EFRE 2020

Simulation of Vacuum Arc with High Average Cathode Current Density

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This work was supported by RFBR Grant Nos. 18-08-00547, 19-08-00783, 19-58-53006.

Abstract — This work presents the results of theoretical modeling of high current vacuum arc (HCVA) with cathode average current density (arc current divided by the cathode area) in the order of 10^5 A/cm^2. This type of HCVA is used as pumping plasma gun in experiments with plasma puff *Z*-pinches [4, 5]. During the simulation of the arc burning we calculated the cathode heating and the following cathode evaporation under the action of heat fluxes from the arc plasma. The vaporized substance supplied the arc plasma in parallel with cathode spots. It was shown that the evaporation of the cathode due to plasma heating can explain the sharp increase in the mass of the plasma liner observed in the experiments.

Introduction

The plasma generated by the vacuum arc is intensively researched and used in various electrophysical devices [1-5]. It is known that in low-current arcs, the rate of plasma generation by cathode spots is directly proportional to the arc current [1, 3]. This proportionality coefficient, known as specific erosion, is in the range of ~ 15 – 170 μg/C for a wide range of metals [3].

For low-current vacuum arcs, when the arc plasma is generated by individual cathode spots, specific erosion does not depend on the arc current [1, 3]. However, there is experimental evidence that in high-current vacuum arcs (HCVA) (arc current >> 1 kA), specific erosion increases significantly [4-10]. These data were obtained using various methods. In [4–6], the mass of a plasma liner pumped by a vacuum-arc gun was estimated from the time of Z-pinch compression. In [8, 9], the mass of a plasma liner was restored using x-ray radiography. In [10], the change in cathode mass was measured by weighing. All these experiments indicate a sharp increase in the coefficient of specific erosion at a high arc current. In [7], a sharp decrease in the mean charge state of plasma ions was observed when the current exceeds a certain threshold value, which also indicates an increase in the plasma mass. In all experiments, it was noted that in HCVA, the type of damage to the cathode surface changes after completion of the arc discharge. The effect of polishing the cathode surface (characteristic of a low-current arc) is replaced by a completely remelted cathode surface [7-10]. It should be noted that the effect of increasing specific erosion at a high arc current is a positive characteristic of the arc for the efficient pumping of plasma liners used in the Z-pinch [4 - 6]. However, for the purpose of experiments [7], (an increase in the average charge state of ions with an increase in the arc current) this HCVA property is negative.

Introduction (2)

Known experiments do not allow us to correctly determine the threshold value of the current or total charge flowing through the cathode, at which a sharp increase in specific erosion begins. In the experiments [4–10], the current pulse lasted several microseconds, and the cathode average current density (total arc current divided by the cathode surface area) reached 10^5-10^6 A/cm^2. This is significantly higher than the average current density in vacuum interrupters, where it usually does not exceed 10^3 A/cm^2 [11]. The duration of the current pulse in interrupters is about 10 milliseconds. Therefore, the total charge per pulse is comparable in all the mentioned types of devices. However, in interrupters, if the anode remains passive, the erosion of the electrodes does not significantly differ from the specific erosion in low-current arcs [11]. Probably, the driver of the increase in specific erosion is primarily the high (~10^5 A/cm^2) cathode average current density.

It was repeatedly suggested that the increase in specific erosion in these cases is due to the fact that the plasma begins to be delivered into the interelectrode gap not only by cathode spots, but also as a result of metal evaporation from the entire cathode surface [6-10]. This article presents preliminary results of a theoretical research of this process using numerical simulation.

Model description

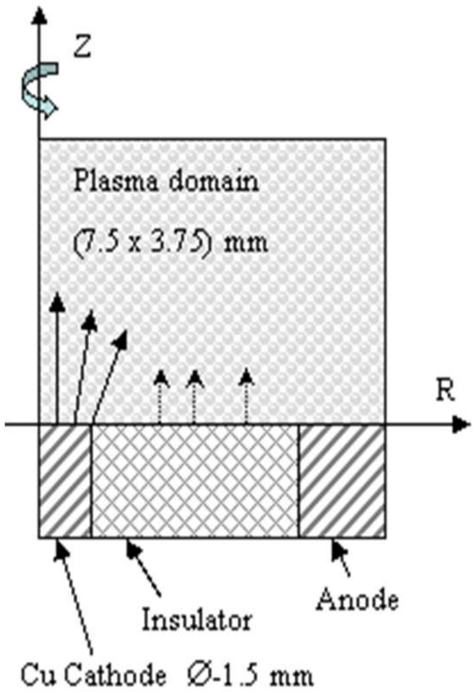


Fig.1 Sketch of model geometry.

The model is formulated in two-dimensional axially symmetric geometry (Fig. 1). A system with a copper cathode and anode located in the same plane is investigated. The cathode radius in these calculations is 0.75 mm, the outer radius of the insulator is 3 mm. The anode is a passive collector of ions and electrons. It is assumed that the insulator uniformly delivers a subsonic "auxiliary" plasma with a specific erosion of 1% of normal cathode erosion into the gap. The main plasma source in the model is the cathode surface. The current pulse duration is 20 μs. The shape of the current pulse was taken from experiment [10].

As in [11], it is assumed that the current is uniformly distributed over the cathode surface. At the beginning of the current pulse, the cathode is considered cold. All current is provided by cathode spots with constant specific erosion – 40 μg/C. Ions from the cathode spots enter the gap at a speed of 10^6 cm/s and have a mean charge state of 1.85.

Model description (2)

Further plasma evolution in the gap is calculated using the hybrid model [12, 13], with radiation heat transfer calculated with the help of P1 approximation. The hybrid model allows us to calculate the flow of particles (atoms and ions) from the plasma to the cathode. Further, we can determine the density of the ion current on the cathode – J_i. Physically, this ion current is between the cathode spots. But in the model, this separation does not occur in the configuration space, but in the phase space. Further, assuming that the cathode potential drop in the near cathode sheath (between the cathode spots) is 15 V, using the generalized Mackeown formula [14] we determine the current density of the thermionic emission – J_{eem}. Assuming that the average current density at the cathode (J_0) is independent of the radius, we write the expression for the average current density passing through the cathode spots (J_{spot}) in the following form:

$$J_{spot} = J_0 - J_i - J_{eem} \tag{1}$$

Next, we calculate the cathode heating (neglecting the Joule effect) due to the heat flux to the cathode surface (Q_c), written as follows:

$$Q_c = J_{spot} U_{eff} + Q_i + Q_a + Q_{rad} - Q_{evap} - Q_{eem} \tag{2}$$

where U_{eff} – effective cathode heating voltage [15, 16]; Q_i - ion heating flux; Q_a – returning atom heating flux; Q_{rad} – radiation heating flux from plasma; Q_{evap} – evaporation cooling; Q_{eem} – electron emission cooling. Effective cathode heating voltage U_{eff} is assumed to be equals 5 V.

Results of simulations

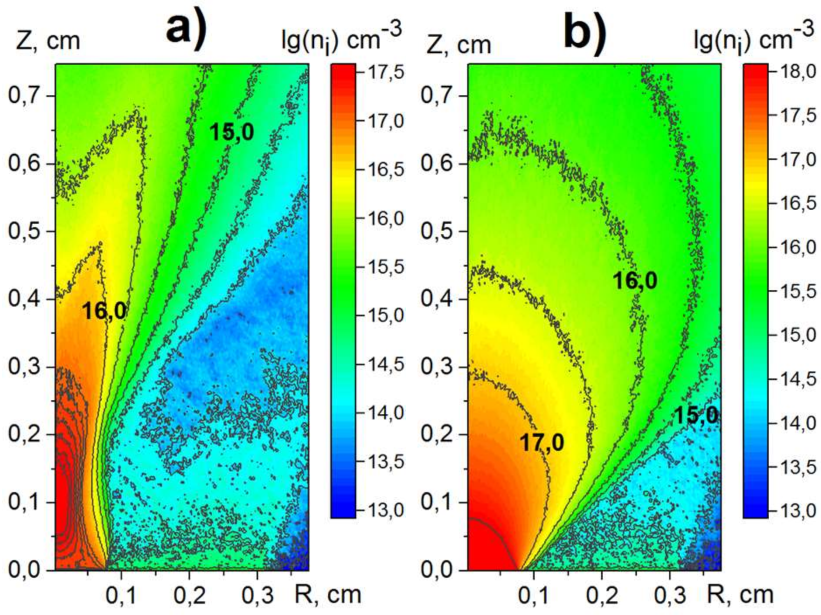


Fig.2 Typical ion density distributions in plasma jet just before start of strong evaporation (a), and after beginning of strong evaporation from the cathode(b); a)-instant 3 μs, arc current 6.2 kA; b) instant 4 μs, arc current 7.3 kA.

At the beginning of the calculation, the cathode is heated only by cathode spots (first term in RHS (2)). As the current and plasma density in the gap increase, the ion current and the corresponding heat flux from the plasma to the cathode also increase. After the cathode surface reaches a temperature on the order of the boiling point, intense evaporation begins from the cathode surface. Metal atoms enter the gap with thermal velocity, where they are ionized, scattered in collisions with ions, and fly further into the gap. This flow creates additional cathode erosion, leads to a decrease in the average plasma velocity and, as a result, to a sharp increase in the plasma mass in the gap.

Typical ion density distributions in a plasma jet are shown in Fig. 2. It can be seen that before strong evaporation from the cathode surface begins, the plasma jet is substantially compressed under the action of its own magnetic field. After the cathode begins to evaporate, the plasma density increases rapidly, the pinch effect decreases, and as a result, the angle of the plasma jet increases.

Results of simulations (2)

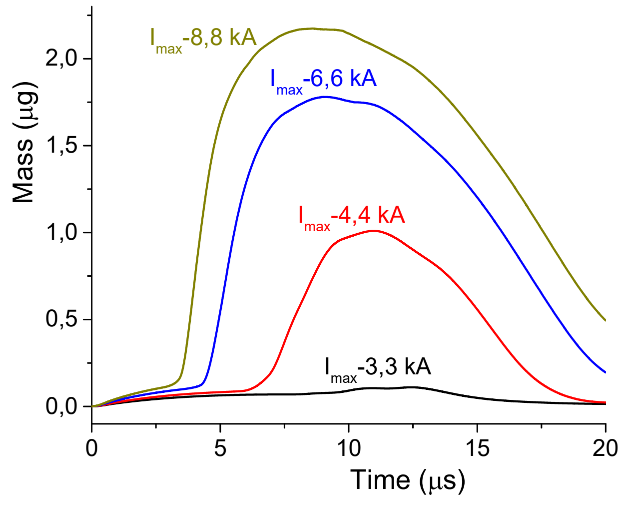
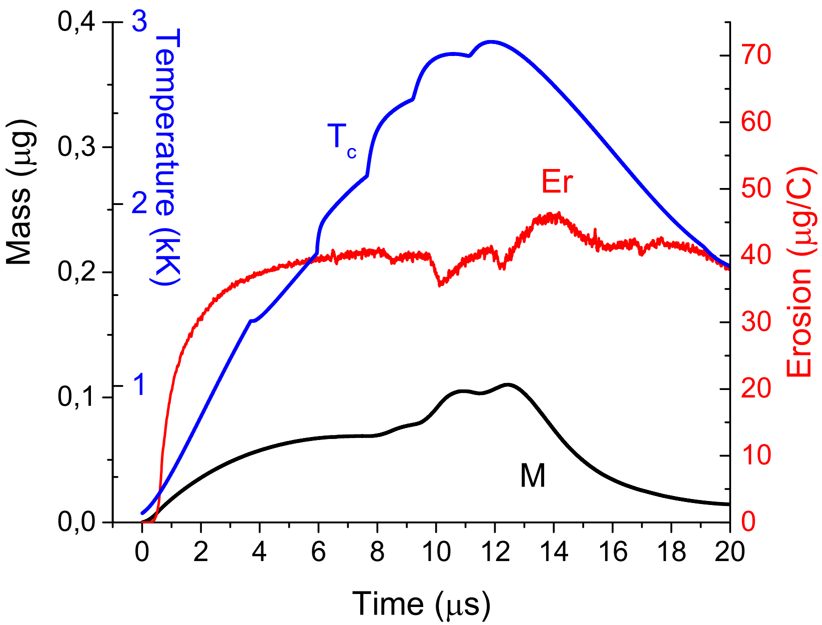


Fig.3 A change in the plasma mass in the interelectrode gap at various current pulse amplitudes.

Fig. 3 shows the change in plasma mass in the interelectrode gap for current pulses with different amplitudes. In the case of a current pulse with an amplitude of 3.3 kA, the plasma mass changes relatively weakly. In this case, the cathode surface temperature does not exceed 3 kK. The total specific erosion from the cathode (measured by the mass flow through the upper boundary of the calculated domain) is practically the same as that specified for ion erosion through cathode spots (Fig. 4). In this case, the cathode surface does not heat up to a high temperature so that the evaporation of the metal from the cathode surface does not significantly contribute to the complete erosion of the cathode. In cases of a current pulse with higher amplitudes, the plasma mass in the gap, starting from a certain moment, increases sharply (Fig. 3). As can be seen from Fig. 5, the cathode surface temperature in this case approaches 4 kK, and the plasma mass in the gap increases by more than ten times. Obviously, in this case, the main contribution to cathodic erosion comes from evaporation from the cathode surface between the cathode spots.

Results of simulations (3)



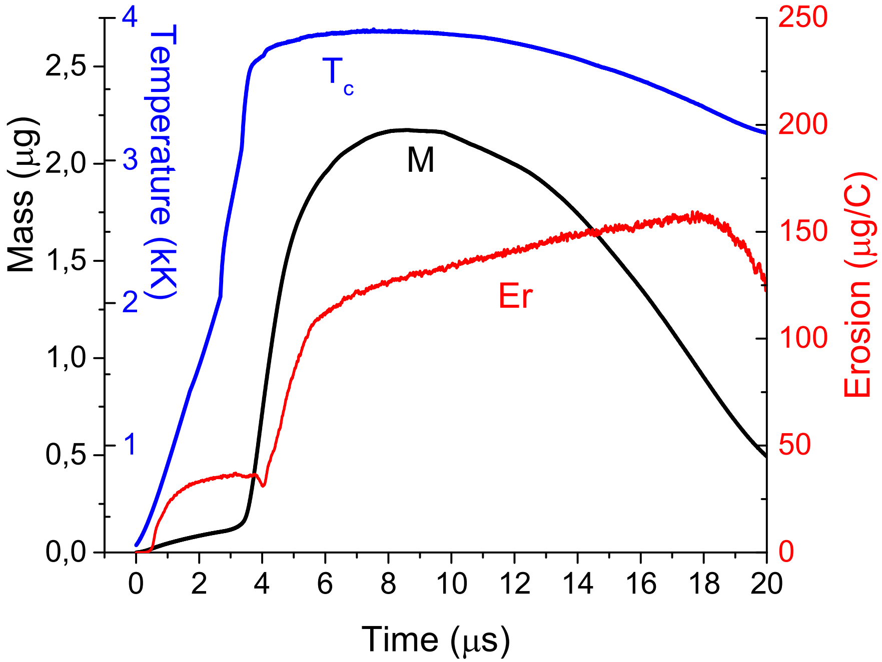


Fig.4 Plasma mass (M), erosion (Er), and cathode surface maximal temperature (T_c) as functions of time for the current pulse with amplitude 3.3 kA.

Fig.5 Plasma mass (M), erosion (Er), and cathode surface maximal temperature (T_c) as functions of time for the current pulse with amplitude 8.8 kA.

Results of simulations (4)

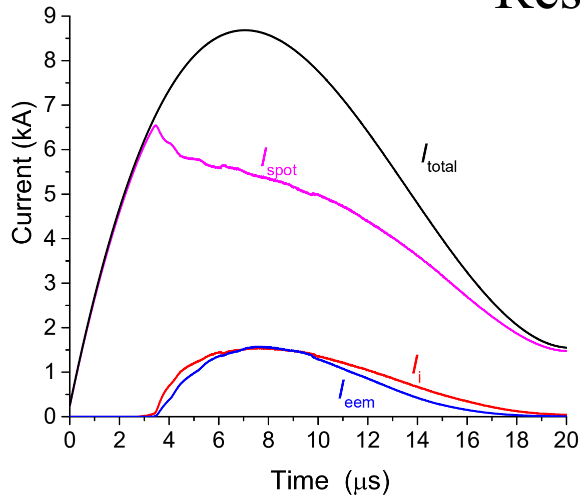


Fig.6 Total current (I_{total}) and different current components as functions of time for pulse with amplitude 8.8 kA.

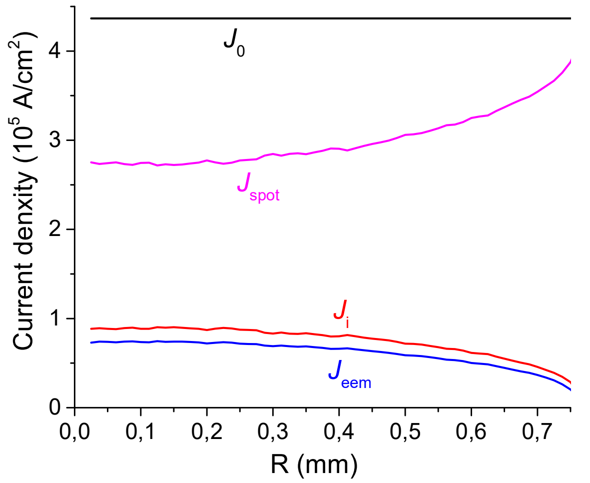


Fig.7 Distributions of current density components over cathode surface for instant 5 μs for current pulse with amplitude 8.8 kA.

It can be seen from Fig. 5 that the rate of change in plasma mass is quite different from the rate of change in cathode erosion. This is because the onset of strong evaporation, the plasma drift velocity in the gap decreases. Cathode spots deliver plasma at a high supersonic speed, but upon evaporation, the substance arrives at a subsonic speed. With strong evaporation, the plasma flow near the cathode is completely subsonic. The decrease in velocity makes an additional contribution to the increase in plasma mass in the gap in addition to the contribution to the increase in mass from the increase in cathodic erosion.

Fig. 6 shows the contribution of various current components to the total arc current. It can be seen that the ion and emission currents contribute in total up to about 30% of the total current. The maxima of the density of ion and emission current are reached in the center of the cathode (Fig 7). The contribution of additional currents to the heat flux to the cathode is more pronounced. A large contribution to the heating of the cathode is made by the flow of ions from the plasma (Fig. 8).

Results of simulations (5)

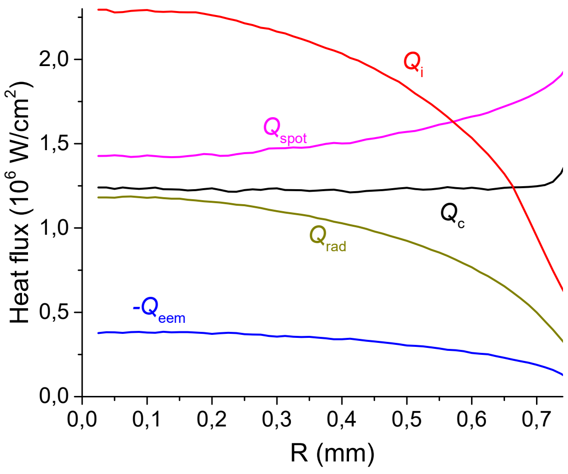


Fig.8 Distributions of heat flux components over cathode surface for instant 5 μs for current pulse with amplitude 8.8 kA.

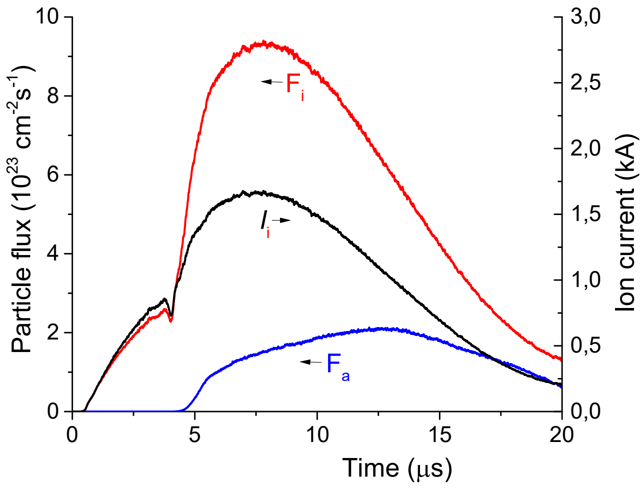


Fig.9 Particle flux of ions (F_i) and atoms (F_a) vs time and ion current (I_i) for current pulse with amplitude 8.8 kA.

There is an important practical question: is it possible to evaluate the change in cathode erosion by measuring the ion current of the arc with probes as in [10]? Our calculations show that this is rather difficult. Indeed, as follows from Fig. 9, the ion current changes much weaker than the flow of particles (ions and atoms) through the upper boundary of the gap. This is due to the fact that with increasing plasma mass the mean charge state of the ions decreases. Moreover, a significant part of the ions in the plasma jet recombines down to the state of the atom. All this leads to the fact that the change in the ion current weakly reflects the change in cathodic erosion.

Conclusion

A numerical simulation of a high-current vacuum arc with a cathode average current density of the order of 10^5 A / cm^2 has been carried out. It is shown that in this case the cathode surface can reach a temperature well above the boiling point. In this case, evaporation from the cathode surface makes a significant contribution to cathode erosion in addition to erosion from cathode spots. A sharp increase in cathode erosion leads to a decrease in the average velocity in the plasma jet and, therefore, to an even sharper increase in the plasma mass in the interelectrode gap. Thus, the results of our modeling are in good agreement with the results of experiments [4–6, 8, 9] on measuring the mass of a plasma liner pumped by a vacuum-arc plasma gun for subsequent Z-pinch compression.

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