

Single Bubble Behavior in Direct Current Electric Field*

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Abstract The investigation on bubble behavior in electric field helps to analyze the mechanism of electric enhancement of boiling heat transfer. Experiments were performed to investigate the bubble deformation in direct current (DC) electric field with bubbles attached to the orifice. The air bubbles were slowly generated in the transformer oil pool at different orifices, so that the effect of flow on bubble shape was eliminated. The results showed that the bubbles were elongated and the departure volume decreased when the electric field was intensified. The major and minor axes, aspect ratio and departure volume increased with increasing the orifice diameter. Both the electric field and orifice size have great influence on bubble behavior. The bubble deformation was also simulated to compare with the experimental results. The numerical and experimental data qualitatively agree with each other.

Keywords electrohydrodynamic enhancement, multiphase flow, bubble behavior, direct current electric field

1 INTRODUCTION

The electrohydrodynamic (EHD) technique is referred to the one that enhances the heat transfer capacity by using the electric field. This technique has potential use in chemical industry, energy industry *etc.* because of the great enhancement capability. The early research mainly focused on the experimental measurements of macroparameters, such as the heat transfer coefficient, h , and the heat flux, q . The application of EHD technique on boiling heat transfer was also widely studied due to the remarkable enhancement effects [1–3].

However, the coupled electric, flow and temperature fields complicate the research on boiling heat transfer. Consequently, the bubbles were injected from orifices to insulate the temperature field in many investigations [4–7]. Some experimental results have been obtained [8–14]. Bubble shape elongates along the electric field direction and the bubble departure volume decreases when the strong electric field is applied. Some parameters, including electric field intensity, electric field nonuniformity, microgravity condition *etc.*, affecting the bubble behavior under the electric field, have also been considered. For example Cipriani *et al.* [11] showed that bubbles were pressed against the plate, driven to the liquid or pushed to slide along the plate surface due to different electrode configurations. The electric field nonuniformity also affected the bubble deformation, which increased with enhancing electric field nonuniformity [4]. Experiments performed in microgravity showed that the bubble departure volume decreased in the electric field, and bubble departure became easier [6]. Herman and Iacona [12] simulated the bubble contours in microgravity and the results agreed with the experimental data in low strength electric field.

Except for the extensive experimental research, Herman and Iacona [12] and Cheng and Chaddock [13, 14] also accomplished theoretical calculations of bubble elongation in the presence of electric fields. However, both the above-mentioned calculations were

based on the hypothesis of spherical bubbles. Thus the deviation between Herman's calculation and his own experimental results increased as applied electric fields strengthened. The calculation corresponding to actual experiment is absent to date.

This article described the bubble deformation in direct current (DC) electric fields. The bubbles were generated as the air was heated to expand at different orifices. This method for slowly generating bubbles also eliminates the air flow effect on bubble shape. Besides, the influence of orifice size was also discussed. The results showed that both electric field and orifice size had great effects on bubble behavior in electric fields. The numerical results were compared with the experimental data.

2 EXPERIMENTAL SETUP

The experimental setup included a test cell, a recording system and a high voltage supply, as shown in Fig. 1. The test cell was made of resin for its electric insulation, with the size of 11.2 cm (length)×14.5 cm (height)×2.0 cm (thickness). The upper brass mesh electrode was connected with a positive high voltage supply (Glassman ER50R06-DM22), and the spacing between 0.5 mm-diameter brass wires was 3 mm. The

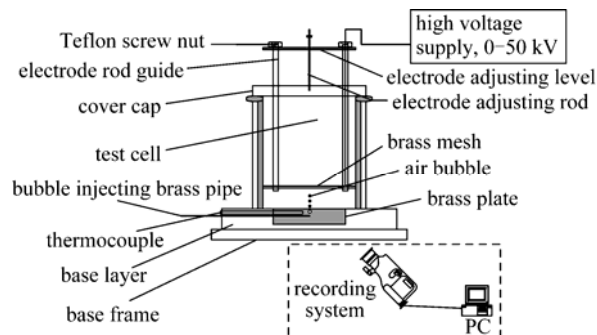


Figure 1 Schematic of the experimental setup (not drawn in proportion)

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lower brass plate electrode was grounded as the negative electrode. The voltage distribution between the upper and lower electrode was shown in Fig. 2, indicating that the electrode configuration helped to build a quasi linear electric field near the lower electrode where the bubbles were generated, even when a bubble was present. The electrode distance, L , was 8 mm. The computational results showed that the electric field intensity, E , near the lower electrode was approximately calculated as U/L , where U is the applied voltage. Three orifices of different diameters (0.5 mm, 1.0 mm and 1.5 mm) were drilled in the brass plate, with the vertical outlets. Three brass tubes were horizontally connected with the orifices and plugged to create an air chamber. The electric heaters were equipped underneath the tubes. In these experiments, the air in the chamber was heated by the electric heater and the air bubble was pinched from the orifice, then the bubble slowly grew until it completely departed from the orifice at 5 min intervals. The air in the tube was enough to generate a few bubbles of the same size, among which a typical bubble growth cycle was captured and recorded for further analysis. The front and back of the test cell were made of glass for visual observation.

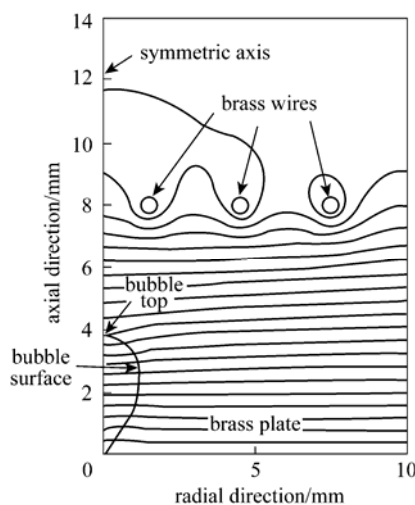


Figure 2 Simulated voltage distributions in the half cell

A high speed camera was used to record the bubble growth from the orifice. The frame rate was 2000 frames per second. And the resolution was 320×258 pixels. A LED matrix was located behind the test cell to illuminate the bubble. Due to different focal lengths, the length represented by one pixel is different, as shown in Table 1.

Table 1 Length (mm) represented by a pixel for different orifices

Orifice diameter/mm	Length represented by a pixel/ 10^{-3} /mm
0.5	7.6
1.0	9.8
1.5	10.7

Before the bubble departure, the bubble images captured by the high speed camera were almost still due to the long growth time; when the departure took place, the acceleration of the bubble top was observed in the images, which was used as the criteria to detect the bubble departure as shown in Fig. 2.

Three experimental runs were performed for each orifice with different electric field strengths, and in each run 3 bubbles were generated and measured. The bubble edge measurement was subject to error of about 1 pixel. Since the bubble minor axis length is the distance between the left and right edges of the bubble, the error in this measurement is about 2 pixels. The major axis length is the distance between orifice center and bubble top. The location of the orifice center is fixed. The measurement error of the bubble top is 1 pixel, and an inaccuracy in determining the bubble acceleration, which is estimated to be 2 pixels. Therefore, the error in the major axis length is about 3 pixels. The measurement of the distance between the minor axis and the bubble top requires locating the vertical position of the minor axis with error of 1 pixel, thus the measurement error is about 4 pixels.

The working fluids in the experiments were the air and the transformer oil with their properties listed in Table 2. The experiments were performed at ambient temperature and atmospheric pressure. The heated air resulted in small variation in electrical permittivities, which was not accounted for in this article.

Table 2 Properties of working fluids

Working fluid	Density ρ / $\text{kg}\cdot\text{m}^{-3}$	Relative electric permittivity ϵ_r	Surface tension $\sigma/\text{N}\cdot\text{m}^{-1}$
air	1.2	1.0	–
transformer oil	849	2.1	0.044

3 THEORETICAL MODEL

According to the hydrostatic principle on the bubble surface, the bubble contour satisfies the following Laplace equation [13, 14]:

$$-\frac{d^2x/dy^2}{[1+(dx/dy)^2]^{1.5}} + \frac{1}{x[1+(dx/dy)^2]^{0.5}} = 2 - \beta y \quad (1)$$

where x and y are the dimensionless coordinates defined as $x = X/R$, $y = Y/R$, as shown in Fig. 3. (X , Y) are the coordinates of the bubble interface and R is the curvature radius at the bubble top. $\beta = \Delta\rho g R^2 / \sigma$, is the bubble scale factor, where $\Delta\rho$ is the density difference between liquid and gas, and σ is the surface tension.

In the original model, the balance of surface tension and buoyancy determines the bubble departure; however, the bubble necking (see Fig. 4) was observed before the departure took place in the experiments, which was then used as departure criteria in the simulation. The bubble aspect ratio at departure was defined in Eq. (2):

$$\alpha = b/a \quad (2)$$

The definitions of major axis length, b , and minor axis length, a , are shown in Fig. 3.

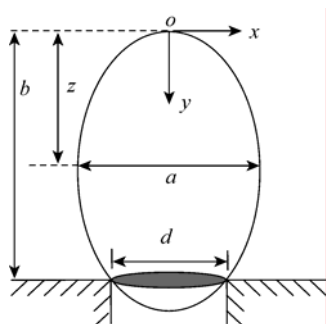


Figure 3 Definitions for the bubble major axis length b , minor axis length a , neck diameter d , and the distance z from minor axis to the bubble tip

Based on the analysis of Landau *et al.* [15], Cheng and Chaddock [14] considered the variation of free energy of the bubble and obtained the differential equation of the bubble aspect ratio when applying the external electric field:

$$\frac{\partial}{\partial \alpha} \left(\alpha^{-2/3} + \alpha^{1/3} \frac{\sin^{-1} e}{e} \right) - \frac{\varepsilon_0 E^2 r}{3\sigma} \frac{\partial H}{\partial \alpha} = 0 \quad (3)$$

$$H = \frac{(\varepsilon_g - \varepsilon_l) \varepsilon_l}{(1-n) \varepsilon_l + n \varepsilon_g} \quad (4)$$

$$n = \frac{1-e^2}{2e^3} \left(\ln \frac{1+e}{1-e} - 2e \right) \quad (5)$$

$$\alpha = (1-e^2)^{-1/2} \quad (6)$$

where ε_0 is the permittivity in free space, $\varepsilon_0 = 8.854 \times 10^{-12} \text{ F} \cdot \text{m}^{-1}$; ε_l and ε_g is permittivities for liquid and gas, respectively; E is the electric field

without the bubble presence; H and e are the intermediate variables. Based on the assumption that the bubble became ellipsoid in the electric field, the major axis length b_e and minor axis a_e in electric field were

$$b_e = \alpha^{2/3} b_0, a_e = \alpha^{-1/3} a_0 \quad (7)$$

where b_0 and a_0 are the axis length without the electric field.

Equation (1) calculates the bubble contour coordinates attached to a wall without electric field. Eqs. (3)–(6) calculate α in electric field. The lengths of a and b in the electric field are determined by Eq. (7). Therefore, the bubble aspect ratio, major axis length and minor axis length in electric field were simulated in the present investigation.

4 EXPERIMENTAL RESULTS AND ANALYSIS

All the parameters analyzed in this section were from bubbles at departure. The bubble aspect ratio α , major axis length b and minor axis length a were experimentally and numerically investigated to analyze the electric field effect on bubble behavior, while the departure volume V were only experimentally studied because of the model deficiency.

4.1 Bubble images at departure

The bubble began to accelerate upwards and finally detached from the orifice after all the forces on bubble reached a balance. The acceleration was defined as the departure mark, rather than the separation from the orifice. The experimental results were shown in Fig. 4.

The results in Fig. 4 qualitatively agree with the results by Cho *et al.* [4], Di Marco *et al.* [6] and Herman and Iacona [12], which shows distinct elongation

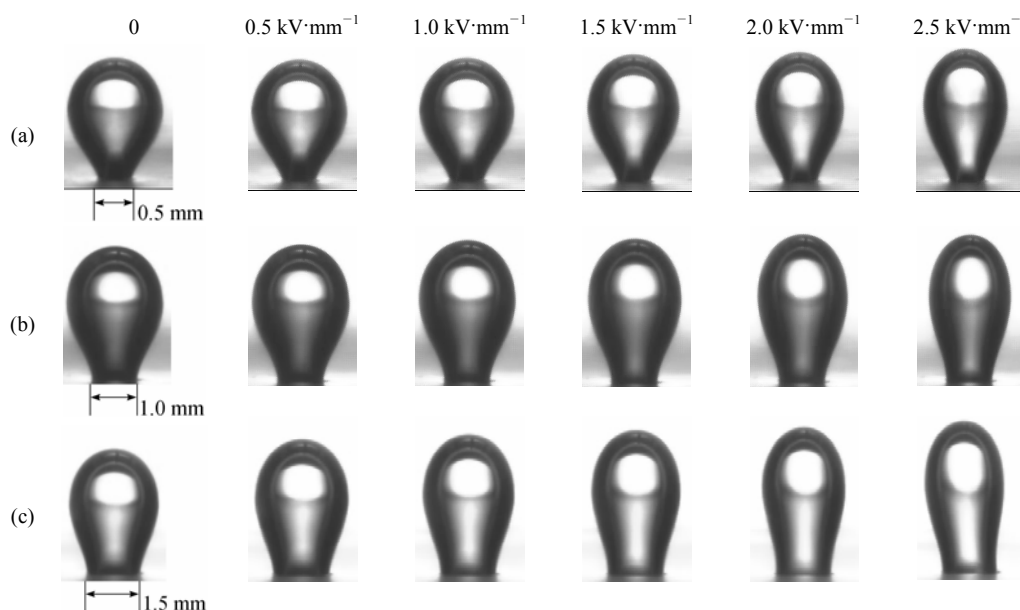


Figure 4 Bubbles images at departure with various electric fields orifice diameter: (a) 0.5 mm; (b) 1.0 mm; (c) 1.5 mm

on bubble shape along the electric field direction. The weak electric field lower than $1.0 \text{ kV}\cdot\text{mm}^{-1}$ has little effect on bubble shape; however, the higher field intensity causes much greater deformation. In Fig. 4, the bubble asymmetry in the largest electric field is due to bubble oscillation.

The upper half of the bubbles on all three orifices is similar to the sphere when no electric field is present, but it transforms to ellipsoid in the electric field. The lower half of the bubbles differs among orifices. The experimental images show that the bubble neck diameter, d , does not change with the electric fields. The ratio of the minor axis length to the bubble neck diameter (see Fig. 3 for definition) decreases with the orifice diameter. The bubbles become more columnar on larger orifice under stronger DC electric field.

The orifice size also influences the bubble shape and size, as shown in Fig. 5. The bubble major and minor axis lengths increase with increasing orifice diameter and so do the departure volumes. At higher electric field, bubble major axes are elongated and minor axes are compressed in the electric fields for the 0.5 mm and 1.0 mm orifices, while bubbles for the 1.5 mm orifice not only deform but also become asymmetrical [Fig. 5 (d)], indicating more remarkable electric field effect for larger bubbles.

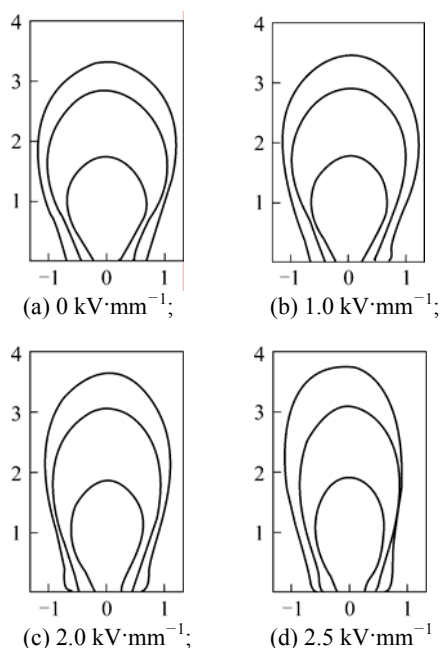


Figure 5 Bubble contours for three orifices under different electric field intensities (Indications of axes are the same with that in Fig. 2)

4.2 Bubble aspect ratio at departure

The results in Fig. 6 show that both the experimental and numerical bubble aspect ratios increase with the electric field. In the same electric field, the aspect ratio also increases with the orifice diameter, indicating a more spherical bubble for smaller orifices. The bubble therefore becomes nearly spherical if injected from a much smaller orifice, as shown in the investigations of Cho *et al.* [5] and Cosentino *et al.*

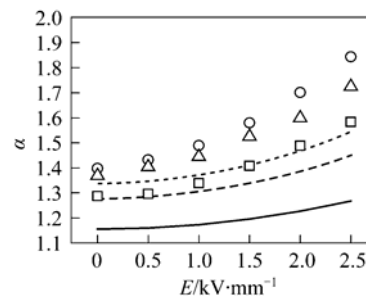


Figure 6 Variations of bubble aspect ratios with different electric fields

□ 0.5 mm (exp.); — 0.5 mm (numerical);
△ 1.0 mm (exp.); - - - 1.0 mm (numerical);
○ 1.5 mm (exp.); - · - · 1.5 mm (numerical)

[16]. Fig. 6 also shows that the aspect ratio difference between orifices enlarges with increasing electric field.

The experimental results are greater than the numerical data for all three orifices, and their differences enlarge with the increasing electric field. Eq. (3) shows that the bubble aspect ratio in electric field is calculated by using the uniform electric field intensity, E , when no bubble is present. However, the electric field becomes nonuniform around the bubble interface due to the different electrical permittivities of liquid and gas [17]. Cho *et al.* [4] showed that the nonuniformity had large influence on the bubble behavior, as the field nonuniformity increased the bubble deformation. Therefore, Eq. (3) underestimates the effect of field nonuniformity.

Figures 7 and 8 show the major and minor axis lengths in electric field, respectively. The numerical results in Fig. 7 are smaller than the experimental data for all three orifices; however, the numerical minor axis lengths exceed the experimental data for 0.5 mm and 1.0 mm orifices, but for 1.5 mm orifice are smaller than the experimental ones in weaker field and larger in stronger field. The difference between numerical and experimental minor axis lengths becomes greater as increasing the electric field, indicating the underestimation of electric effect on bubble deformation in the model.

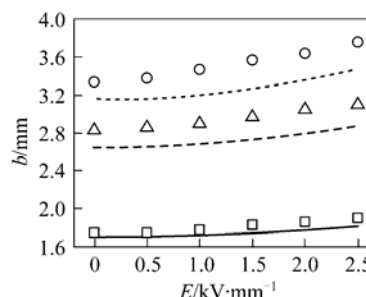


Figure 7 Major axis lengths for various electric fields

□ 0.5 mm (exp.); — 0.5 mm (numerical);
△ 1.0 mm (exp.); - - - 1.0 mm (numerical);
○ 1.5 mm (exp.); - · - · 1.5 mm (numerical)

The experimental results satisfy generally the following equation:

$$b_e = \alpha^\gamma b_0, \quad a_e = \alpha^{\gamma-1} a_0 \quad (8)$$

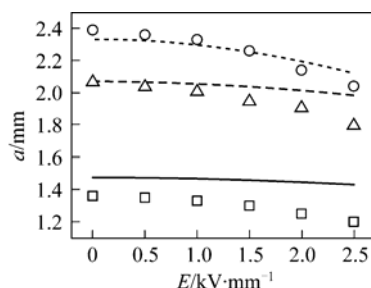


Figure 8 Minor axis lengths for various electric fields

□ 0.5 mm (exp.); — 0.5 mm (numerical);
 △ 1.0 mm (exp.); --- 1.0 mm (numerical);
 ○ 1.5 mm (exp.); ---- 1.5 mm (numerical)

In the present numerical simulation, γ was 2/3 based on the constant volume assumption. However, γ in experiments was calculated by using exponential curve fitting. The results were shown in Table 3.

Table 3 γ for different orifices

Orifice diameter/mm	γ
0.5	0.32
1.0	0.36
1.5	0.42

Table 3 shows that γ in all cases are smaller than 0.5, indicating that the electric compressing effect on the bubble side is greater than the pulling effect on the bubble top. The electric field effect on the bubble is exerted by the electric stress on the bubble interface [18]. The calculated results by Chen *et al.* [17] showed that the electric compressing stress on the bubble side was greater than the stress on the top, which pulled the bubble upwards. Besides, the acting area of the compressing stress was also larger than the pulling stress. These two factors lead to the greater compressing effect.

Equations (4)–(6) show that e and H are the function of α only; therefore, α is only determined by $\varepsilon E^2 r / \sigma$ from Eq. (3). $\varepsilon E^2 r / \sigma$ is the electrical Weber number We , which indicates the influences of the electric field intensity and the fluid properties on the bubble deformation. The correlation between α and We in the present experiments was plotted in Fig. 9. The bubble aspect ratios for three orifices linearly increase as the electrical Weber number increases, as

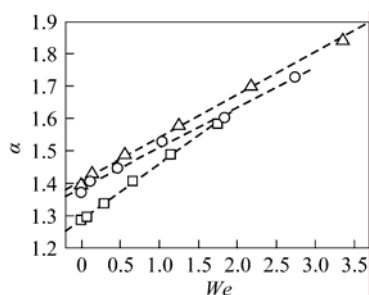


Figure 9 Bubble aspect ratios vary with different electrical Weber numbers

□ 0.5 mm; ○ 1.0 mm; △ 1.5 mm; --- fitting curve

shown in Fig. 9. The bubble aspect ratio is only determined by the equivalent radius, r , at a given electric field intensity, since the fluid properties are constant. The bubble for larger orifice has greater equivalent radius, which leads to larger electrical Weber number and hence greater deformation.

4.3 Bubble departure volume

Herman and Iacona [12], Cosentino *et al.* [16] and Chen *et al.* [17] showed that the bubble departure volume decreased in the electric field, while Cho *et al.* [4] presented that the DC electric field has little effect on the bubble departure volume. In the present investigation, the bubble volume is the sum of the volumes of the upper and lower halves. The upper half resembles a half ellipsoid, so the volume is assumed to be $\pi a^2 z / 6$, while the lower half similar to a frustum of a cone, with the volume of $\pi(b-z)(a^2 + ad + d^2) / 12$.

The results in Fig. 10 show that the bubble departure volumes decrease moderately but progressively with the increasing electric field. The surface tension and buoyancy balance at bubble departure without electric field. However, in electric field, the surface tension increases, because its direction becomes more vertical (Fig. 4), while the bubble elongation and the decreased departure volume bring about the reduced buoyancy. The resultant force of the electric force, therefore, has the same direction as the buoyancy and served as the additional buoyancy, so as to facilitate the bubble departure, which has been studied in details by Chen [19].

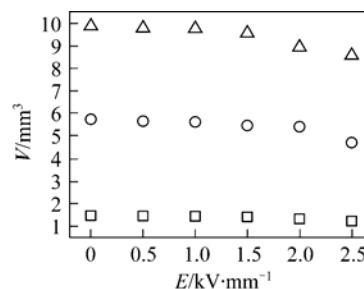


Figure 10 Bubble departure volumes for various electric fields

□ 0.5 mm; ○ 1.0 mm; △ 1.5 mm

The model used in the simulation assumed that the bubble departure volume remained constant in the electric field. However, the experimental results show that this assumption is justified only when the electric field intensity is weak. As the field intensity increases, the electric field has more influence on the bubble departure volume, which contradicts to the model assumption. Therefore, the model was not used in the departure volume prediction.

5 CONCLUSIONS

Experiments were performed to investigate bubble behaviors in DC electric fields. The bubbles were

generated as the air was heated to expand from three orifices underneath a transformer oil pool. The experimental results show that the minor axis length and departure volume decrease, but the major axis length and aspect ratio increase with the increasing electric field. The electrical Weber number was shown to have linear correlation with the bubble aspect ratio.

The orifice size has significant effect on bubble size and formation. The ratio of the bubble neck diameter to the minor axis increases with the increasing orifice diameter, resulting in a more columnar bubble for larger orifice. The bubble major and minor axis lengths, aspect ratio and bubble departure volume are also augmented as the orifice diameter increases. Because the bubble aspect ratio linearly increases with the electrical Weber number, the greater equivalent radius leads to larger bubble deformation at given electric field.

NOMENCLATURE

a	bubble minor axis length, mm
b	bubble major axis length, mm
d	bubble neck diameter, m
E	electric field intensity, $V \cdot m^{-1}$
e	intermediate variable, function of α
H	intermediate variable, function of α
L	electrode distance, m
U	applied voltage, V
V	bubble departure volume, mm^3
z	distance from the minor axis to the bubble tip, m
α	bubble aspect ratio, dimensionless
ε	electrical permittivity, $F \cdot m^{-1}$
ε_0	electrical permittivity in free space, $F \cdot m^{-1}$
ρ	density, $kg \cdot m^{-3}$
$\Delta\rho$	density difference between liquid and gas, $kg \cdot m^{-3}$
σ	surface tension, $N \cdot m^{-1}$

Subscripts

e	refers to values with the electric field
g	gas
l	liquid
0	refers to values without the electric field

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