Determination of the voltage drop on a high-current vacuum arc discharge under conditions of a limited cross-section of the plasma flow

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Abstract. The work is devoted to the study of the high-current vacuum arc discharge characteristics under conditions of a limited cross-section of the plasma flow. The experiments were carried out on the IMRI-5 setup with a sinusoidal arc current amplitude of 300–350 kA and a rise time of 500 ns. Aluminum rods with diameters from 3 to 7 mm were used as a cathode. The plasma flow was formed in a channel whose diameter was equal to that of the cathode. The features of the formation of a plasma jet with various configurations of the used plasma gun are described. The electrophysical parameters of the arc discharge are presented. Theoretical estimates of the voltage drop across the high-current arc during the outflow of a plasma flow through holes with a limited diameter are provided.

1. Introduction

One of the many vacuum arc discharge applications is the use of the cathode and anode evaporated material as a source of material for the formation of Z- and PZ-pinches [1, 2]. One of the main parameters that determines both the dynamics of the pinch’s implosion and the output of X-ray radiation is the mass of the substance participating in the pinch compression. In order to get the required linear mass (from tens to hundreds of micrograms per centimetre of liner length) evaporated from the electrodes surface, the arc discharge current density must be from 0.4 to 2 MA/cm². Since the linear mass of the plasma jet (or plasma sheath) is determined by the balance between the amount of plasma entering the interelectrode gap from the vacuum arc discharge and the amount of plasma leaving it, the plasma-metal liner formation time will be determined by the plasma movement speed and the rate of its production. The typical arc discharge plasma velocity is a few centimetres per microsecond [3], which means that the formation time of such structures is 1-10 µs, depending on the generator parameters on which such a system is used, as well as the interelectrode gap length. High-current vacuum arc discharges with the above-described parameters are still not well studied. It was experimentally obtained that at an arc current of 100-200 kA and a cathode diameter of several millimetres, when a plasma jet is formed in a confined space, the arc burning voltage can be up to several kilovolts. Obviously, such a high voltage drop across the arc is a very atypical phenomenon and requires an explanation. In this regard, we made an attempt to study the combustion characteristics...
of such arc discharges and to determine the reasons why, with an increase in the current density, there is a significant increase in both the arc discharge voltage and the value of ion erosion (in comparison with the tabular values determined at relatively low densities arc current [4]).

2. Experimental setup
The experiments were carried out on a high-current generator IMRI-5 (450 kA, 450 ns in the short circuit mode with low inductance) [5]. The arc current source was the IMRI-5 high-current generator itself. In fact, the IMRI-5 generator is a capacitor bank with a capacity of $C_0 = 3.2 \mu$F. The charging voltage of the IMRI-5 generator was $U_0 = 70$ kV, the half-period of the arc discharge current oscillation was $T_{1/2} = 1.3$ $\mu$s, and the arc discharge current amplitude was about $I_0 = 360$ kA. The maximum current growth rate was $\frac{dI(t)}{dt} = 1$ kA/ns.

![Figure 1. Plasma gun design and location of electrophysical diagnostics.](image)

In the presented experiments, a scheme was investigated in which the end face of the plasma gun aluminium cathode was deepened into the insulator and located at a distance of 3 mm from the hole in the anode electrode (see figure 1). A vacuum arc discharge was initiated upon a breakdown along a 3-mm-high polyethylene insulator separating the end of the plasma gun cathode and the adjacent anode. The diameter of the aluminium cathode was $d_c = 3$ mm. When a vacuum arc discharge ignited, a plasma jet was formed, extending upward from the high-voltage cathode through the hole in the insulator and the anode into the IMRI-5 vacuum chamber. The hole diameter in the insulator and the anode was 3 mm.

3. Diagnostics
3.1. Optical measurements
To register the plasma jet image in the optical spectrum range, we used a 4-frame optical camera HFSC-Pro. The exposure of frames was 10 ns, and the time between frames was 100 ns. The image was built using a lens with a built-in diaphragm, while the focal length was 30 cm.
3.2. Electrophysical diagnostics

To measure the arc voltage $U_{arc}(t)$, the arc current $I_{arc}(t)$, and the derivative of the arc current $dI_{arc}(t)/dt$, we used an active divider, a Rogowski coil, and an inductive loop, respectively. The inductive loop was calibrated according to the Rogowski coil indications, while the loop sensitivity was determined from the equation:

$$K_{loop} = I_{arc}(t)/\int_0^{t_0} U_{loop}(t) \, dt,$$

where $t_0$ is the time at which the current derivative value is zero, $I_{arc}(t_0)$ is the current value determined from the readings of the Rogowski coil at time $t_0$, $U_{loop}(t)$ is the signal from the inductive loop. The voltage division factor of the active divider was $K_{div} = 2041$, the Rogowski coil contained $N = 1040$ turns loaded on a shunt with a resistance $r_{sh} = 0.196$ Ohm. Thus, the inductive loop had a sensitivity of $K_{loop} = 88 \text{ A/(V‧ns)}$. Oscillograms were recorded on a TDS 2024C oscilloscope. The voltage drop in the circuit section was it is measured is described by the formula:

$$U_c(t) = d(L_c(t) \cdot I_{arc}(t))/dt + I_{arc}(t) \cdot r_c(t),$$

where $L_c(t)$ and $r_c(t)$ are, respectively, the inductance and resistance of the circuit section where the voltage drop is measured. It was shown in [7] that the arc discharge current flows only inside the cavity separating the cathode and anode. In other words, in that part of the plasma that escapes from the hole in the anode, the arc discharge current does not flow. This experimental observation allows us to assert that for this plasma gun modification, the circuit section inductance, on which the voltage drop is measured remains constant ($L_c = L_0 = \text{const}$). The resistance $r_c$ should be the sum of the electrode resistance $r_0$ and the plasma resistance $r_{pl}$ ($r_c = r_0 + r_{pl}$). To determine the values of $L_0$ and $r_0$, additional measurements were carried out, in which the circuit section on which the arc burns was replaced by a metal rod connected to a grounded electrode. From the condition that in the short-circuit mode (SC) the following equation must be used:

$$U_c(t) = L_0 \cdot dI_{arc}(t)/dt + I_{arc}(t) \cdot r_0,$$

it was found that $L_0 = 20 \text{ nH}$, and $r_0 = 2 \text{ mΩ}$. Similar calculations were carried out for a circuit with an arc discharge.

4. Discussion of the obtained results

Figure 2 shows plasma jet images obtained at different times relative to the beginning of the arc discharge current, obtained with a 4-frame HSFC-Pro optical camera. It is clearly seen that when using this plasma gun modification, a wide plasma flow is formed. The plasma flow structure has a distinct division into the region of the cathode plasma (in the center) and the region of the anode plasma at the image periphery.

In figure 3 shows together the oscillograms of voltage and current obtained in the short-circuit mode and during the burning of an arc discharge. For ease of perception, the voltage waveforms were smoothed with sixth-order polynomials. From a comparison of the oscillograms obtained in the short-circuit mode and in the arc mode, it was found that during the arc current flowing, the loop inductance does not change ($L_c = L_0 = 20 \text{ nH}$), and the resistance $r_c = r_0 + r_{pl} = 16 \text{ mΩ}$. From shots in the short circuit mode, it was obtained that $r_0 = 2 \text{ mΩ}$. Thus, the resistance of a plasma channel with a diameter of 3 mm and a length of 3 mm is about $r_{pl} = 14 \text{ mΩ}$. As can be seen from figure 3, when the arc discharge current exceeds 100 kA (current density above 1.4 MA/cm²), even such a small plasma column resistance in full accordance with eq. (3) leads to a significant increase in the arc voltage.

For typical arc discharge plasma parameters, the plasma electron temperature is $T = 3.5 \text{ eV}$, the Coulomb logarithm $\ln \Lambda = 10$, and the average degree of ionization is $Z = 1.7$. Transverse Spitzer resistivity can be written as a ratio:
where the height $h_{pl}$ and the cross-sectional area $S_{pl}$ of the plasma gap are taken in cm and cm$^2$, respectively.

![Figure 2. Plasma jet images, obtained at different times relative to the beginning of the arc discharge current, obtained using a 4-frame HSFC-Pro optical camera for a plasma gun of the first modification.](image)

![Figure 3. Oscillograms of voltage and current obtained in the short circuit mode and during the burning of an arc discharge for a plasma gun of the first modification.](image)

The height and cross-sectional area of the plasma channel are determined by the geometric dimensions of the hole in the insulator (see figure 1) and are, respectively, $h_{pl} = 0.3$ cm and $S_{pl} = \pi d_c^2/4 = 0.07$ cm$^2$. Then the plasma channel resistance in accordance with formula (4) should be $r_{pl} = 260–66$ m$\Omega$, which is noticeably higher than the experimental values. Lower resistance values (higher conductivity) of the plasma channel in comparison with the estimated values can be caused by the following factors. As a result of the fact that, due to the limited cross-section of the current flow, a noticeable plasma resistance arises in the local zone, local heating of both the plasma itself and the adjacent electrodes should occur.

5. Conclusion

Since the plasma density in a narrow plasma channel can reach large values ($10^{19}–10^{20}$ cm$^{-3}$), then the heat exchange with the electrodes can be significant. As a result of such local heating of the cathode
and anode surfaces, the amount of evaporated material also increases, as a result of which we observe increased erosion of electrodes in arc discharges at high current densities [5-7]. It was shown in [8] that with an increase in the concentration of particles due to the predominance of the transport cross section for the interaction of electrons with ions over the Coulomb interactions, the Coulomb logarithm decreases and may be less than 1. In addition, with an increase in the concentration of particles, a decrease in the average degree of plasma ionization $Z$ and an increase in the proportion of neutrals should also be observed, which will also lead to a decrease in the plasma resistance. Apparently, this is exactly what happens in our case with a local increase in the concentration of ionized matter in a geometrically limited region of the arc discharge.

**Acknowledgment**

The authors wish to thank the Tomsk Regional Engineering Center of Collective Use of SB RAS for providing the ICCD camera HSFC-Pro. The work supported by a grant from the Russian Science Foundation No 20-19-00364.

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