Micro Bubble Formation on sub-mm Tip Electrode Discharge in the Electrolyte Solution

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Abstract: Discharge in electrolyte solution is initiated after the tip electrode is fully covered with micro bubbles. The bubbles are generated through the ohmic heating by the conduction current, thus the film boiling plays an important role in bubble generation on the tip electrode. The surface charges of bubble give the unique characteristics on the formation and dynamics of micro bubble. This understanding of bubble generation in electrolyte is required to breakdown the micro discharge in electrolyte.

Keywords: Micro plasma, micro discharge, discharge in liquid, electrolyte discharge, bubble discharge

1. Introduction

The discharge in the liquid media has a quite different discharge mechanism and characteristics from that in the gas phase media. Especially the discharge in an electrolyte has not been investigated in detail, however it becomes more attractive due to its wide medical and environment applications.

In this study, the micro plasma generation on the sub-mm size tip of electrode was considered in the electrolyte solution which was a saline solution (NaCl(aq)). The concentration of electrolyte was chosen as the similar condition of human body. Because of high conductivity of electrolyte, the high conduction current was flown on the electrode which played an important role in the discharges of electrolyte. The current was induced the ohmic heating on the electrode and the bubble was formed to work as an insulation layer around the electrode, where the strong electric field can be accumulated to breakdown the gas in the bubble. Thus the bubble formation and dynamics are necessary to understand the micro-bubble discharge in a liquid media. This work has been focused on the characteristics of bubble formation.

2. Experimental Setup

Experiment was conducted with a 1 mm-diameter tip electrode in the electrolytes applied with 10, 20, 30, 40, 50, and 60W of 350 kHz sine wave MF power. Structure of tip electrode is similar to the coaxial cable as shown in Fig. 1. Part A is made of stainless steel where the power $V_1=V_0 \sin(t)$ was applied. Out of phase power $V_2=V_0 \sin(t+\pi)$ was applied to part C which was made of tungsten. Part B is a quartz as for the insulation between two electrodes. Thus the gap voltage of $V_1-V_2$ was sustained between two electrodes. Saline of 0.9% NaCl solution was chosen as electrolyte.

Fig. 2(a) represents to the structure of tip electrode and the simulation result of electric field distribution using CFD (Computational Fluid Dynamics)-ACE simulator. Direction of electric field is toward the tip end of electrode. Fig. 2(b) shows the spatially maximum electric field strength ($E_{\text{max}}$) with operating frequency with the same geometry with tip electrode used in experiments. Electric field strength has a maximum value at 350 kHz operation which was fixed during the experiment. V-I signals on the system and ICCD images were employed to the measurement.

![Image](image_url)

Fig.1 Experimental apparatus and conditions (a) tip electrode and (b) schematic diagram of micro discharge.
3. Results and Discussion

When MF power of 10 W was introduced to the tip electrode, the bubbles were barely generated and the discharge could not be generated as shown in Fig. 3(a). V-I signal varied in phase, revealing the tendency of V=IR. It implies that just conduction current, dominantly an electrolyte current, was flown on the electrode and the impedance corresponded to approximately 400Ω.

Fig.3 (b) was obtained at power of 30 W. The bubble began to cover the tip of electrode entirely. V-I signal revealed V=IR and the impedance was rapidly increased up to 4.8 kΩ. Increase of impedance implies to the formation of resistive in the current path of electrolyte current flow to the electrode which was the bubble. Since the accumulated electric field was not enough, the discharge was not occurred at this power.

When the power was increased to 50 W, the discharge was ignited as shown in Fig. 3(c). The relation of V=IR was not in valid anymore and it rather had the negative impedance. Bubble size was increased with power as shown in Fig.5. The electric field was built up between the surface of bubble and the electrode. As shown in figure, the breakdown can be observed in current profile at 0.2 μsec ~ 1.4 μsec. Fig. 3(d) of 60 W reveals the several breakdowns at -0.6 μsec ~ 0.4 μsec. When the gas was broken down in the bubble, the impedance became to negative as mentioned earlier.

There are two mechanisms of bubble formation. Because the high power was applied on the small tip electrode, the ohmic heating of the tip electrode caused the film boiling on the surface of electrode. On the other hand, the electric field around the electrode was approximately 10^6 V/m so that electrolysis can be expected to bubble generation. Firstly, the ohmic heating due to large electrolyte current is considered to film boiling around the tip electrode. Thickness of bubble can be estimated from the energy balance on a shell of bubble volume on the electrode as 2πrLΔr q_e, where q_e is heat flow, L is the length of the cylindrical tip, r is radius, and Δr is the thickness of...
Growing bubble has limit on its size until it escapes from the tip electrode surface. Escaping condition of bubble can be investigated with Dupre equation, which represents the work of adhesion [2]. To separate the two attached materials 1 and 2 against their intermolecular adhesive force, a certain energy called ‘work of adhesion’ is required. Dupre equation is given as

\[ W = \gamma_1 + \gamma_2 - \gamma_{12} \]  

where \( W \) is the work of adhesion, \( \gamma_1 \) and \( \gamma_2 \) are surface tension against the air, and \( \gamma_{12} \) is surface tension between material 1 and 2. \( W \) is collected as the adhesive strength \( G \), additionally temperature and viscosity effects are considered on \( W \).

Estimated bubble size is shown in Fig. 5 and, which are compared to the measured size by ICCD. Estimated size is smaller than measured result, because the effect of surface charge on the bubble surface could not be considered in Equation (2).

This surface charge effect is started from the size of the bubble. Diameter of bubbles is approximately a few mm ~ \( \mu \text{m} \). These 10-1000 \( \mu \text{m} \) diameter bubbles can be treated like as a colloid particle which named as ‘micro bubble’ [3]. In general, their motions can be described by using Stokes’ equation, considered as laminar flow [4]. Micro bubbles have relatively large surface area compared to the volume, thus the charges can be accumulated on its surface [5].

The positive charge (corresponded to sodium ion) and the negative charge (corresponded chlorine ion) in the saline solutions have different collision rates be-
cause of their mass difference. It leads unbalance of charge accumulation on the surface, thus the positive surface potential is generated which corresponds to ‘zeta potential’ [6]. It is a function of various parameters, especially, electric field strength around the bubble [7]. For 0.5 mm tip electrode, the zeta potential is estimated as 28 V for 40 W and 350 kHz [8].

This surface charge effect on the surface tension is considered from the modified Lippman equation. The surface charge accumulation on the interface between the bubble and electrolyte increases the surface tension resulting in increase the work of adhesion. Larger work of adhesion leads larger size of a bubble. When the 40W power was applied, its zeta potential corresponds to 28 V and the surface charge density is 19.8 μC/m². This represents to 1.41 times larger of bubble size than the expected bubble size without the consideration of surface charge, which is similar to the ICCD observation as shown at 40 W data in figure. At higher powers, the discrepancy between the bubble size was observed which may due to the extra charge supplied from the breakdown of gas in the bubble.

To carry on the confirmation of the surface charge effect on the bubble formation, the motion of micro bubbles were observed in the electrolyte medium where the strong electric field is distributed as shown in Fig 2. The strong electric field of 10 MV/m gives the strong electric force ($F_{ele} = QE$) on the surface charges of a bubble. The field leads the drag force on the motion of the micro bubble like colloid larger. Drag force is given by Stokes’ equation, is proportional to the bubble size and velocity [9]. The speed of micro bubble from the force balance in the electrolyte under the electric field can be estimated. This equation was established for 1-dimensional case. The direction of bubble motion is forward from the tip of electrode as if a jet stream in the geometry of Fig 2. When the bubble goes far away from the electrode, the buoyancy is considered dominantly in the force balance equation rather than the electric force because of spatially decreased the electric field compared to near the tip electrode surface. Finally the bubbles are floated up. The speed of bubble escape is 0.308 m/sec at 0.48 sec after the generation of bubble while the observed velocity from ICCD images is approximately 0.4 m/sec for 1mm-diameter bubble. This motion gives the value of surface charge Q, being agreed with the estimated value from zeta potential.

4. Conclusion
In the micro plasma discharge of electrolyte, the bubble generation plays in an important role. Main mechanism of bubble generation is the film boiling by the ohmic heating of the electrolyte near the tip electrode. This is induced from the characteristics of high conductivity electrolyte media as high conduction current. Generated micro bubbles be treated as colloid particles and their large volume to surface ratio enhances the surface tension effects as increasing the zeta potential, which also contribute to increase the size of the bubble and the escaping speed of bubble from the electrode.

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References