HEAT TRANSFER ENHANCEMENT OF SUBCOOLED FLOW BOILING IN MICRO-SLIT-CHANNEL BY ELECTROSTATIC PRESSURE

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ABSTRACT

Pool boiling heat transfer with electric field offers attractive performance characteristics for thermal management of high heat flux components. Two-phase operation enhanced by electric field provides high heat transfer coefficient while suppressing the increase of boiling surface temperature. To investigate further enhancements in heat transfer coefficients and increases in the critical heat flux operated by subcooled flow boiling problem, an experimental study of electric filed enhancement is performed using a dielectric liquid AE-3000. The electric field is generated by a micro slit electrode that is designed to produce electrostatic pressure at the liquid-vapor interfaces. In addition to employ the electric field enhancement, the micro-structured surface is constructed by electrodepositing diamond particles on the boiling surface in order to reduce the contact angle and increase the number of bubble nucleates. As a result, the heat transfer rate was strongly increased from 7 kW/(m\(^2\) · K) to 23 kW/(m\(^2\) · K) by the effects of electric field and the micro-structured surface.

INTRODUCTION

Increasing attention is focused on high performance cooling methods owing to the evident rise in demand for heat dissipation from electrical devices such as central processing units, laser diodes, and light emitting diodes [1]. Critical heat flux (CHF) is the most important design parameter for the thermal management of electronics because the heat transfer coefficient (HTC) of boiling heat transfer is the highest when compared to those of other heat transportation mechanisms. However, the heat flux in the boiling heat transfer involves a CHF as a thin vapor layer develops over the boiling surface (called as a film boiling) that strongly decreases heat dissipation [2]. The resulting film boiling regime causes a sudden increase in the temperature of the boiling surface that result in the melting of the surface material. Thus, it is important to study strategies for increasing the CHF. A high CHF will aid in designing efficient cooling equipment for the electrical devices with low flow rates and space saving.

The high electric field in the dielectric liquid generates an electro-hydro-dynamic (EHD) force [3], [4]. It is possible to use the EHD force as a pump with no moving parts, a simple design, and a low weight. Hence, it has been the focus of several theoretical and experimental investigations in the early 1960s owing to the aforementioned advantages [5], [6]. However, the applied voltages to produce the EHD are very high (exceeding 10 kV).

Recently, the combination of two effective heat removal mechanisms - boiling and EHD forces - contributes to the design of efficient and compact technologies that can solve the thermal operation problem of high heat fluxes dissipated from a variety of electrical devices [7]-[11]. The EHD force is consisting of Coulomb force, dielectric force, and electrostriction force. Especially, electrostatic pressure is created as a results of dielectric force when a strong electric field is applied horizontally to the interface between a dielectric liquid and its vapor [3], [4], [10]-[14]. Kano et al. [14] demonstrated that this electrostatic pressure strongly increased the CHF when a micro-slit-electrode (with arrays of 10 narrow slits with a width of 700 μm) was placed over the boiling surface at distances in range of 200–600 μm. This type of electrode was used to successfully decrease the applied voltage to the range of 100–3000 V, while the CHF increased to a maximum of 86 W/cm\(^2\) that is four times greater than that of the pool boiling CHF. In addition to the boiling curves, bubble behavior was also observed above the electrode and the heater surface using transparent indium tin oxide (ITO) coated electrode [13]. The observation results indicated that the electrostatic pressure induced by Kelvin-Helmholtz instabilities divided large bubbles into small ones. The visualizations were also used to make the argument that the increased heat transfer was due to the periodic thin film creation by the electrostatic pressure at the bottom limb of the vapor columns. Kano [15] also conducted the classical Kelvin-Helmholtz instability analysis on the liquid-vapor interface and applied it to Zuber equation [1] by taking account into electrostatic pressure. The experimental CHF was predicted well by the analytical equation.

The influence of boiling surface characteristics, such as roughness, wettability, and porosity, were investigated on pool boiling that allowed the optimization of heat removal capacity [15]-[22]. O’Connor et al. [17] investigated the effect of the three micro structured surfaces, sprayed alumina 0.3-5.0 μm, painted diamond 1-3 μm, and 8-12 μm on the boiling curve. They reported that a silicon test-tip surface painted with diamond particles (8-12 μm) in a saturated dielectric liquid (FC-72) increased the CHF from 49 W/cm\(^2\) (untreated surface) to 79 W/cm\(^2\). In addition to the saturated condition, the CHF in the subcooled liquid (45°C) was tested, and strongly increased to 159 W/cm\(^2\). Furthermore, the heat dissipation goal for electrical devices of 100W/cm\(^2\) was achieved at a junction temperature of 85°C by the sprayed alumina surface. Das et al. [18] examined topographically different surfaces by drilling holes with a diameter of 600 μm and a depth of 2 mm using distilled water as a working fluid. They proposed an empirical equation to predict the heat flux that was
proportional to the number of nucleation sites to the power of 0.52.

Lüttch et al. [23] pointed out that interfacial area density between the vapor and the liquid adjacent to the boiling surface plays an important role in limiting the CHF. The interfacial area density depends on the macroscopic contact angle that represents the boiling surface characteristics. They successfully correlated the experimental CHF of boiling water with various contact angles ranging from 20° to 110°. According to their approach, Kano [24]-[25] semi-empirically correlated the experimental CHF of a boiling dielectric liquid with contact angles ranging from 8° to 15° that was varied by electrically depositing with various metals (Cr, NiB, and Sn) on a copper surface, and by electrically co-depositing with diamond-particles of various diameters (5 μm, 10μm, 15μm, and a mixture of 5μm and 1.5 μm) and nickel. The semi-empirical equation predicted the experimental CHF within ±15%.

The present study examines the determination of CHF for forced convective flow through a micro-slit-electrode. The micro-slit-electrode was designed to produce a high electric field above the boiling surface with applying voltage. In contrast to most extent studies on two-phase micro-channels, in the present study, cooling is enhanced by the EHD effect that successfully increases the CHF (≈ 100 W/cm²) with a very low flow rate (40 ml/min) and low pressure drop (< 2.5 kPa). This study includes data detailing the effect of electric field strength on the CHF at a fixed electrode height (600 μm).

SUBCOOLED FLOW BOILING ENHANCEMENT BY THE ELECTRIC FIELD

Kano [14] reported that the energized micro-slit-electrode installed above the boiling surface with distances 200 ~ 600 μm strongly increased the CHF that was four times larger than that of the horizontal plane surface in the pool boiling problem. The micro-slits in 700 μm wide were fabricated in the electrode. They also proposed the boiling heat transfer enhancement model. The detailed configuration of the boiling model was described in reference [14]. Additionally, He derived a mathematical expression to predict the maximum heat flux in saturated pool boiling by incorporating electrostatic pressure in hydrodynamic theory as follows:

\[
q_{\text{max, EHD}} = \frac{\pi \lambda}{48} L \rho_v L_s \frac{\lambda}{A} \times \left[ \rho_l + \rho_v \left( \frac{2 \pi \sigma}{\lambda} + \frac{E^2 (\varepsilon_l - \varepsilon_v)}{\varepsilon_l} \right) \right]^{1/2},
\]

where \( \lambda \) denotes the wavelength, which depends on the electrode height \( H \) via the following expression:

\[
\lambda = 2H.
\]

\( W_E \) denotes the electrode width.

Also, Kano [14] showed that CHF with the EHD effect could be successfully predicted by Eq. (1). Then, the relationship between the normalized CHF \( \left( = \frac{CHF}{q_{\text{max, EHD}}} \right) \) and the contact angle on the boiling surface is semi-empirically correlated [24] as follows:

\[
\frac{CHF}{q_{\text{max, EHD}}} = C_A \frac{\cos \phi}{\sin \phi} + C_B \frac{1}{\sin \phi},
\]

where \( C_A = -0.00766 \) and \( C_B = 0.283 \). This equation fully predicted the CHF with various electric fields.

In the flow boiling problem, it is necessary to consider both sensible heat and latent heat for cooling the boiling surface. Latent heat is calculated using Eq. (3). Additionally, the sensible heat owing to the liquid flow is calculated by the following equation:

\[
q_s = Q \rho (\Delta T_l)/A,
\]

where \( \Delta T_l \) denotes the liquid temperature difference as given by the following equation:

\[
\Delta T_l = T_{\text{sat}} - T_0.
\]

If the \( T_{\text{sat}} \) reached to the saturated temperature, \( \Delta T_l \) and \( q_s \) would show the maximum. Then, the heat flux by the sensible heat could not follow the total heat flux through the boiling surface. The maximum sensible heat is calculated by the following equations:

\[
q_{s,\text{max}} = Q \rho (\Delta T_{l,\text{max}})/A, \quad \Delta T_{l,\text{max}} = T_{\text{sat}} - T_0.
\]

Moreover, it is necessary to consider the limitation in boiling caused by the complete vaporization of the inlet liquid by using the following equation:

\[
q_{\text{lim}} = Q \rho v L/A.
\]

If \( CHF < q_{\text{lim}} \), then the CHF for subcooled flow boiling is predicted by the following equation:

\[
CHF_{\text{sfb}} = q_{s,\text{max}} + CHF.
\]

In contrast, if \( CHF > q_{\text{lim}} \), then the CHF is predicted by the following equation:

\[
CHF_{\text{sfb}} = q_{s,\text{max}} + q_{\text{lim}}.
\]

EXPERIMENTAL SYSTEM

Figure 1 shows the schematic of the flow control system used for the experiments in the present study. The system consisted of a dielectric liquid circuit that contained the micro-slit-channel test module, a condenser, a flow control system, and a constant temperature bath.
The dielectric liquid was subcooled through the temperature controlled water bath (AS ONE, LTB-250). The vapor boiled in the test modules condensed at the condenser that was cooled with circulating water chilled at 10 °C by a refrigeration system (Tokyo Rikakikai Co. Ltd, CA-1113). A smooth flow pump (TACMINA, Q-100-VE-P-S) was used to pump the liquid with reproducibility within 1 ml/min. The complete setup was installed in a drying room (Takasago Thermal Engineering, TD-45) with a low dew point corresponding to -30 °C or lower, and the room air was passed through high efficiency particle filters, in order not to contain the moisture and particles in the working fluid. The room temperature was controlled at 25±5 °C.

The test module is illustrated in Fig. 2. The module consisted of transparent polycarbonate housing, a slit electrode, a Teflon block, and a copper block as shown in Fig. 2(a). Six 200 W electric cartridge heaters (Hakko, HLE1201) that are 10 mm in diameter and 50 mm in length were embedded at the bottom of the copper block. The heaters were connected in a parallel configuration, and their total resistances correspond to 8.3 Ω. The copper block was prepared as the heating block, and its 15 mm diameter top surface, with a microstructure containing diamond particles, was used as the boiling surface. The side of the block was insulated with the Teflon block, and the entire setup was covered with glass wool. The heat flux and surface temperature measurements used for the experimental investigations are identical to that used in a previous study [24]. The temperature gradient in the center of the copper block was measured by three T-type thermocouples (Keyence, NR-TH08, and CHINO, GT-1) with an uncertainty corresponding to 0.04 K. The position of the thermocouples is shown in Fig. 2 (b). The thermocouples were calibrated by the precision thermometer (ASL, CAB-F201, and CHINO, R900-F25) with uncertainty of ± 0.025K. The heat flux was calculated from Fourier’s equation \( q = -k \frac{\text{grad}T}{} \) with a maximum uncertainty corresponding to ± 0.349 W/cm² at 50W/cm² and ± 0.263 W/cm² at 10 W/cm². The wall temperature, \( T_w \), was extrapolated from the temperature gradient with a maximum error corresponding to ± 3% rdg that was confirmed by directly measuring the wall surface temperature prior to the boiling experiments. Figures 2 (c) and (d) show the top section and the side section views of the test module. The rectangular boiling section possessed internal dimensions of 22 × 21 × 31 mm. It contained a working fluid, an electrode, pressure sensors, and T-type thermocouples. A refrigerant inlet was positioned on the side of the chamber, and a vaporized refrigerant outlet was positioned on top of the chamber. The inlet and outlet pressures were measured with an uncertainty of ±147 Pa by pressure transducers (KYOWA, PHL-A-2MP) that were calibrated in the range of 20 kPa using a low-pressure gage with an uncertainty corresponding to ± 70 Pa.

During each test, the temperature difference between the wall and liquid, \( \Delta T \), is calculated as follows:

\[
\Delta T = T_w - \frac{T_0 + T_{out}}{2},
\]

and the associated HTC is calculated as follows:

\[
HTC = \frac{q}{\Delta T}.
\]

Dielectric liquid AE-3000 (AGC) was selected to test the boiling process, and the properties of the liquid are listed in Table 1. The working fluid was boiled at a
moderate heat flux (approximately in the range of 6.5 W/cm$^2$ - 8.0 W/cm$^2$) for 120 min to remove any remaining trapped gas.

Figure 3 shows a sketch of the cross sectional boiling chamber and an electrical circuit. The electric field was generated by a high-voltage dc power supply (Matsusada Precision, HEOPS-5B6) that provided voltages up to $-5$ kV with an uncertainty corresponding to $\pm 1\%$ FS. To decrease the wall surface temperature and increase the maximum heat flux, the electro co-deposition method using nickel and diamond particles (a mixture of two diameters of 5 μm and 1.5 μm) was used to apply the enhancement microstructure on the boiling surface. Details of the method were described in a study by Kano [24]. The average surface roughness, Ra, before and after the experiment corresponding to $0.19 \pm 0.022$ μm, and $0.21 \pm 0.021$ μm (N = 18), respectively. Additionally, the contact angle with the dielectric liquid before and after the experiments corresponded to $10.2 \pm 0.59^\circ$, $9.8 \pm 0.387^\circ$ (N = 18), respectively. It was evident that the surface roughness and contact angle were not changed by the boiling process. The density of the diamond particles corresponded to 51563 particles/mm$^2$. A sessile drop method was used to measure the static contact angle based on the JIS R3257 standard. A liquid droplet with a volume of 2.0 μl that was exposed to air was placed on the boiling surface. The contact angle was determined from the sequence photographs recorded at 100 frames/sec. The uncertainty in the measured contact angle corresponded to 0.3°.

As shown in Fig. 4, a micro-slit electrode was prepared. The narrow slits were fabricated in the electrode to remove the vapor bubbles from the boiling surface by electro static force. The electrode was mounted 600 μm above the boiling surface by a double sided adhesive tape (Nitto Denko, HJ-3160W).

![Diagram](image)

Fig. 2 Micro-slit-channel test module. (a) Isotropic view, (b) detailed structure of the measurement block for heat flux, (c) top section view, and (d) side section view (A – A).
In order to study the effect of electric field, the electric field was changed from 0 kV/mm to -5kV/mm at fixed initial temperature of 30 °C and flow rate of 40 ml/min. The average velocity through the electrode slits was very low at 3.3 mm/s and Reynolds number defined by the average velocity and the slit width was calculated as

\[
\text{Re} = \frac{\text{u} \times \text{W}}{\nu}
\]

Eq. (13) shows the present flow condition was characterized by low Reynolds numbers.

Data, including thermocouple outputs and pressures, was logged for 200 s at 10 s intervals after reaching a steady condition. The steady condition was determined when the three thermocouples in the copper block continuously showed a constant value within the sensor uncertainty of ±0.04 K for 60 s at 10 s intervals. The CHF was detected by the sudden increase in the thermocouples in the copper block.

**EXPERIMENTAL RESULTS AND DISCUSSION**

Figure 5 shows total and sensible heat fluxes, \( q \) and \( q_s \), outlet temperature, \( T_{\text{out}} \), pressure drop for \( E = -5 \) kV/mm, \( T_0 = 30 \) °C, and \( Q = 40 \) ml/min. These results reference the temperature difference between the wall surface temperature and saturation temperature, which is denoted as \( T_w - T_{\text{sat}} \). As shown in Fig. 5 (a), the total and sensible heat fluxes, \( q \) and \( q_s \), are gradually increased as the wall temperature is increased. Also, the liquid temperature in boiling chamber, \( T_{\text{out}} \), is sensitively increased to the increase of the wall temperature due to the low flow rate. \( T_{\text{out}} \) reaches a saturated temperature at a super heat of 19.3K resulting in the maximum sensible heat. As the total heat flux, \( q \), approaches a CHF, the inclination of the \( q \) curve becomes smaller because partial dry-out at the wall surface occurs. Finally, the heat flux reaches to 94 W/cm² at a superheat temperature of 36 °C (boiling surface temperature of 91 °C). The bubble behavior above the slit electrode is shown in Fig. 6. Subcooled nucleate boiling (SNB) is initiated from when the wall temperature, \( T_w \), is super-heated, and then fully-developed nucleate boiling (FDNB) is observed exceeding a super-heat of 13.5 K. The total heat flux, \( q \), is suddenly increased in the FDNB regime as deviating from sensible heat flux, \( q_s \), because the latent heat is increased by the developed boiling process. In the two regions, SNB and FDNB, the diameter of bubbles is not increased as rising in the chamber because the boiling process is under the subcooled conditions. However, the bubbles are increased and combined each other once the \( T_{\text{out}} \) reaches to the saturated temperature at a super heat of 19.3 K.

Figure 5 (b) shows the pressure drop. The pressure drop in the approximate range of 0.5 ~ 2.0 kPa is observed. The pressure drop is increased as the temperature difference,
$T_w - T_{sat}$ is increased and shows the unstable behavior after FDNB because the pressure sensor detects the bubble collapse or growth. Finally, the pressure drop suddenly decreases toward the CHF since the vapor flows backward to the inlet space.

Heat flux and HTC relative to various electric fields are shown in Fig. 7. In this figure, the heat flux and HTC without electric fields are also depicted with $T_0 = 30$ °C, and $q = 40$ ml/min. The dashed line shows the limitation in boiling caused by the complete vaporization of the inflow liquid. The application of the electric field significantly increases both the heat flux and HTC. The HTC reaches a maximum after a strong increase, and then gradually decreases because the surface temperature is increased. The CHF under an electric field of $-5$ kV/mm shows $94.3$ W/cm$^2$, which is $3.7$ times greater than the CHF without the electric field ($25.5$ W/cm$^2$), and the maximum HTC corresponds to $23.0$ kW/m$^2$K, which is $3.2$ times greater than the HTC without the electric field ($7.1$ kW/m$^2$K). A high electric field of $-5$ kV/mm successfully maintains the supply of liquid until all the inlet liquid completely vaporizes.

The CHF values predicted using Eqs. (9) and (10) are plotted in Fig. 8. In this figure, the maximum sensible heat flux, $q_{s,max}$, calculated from the sensible heat, and the limitation, $q_{lim}$, in boiling caused by the complete vaporization of the inlet liquid are plotted as dashed lines. As shown in the figure, the experimental values fall within ±30% of the predicted value. It should be noted that it is possible to apply the Eq. (3) for pool boiling problems to predict CHF in the flow boiling problems by adding the sensible heat for the flow problems.

CONCLUSIONS

The heat transfer enhancement of the subcooled flow boiling in a micro slit channel by electrostatic pressure is investigated. The slit electrode was installed over the

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Fig. 5 Behavior of total and sensible heat fluxes, outlet liquid temperature, pressure drop. (a) Total and sensible heat fluxes and outlet liquid temperature, (b) pressure drop as a function of temperature difference ($E = -5$ kV/mm, $T_0 = 30$ °C, $Q = 40$ ml/min).

(a) $q = 9.3$ W/cm$^2$

(b) $q = 17.1$ W/cm$^2$

(c) $q = 45.1$ W/cm$^2$

(d) $q = 87.0$ W/cm$^2$

Fig. 6 Bubble behaviors above the slit electrode with variations in the heat flux ($E = -5$ kV/mm, $T_0 = 30$ °C, $Q = 40$ ml/min).
boiling surface with a distance of 600 μm. The narrow slits were fabricated in the electrode to remove the vapor bubbles from the boiling surface by electrostatic pressure. A surface electrically deposited with diamond particles (a mixture of two diameters of 5 μm and 1.5 μm) was employed for enhancing the subcooled flow boiling. Results were obtained at two different electric field strengths (E = 0, -5 kV/mm).

The representative enhancing behaviors of boiling curve were observed under a condition of E = -5 kV/mm, T₀ = 30 ℃, and Q = 40 ml/min. The significant increase in heat flux after subcooled nucleate boiling was observed. The pressure drop exhibited very low values in the range of 0.5 kPa ~ 2.0 kPa since the flow rate and the friction loss in the slit electrode were very low.

The electric field was varied from 0 kV/mm to -5 kV/mm. The application of the electric field strongly increased both heat flux and HTC. The HTC showed a maximum after a strong increase, and this was followed by a gradual decrease. The CHF with the application of electric field of -5 kV/mm reached 94 W/cm², which was 3.7 times greater than the CHF in the absence of the electric field (25.5 W/cm²). The maximum HTC showed 23 kW/m²K, which was 3.2 times greater than the HTC without the electric field (7.1 kW/m²K).

The predictive CHF was proposed using latent heat for the case of pool boiling as suggested by Kano [24] in addition to the sensible heat for the case of the liquid temperature difference between the initial and outlet flow temperatures. The prediction effectively indicated a good performance within ±30%.

ACKNOWLEDGEMENT
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NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>A</td>
<td>wall surface area, m²</td>
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<tr>
<td>CHF</td>
<td>critical heat flux, W/m²</td>
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<tr>
<td>C</td>
<td>specific heat, kJ/kg/K</td>
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<tr>
<td>D</td>
<td>diamond-particle diameter, m</td>
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<tr>
<td>E</td>
<td>electric field, V/m</td>
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<td>H</td>
<td>vertical distance between the boiling surface and electrode, m</td>
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<tr>
<td>HTC</td>
<td>heat transfer coefficient, W/m²/K</td>
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<tr>
<td>k</td>
<td>thermal conductivity, W/m/K</td>
</tr>
<tr>
<td>L</td>
<td>latent heat or slit length, kJ/kg, m</td>
</tr>
<tr>
<td>Lₘₙ</td>
<td>total slit length above the boiling surface, m</td>
</tr>
<tr>
<td>q</td>
<td>heat flux, W/m²</td>
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<td>Q</td>
<td>flow rate, m³/s</td>
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<td>resistance, Ω</td>
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<tr>
<td>Re</td>
<td>Reynolds number, -</td>
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<td>Tₛₐₜ</td>
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<td>φ</td>
<td>contact angle, degree</td>
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Subscripts

0 = Initial flow
EHD = electrohydrodynamic
in = inlet flow
l = liquid
lim = limitation in boiling
max = maximum value

Fig. 7 Behavior of the boiling curves and heat transfer coefficient with variations in the strength of the electric field (T₀ = 30 ℃, Q = 40 ml/min). (a) Heat flux and (b) heat transfer coefficient as a function of the temperature difference.

Fig. 8 Comparison between the experimental results and predicted values.
out = outlet flow  
s = sensible heat  
sat = saturated condition of liquid  
sfb = subcooled flow boiling  
v = vapor  
W = wall

REFERENCES