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Investigation of gas flows created by a discharge with a liquid electrolyte cathode

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The discharge with a liquid electrolyte cathode at atmospheric pressure in the air was studied using PIV and high-speed photography methods. The velocity field of the gas flows created by the discharge was found. It was shown that the gas flow created by the discharge moves down along the discharge channel to the surface of the solution, reaching a maximum velocity near its surface. Meeting with the surface of the solution, the gas begins to spread along it in a thin layer about two millimeters thick. Thus, it was found that the components of the solution transferred from the solution to the gas phase under the action of a discharge with a liquid cathode are removed from the discharge zone in a horizontal direction, along the surface of the solution.

Keywords: Particle Image Velocimetry (PIV); gas flows; electric discharge; liquid cathode; atmospheric pressure; air; transfer of solution components to the gas phase.

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Introduction

The interaction of electrodischarge plasma with the surface of liquid and, in particular, surface of aqueous solutions is the matter of great interest to researchers in recent years [1]. If the liquid is electrically conductive, the simplest and the most effective way to organize interaction of electrodischarge plasma with its surface is to create electrical discharge in which this liquid will serve as one of electrodes. Such discharge with liquid electrode with a characteristic current from several milliamperes to several hundred milliamperes is a glow discharge at atmospheric pressure [2].

If the solution in this discharge is a cathode, bombardment of solution surface by positive ions results in intensive plasma-chemical reaction in liquid [2, 3]. Therefore, the study of discharge with liquid cathode is of great interest from the point of view of plasma-chemical applications. Liquid cathode discharges have prospects of

practical application in new water purification methods, modification of high-molecular weight compounds, sterilization of aqueous solutions, metal content analysis of solutions, biomedical applications and other applications [3–15]. Prospects of practical application make the researches of liquid cathode discharges relevant [16–28].

The value of cathode potential drop in the liquid cathode discharge is quite large and ranges from 400 to 700 V [2, 3] depending on the liquid cathode composition. Therefore, ion bombardment of the liquid cathode surface results in intensive transfer of solution components to gas phase. Transfer of solution components to gas phase under the influence of liquid cathode solution is usually characterized by transfer ratio which is equal to number of substance molecules transferred to the gas phase per one ion bombarding the solution surface [2]. At the same time, not only volatile but also non-volatile solution components, such as metal ions, are

transferred to the gas phase which in particular, allows to detect them in discharge plasma with liquid cathode by emission spectra [8–10, 21, 24].

However, water is transferred most intensively from diluted solution to the gas phase in a discharge with liquid cathode. There are different data on the water transfer to the gas phase in a discharge with liquid cathode because this process apparently depends on many factors such as solution temperature, its mixing mode, etc. [25]. However, in the simplest case, when a discharge with liquid cathode occurs in a non-flowing discharge cell with natural mixing of solution and its natural cooling due to interaction with atmosphere, the transfer ratio of water to gas phase at discharge current of 50 mA is about 500 molecules/ion [29]. According to data [30], current density in cathode spot on the solution surface is 0.5 A/cm^2 , and water vapor density at atmospheric pressure and temperature of 100°C is 0.6 kg/m^3 . Under these conditions, an estimate of 0.8 m/s is obtained for average flow rate of water vapor from the cathode spot. At higher vapor temperature the average flow rate from the cathode spot will obviously be even higher.

After flowing from the cathode spot, vapor starts interacting with atmospheric pressure. Obviously, as a result of interaction with atmospheric air, temperature of water vapor will eventually become lower than 100°C and then its partial pressure will become lower than the atmospheric one. Therefore, water vapor can only leave discharge area with air flow. Therefore, the movement of atmospheric air near liquid cathode should have an extremely strong effect on the measured water transfer ratio from aqueous solution.

In this paper we investigate the air movement near discharge channel of the discharge with liquid cathode by particle image velocimetry (PIV) method.

PIV method belongs to the class of non-contact measuring methods of flow velocity. It occupies a special place among other tools for studying the structure of flows due to the ability to record instant spatial distributions of velocity. Measurement of instantaneous field of flow velocity in given cross-section is based on measurement of impurity particles movement located in the cross-section plane over a fixed period of time.

Small particles (tracers) are added to the liquid or gas flow. Laser beam is formed into a light sheet illuminating seeded particles twice with a short time interval. The measuring area of the flow is considered to be a plane cut by “light sheet”. The light scattered by the particles is recorded on two consecutive frames of high-resolution digital camera. Subsequent image processing makes it possible to calculate particle displacements during time between flashes of light source and build two-component velocity field. Measured two-component values of vectors are projections of real (three-dimensional) vectors to the plane perpendicular to the optical axis registering particle images of the equipment [31].

Experimental unit and measurement method

To study the velocity field of gas flows near the discharge channel and solution surface, a liquid cathode discharge was used at atmospheric pressure. The discharge was created between a rod tungsten electrode with a diameter of 2 mm and solution surface. Distance between the rod electrode and solution surface was 4 mm, discharge current – 60 mA.

The solution was in non-flowing cylindrical discharge glass cell with a volume of 100 ml. The depth of discharge cell was 14 mm. The solution level coincided with the edge of discharge cell.

Sodium nitrate solution in distilled water with specific electrical conductivity of $300 \mu\text{S/cm}$ and pH level = 4.7 was used as solution.

Nikon D500 camera was used to obtain high-speed images of discharge channel with high space resolution. Exposure time of one frame during photo-shooting was $125 \mu\text{s}$.

The LaVision FlouMaster Stereo PIV measuring system with resolution up to $50 \mu\text{s}$ was used to determine velocity of gas flows near the discharge channel and surface of liquid cathode.

Light sheet with a thickness of 0.5 mm formed by laser beam was created in vertical plane at a distance of 1 mm in front of electrode the role of which was performed by tungsten rod with a diameter of 2 mm. Therefore, the survey was conducted in vertical section located at a distance of about 2 mm from the discharge axis. The nearest 0.5 mm near the solution surface did

not fall into the survey area to avoid reflection of laser radiation from the solution surface.

Experimental results and their discussion

High-speed photography (fig. 1) is used to determine the general type of liquid cathode discharge with a discharge gap of 4 mm and discharge current 60 mA for sodium nitrate solution with electrical conductivity of 300 $\mu\text{S}/\text{cm}$ and pH level = 4.7.

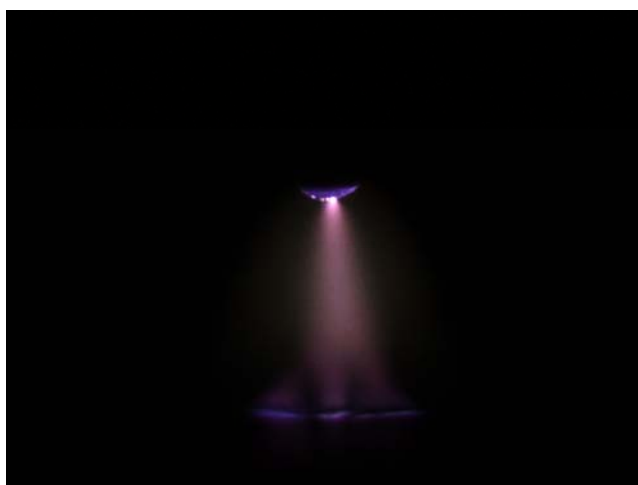


Fig. 1. Photo of discharge with liquid cathode. Discharge gap of 4 mm, discharge current 60 mA. Sodium nitrate solution with electrical conductivity of 300 $\mu\text{S}/\text{cm}$ and pH level = 4.7

Data of high-speed photography showed that the discharge has a shape close to a cone. Cone apex rests again the point of discharge

anchoring to the tungsten electrode surface. Solution surface is a cone base. Near the solution surface the discharge channel is divided into separate filaments and each of them ends with separate cathode spot. Study of high-speed photography data showed that the number of filaments and their location changes in time. The diameter of area occupied by cathode spots on the solution surface also changes. The diameter of area occupied by cathode spots does not exceed 4 mm which is in good agreement with data for medium density of cathode current from [8, 9].

Since the light sheet formed by laser beam is quite close to the metal electrode (approximate distance 1 mm), the electrode surface is slightly illuminated by it. A photograph of laser radiation scattering to metal electrode and suspended in air particles made it possible to link the position of electrode and surface solution to the grid (fig. 2). According to this link, the lower electrode limit was at a level of -4 mm and the solution surface was at a level of -8 mm.

Determination of gas flows velocity distribution in the discharge with liquid cathode by PIV method showed that the gas velocity in the area of discharge channel is directed vertically downward (fig. 3). At the same time, the gas flow velocity increases with movement from the tip of metal electrode to the solution surface. The gas flow velocity near the tip of metal electrode is approximately 0.3 m/s and near the solution surface is approximately 0.85 m/s. White vertical line in fig. 3 – result of illumination cause by laser radiation scattering on the electrode surface.

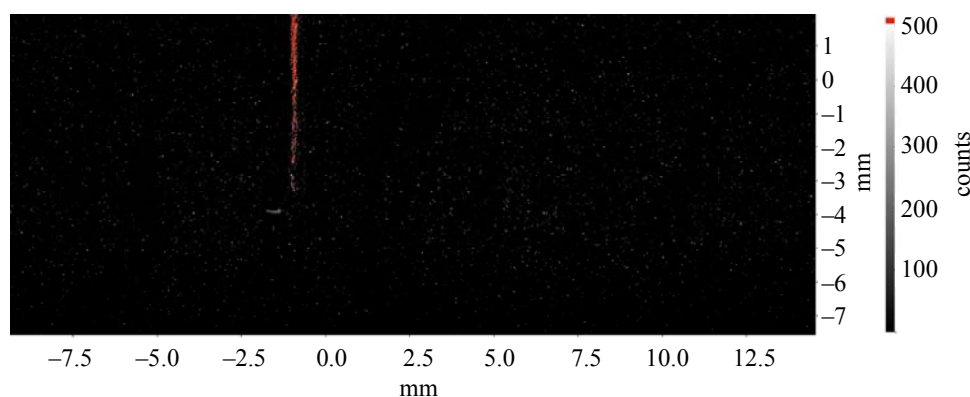


Fig. 2. A photograph of laser radiation scattering to metal electrode and suspended in air particles with linked grid

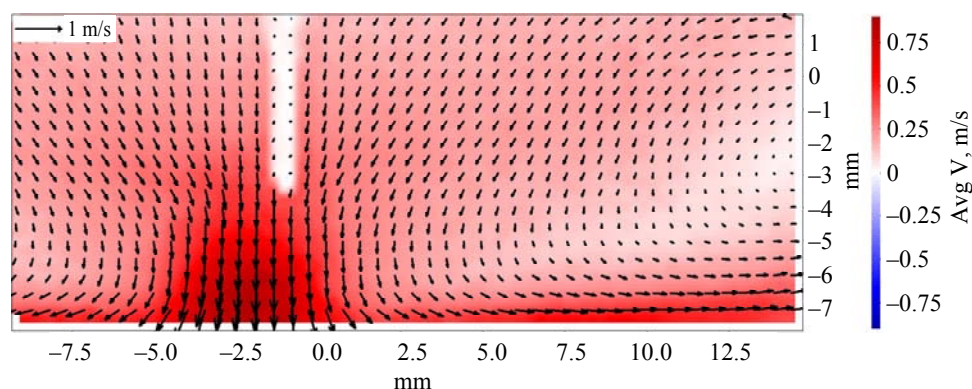


Fig. 3. *Distribution of gas flow velocities near the discharge with liquid cathode. Module of gas flow velocity is shown with color*

Near the solution surface the gas flow reverses and starts spreading from discharge axis in all directions along the solution surface. Maximum horizontal velocity of the gas flow velocity is achieved near the solution surface at a distance of 0.5 mm from the surface (the layers closer to the surface did not fall into the survey area). The maximum horizontal velocity of the gas flow velocity near the surface is 0.2 m/s (fig. 4).

There is downward vertical velocity of the gas flow velocity at a distance of at least 10 mm from the discharge axis near the solution surface. Gas flow moves almost horizontally along the solution surface at a distance of at least 10–15 mm. Horizontal velocity in this area reaches its maximum. Vertical velocity of the flow velocity directed from the solution surface appears at a distance exceeding 15 mm from the discharge axis.

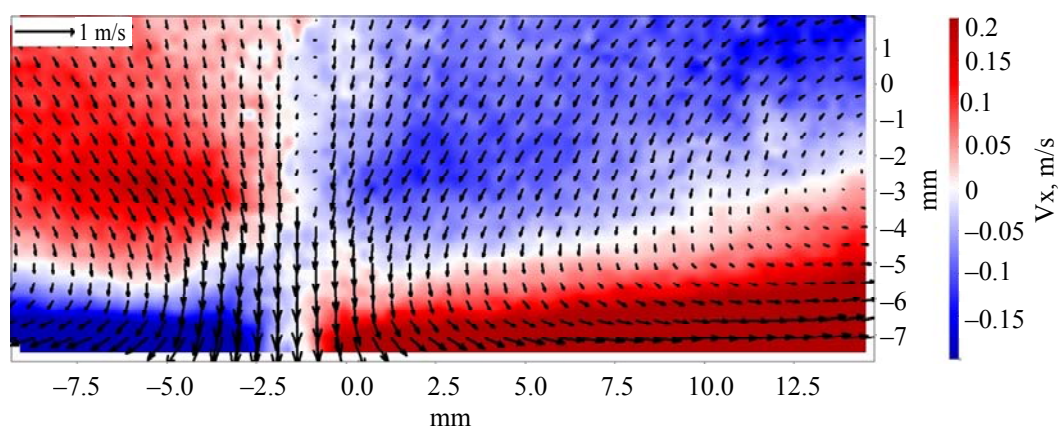


Fig. 4. *Distribution of gas flow velocities near the discharge with liquid cathode. Velocity projection to the horizontal axis is shown with color*

It can be assumed that in a discharge with a liquid electrolyte cathode the movement of positive ions (the concentration of which considering partial attachment of electrons is higher than the concentration of negative ions) drives the neutral component of the gas which leads to the suction of ambient air from the area near metal electrode and its movement downward to the solution surface. To confirm the mechanism of acceleration of neutral gas component it is planned to conduct further researches that will include analysis of all factors

that can cause movement of neutral particles, as well as experiments with polarity change of electrodes.

This work shows that near discharge with a liquid electrolyte cathode gas moves along the discharge channel downward to the solution surface and spreads along the solution surface in a thin layer with a thickness of approximately 2 mm and maximum horizontal velocity of 0.2 m/s. The importance of this result is that in the same thin layer together with gas flows water in the form of vapor and solution microdrops

transferred to the gas phase under the impact of liquid cathode discharge will also be removed from the discharge area. However, due to the thinness of this layer and its proximity to the solution surface, diffusion transfer of solution components from gas phase back to the solution is possible. Vertical velocity of the flow velocity directed from the solution surface appears at a distance exceeding 15 mm from the discharge axis. In this area, the irreversible removal of solution component transferred to the gas phase from discharge cell begins.

Conclusion

The discharge with liquid cathode at discharge gap of 4 mm and discharge current of 60 mA at atmospheric air pressured was studied using high-speed photography and PIV methods. The velocity field of gas flows near the discharge channel and solution surface was measured using PIV method. It is shown that the gas flow created

by electric discharge moves downward along the discharge channel to the solution surface. Maximum velocity of vertical gas movement is achieved near discharge channel near the solution surface and is equal to 0.85 m/s. Next, the gas spreads along the solution surface in thin layer about 2 mm thick with a thickness of maximum horizontal velocity of 0.2 m/s. Solution components transferred from the solution to gas phase under the impact of liquid cathode discharge are removed from the discharge area by this gas channel. Considering small thickness of this gas flow and large area of its contact with the solution surface, it can be assumed that some part of solution component transferred to the gas phase can return back to the solution.

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