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Observations of Pulsed Bi-polar Discharges in Saline Solutions with Pin to Plate Electrodes

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Abstract – In this study, we have been investigated pin to plate pulsed bi-polar discharges in saline solutions, where bubble generation occurs. We integrate basic I-V-t electrical characteristics with the ICCD shadowgraph images, and finally instant and time averaged I-V waveforms. We observed that the bubble formation phase dynamics is quite different corresponding to the polarity applied to the pin electrode. When the pin electrode is a cathode, the bubble tends to be periodically detached from the pin electrode and the numerous tiny voltage spikes occur related to the electron emission from a pin cathode casing via, we judge from, direct dissociation of water molecules by energetic electrons. On the contrary, the bubble tends to stick to the pin electrode, when the pin electrode is anode; the bubble grows in size throughout the pulse duration. The dynamic electrical characteristics relative to the applied polarity of a pin electrode are presented and discussed by analysis of time averaged I-V waveforms.

Keywords: Pulsed Bi-polar discharge, Saline solution, Pin to plate electrode.

1. Introduction

There has been considerable interest in the study of the electrical discharges created in liquids, where the species densities are often 10^4 higher in comparison with gases. Various applications including pulsed power systems, high voltage insulation, pollution remediation, medical applications, and nanomaterial synthesis have all employed liquid plasmas [1-4]. In gases, the physical mechanisms of plasma discharge are well understood, based on the electron avalanche by the Townsend mechanism at low pd product values (pressure, p times electrode gap, d), whereas streamer mechanisms operate at high pd values. It is difficult to initiate electron avalanche processes in liquids under the large electrode gap due to low mobility and high recombination rates in liquid media.

Currently, there is no unified understanding of plasma discharges in liquids. However, many researchers have suggested that there must be a phase change next to the electrodes before the electron avalanches occur [5, 6]. Two proposed mechanism of discharge in liquids with two opposing needle electrodes driven by voltage sources take two different approaches. One is a two-step process involving heat-driven vapor bubble phase change mechanisms, which is subsequently combined with traditional high-pressure gas breakdown theory. The bubble layer in front of the electrode is formed by localized liquid heating in the strong electric field region near the tip of the electrode. Since the largest electric field occurs over the smallest distance, discharges are subsequently generated first within a vapor bubble. Accordingly, bubble formation must first occur, before we generate discharges in liquids. The bubble time evolution is the main parameter to control the temporal characteristics of pulsed discharges in liquid. A liquid saline discharge can be generated under the low voltage (below 500V) with the proper molar level of salt solutes in the water solvent, and provided we employ specific electrode configurations [7-9]. The second mechanism invokes direct one step electron multiplication effects in the ultra-thin double layer formed in saline discharges, with subsequent partial electrical discharge and spark discharge causing direct dissociation of the liquid by electron impact to form vapor layers.

In this study, we investigate the basic electrical characteristics of pin to plate electrical discharges in saline solutions to get insight into the two different mechanisms of plasma formation. The discharge is generated by repetitive square pulse with repetition frequency of 10Hz and a pulse duration of 3ms. Both positive and negative polarity were applied to the pin electrode resulted in very distinct results. We have minimized the observed erosion of pin electrode, to insure reliable I-V and shadowgraph data. It is mainly achieved by minimizing the discharge current in the conductive liquids examined. Furthermore, it is possible to observe changes in the I-V characteristic in detail by changing the bubble generation time scale very slowly.

The organization of this paper is as follows. In section II, we give the description of the experimental apparatus for measuring electrical properties of the saline discharges, as we vary electrode conditions. In section III, we report

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the ICCD shadowgraph images of bubble evolution versus time. The electrical measurements are provided with instant and multi-pulse averaged I-V results versus time. Finally, in section IV, a summary of the experimental results is given and our speculations as to the meaning of the data.

2. Experimental Set-up

The schematic diagram of the bi-polar driven saline solution experimental apparatus is shown in Fig. 1. The rectangular glass cuvette is used and carbon plate electrode is placed on the bottom of the cuvette. The pin electrode is used as a 400 μm-diameter tungsten wire covered by the ceramic tube to precisely define the area exposed to the electrolyte solution. The distance between the pin and plate electrode is 1 cm. In this experiment, the asymmetric electrode structure (pin-plate electrode) is chosen to make sure that the discharge is ignited at the pin electrode because the local heating is concentrating on the pin electrode resulting in forming the bubbles on the pin electrode. The saline solution of distilled water and 0.9% molar NaCl is used in this study.

The bi-polar high voltage power source (Matsusada precision, EJ-series) with pulse generator (Directed energy Inc, PVX-4140) is used. The 10Hz square pulse with duty ratio of 3% (3ms of on duration) is applied to the electrodes with a 1 kΩ external series resistor to limit discharge current and thereby minimize the erosion of pin electrode. In addition, when we employ the external resistor in the discharge circuit, the time scale of the bubble formation time changes as does the I-V characteristics of the liquid plasma. By analyzing the time-varying voltage and current waveforms, we can calculate the time-varying impedance of saline solution. Coupled with shadow graph images, we can clearly understand the characteristics of the time and spatial evolution of bubble formation.

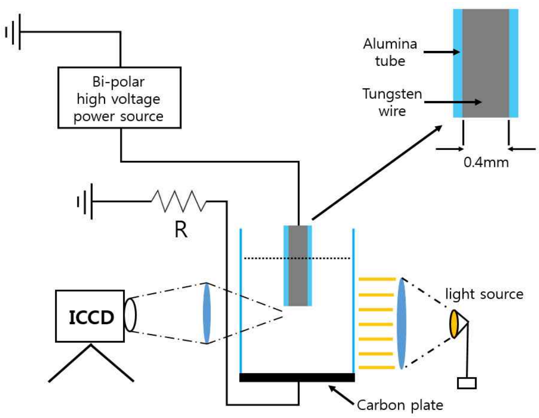


Fig. 1. Schematic diagram of the experimental set-up to investigate the characteristics of pulsed bi-polar discharges in saline solutions with pin to plate electrodes

The electrical measurements are performed using a fast digital oscilloscope (Lecroy, Wavepro7000). A shadow-graph ICCD measurement system allows us to track the spatial and time evolution of the bubble formation. The application of positive and negative voltages to the pin electrode results in very distinct shadowgraph images and I-V waveforms as described below. Below we term negative pin driven voltage as PC (= Pin Cathode) and positive driven voltage as PA (= Pin Anode).

3. Results and Disccusions

3.1 ICCD shadowgraph images of bubble evolution versus time

Fig. 2 shows the ICCD distinct bubble evolution images obtained with opposite polarity but equal voltages applied

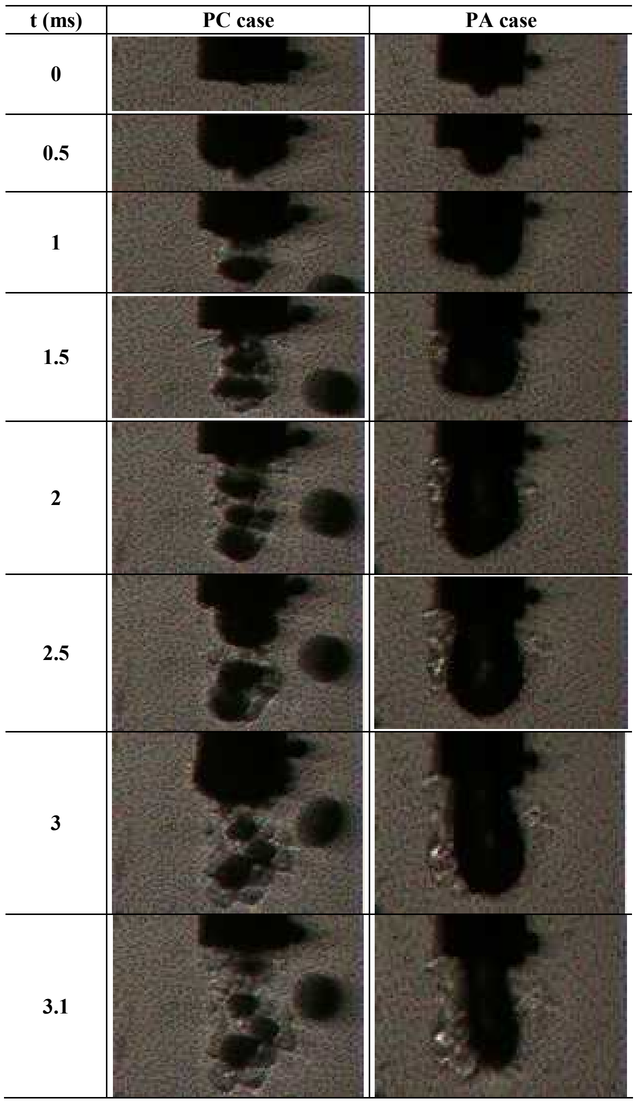
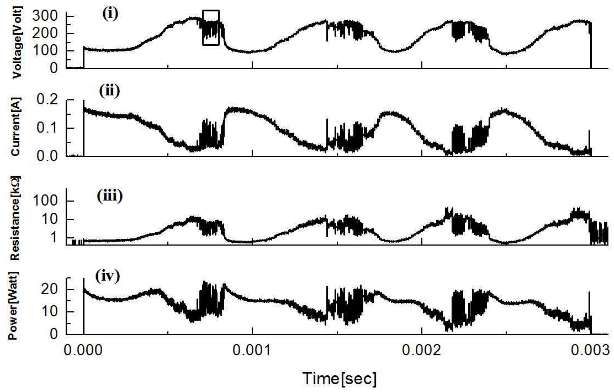


Fig. 2. ICCD shadowgraph images when the applied voltage of 300V is below the breakdown voltage

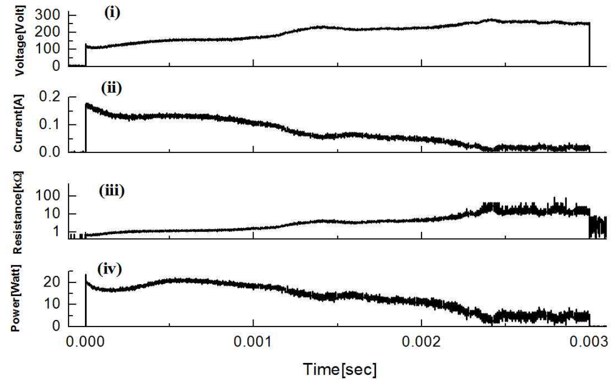
to the pin electrode with total pulse duration of 3ms. Fig. 2 is taken under condition below the breakdown or plasma ignition voltage. Shadowgraphs versus time indicate that the bubble is initially starting to form at the pin electrode and continuously growing along the electric field direction. As shown in Fig. 2 of PC case, the bubbles are periodically detached from the pin electrode when the pin electrode is driven by negative polarity. Therefore, the bubble is not having cumulative growth. In contrast it is observed from shadowgraphs that the bubbles stick to the pin electrode and are continuously growing in size when the pin electrode is driven by positive polarity. Accordingly, the breakdown voltage of PA case is higher than that of PC case due to the larger size of vapor bubble.

3.2 Instant waveform analysis

Figs. 3(a) and (b) show five distinct time varying waveforms including; (i) voltage across the liquid, (ii) current through the liquid, (iii) liquid resistance, and (iv) power delivered to liquid over the entire pulse duration. Fig. 3(a) is for PC case and 3 (b) for PA case. In general,



(a)



(b)

Fig. 3. Instant waveforms when the applied voltage is 300V (below the breakdown voltage) (a) PC case (b) PA case - i) liquid voltage, ii) liquid current, iii) liquid resistance, and iv) power delivered to the liquid

when the applied voltage is sufficiently low, the saline solution acts as a resistive load. Accordingly, the inception voltage of saline solution is dependent on the external resistor and equivalent resistance of saline solution which is related to not only magnitude of voltage but polarity of voltage applied to the electrode. When the applied voltage is over a certain threshold value, shadowgraphs show that micro-bubbles start to develop on the pin electrode due to the local ohmic heating. As the size and number of micro-bubbles increase, the total resistance of the conducting path through vapor and liquid is increased. The voltage applied to the saline solution gradually increases with the formation of bubbles. When the pin electrode is fully covered with bubbles, the applied voltage appears primarily across the bubbles and not the saline solution. During this period, bubbles can be detached from the pin electrode. With a further applied voltage increase, the successive discharges are generated within the bubbles as evidenced by when the electric field strength is sufficient to generate the plasma discharge. Therefore, the evolution of bubble is most important factor for generating the plasma discharge.

As shown in Fig. 3(a)-(i) and (b)-(i) of the respective PC and PA voltage versus time waveforms, we can clearly observe the bubble formation and extinction phases due to the external resistor. As shown in Fig. 3(a)-(i) of PC case, the voltage trace has several periodical fluctuations and numerous tiny spikes. The periodical fluctuations are caused by chaotic separation of bubbles from the pin electrode, which is corresponding to the results of shadowgraph Fig. 2. Numerous tiny spikes of voltage trace can be clearly seen as shown in Fig. 4, which is magnifying rectangular section in Fig. 3(a)-(i). These tiny spikes cannot easily find out when the external resistor is removed. In other word, this tiny spike is amplifying due to the external resistor. The width of tiny voltage spike is around 1~2us. We judge that the numerous tiny voltage spikes are related to the micro-bubble formation due to the electron emission from the pin cathode and direct dissociation of water molecules [10, 11]. This tiny spike is the most striking features related to the PC case, but still needs further study. On the contrary, as shown in Fig. 3(b)-(i) of PA case, the voltage trace is slightly increasing which is corresponding to growing of bubble size. And the constant voltage region might be related to the fully growing of bubble size as evidenced by shadowgraph images of Fig. 2.

Fig. 3(a)-(ii) and (b)-(ii) show the current waveforms of the PC and PA cases, respectively. In general, the current through the liquid is decreased as the bubbles are growing because the pin electrode is more fully covered with a bubble or vapor layer. Accordingly, liquid/bubble resistance versus time waveforms vary relative to the polarity of pin electrode as shown in Fig. 3(a)-(iii) and (b)-(iii). In the PA case, the liquid/bubble resistance is continuously increased as the bubbles are growing. On the country, in the PC case, the resistance trace also has the periodical fluctuation similar to the voltage trace. Fig. 3(a)-(iv) and (b)-(iv) show

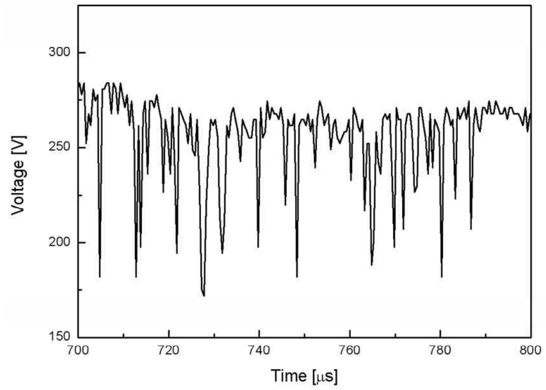


Fig. 4. Magnifying the marked rectangular section as shown in Fig. 3(a)-(i)

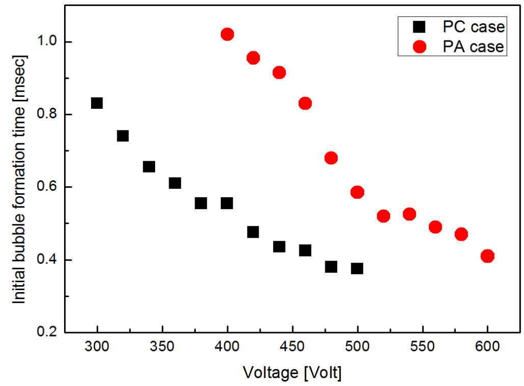


Fig. 6. Bubble formation time as a function of the applied voltage relative to the PC and PA condition

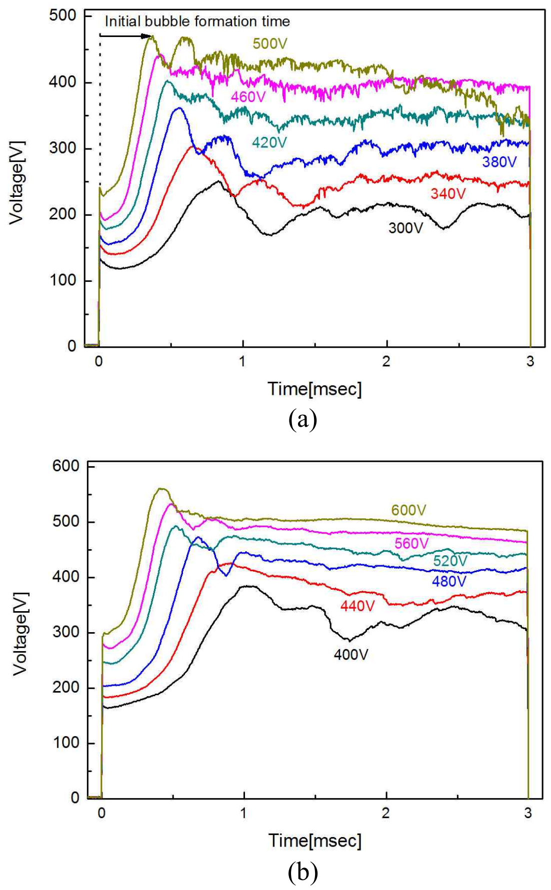


Fig. 5. Voltage waveform relative to the applied voltage (a) PC case & (b) PA case

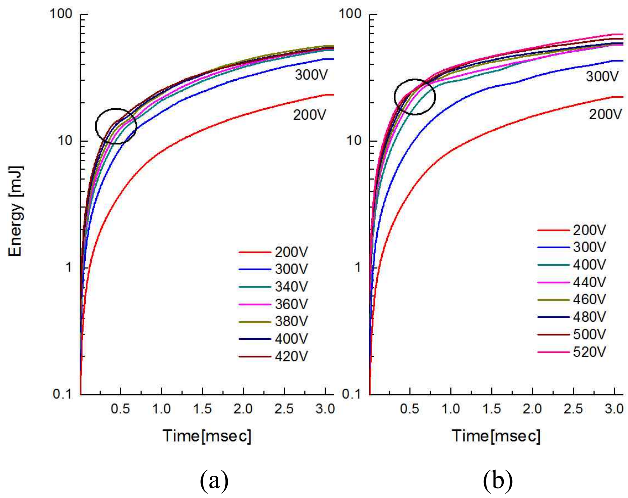


Fig. 7. Energy characteristics relative to the applied voltage (a) PC case & (b) PA case

the power dissipation waveforms of the PC and PA case, respectively. The power dissipation waveforms are similar to the current waveforms, which mean that the power dissipation is mostly determined by current through the saline solution.

3.3 Time averaged waveform analysis

In general, the formation and evolution of bubbles as well as plasma discharge in liquid are irregular and change form pulse to pulse. Therefore, it is very difficult to analyze the individual instant waveforms of voltage and current versus time. Therefore, we averaged 20 pulsed waveforms of voltage and current to obtain an average waveform. The analysis below is based on the 20 pulse averaged waveforms of voltage and current to increase average repeatability.

Fig. 5(a) and (b) show the averaged voltage waveform of the saline solution relative to the applied voltage for PC and PA case, respectively. The initial bubble formation time is defined as shown in Fig. 5(a), which is very reproducible. Fig. 6 shows the initial bubble formation time based on the result of Fig. 5. As shown in Fig. 6, the initial bubble formation time of PC case is much shorter than that of PA case at the same applied voltage, which we attribute to direct dissociation of water molecules. And the initial bubble formation time of PA case is more sharply reduced than that of PC case with the applied voltage. However, it is slightly reduced when the applied voltage reached the vapor breakdown voltage.

Fig. 7 shows the log plot of average energy delivered into the liquid plasma as a function of time versus the polarity of the applied voltage to the pin electrode. As shown in Fig. 7 (a) and (b), the energy dissipation is increased with the applied voltage. However, it should be noted that when the applied voltage is greater than the breakdown voltage, the energy dissipation saturates with the applied voltage. Note that the two slopes of energy trace are marked with circle shown in Fig. 7 (a) and (b) to distinguish when the energy dissipation into the bubble formation is larger than that into plasma. Interestingly, the cross point of two slope is quite corresponding to the initial bubble formation time as shown in Fig.6. Estimating from Fig. 7(a) and (b), the required energies for initial bubble formation of PC and PA case are around 15 mJ and 30 mJ, respectively.

4. Conclusion

In this study, we investigated the basic electrical characteristics of pin to plate electrical discharges in saline/ vapor bubble solutions. It has been determined from correlated the ICCD shadowgraphs and instant I-V waveforms that the vapor bubble tends to stick to the pin electrode and grows in size when the pin electrode is anode. In contrast, the vapor bubble tends to be periodically detached from the pin electrode when the pin electrode is cathode. Accordingly, the breakdown voltage of PC case is lower than that of PA case. From the measurement of the instant I-V waveforms, when the pin electrode is cathode, it has been also observed that there are numerous tiny voltage spikes which are related to the micro-bubble formation, we judge, due to the electron emission from the pin cathode causing direct dissociation of water molecules. This tiny spike is the most striking features related to the PC case and does not appear in PA case.

From analysis of time averaged I-V waveforms, for both PC and PA cases we have determined the following. The initial bubble formation time of PC case is much shorter than that of PA case. And it decreases as increases applied voltage below the breakdown voltage but slightly decreases when the liquid plasma occurs. The log plot of the energy dissipation delivered to liquid tells us that the required energies for initial bubble formation of PC and PA cases are approximately 15 mJ and 30 mJ, respectively.

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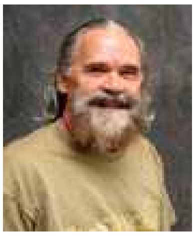

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