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Tunable Pool Boiling Performance over a Copper Tube by Controlling Electric Field and Achievement of Extremely Low Critical Heat Flux

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Abstract **-** In this study, an active method was employed to investigate pool boiling heat transfer using copper tubes under a saturated condition at atmospheric pressure. The active method consisted of a working fluid with charged surfactants and involved controlling the electric field. The boiling curves and high-speed visualization results indicated that the heat transfer coefficient and the critical heat flux values could be altered by controlling the timing of the applied electric field. By turning the electric field on and off, the bubble nucleation behaviors can be manipulated and the heat transfer performance can thus be altered.

Keywords**:** Pool boiling, Bubble dynamics, Charged surfactants, Electric field, Heat transfer coefficient, Critical heat flux.

1. Introduction

Boiling heat transfer is an effective method in heat transfer applications. The main mechanism involved is the liquid–vapor phase change, which allows the transport of large amounts of heat with the assistance of latent heat. The boiling heat transfer mechanism helps improve the thermal performance of power plants, spacecraft, cooling systems, inkjet printers, etc.

Currently, methods for changing the surface roughness and wettability to investigate the boiling heat transfer are categorized as passive or active. Passive techniques include chemical deposition [1], machining [2], and ultrafast laser texturing [3,4]. Active techniques, such as light-induced methods [5] and electric field control [6], have been developed in recent years. Liu et al. [5] prepared a TiO2-coated surface and employed UV light irradiation to alter the surface wettability. Thus, the effect of light-induced surfaces on boiling heat transfer was experimentally studied. Cho et al. [6] investigated boiling performance by using charged surfactants in the working fluid and an electric field. They found that the bubbles could be controlled which indicated that bubbles could be generated or made to disappear to adjust the boiling performance.

Studies on the use of a tubular surface in pool boiling using active techniques are scarce. Investigation of the pool boiling heat transfer over a tubular surface could help increase the thermal performance of boiled tubes in a power plant or coil–shell heat exchangers. In this study, we investigated the pool boiling heat transfer over a cylindrical surface by using charged surfactants and an additional electric field. Furthermore, a high-speed camera was used to analyze the bubble dynamics under different test conditions.

2. Experiments

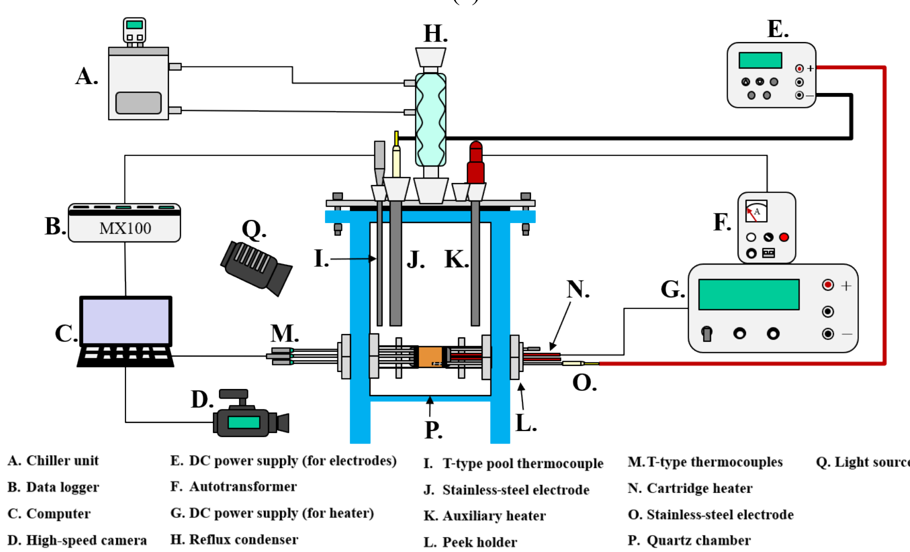
2.1 Experimental setup

The experimental setup in this present work is virtually the same as that in our previous works [3,4,7,8], with the main difference being the design of the active method, which involves the use of an electric field and the use of charged surfactants in the working fluid. The active technique was referred to the aforementioned research done by Cho et al.

[6]. The experimental setup is shown in Fig. 1(a). This setup was used to investigate the effect of control of the electric field on a tubular surface along a horizontal direction exerted by pool boiling. All the experiments were conducted under atmospheric pressure and ambient temperature. The working fluid which can be mainly categorized into pure deionized (DI) water and DI water with charged surfactants. A high-speed camera (Whited Co., HSP 130) was used to record the bubble dynamics during the boiling experiments, and a white LED was used for illuminance during the recording of high-speed images. To ensure that the working fluid remained in a saturated state, an auxiliary heater (CCTCL) was used, and a T-type thermocouple (CCTCL) was employed to monitor the temperature of the working fluid. The auxiliary heater was connected to an autotransformer (CCTCL), and a reflux condenser (CCTCL) was connected to a cooling system to condensate the vapor from the fluid to maintain the amount of working fluid during boiling.

A cartridge heater (CCTLC, 220 V/800 W) was inserted into the copper tube; the cartridge heater was connected to a DC power supply (GW Instek, GPR-20H50D) to control the input power to the tubular piece. Eight T-type thermocouples (CCTCL) were placed circumferentially at the left-hand side of the chamber in intervals of 45° into the test copper tube at alternate depths of 5 and 10 mm for conducting the heat transfer analysis. Thermocouples were connected to a data logger (MX 100), and the recorded temperature data were transmitted to a computer. As seen in Fig. 1(b), one stainless-steel electrode (AUBOTECH) was inserted into the copper tube and another (AUBOTECH) was inserted from the cover of the chamber into the working fluid. Both electrodes were connected to an additional DC power supply (Major Science, MP-300V) to control the electric field. For controlling the electric field, we ensured that the electrode inserted in the copper tube was positively charged and the one immersed in the working fluid was negatively charged. The electric potential applied between the copper surface and the counter electrode immersed in the working fluid was maintained at 10 V.

(a)



(b)

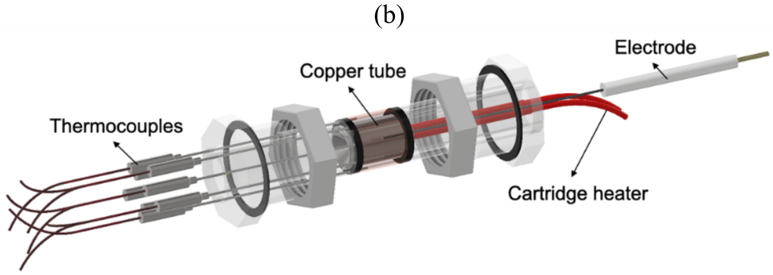


Fig. 1: (a) Schematic of entire experimental setup. (b) Details of the test section.

2.2 Experimental procedure

Prior to the experiments, 1 L of DI water was boiled twice for degassing, after which the water was poured into the chamber. Then, the autotransformer was turned on to start the auxiliary heater to increase the temperature of the working fluid to its saturation temperature. After saturated temperature was reached, we waited for 20 min before starting the experiments. Subsequently, the DC power was turned on and the data logger started to record the temperature readings. The power input into the copper tubes was controlled using the DC power supply by adjusting the current. The current was increased at certain intervals, and 3 min was waited to allow the fluid to reach the steady-state condition. Owing to limitations in the cartridge heater capacity, T1 and T2 do not achieve their CHF, and no additional electric field was applied in these two test conditions. T1 was boiled over a plain copper surface with pure DI water, and T2 was boiled using the working fluid with charged surfactants. In terms of T3 and T4, the additional power supply was turned on at specific current intervals with the use of charged surfactants when the experiments started, and thus, an electric field was created between the test sample and fluid. In T3, the electric field is on for the entire boiling process. In T4, the electric field is on during the heat flux interval of 0 to ~64.91 kW/m^2. The CHF was attained in these two test conditions. When the CHF was reached, film boiling occurred on the copper tubes, with the surface temperature increasing suddenly up to more than 200 °C. Details of the experimental conditions are provided in Table 1.

Table 1: Description of different experimental conditions.

Test conditions	Working fluid	Applied electric potential (10 V)
T1	DI water	Off
T2	SDS (500 ppm)	Off
T3	SDS (500 ppm)	On (entire boiling process)
T4	SDS (500 ppm)	On (turn off when heat flux at ~ 64.91 kW/m^2)

2.3 Data curation

The input power (Q_{in}) from the DC power supply was estimated using Eq. (1).

$$Q_{in} = I \times V \tag{1}$$

where I and V are the current and voltage displayed on the screen of the power supply, respectively.The heat loss (Q_{loss}) in the axial direction was calculated using Eq. (2), and heat loss percentages in each experiment were in 15%.

$$Q_{loss} = 2 \times k \times A_c \times \frac{(T_{10} - T_5)}{\Delta x} \tag{2}$$

where T_{10} and T_5 are the averaged temperature values at different depths of the copper tubes. Δx is the distance between the T_{10} and T_5 thermocouples. A_c is the cross-sectional area of the test sample, and k is the thermal conductivity of copper (400 W/mK).

The heat flux q'' was calculated using Eq. (3).

$$q'' = \frac{Q_{in} - Q_{loss}}{A_s} \tag{3}$$

where A_s is the total surface area of the copper tube.

The wall superheat (ΔT_w) was estimated using Eq. (4).

$$\Delta T_w = T_m - \left(\frac{Q_{in} - Q_{loss}}{2\pi Lk}\right) \times ln\left(\frac{r_o}{r_c}\right) - T_{sat} \tag{4}$$

where T_m is the mean temperature of the four T_{10} thermocouples and L is the length of the copper samples. r_o is the outer radius of the sample, and r_c is the distance from the center of the copper tube cross section to central thermocouple-measuring holes. T_{sat} is the saturated temperature of the working fluid.
The HTC (h) was estimated using Eq. (5).

$$h = \frac{q''}{\Delta T_w} \tag{5}$$

3. Results and discussion

3.1 Pool boiling tests

First, to verify the reliability of our experiments, Rohsenow correlation [9] was plotted in Fig. 2. Compared with the Rohsenow correlation curve, our pool boiling curve for the plain copper surface by using DI water as a working fluid showed a great fit. In addition, the pool boiling curves obtained in previous studies with a plain copper surface as the test sample and DI water as a working fluid [3,4,8] were in good agreement with our results.

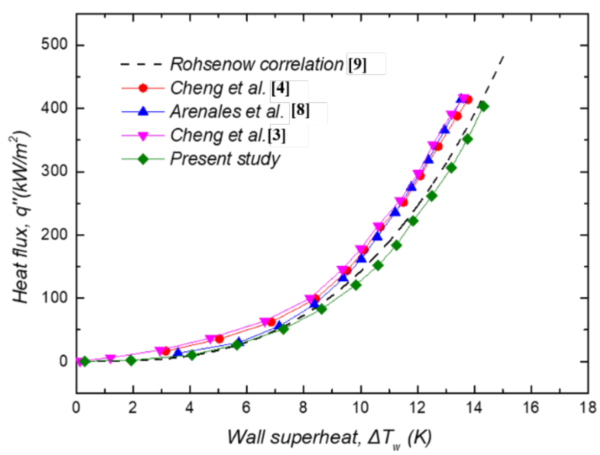
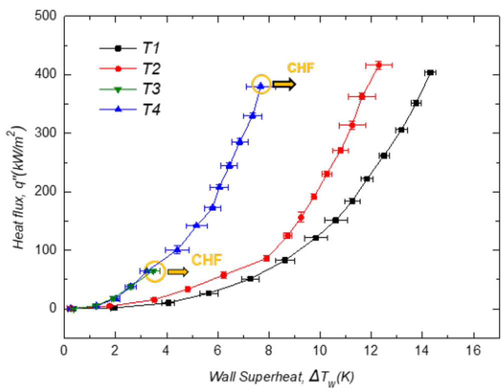


Fig. 2: Comparison of boiling curves over plain copper surfaces using DI water as a working fluid.

3.2 Evaluations of pool boiling heat transfer data

Fig. 3 shows the boiling curves and heat transfer coefficients for different test conditions. The boiling results of the plain copper surface using DI water as a working fluid were selected as reference data. The increases in the HTC under all test conditions with respect to the reference data (T1) at the heat flux interval of ~59.56 kW/m^2 are presented in Table 3. Except for T3 and T4, in which the CHF was attained, the other experiments were conducted to a maximum heat flux regime of approximately 409.86 kW/m^2, indicating that the CHF was not attained under those test conditions (T1 and T2) because of limitations in the cartridge heater. T3 exhibited a left-hand-shifted boiling curve, and the HTC in T3 was 2.67 times that of T1; T3 also exhibited the lowest CHF of ~64.91 kW/m^2. Compared with the heat transfer rate in T3, the heat transfer rate in T4 was a bit higher; moreover, the CHF was considerably enhanced to ~380.20 kW/m^2. The HTCs under the T1 and T2 test conditions, in which no electric field was applied, were considerably lower than those under the T3 and T4 conditions, in which an electric field was applied. The tests without the application of electric field condition exhibited higher CHF values than those assisted by electric field. In terms of T1 and T2, the HTC in T2 was approximately 1.32 times higher than that in T1. The heat transfer performance is elucidated through the high-speed visualization of the bubble dynamics in the next section.

(a)



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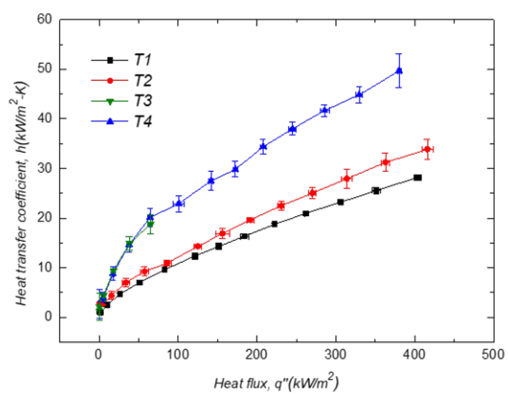

Fig. 3: (a) Boiling curves for copper tubes under different experimental conditions. (b) Boiling heat transfer coefficient versus heat flux under different test conditions.

Table 3: Increase in heat transfer coefficients with respect to heat transfer coefficient obtained in T1 under different test conditions at a heat flux of ~59.56 kW/m².

Test conditions	h_{TN}/ h_{T1}
T1	--
T2	1.32
T3	2.67
T4	2.86

3.3 Analysis of bubble dynamics

The bubble dynamics at different heat flux intervals are shown in Fig. 4. T1 and T2 are the test conditions in which no electric field is applied. In T1, the boiling experiments are conducted using pure DI water as a working fluid, and in T2, the boiling experiments are conducted using charged surfactants. Copper is a metal with high thermal and electrical conductivity; some free electrons easily escape from the surface of the test sample when energy is input, and thus, a few positive electron holes are formed on the surface. Therefore, unlike under the T1 condition, some negatively charged surfactants attach to the tubular copper sample under the T2 condition, causing part of the surface to become more hydrophobic. First, because negatively charged surfactants attached to the surface, the onset of nucleate boiling (ONB) was earlier on a hydrophobic surface, as seen in Fig. 3(a). Subsequently, the number of bubble nucleation sites in T2 was more than that in T1 at each heat flux regime (Fig. 4). With more bubble generation and departure from the heated surface, the surface in T2 was able to transfer more heat with the assistance of latent heat resulting from the liquid–vapor phase change. An increase in the heat transfer performance in T2 is observed in Fig. 3, indicating that a working fluid with surfactants (SDS) helps lower the wall superheat and increases the HTC.

In terms of the experiments in which an electric field was applied (T3 and T4), T3 exhibited the high HTC and the lowest CHF among all test conditions. In T3, the electric field was applied during the entire boiling experiment. Fig. 5 shows the mechanism of bubble nucleation with the use of charged surfactants and an electric field. Unlike in T1 and T2, in T3 and T4, bubbles started to nucleate at the very beginning (~4.32 kW/m^2), as seen in Fig. 4. This was attributed to the attachment of the negatively charged surfactants to the surface. After the additional electric field was applied, the copper sample became positively charged, and thus, the negatively charged SDS ions attached to its surface, rendering the entire surface hydrophobic. Therefore, bubbles began to nucleate at low heat flux intervals, indicating a earlier ONB (Fig. 3(a)). Many bubbles nucleated and departed from the surface, increasing the heat transfer rate owing to the mechanism of two-phase heat transfer. However, at the heat flux of ~64.91 kW/m^2, the bubbles generated did not have enough time to depart from the heated surface. Subsequently, these numerous bubbles coalesced with each other, covering the entire surface with a vapor film. Because of the low thermal conductivity of the vapor film, heat was not transferred effectively, and thus, the film boiling took place representing the earlier occurrence of CHF. Applying an electric field to the copper samples during the entire boiling period substantially increased the HTCs; moreover, the CHF was decreased to an extremely low heat flux (~64.91 kW/m^2).

In T3, the CHF was ~64.91 kW/m^2. As a result, in T4, the electric field was applied at the start of the boiling test and turned off when a heat flux of ~64.91 kW/m^2 was reached to prolong the occurrence of CHF. As seen in Fig. 3, the heat transfer rate in T4 was comparable to that in T3 because the negatively charged SDS attached to the positively charged copper tube, rendering the surface hydrophobic. Consequently, the high nucleation densities helped the surface lower the wall superheat and achieve a high heat transfer rate. After a heat flux of ~64.91 kW/m^2 was achieved, the electric field was turned off and the negatively charged surfactants attaching to the surface started to slightly decrease. As shown in Fig. 4, because the surface turned out to be less hydrophobic than that in T3, the number of nucleation sites was slightly lower than that of T4 at the same heat flux of ~59.56 kW/m^2. As a result, the bubbles had a lower chance to coalesce with each other at moderate heat fluxes, and thus the CHF in T4 was increased up to ~380.20 kW/m^2. After a high heat flux of 380.20 kW/m^2 was reached, the generated bubbles began to form a vapor film, causing film boiling.

As the results indicated, an extremely low CHF was achieved without any additional coating method. A CHF of ~64.91 kW/m^2 was obtained through the active technique consisting of charged surfactants and the application of an electric field. The extremely low CHF is suitable for inkjet printing with a thermal-bubble printhead, whose main mechanism involves film boiling. A typical thermal-bubble inkjet printer consists of a thin-film heater and an ink nozzle. After the thin-film heater is heated, a film bubble is formed because of the high heat flux input, resulting in a large increase in temperature.Subsequently, the growth of a vapor bubble leads to ink flow in the nozzle, after which the ink is ejected. With the use of the active technique, the CHF decreased considerably and film boiling occurred earlier so that the thermal-bubble printhead functioned with less energy input. This indicates that film boiling can be achieved much earlier with the electric power of the printer, and only charged surfactants are required to be added. Overall, a much lower heat supplied into the film heater can expected due to the achievement of extremely low CHF.

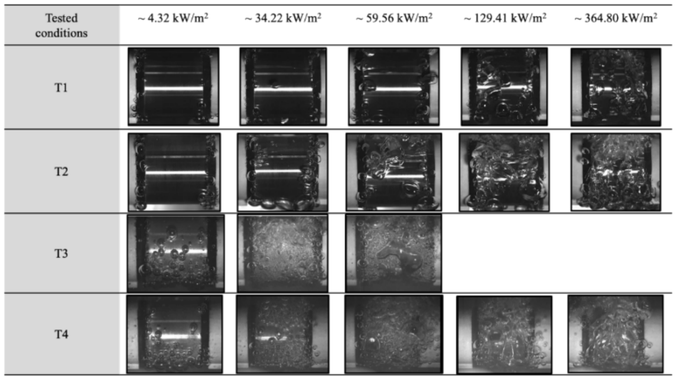

Fig. 4: High-speed images of bubble dynamics under different test conditions.

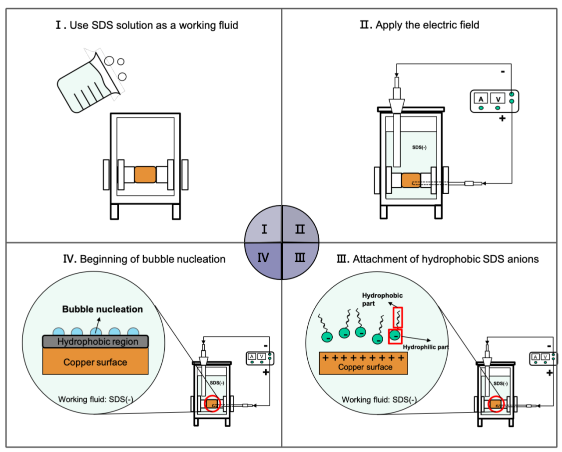

Fig. 5. Bubble nucleation mechanism under the application of charged surfactants and electric field.

4. Conclusion

In this work, an active technique involving the use of charged surfactants and an electric field was employed to study the pool boiling heat transfer over a copper tube under a saturated condition at atmospheric pressure. By controlling the on and off duration of the electric field, bubble generation could be controlled. As a result, the heat transfer rate and CHF were varied. When the electric field was applied for the entire boiling period, the HTC increased by 2.67 times that when no electric field was applied and no surfactant was used because of more bubble nucleation sites. Additionally, an extremely low CHF of ~64.91 kW/m^2 was obtained because the large number of bubbles coalesced with each other, causing film boiling. For the test condition in which an electric field was applied at the start of the boiling experiment and turned off at a heat flux of ~64.91 kW/m^2, the HTC increased by a factor of 2.86 compared with the HTC when boiling heat transfer took place over a plain copper surface using DI water as a working fluid. This is because of the bubble generation and departure with the assistance of the liquid–vapor heat transfer mechanism. Furthermore, the CHF under the test condition when the electric field was applied from 0 to ~64.91 kW/m^2 was 5.86 times higher than the CHF under the test condition when the electric field was applied during the entire boiling process. This was attributed to a moderate control timing of the additional electric field and thus the generation of bubbles could be regulated.

Acknowledgments

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