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UTILISATION OF THE HIGH SPEED CAMERA FOR THE PIN-HOLE DISCHARGE DIAGNOSTICS

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Abstract. The high speed camera was utilised for plasma diagnostics of the DC pin-hole discharge in electrolyte solutions. Two discharge modes were determined. Plasma channels were observed either in the bubble or outside the bubble in the bulk solution, which confirms both thermal and electron theory of the discharge ignition in liquid. In the diaphragm discharge, plasma streamers were better visible on the cathode side of the dielectric barrier because they formed significantly longer channels.

Keywords: discharge in liquid, pin-hole discharge, high speed camera, plasma diagnostics.

1. Introduction

The problem of discharges in liquids has been in an intensive focus of researches for the last three decades, only. Although several applications such as water treatment [1], surface treatment [2], or plasma sterilization[3] have been developed during the underwater research, exact mechanisms of the discharge creation and related processes still desire a detail study and description.

Non-thermal plasma of underwater discharges can be generated by various electrode configurations and voltage regimes. The most studied configuration is a point-to-plate electrode geometry[4] where DC pulsed high voltage up to tens of kV is applied. Next configurations suitable for the discharge creation under the water surface are coaxial[5] and pin-hole systems[6][7][8]. Besides the DC pulsed high voltage, also high frequency, microwave or DC non-pulsed voltage regimes can be used for the discharge generation.

The pin-hole discharge can be distinguished as a diaphragm or capillary configuration. In the case of the diaphragm system, high voltage electrodes are separated by a thin dielectric barrier which thickness is approximately the same size as the diameter of an orifice connecting both reactor parts[9]. On the other hand, the capillary system uses a thick dielectric barrier which thickness is remarkably bigger than the orifice diameter[6]. In both cases, the discharge can be generated in the orifice using either DC or AC high voltage. The liquid medium is an electrolyte solution.

Plasma diagnostics by the ICCD camera has an important force among other diagnostic methods utilised for the characterisation of the discharge in liquids. Due to the still indefinite mechanism of the discharge ignition and propagation in the liquid phase, the usage of the high speed camera enables a proper capture of different processes taking place before, within and after the discharge breakdown moment in the system. Together with an employment of electric measurements, the ICCD imaging can reveal processes such as the bubble formation, the discharge breakdown in the bubble, the propagation of plasma streamers in and outside the bubble, the bubble cavitation, etc.

Following pages demonstrate a complex image study of the pin-hole discharge in the electrolyte solution. It is focused on the determination of particular processes taking place in the plasma reactor during the discharge ignition, and on the confirmation of the discharge breakdown theory (electron or thermal theory[10]). Further, a comparison of the diaphragm and capillary discharge is enabled due to the utilisation of the high speed camera records.

2. Experimental setup

Plasma diagnostics of the pin-hole discharge was carried out in plasma reactor shown in Figure 1. Its total volume was 100 ml. Two high voltage electrodes made of platinum were separated by a wall made of POM-C (Polyoxymethylene (Copolymer), thickness of 1 mm). There was an orifice (10 mm in diameter) in the centre of the wall into which a dielectric barrier made of ceramics Shapal-M^{TM} (thickness variable from 0.3 to 2 mm) was installed. One central pin-hole with the diameter of 0.2–0.6 mm was connecting both electrode parts.

High voltage was supplied from the DC self-pulsing source (high voltage amplitude up to 4 kV, power up to 300 W). Water solutions containing NaCl electrolyte with initial conductivity of 275 µS cm^{-1} were used in presented experiments.

An intensified CCD camera (ICCD) Andor iStar with an objective Cosmicar/Pentax TV lens 50 mm (1:2.8) was used for visual records of bubbles and plasma streamers. The microsecond time resolution was used for these measurements. The ICCD camera was synchronized with the discharge operation by current evaluation determined by a four-channel oscilloscope LeCroy LT374L with a high voltage probe ELDITEST GE 3830 30 kV (attenuation 1:1000).

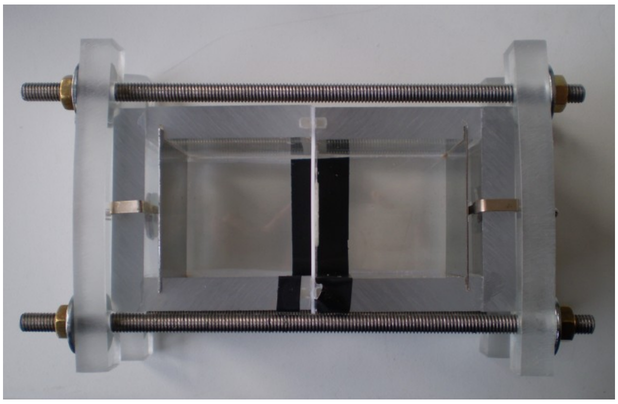

Figure 1. Plasma reactor used for the image diagnostics of the pin-hole discharge.

3. Results

The utilisation of the ICCD high speed camera had enabled the detail characterization of the discharge ignition, its regular operation as well as the identification of related processes such as the bubble formation. The moment representing the discharge breakdown in the pin-hole was confirmed both by time resolved current-voltage characteristics and light emission records by optical emission spectroscopy[9][11][12]. Camera records represented by photographs of a particular discharge moment had been completed by time resolved electric characteristics of discharge current and camera triggering. The ICCD camera was switched on automatically when the current signal rapidly increased which indicated the discharge ignition (see Figure 2).

The camera images were taken vertically to the dielectric barrier separating the anode and cathode parts of the plasma reactor. In the photograph, the dielectric barrier is the white central stripe from the left to the right (its thickness is approximately 1 mm). There is an orifice in the barrier onto which a particular diaphragm or capillary is installed. The diaphragm or capillary is not visible in the photograph because it is hidden within the barrier. The pin-hole connecting both electrode parts is approximately in the middle of the picture. The anode is set in the upper part while the cathode lies in the bottom part of the photographs.

Increasing the applied voltage on the electrodes, tiny microbubbles appear in the pin-hole due to the liquid heating. Microbubbles are dragged from the pin-hole to the bulk solution. When the applied voltage exceeds the breakdown value (over 1200 V), the discharge is ignited in the pin-hole. According to the image records, the discharge is created primary in the bubble of the evaporated liquid. This fact confirms the thermal theory of the discharge ignition in liquids.

Formation of the bubble is associated with a substantial increase of system resistance. Subsequently, different potentials formed on the inner and outer surface of the bubble lead to the breakdown of the liquid vapour inside the bubble. Simultaneous decrease of system resistance induces an intensive current increase which is represented by a significant peak on the current characteristics. The camera triggering was adjusted to this current enhancement, as it seen in the Figure 2.

Further increase of the applied voltage ensures the stable discharge operation. However, two discharge modes have been detected using the high speed camera images. The first one is represented by the further discharge propagation in the bubble (Figure 3), according to the thermal theory. The photograph clearly shows plasma streamers in the bubble on the cathode side of the dielectric barrier.

The second mode of the pin-hole discharge operation is represented by further propagation of plasma streamers outside the bubble (Figure 4). We suppose that this discharge mode corresponds to the electron theory. When plasma streamers primary created in the vapour phase reach the bubble inner surface, ionisation of liquid molecules starts outside the bubble, and plasma channels can propagate further into the bulk solution. If the applied voltage is high enough, the discharge operation is possible even though the bubble explodes.

Based on obtained images we have assumed that both breakdown theories fit for the discharge ignition in liquids. Primary, the discharge ignition starts in the bubble of the liquid vapour due to the lower ionisation potential needed for the breakdown. This phase corresponds to the thermal (bubble) theory. On the other hand, further propagation of plasma channels into the liquid is possible outside the bubble as well. This fact reflects on the electron theory of electron avalanches. Thus mechanisms of the pin-hole discharge operation are a combination of both theories. This fact is valid in systems where a slow voltage increase is used for the discharge ignition. Moreover, this phenomenon was also observed when gas bubbles were additionally introduced into the system through the HV electrode[13]. In the case of pulsed nanosecond discharges, a proceeding of the thermal theory is impossible due to a lack of time necessary for the liquid evaporation. In such systems, the discharge operates directly by streamers in the liquid phase.

3.1. Comparison of the diaphragm and capillary discharge

This result section compares the shape of plasma streamers created in the diaphragm and capillary configuration. The diaphragm configuration means that the dielectric barrier parameters are approximately equal, i.e. the barrier thickness of 0.3 mm and the pin-hole diameter of 0.3 mm. In the capillary configuration, the barrier thickness is substantially higher than the pin-hole diameter, i.e. the thickness of 1.5 mm and the pin-hole diameter of 0.3 mm.

The camera imaging of the discharge created in the pin-hole was adjusted according the same conditions

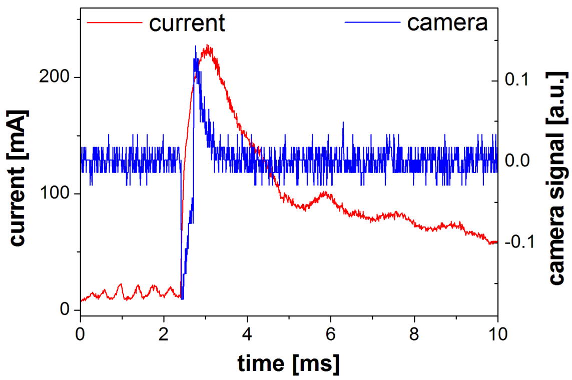

Figure 2. Time resolved record of discharge current and camera signal during the discharge breakdown in the diaphragm.

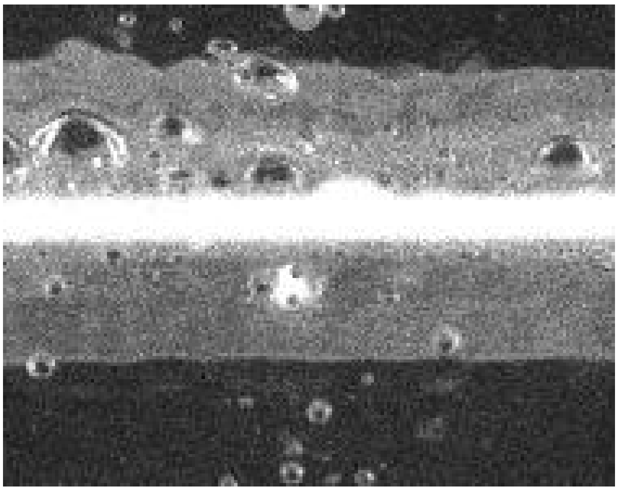

Figure 3. Discharge creation in the bubble on the cathode side of the dielectric barrier; mean applied voltage of 1540 V (diaphragm configuration: ceramic barrier thickness of 0.3 mm, central pin-hole with diameter of 0.3 mm).

as in the previously mentioned experiments. The camera triggering was set at the current increasing phase. Both discharge modes (i.e. plasma streamers propagation in the bubble or outside the bubble) has been recorded in all tested configurations. Images obtained in the capillary configuration are presented in Figures 5 and 6. Figure 5 represents plasma streamers formed in the bubble while Figure 6 shows plasma streamers propagating outside the bubble into the bulk solution.

In the diaphragm configuration (Figures 3 and 4), plasma channels are well visible only on one side of the dielectric barrier where the cathode is installed. This phenomenon indicates a different shape of plasma streamers in the DC voltage regime. According to the theoretical assumption[14], longer plasma channels are created on the cathode side while shorter plasma channels on a spherical shape are formed on the anode side. Presented images confirm this assumption for

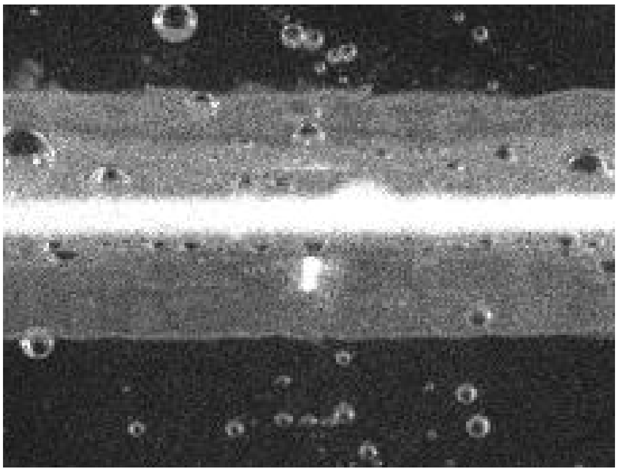

Figure 4. Plasma streamers propagating outside the bubble from the pin-hole towards the cathode; mean applied voltage of 1540 V (diaphragm configuration: ceramic barrier thickness of 0.3 mm, central pin-hole with diameter of 0.3 mm).

the diaphragm discharge because longer streamers are observed just on the cathode side.

In the capillary configuration (Figures 5 and 6), plasma streamers are visible on both sides of the dielectric barrier. However, the shape of the channels seems different similarly to the diaphragm configuration. Recorded plasma streamers are more intensive on the cathode side of the barrier. Moreover, there is an interesting difference of the discharge creation in the bubble or in the liquid, only. When a bubble is formed in the pin-hole and the discharge is ignited in it, plasma channels fill almost the whole space of the bubble. This effect is more obvious in the case of the thicker barrier (1.5 mm). Therefore, the discharge seems more intensive in the bubble mode because energy is mostly dissipated inside the bubble, i.e. in the gas phase. Another effect of the capillary configuration is that both bubbles and plasma channels are dragged from the pin-hole (capillary) towards the bulk solution. Especially in the case of the thicker barrier (1.5 mm), the bubble on the cathode side is significantly enhanced, and it forms a conical shape. It corresponds to the effect of pumping which was already observed in the capillary configuration[6].

4. Conclusions

The high speed camera was utilised for plasma diagnostics of the DC pin-hole discharge in electrolyte solutions. This device has been assumed as an important tool for a detailed imaging of plasma streamers and bubble formation. Based on the camera records together with the time resolved characteristics of electric parameters, particular processes before, within and after the discharge breakdown have been detected. According to detailed photographs, two discharge modes have been determined. Plasma channels were observed either in the bubble or outside the bubble in the bulk

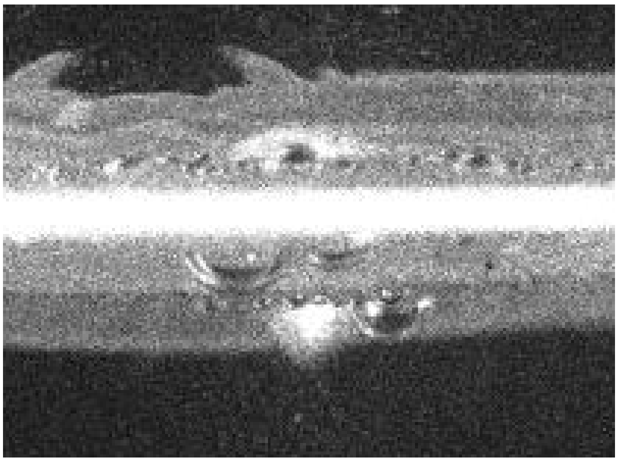

Figure 5. Discharge creation in the bubble; mean applied voltage of 2020 V (capillary configuration: ceramic barrier thickness of 1.5 mm, central pin-hole with diameter of 0.3 mm).

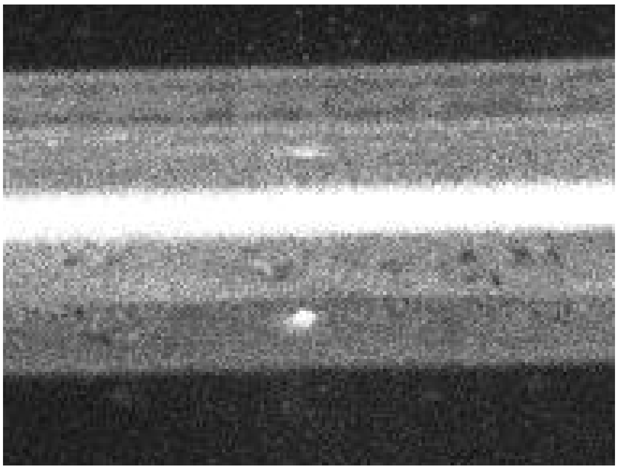

Figure 6. Discharge creation outside the bubble; mean applied voltage of 1920 V (capillary configuration: ceramic barrier thickness of 1.5 mm, central pin-hole with diameter of 0.3 mm).

solution. These results confirm both theories of the discharge ignition in liquid, thermal and electron theory.

The ICCD imaging also helped to compare the discharge creation in the diaphragm and capillary configuration. In the case of the diaphragm discharge, plasma streamers were better visible on the cathode side of the dielectric barrier because they formed significantly longer channels. In the case of the capillary, plasma channels propagate further from the pin-hole into the solution and thus they were well visible on both sides of the dielectric barrier.

Acknowledgements

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