Study of gas discharge with a liquid cathode at maximum thermal load to the cathode

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Abstract. Thermal phenomena were experimentally studied in the atmospheric pressure gas discharge between the electrolyte liquid cathode and the metal anode under conditions in which the electrolyte temperature is close to the boiling temperature. It is shown that electrolyte mass discharge can only be reduced to a certain limit, while maintaining stable mode of burning discharge.

1. Introduction
Gas discharges with liquid electrodes is of concern due to the fact that they have large possibilities of practical application. It is also important that they can be obtained by relatively simple technical means in a wide range of current and power. When burning of gas discharge between the electrodes, liquid plasma is in contact with the liquid. There are complex processes of heat and mass transfer between the electrolyte and the plasma. The electrolyte is heated, evaporated and subjected to sputtering. Under these conditions, the gas discharge characteristics largely depend on the cooling conditions of the electrolyte. In works [1, 2] experimentally have been investigated the energy characteristics of a gas discharge with electrolyte cathode flow at relatively high currents and capacities, respectively (7 - 22) A and (8 - 33) kW. It showed a reduction of heat losses by reducing the mass flow rate of the electrolyte. In this study, the study continued in a small electrolyte entering the nip with the discharge.

2. Experiment
Fig. 1 schematically shows a cathode assembly of gas discharge device. Key elements of its structure: pin 1, a housing 2 and an outlet 3. The pin 1 is copper. Its diameter is 10 mm, the rounded radius is 5 mm. The housing 2 and the outlet 3 are made of a dielectric material. The outlet 3 is removable. In experiments three different branches’ diameters were used: 12.7; 20.0 and 28.0 mm. The wall thickness was 2 mm.

The electrolyte 4 was supplied inside the outlet 3. It is poured through the edge of the outlet 3 into the groove 5 and there from merged into the cooling system. Immersion depth h of a copper rod 1 into the electrolyte 4 was varied by moving it vertically. To measure the voltage drop within the electrolyte \( \Delta U_k \) electric probe 6 was used. It consisted of a tungsten wire with a diameter of 0.15 mm, inserted
into a tube of quartz glass. In the experiments the working end of the probe was placed on the edge of the outlet 3 as shown in figure 1. Power of Joule heat in the electrolyte was calculated by the formula:

\[ Q_j = I \cdot \Delta U_k, \]  

where \( I \) – discharge current.

![Figure 1. Cathode assembly.](image)

Heat loss at the cathode is determined by a calorimetric method.

\[ Q_k = m_{exit} \cdot c \cdot \Delta t. \]  

There \( m_{exit} \) – electrolyte flow through the cathode assembly; \( c \) - heat capacity of the electrolyte; \( \Delta t \) - the difference between the indications of chromel-alumel thermocouples installed at the entrance to the cathode assembly 7 and at its exit 8.

Electrolyte flow was defined as the proportion of electrolyte amount leaked from the cathode assembly to the time interval during which the electrolyte is flowed. Electrolyte flow measurements were carried out before the gas discharge ignition (\( m_{ent} \)) and during its burning time (\( m_{exit} \)). Flow difference was taken as the mass carry over of electrolyte \( G \), occurring under the influence of the gas discharge.

\[ G = m_{ent} - m_{exit}. \]  

As an electrolyte weakly concentrated solution of sodium chloride in distilled water was used. Specific electrical conductivity \( \sigma \) of the electrolyte was measured by conductometer ANION 4150. Solution was prepared with \( \sigma = 10.00 \) mCm/sm. It is known that electrolytic processes and the impact of the plasma discharge cause changes in the electrical properties of the electrolyte. Thus, after each small series of experiments adjusting of the value \( \sigma \) was carried out. Deviations after each initial value does not exceed \( \pm 0.20 \) mCm/sm.

Current was measured by needle multirange indicator of type M 2015 of accuracy class 0.2. A power source based on inverter converter was used. The choice was dictated by the fact that the sources of this power type have protection against short-circuit and provide sustained combustion gas discharge at any point in the current-voltage characteristics. In this constant current regulation errors does not exceed 1%.

3. The experimental results and their analysis.

The graphs, described in figure 2 shows how the heat losses of the cathode \( Q_k \) are changing and the power Joule heat \( Q_j \) within the electrolyte at low constant electrolyte flow \( m = const. \) With the current increase in the intensity of heat and mass transfer processes between the electrolyte cathode and gas plasma enhanced. Accordingly, heat loss at the cathode \( Q_k \) is increasing. Along with this comes an
increase in the power of Joule heat \( Q_j \). As can be seen, \( Q_k \) and \( Q_j \) graphics virtually converge with increasing current. However, in practice, we cannot achieve intersection of \( Q_k \) and \( Q_j \) graphics as when approaching such regimes there is a breakdown of the electrolyte layer over the current lead.

![Figure 2. Dependence on current: heat loss on cathode \( Q_k \) and capacity of power Joule heat in electrolyte \( Q_j \), volume electrolyte velocity \( m = 10 \text{ g/s} \).](image)

At higher currents, the electrolyte hardly heats up and reaches a boiling state. The bubbles of steam break the electrolyte layer. Apparently due to such phenomena there comes a breakdown.

Breakdown stops occurring with increasing thickness of electrolyte layer. In this variant electrolyte boiling leads to complete rupture of the current channel, and the discharge is extinguished by achievement of current to some certain limit. As the experiments showed the smaller the mass of the electrolyte flow rate is, the lower the numerical value of the current limit. Occurrence of instability of the discharge burning at a low mass flow rate of the electrolyte was observed on the oscillograms of currents and voltages, as well as on instant photographs of the gas discharge.

In the limit, the heat loss at the cathode and the power of Joule heat in the electrolyte can be considered numerically equal to:

\[
m_{\text{exit}}^* \cdot c \cdot \Delta t \approx I^* \cdot \Delta U_k.
\]

Here, \( I^* \) and \( m_{\text{exit}}^* \) – limits of current and flow through the electrolyte through cathode assembly.

Using equation (4) it is possible to determine the minimum flow of the electrolyte, which is necessary for sustaining constant combustion gas discharge.

\[
m_{\text{exit}}^* \approx \frac{(I^*)^2 \cdot R_k}{c \cdot \Delta t}.
\]

Here \( R_k \) – the ohmic resistance of the cathode assembly. The numerical value can be taken as water equal to 4.19 kJ/(kg·K), and \( \Delta t \) as the difference \( 100 - t_{\text{ent}} \), where \( t_{\text{ent}} \) – electrolyte temperature at the inlet of cathode assembly.

From formula (5) it follows that the electrolyte flow required for work near critical thermal conditions, along with it, the heat loss at the cathode it can be minimized by taking measures to reduce \( R_k \).

On figure 3 are graphs constructed from the results of experiments. The parabolic shape of the curves indicates the legitimacy of the assumptions on which the formula (5) is obtained. The same figure shows the results of mass carry over of electrolyte calculation formula (3) for critical conditions. As can be seen the mass carry over of electrolyte is increasing substantially proportional to...
the current. This principle can be regarded as a characteristic feature of the gas discharge with liquid electrolyte cathode, as it manifests itself in other experimental conditions [3-4]. The proportionality factor varies within narrow limits depending on the properties of the electrolyte and its cooling conditions. In this work you can take it as \( k = 0.09 \cdot 10^{-3} \text{ kg/(s \cdot A)} \).

Thus, given the mass flow carry over of the electrolyte estimated value into the cathode at the input node may be defined by the formula

\[
m_{\text{exit}}^* = \frac{(I^*)^2 \cdot R}{c \cdot \Delta t} + k \cdot I^*.
\]

Formula (6) can be used to determine the minimum flow of the electrolyte through the cathode assembly at the design stage of discharge devices.

![Diagram](image)

**Figure 3.** Diagrams modes with a maximum heat load. The diameter of the outlet of the cathode assembly: 1 – 12.7 mm; 2 – 20.0; 3 – 28.0.

4. **Conclusions**

The mass flow of the electrolyte can be reduced only to a certain limit. In this case should be taken actions to prevent boiling of electrolyte battery into the zone of discharge binding.

**References**

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