiments. In subcooled quasi-pool boiling, the critical heat flux is strongly depended by the alcohol concentration, and the maximum critical heat flux is indicated at 10 mass% for Ethanol, 7.5 mass % for Propanol and 2 mass% for Butanol. Microbubble emission boiling occurs in the beginning of transition boiling and the heat fluxes of the mixtures are little higher than that of water.

In subcooled flow boiling, MEB occurs in horizontal rectangular and circular channels and the heat fluxes of the mixtures in MEB are higher than that of water. The pressure fluctuations in MEB of the mixtures are smaller than that of water.

According to the experimental results, it is effective to use alcohol-water mixture in subcooled boiling for acceleration of MEB and enhancement of boiling heat transfer.

The experiments were carried out in the project of "Fundamental Technology Development for Energy Conservation" promoted by NEDO (New Energy and Industrial Technology Development Organization of Japan) in 2002~2005 and in the support of Grant in Aid for Scientific Research promoted by JSPS (Japan Society for the promotion of Science) in 2002~2005. The author greatly appreciates the support of NEDO and JSPS for the experimental studies.

References:

[1] Fujibayashi A., Kumagai S. and Takeyama T., , Heat Transfer in Highly Subcooled Convective Fluid Flow Direction, *Transaction of JSME*, Vol.B51, No.463, 1985,pp.919-927.

[2] Kubo R. and Kumagai S., Occurrence and Stability of Microbubble Emission Boiling, *Transaction of JSME*, Vol.B58, No.546, 1992, pp.497-502.

[3] Kubo R. , Shimada R. and Kumagai S., Relationship between Sound and Heat Transfer on Microbubble Emission Boiling, *Transaction of JSME*, Vol.B59, No.557, 1993, pp.183-190.

[4] Suzuki K., Torikai K., Satoh H., Ishimaru J. and Tanaka Y., Boiling Heat Transfer of Subcooled Water in a Horizontal Rectangular Channel (Observation of MEB and MEB generation), Transaction of JSME, Vol.B65, No.637, 1999,pp.3097-3104.

[5] Kumagai S, Murata S., Izumi M. and Shimada R., Heat Transfer Mechanism on Temperature Profile and Bubble Motion in Microbubble Emission Boiling, *Proceedings of the 6 th ASME-JSME Thermal Engineering Conference*, 2003, CD-ROM TED-AJ03-219.

[6] Suzuki K., Saitoh H. and Matsumoto K., High Heat Flux Cooling by Microbubble Emission Boiling, Annals of New York Academy of Sciences, Vol.974, 2002, pp.364-377.

[7] Suzuki K. and Kawada R., On Subcooled Flow Boiling with Microbubble Emission in a Horizontal Circular Channel, *Procedings of the 1st International Symposium on Micro-Nano Technology* , 2004, CD-ROM V1-01.

[8] Hovestreudt, J., The influence of the surface tension difference on the boiling of mixtures, *Chemical Engineering Science*, Vol.18, 1963, pp.631-639.

[9] Suzuki, K., Nakano, H. and Itoh, M., Subcooled boiling of aqueous solution of alcohols, *Proceedings of the 6th KSME-JSME Thermal and Fluid Engineering Conference*, 2005, CD-ROM-1977.

[10] Suzuki, K., A Study on High Heat Flux Cooling for Electronic Devices using Subcooled Flow Boiling (Microbubble emission boiling of binary mixtures), *Proceedings of National Conference on Thermal Engineering 2003*, 2003, pp.83-84.