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Basic study on the enhancement of nucleate boiling heat transfer by applying electric fields

JUNJI OGATA
Mitsubishi Heavy Industries, Ltd, 2-1-1, Shinhama, Arai-cho, Takasago City, Japan

and

AKIRA YABE
Mechanical Engineering Laboratory, MITI, 1-chome, Namiki, Tsukuba City, Japan

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Abstract—New EHD (electrohydrodynamic) phenomena for promoting bubble generation and augmenting boiling heat transfer are introduced in this study. Test results reveal an enhancement factor for the boiling heat transfer with an applied electric field of approximately 8.5 times the maximum value obtained without an electric field. In order to investigate the mechanism of this enhancement, basic experiments and analyses were carried out for bubbles in an electric field. It was clarified that the bubbles were pushed against the bubble-injection surface by the vertical component of the electrostatic forces (Maxwell stress and electrostriction force) and became mobile due to the radial component.

1. INTRODUCTION

For many years, various techniques for heat transfer augmentation have been applied to practical heat exchangers. For example, much effort has been concentrated on developing enhanced heat transfer tubes for evaporators, such as low-finned tubes or tubes with porous surfaces. Porous surfaces with re-entrant cavities are currently the most effective boiling heat transfer surfaces for commercial evaporators. However, more enhanced heat transfer surfaces are needed for applications such as in the cooling of electronic devices. Furthermore, the controllability of heat transfer will be needed for use in space, in addition to augmentation; present techniques cannot be implemented in this particular case. Recently it has become popular to utilize the electrohydrodynamic (EHD) effect as one of the techniques of augmenting heat transfer, and certain EHD techniques have been attempted in practical heat exchangers [1]. An advantage of utilizing an EHD technique is that the heat transfer performance can be easily controlled by varying the applied voltage; present heat exchangers have no control over the system performance. Therefore, if more effective augmentation of heat transfer by the EHD technique becomes practical, present heat exchangers will be replaced by ones which use EHD in many fields.

The expected area of application of this technique is a thermal control system in a space station where, due to a large amount of exhaust heat, a two-phase thermal control system is needed. However, there are serious problems with two-phase heat transfer in space. Because of reduced gravity, the specific weights of liquid and vapour become equal. The bubbles generated during boiling cannot be smoothly removed from the boiling surface, which can cause deterioration of heat transfer. In order to solve this problem, electric forces are a promising replacement for gravity.

It has been reported that the aspect of boiling changes when an electric field is applied to the boiling fluid. Since such an effect is more pronounced in the critical heat flux region, many researchers have investigated EHD phenomena in this region. In the lower heat flux region, where the wall superheat, which is the difference between the temperature of the heat transfer surface and the saturation temperature of the boiling fluid, is small, the augmentation of boiling heat transfer is small and only qualitative results have been reported. For instance, Bonjour *et al.* [2] reported suppression of boiling of various organic fluids such as hydrocarbons under a high electric field. Asch [3] observed that the bubbles produced by boiling R-113 on a wire were attracted to the anode and concluded that the bubble–liquid interface had a negative polarity. However, this conclusion does not seem to be valid for all boiling bubbles. Allen *et al.* [4] reported that the boiling hysteresis disappeared in the electric field, and when an electric field was applied to the heat transfer surface, where there was no previous boiling without an applied electric field, boiling started abruptly. As yet, a detailed explanation of this observation has not been reported.

We investigated the augmentation of boiling heat transfer utilizing the EHD technique [5, 6]. In short, it was found that boiling suppression and aug-

NOMENCLATURE

ΔA	element of surface area [m^2]
d_e	equivalent diameter [m]
E	electric field strength [V m^{-1}]
j	electric current density [A m^{-2}]
n	normal unit
P_D	electrostriction force [Pa]
P_E	electrostatic force [Pa]
P_M	Maxwell stress [Pa]
R	principal radius of curvature [m]
r	radial component of cylindrical coordinate
z	vertical component of cylindrical coordinate.

Greek symbols

α	surface tension [N m^{-1}]
γ	fluid density [kg m^{-3}]
ε	relative dielectric constant
ε_0	absolute dielectric permittivity [F m^{-1}]
θ	angle [deg]
ξ	deformation length of bubble [m]
ρ_e	electric charge density [C m^{-3}]
σ_e	electrical conductivity [A V^{-1} m^{-1}]
τ_e	relaxation time of electric charge [s]
ϕ	electrical potential [V]
φ	angle [deg].

Subscripts and superscripts

~	non-dimensional expression
b	bubble
G	vapour
i	ith component
L	liquid
max	reference value (maximum value)
r	radial component
z	vertical component.

mentation of heat transfer were observed because of the enhancement of convection under non-uniform electric fields. After that, it was clarified that the augmentation of heat transfer depends strongly on the relaxation time of the electrical charge of the working fluid. Therefore, the influences of the electrical properties of the fluids were surveyed by mixing an electrically conducting fluid with a dielectric fluid. The result showed that the boiling became active and heat transfer was greatly enhanced.

This paper describes the experimental results of the boiling enhancement and augmentation of heat transfer in an electric field. Also, basic research on the behaviour of a bubble under the influence of an electric field is discussed.

2. BOILING EXPERIMENTS UNDER THE INFLUENCE OF AN ELECTRIC FIELD

Figure 1 shows a schematic diagram of the overall experimental system. The test section, shown in Fig. 2, consists of a smooth copper tube, electrode wires and teflon insulators. The tube is horizontal, its outer diameter being 22.4 mm. The electrode wires run along the length of the tube, are placed 3 mm away from the heat transfer surface, and have a 7 mm separation distance between adjacent wires. They are bonded to teflon insulators, which are 3 mm thick and are axially placed at equal distances along the tube, about 20 mm apart. These insulators are used to fix the distance between the tube and wires. The surface of the copper tube was polished with emery paper (No. 1000). In the wall near the centre of the tube, four sheathed thermocouples made of chromel–alumel, with an outer diameter of 0.5 mm, are embedded 90° apart. Placed within the tube is a cartridge heater.

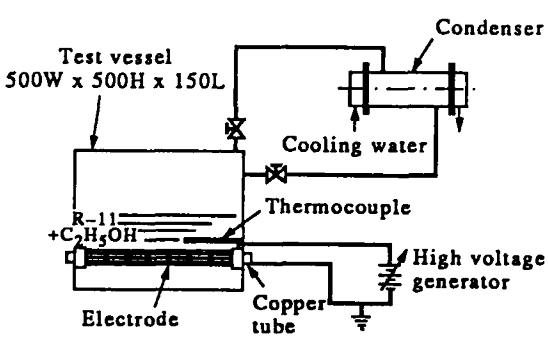


FIG. 1. Schematic diagram of experimental apparatus.

The polarity of the upper electrode is positive d.c. with the tube as ground. The test fluid is a mixture of R-11 (CCl_3F) and ethanol, which is initially 2 wt % included.

The experimental conditions were as follows:

pressure	105 kPa
heat flux	5.8×10^3 W m^{-2}
temperature	25°C
applied voltage	0–25 kV
(electric field strength	0–8.3 MV m^{-1}).

Figure 3 shows photographs of boiling under various electric field strengths. As the electric field strength is increased, various boiling phenomena are observed. When the applied voltage is 10 kV, boiling is suppressed and the number of boiling bubbles decreases, which is the same phenomenon that occurs with pure R-11 [5]. However, when the applied voltage exceeds 15 kV, boiling abruptly becomes active, and the number of bubbles increases. Bubbles are generated along

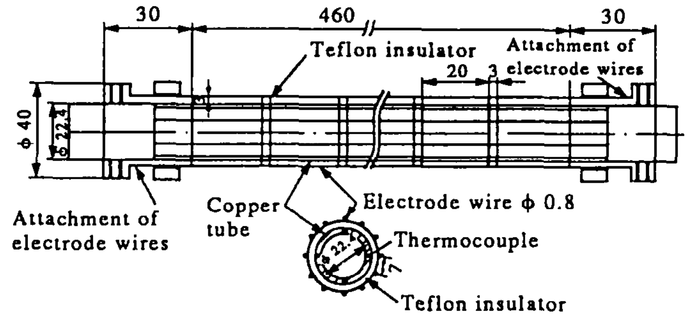
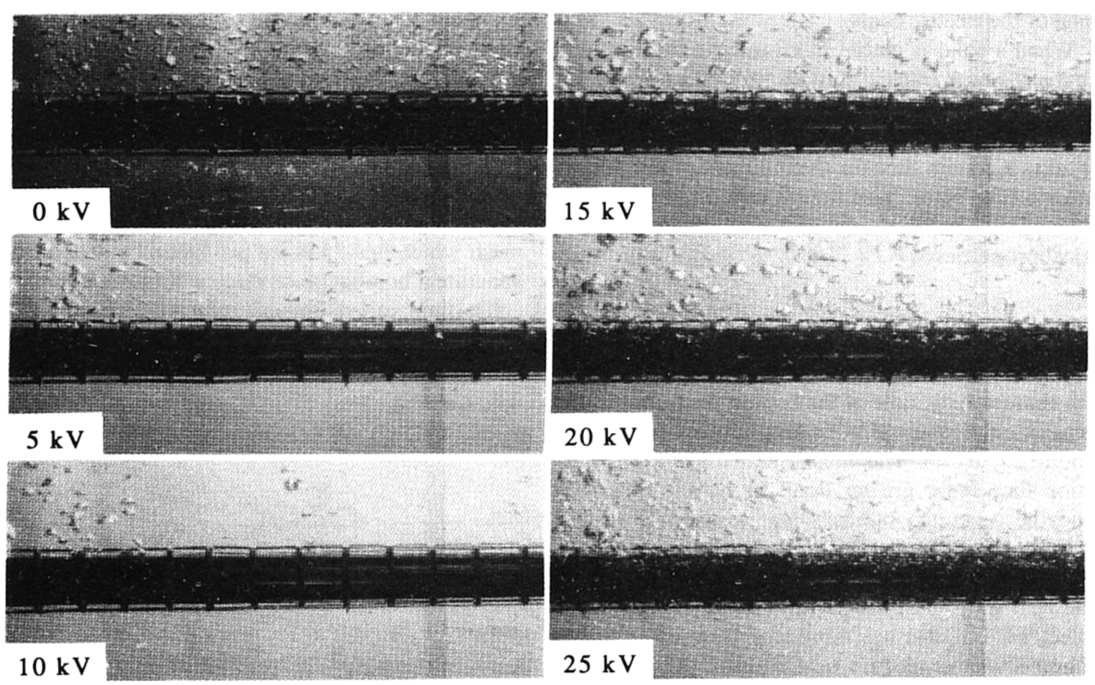


FIG. 2. Schematic diagram of a test tube.

the entire surface of the tube. Each bubble moves violently in the horizontal direction along the tube surface, along the centre line between each of the two electrode wires. Some of the bubbles coalesce and float up to the free surface.

Figure 4(a) shows the heat flux–wall superheat relationship obtained from this experiment together with those reported in other research studies; i.e. boiling data for a porous surface [7] and a mechanically prepared surface with fine tunnels [8]. It shows that the augmentation of boiling heat transfer, on the smoothed surface utilizing the EHD technique, is of the same order of magnitude as that on the other surfaces. Figure 4(b) shows the boiling heat transfer augmentation as a function of the applied voltage. The effect of the electric field on boiling heat transfer of pure R-11 is also shown. This figure shows that the augmentation of EHD boiling is about 8.5 times that without an electric field.

The reason for this augmentation of heat transfer utilizing EHD is considered as follows. There are two effects of high electric fields. One is the electro-convection effect on fluids. The other is the effect on the behaviour of the bubbles. Both effects are depen-



Fluid	R11 + C_2H_5OH 2 wt%	Electrode gap	3 mm
Pressure	atmospheric	Wire pitch	7 mm
Saturation temperature	25 °C	Applied voltage	positive DC

FIG. 3. Photographs of boiling R-11 on a tube with applied electric fields.

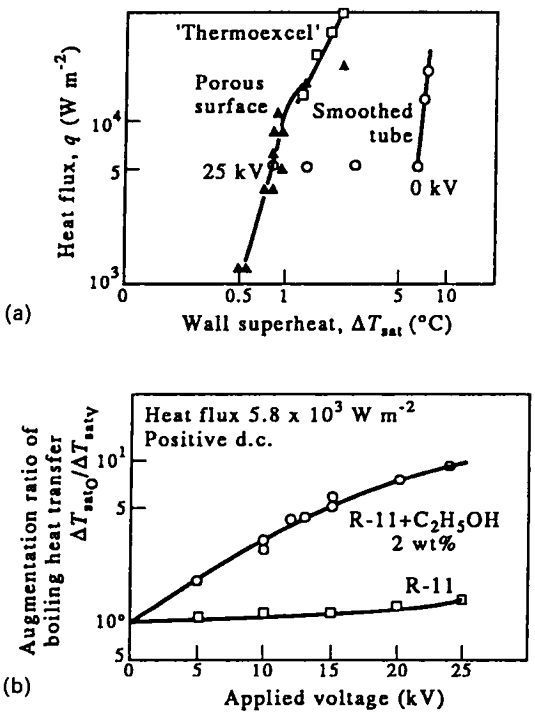


FIG. 4. (a) Experimental results of boiling characteristics. (b) Boiling heat transfer augmentation by applying an electric field.

dent on the electric field strength and the relaxation time of the electric charge.

When a solid is placed in an electric field, electric charges are generated:

$$\rho_e = \varepsilon_0 \varepsilon E\{1-\exp(-\sigma_e t/\varepsilon_0\varepsilon)\}.$$

It takes a certain time for the influence of the electric field to take place. This time is called the relaxation time of the electric charge and is related to the electrical properties as

$$\tau_e = \varepsilon_0\varepsilon/\sigma_e. \quad (1)$$

In Table 1, the charge relaxation times of various fluids are shown. For pure R-11 it is about 1.3 s, while the characteristic time of the boiling fluid, that is, the generation frequency of boiling bubbles of R-11, is about 2×10^{-2} s. This means that the charge relaxation time is far greater than the bubble frequency and the generated bubbles float to the free surface without being affected by the electric field. These bubbles, then, are not forced down to move around on the heat transfer surface. Only the electroconvective effect on the thermal boundary layer, due to the inhomogeneous electric field around the wire electrodes, contributes to the augmentation of heat transfer. This convective effect is the cause of boiling suppression reported in a previous paper [5].

On the other hand, when ethanol, which is conductive, is added to dielectric R-11 (only several percent of the total weight), the relaxation time decreases (see Table 1), becoming much smaller than the bubble

Table 1. Relaxation times of electrical charge for various fluids

	τ_e (s)
R-11	1.3
R-11+C_2H_5OH (2 wt%)	9.2×10^{-3}
R-113	9.8×10^{-1}
R-113+C_2H_5OH (4 wt%)	5.7×10^{-3}
C_2H_5OH	1.9×10^{-3}

frequency. As a result, bubbles are pressed against the heat transfer surface due to the alternating electric potential distribution corresponding to the bubble motion, causing deformation and coalescense of the bubbles by the electric force.

Since these phenomena are considered to be effective for the augmentation of heat transfer, basic experiments and analyses have been performed in order to clarify the bubble generation mechanism and the behaviour of bubbles in an electric field.

3. BEHAVIOUR OF A BUBBLE IN AN ELECTRIC FIELD

3.1. *Experimental observations*

Figure 5 shows a schematic diagram of the experimental apparatus used to observe the bubble behaviour in an electric field. Air bubbles supplied by a compressor were used, since the most important electrical property (dielectric constant) for air is almost the same as that for dielectric fluid. The test vessel is a cube of 200 mm on each side and is made of acryl resin. A bubble injection plate is placed near the bottom of the test vessel and serves as a grounded lower electrode. The gap between the plate and the upper electrode is 5 mm. The upper electrode is a bronze mesh which has 25 holes per inch. These electrodes generate a homogeneous electric field for the bubble.

The fluid, called 'Furonsorubu AE', is an azeotropic mixture of R-113 (96 wt%) and ethanol (4 wt%). At the centre of the bubble injection plate there is a small

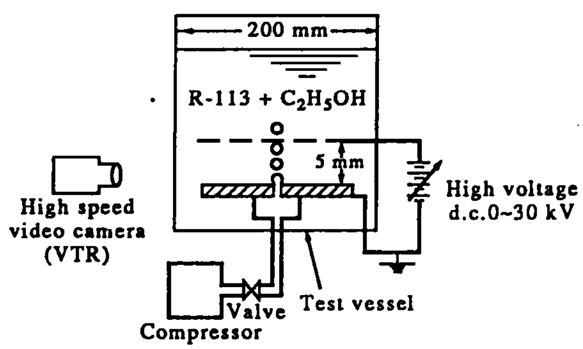


FIG. 5. Schematic diagram of experimental apparatus for observing bubble behaviour under an electric field.

air injection hole with a diameter of 0.1 mm. The polarity of the applied voltage is either positive or negative d.c. A high speed video cassette recorder (Kodak SP-2000) is used to record the bubble behaviour. Test conditions inside the test vessel were as follows:

pressure	103 kPa
temperature	20°C
applied voltage	0–30 kV
electric field strength	0–6 MV m^{-1}.

Figures 6(a) and (b) show photographs of bubbles recorded by the VTR. Figure 6(a) shows spherical bubbles without an applied electric field, the diameter of the bubble as it departs from the injection hole (i.e. departure diameter) being about 1 mm. When the electric field is applied, the shape of the bubbles changes (Fig. 6(b)). The bubbles generated from the injection hole move horizontally on the plate without migrating vertically, become elongated and vibrate up and down while the bottoms of the bubbles maintain contact with the plate. Soon after vibrating, the lower part of the bubble becomes smaller and detaches from the plate and floats to the surface. These elongated bubbles have a maximum length of about 3 mm and become spherical after passing through the upper electrode. Such a bubble motion is characteristic in a positive d.c. applied to the upper electrode. These phenomena are similar to the bubbles of the boiling test in which they moved around the tube violently in the presence of a positive d.c. applied to the upper electrode. In the following, the result of this basic experiment is discussed theoretically.

3.2. *Theoretical analysis of the bubble's behaviour and shape*

In order to study the effect of electric fields on a bubble, the electric potential distribution and the electrostatic forces around a bubble are analysed. Since the relaxation time of the electrical charge is

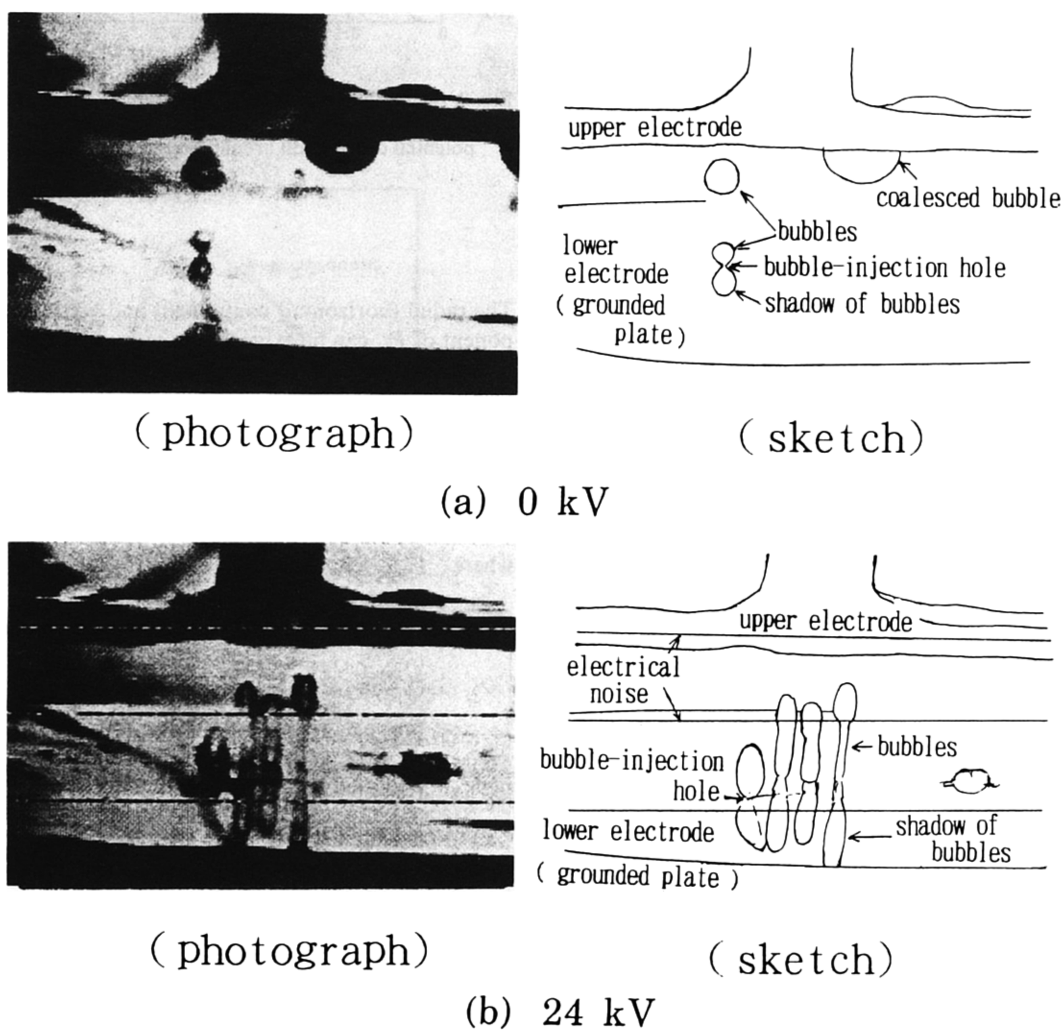


FIG. 6. Bubble shapes under applied voltage of 0 and 24 kV.

much smaller than the boiling frequency, the liquid can be regarded as a conductive fluid. The electric potential around a bubble is calculated from the following Maxwell equations:

(i) continuity equation of electric current, j

$$\nabla \cdot j = 0 \tag{2}$$

(ii) Ohm's law

$$j = \sigma_e E \tag{3}$$

(iii) definition of electric potential, ϕ

$$E = -\nabla\phi \tag{4}$$

where σ_e is the electrical conductivity and E is the electric field strength. When σ_e is assumed to be constant, we obtain from equations (2) to (4):

$$\nabla^2\phi = 0. \tag{5}$$

Equation (5) is written in cylindrical coordinates as

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\phi}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2\phi}{\partial\theta^2}+\frac{\partial^2\phi}{\partial z^2}=0. \tag{6}$$

If axial symmetry is assumed, $\partial^2\phi/\partial\theta^2 = 0$, then equation (6) becomes

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\phi}{\partial r}\right)+\frac{\partial^2\phi}{\partial z^2}=0. \tag{7}$$

Boundary conditions, normalized by the electrode gap distance, are

when

$\tilde{z} = 0$,

$\tilde{z} = 1$,

$\tilde{r} = 1$,

$\tilde{r} = 0$ and $\tilde{z} \geqslant \tilde{z}_b$,

then

$$\tilde{\phi} = 0 \tag{8}$$

$$\tilde{\phi} = 1 \tag{9}$$

$$\tilde{\phi} = z/z_{max} \tag{10}$$

$$\partial\tilde{\phi}/\partial\tilde{r} = 0. \tag{11}$$

In addition, in the direction normal to the liquid–vapour interface,

$$\partial\tilde{\phi}/\partial\tilde{n} = 0 \tag{12}$$

is given. Solving equation (1), with the boundary conditions (8)–(12), the distribution of ϕ around a bubble can be calculated. Figures 7(a) and (b) show the distribution for a spherical bubble and an ellipsoidal bubble, respectively. The shapes of the bubble have been obtained from the experiments. From the distribution of ϕ around the bubble, the electrostatic force, P_E, that acts on these bubbles can be obtained from the Maxwell stress, P_M, and the electrostriction force, P_D. The relationship between these forces is

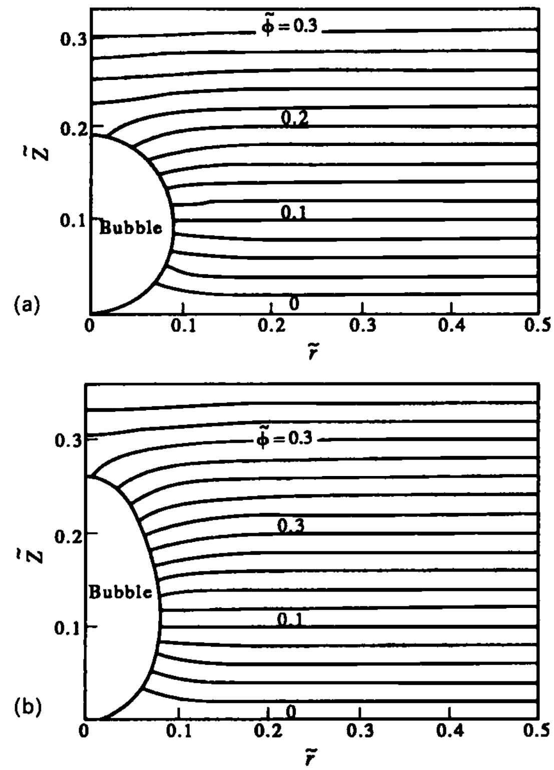


FIG. 7. (a) Analytical result of electric potential distribution around a spherical bubble. (b) Analytical result of electric potential distribution around an ellipsoidal bubble.

$$P_E = P_M + P_D. \tag{13}$$

The radial (horizontal) component and vertical component of P_M can be expressed in terms of the dielectric permittivities of liquid and vapour (ε_L and ε_G, respectively),

$$P_M = P_{M,r} + P_{M,z}$$
$$= \frac{\varepsilon_0}{2}(\varepsilon_L - \varepsilon_G)(E_r^2 + E_z^2) \tag{14}$$

where

$$P_{M,r} = \frac{\varepsilon_0}{2}(\varepsilon_L - \varepsilon_G)E_z^2 \tag{15}$$

$$P_{M,z} = \frac{\varepsilon_0}{2}(\varepsilon_L - \varepsilon_G)E_r^2. \tag{16}$$

The electrostriction force acting on the liquid side of the liquid–bubble interface is

$$P_D = \frac{\varepsilon_0}{2}\left(E^2\gamma_L\frac{\partial\varepsilon_L}{\partial\gamma_L}\right) \tag{17}$$

where γ_L is the liquid density. The term on the right can be rewritten using the Clausius–Mossotti relation:

$$\gamma_L\frac{\partial\varepsilon_L}{\partial\gamma_L} = \tfrac{1}{3}(\varepsilon_L - 1)(\varepsilon_L + 2). \tag{18}$$

Combining equations (17) and (18) yields the following expression for P_D:

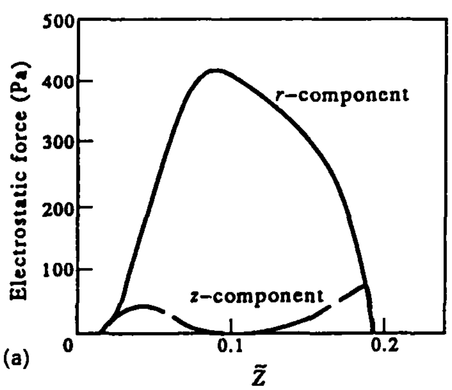
$$P_D = \tfrac{1}{6}\varepsilon_0(\varepsilon_L - 1)(\varepsilon_L + 2)E^2. \quad (19)$$

Figures 8(a) and (b) show the electrostatic forces for a spherical bubble and an ellipsoidal bubble, respectively, calculated using equation (19).

It can be concluded from this analysis that the bubbles in the electric field are easily driven to move horizontally on the grounded plate by the electrostatic forces. The reason is that the r-component (horizontal component) of the Maxwell stress is more than four times larger than the z-component (vertical component), and that the force to press the bubble against the plate is larger than the force pushing the bubble upward: therefore the bubble is pressed against the plate or heat transfer surface by the electric force.

Furthermore, since the difference between these z-components of the electrostatic forces produces a buoyancy force, the equivalent diameter, d_e, of the ellipsoidal bubble is obtained by the following equation:

$$\frac{\pi}{6}d_e^3(\gamma_L - \gamma_G) = \left(\sum_{\text{upper}} P_{M,i}\cdot\Delta A_i - \sum_{\text{lower}} P_{M,i}\cdot\Delta A_i\right). \quad (20)$$



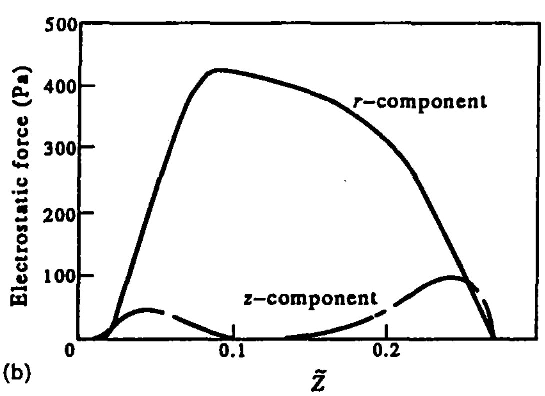


FIG. 8. (a) Analytical result of electrostatic force on a spherical bubble. (b) Analytical result of electrostatic force on an ellipsoidal bubble.

The value of d_e calculated for the ellipsoidal bubble is 1.2 mm, which is near to the diameter of a spherical bubble, 0.98 mm, obtained by the experiments. Therefore, it is also concluded that this analysis of the bubble's behaviour in an electric field is reasonable.

The distortion of the bubbles in the electric field is calculated from a force balance between the surface tension, α, and the electrostatic forces. The assumptions for this analysis are:

(1) the effects of gravity and bubble motion are neglected;

(2) pressure inside the bubble is uniform;

(3) the shape of a bubble is axisymmetric and ellipsoidal;

(4) the volume of the bubble remains constant, independent of the electric field.

The basic equation is then given in the following form:

$$\frac{2\alpha}{R} + \frac{\varepsilon_0}{2}(\varepsilon_L - \varepsilon_G)E^2 + \frac{\varepsilon_0}{2}\left(E^2\gamma_L\frac{\partial \varepsilon_L}{\partial \rho_L}\right) = \text{constant} \quad (21)$$

where R is the radius of curvature of liquid–bubble interface.

The first term in equation (21) can be expressed in terms of the deformation length of the bubble, ξ, and in spherical coordinates

$$\frac{2\alpha}{R} = \alpha\left[\frac{2}{R_i} - \frac{2\xi}{R_i^2} - \frac{1}{R_i^2}\left\{\frac{1}{\sin^2\theta}\frac{\partial^2\xi}{\partial\varphi^2} + \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\xi}{\partial\theta}\right)\right\}\right], \quad (22)$$

where

$$R = R_i + \xi. \quad (23)$$

The following boundary conditions are assumed:

$$\partial\xi/\partial\theta = 0 \quad \text{when} \quad \theta = 0, \pi/2 \quad \text{and} \quad \pi. \quad (24)$$

Figure 9 shows a comparison of bubble shapes from

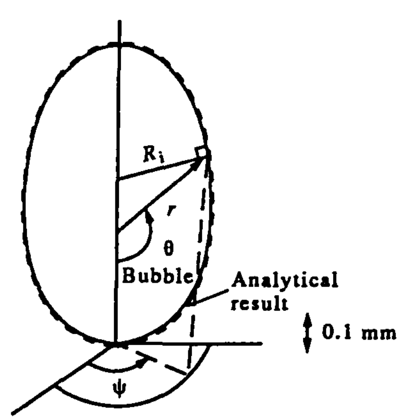


FIG. 9. Comparison of bubble shape between experiment and analysis.

the analytical result determined by equations (22)–(24) and the experimental result. The previous analysis is, therefore, proved to be valid since both shapes of the elongated bubble agree well.

4. CONCLUSIONS

The effect of an electric field on the boiling heat transfer of an organic fluid has been investigated. In order to clarify the details of the mechanism of heat transfer augmentation, basic tests and analysis were performed. The following conclusions were obtained:

(1) The enhancement ratio of boiling heat transfer with an electric field was about 8.5 times the maximum of that with no electric field for a mixture of dielectric fluid (fluorocarbon) and conductive fluid (ethanol) for which the resulting relaxation time of the electrical charge was negligible compared with the boiling frequency.

(2) It was observed that generated bubbles were pushed against the injection plate and initially moved around on it violently prior to migrating through the electric field. This could also be one of the causes of heat transfer augmentation.

(3) By the analysis of the electric field around a bubble, it was confirmed that the bubbles were pushed against the grounded plate electrode by the vertical component of the electrostatic forces (Maxwell stress and electrostriction force) and became mobile due to the corresponding horizontal component, because this horizontal component was four times greater than the vertical component. Consequently, the bubble's behaviour in the electric field was clarified not only qualitatively, but also quantitatively.

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