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To cite this article: D L Shmelev et al 2021 J. Phys.: Conf. Ser. 2064 012030

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On hybrid type of cathode attachment in high current vacuum arcs

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Abstract. This paper discusses the issues of a possible change of the type of cathode attachment of high-current vacuum arcs (HCVA) with an average cathode current density of more than 10⁵ A/cm². This type of HCVA is used as pumping plasma gun in experiments with plasma puff z-pinch. These experiments showed that the measured linear mass of the HCVA plasma jet is much higher (by a factor of 10 or more) than the expected mass, which can be obtained from the assumption that cathode attachment occurs only through a multitude of cathode spots emitting supersonic plasma jets. It is shown that in HCVA of the type under consideration, at some time instant there are two types of cathode attachments - cathode spots and thermionic erosion attachment (TEA). It can be said that HCVA of this type have a hybrid cathodic attachment. Unlike cathode spots, TEA produces a subsonic plasma flow, which contributes to an increase in the linear mass of the HCVA plasma jet.

1. Introduction

The plasma generated by the vacuum arc is intensively researched and used in various electrophysical devices [1-5]. It is known that the cathode attachment of a low-current (~ from a few to hundreds of amperes) vacuum arc consists of separate rapidly moving cathode spots that emit supersonic plasma jets [1, 2]. However, for a high-current (more than a kiloampere) vacuum arc, the structure of the cathode attachment is not so unambiguously determined. It is assumed that in HCVA at relatively low currents (at a cathode average current density less than 10³ A/cm²), the cathode attachment is a combination of a large number of cathode spots, which are approximately uniformly distributed over the entire cathode surface [3, 4]. Erosion and emission with this type of cathode attachment occur due to explosive emission processes in cathode spots. The rate of plasma generation by cathode spots is directly proportional to the arc current [1, 5]. This proportionality coefficient, known as specific erosion, is in the range of ~ 15 – 170 µg/C for a wide range of metals [5].

At relatively high currents, when a contracted arc arises, which is held by its own magnetic field, the cathodic attachment of such an arc can exist in the form of one continuous thermionic erosion attachment (TEA) [6-8]. In this case, the erosion is maintained due to evaporation, and electron emission due to thermo-field emission [9-11]. There is experimental evidence that in such HCVA (arc current >> 1 kA), specific erosion increases significantly in compare to “conventional” arcs [12, 13]. If we take these two limiting points as a basis - multiport attachment at relatively low currents and TEA at very high currents, then it is logical to assume that at intermediate currents there will be both multiple cathode spots and a single TEA. This type of cathodic attachment will be referred to as hybrid...
attachment. This article is devoted to modeling the emergence of a hybrid cathode attachment of a high-current vacuum arc.

2. Model description
The principle of operation of the hybrid cathodic attachment is shown in figure 1. Obviously, with the average cathode current density less than $10^6$ A/cm$^2$, the cathode spots will occupy less than 1% of the cathode surface. The surface between the spots is heated both by the work of the moving cathode spots and by heating by the fluxes of particles and radiation from the plasma column arising from the mixing of plasma jets of individual spots. It is possible that, at a certain temperature, the cathode surface between spots, through evaporation and thermo-field emission, can provide erosion and electron emission at a level comparable to those for cathode spots due to a significantly larger “active” area. In this case, it is necessary to take into account additional erosion and emissions in the overall balance of the arc.

![Figure 1. Sketch of the hybrid cathode attachment zone.](image)

At present, it is not known how the appearance of such an “active surface” affects the distribution of cathode spots. In our model, we use a simple relationship for current density component:

$$J_{\text{Total}} = J_{\text{spot}} + J_i + J_{\text{em}},$$

where $J_{\text{Total}}$ - total average current density on the cathode surface, $J_{\text{spot}}$ - average spot current density, $J_i$ - ion current density, $J_{\text{em}}$ - electron emission current density. The currents $J_i$ and $J_{\text{em}}$ are related to “active surface” between cathode spot. The $J_{\text{spot}}$ – is not the density inside the cathode spot, but the average current density, which is equal to the current carried by the cathode spots divided by the cathode surface area. The $J_{\text{Total}}$ is the total current divided by the total cathode area. Thus, it is assumed that total current is homogenously distributed over cathode surface. We also assume that the “active surface” displaces the cathode spots. Those the emergence of $J_i$ and $J_{\text{em}}$ leads to a decrease in $J_{\text{spot}}$.

At the beginning of the current pulse, the cathode (copper) is considered cold. All current is provided by cathode spots with constant specific erosion – 40 $\mu$g/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. Further plasma evolution in the gap is calculated using the hybrid model [14], with radiation heat transfer calculated with the help of P1 approximation [7]. The hybrid model allows us to calculate the flow of particles (atoms and ions) from the plasma to the cathode. Due to this 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 16 V, with the help of the Mackeown formula we determine the current density - $J_{\text{em}}$, using the Richardson-Dushman approximation with Schottky correction.
Further, we calculate the cathode heating (neglecting the Joule effect) due to the heat flux to the cathode surface ($Q_c$), written as follows:

$$Q_c = J_{sp} U_{eff} + Q_i + Q_a + Q_{rad} - Q_{evap} - Q_{eem}, \quad (2)$$

where $U_{eff}$ is the effective cathode heating voltage; $Q_i$ is the ion heating flux; $Q_a$ is the returning atom heating flux; $Q_{rad}$ is the radiation heating flux from plasma; $Q_{evap}$ is evaporation cooling; $Q_{eem}$ is electron emission cooling. Effective cathode heating voltage $U_{eff}$ is taken to be 6 V.

At the beginning of the calculation, the cathode is heated only by the 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 of the order of the boiling point, intense evaporation occurs 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. At the same time, erosion from cathode spots decreases because of the decrease in $J_{sp}$ according to (1).

3. Results of simulations

The model is formulated in two-dimensional axially symmetric geometry (figure 2). 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 is the cathode surface. The current pulse duration is 20 µs. The shape of the current pulse was taken from experiment [13].

Figure 3 shows the change in current components during the current pulse. It can be seen that at first all the current is carried by the cathode spots. Over time, the cathode heats up, ionic and emission components of currents appear, which causes a decrease in the current through the cathode spots.
the end of the current pulse, the cathode is cooled, and all the current is again carried by the cathode spots.

Evolution of the heat flux components to the cathode is shown in figure 4. At first, the cathode is heated only by the cathode spots. After the formation of a dense plasma above the cathode, the cathode is heated by the ion current and radiation from the plasma. After sufficient heating of the cathode, cooling by evaporation and electron emission occurs.

Distributions of current densities and heat fluxes at the cathode are shown in figure 5 and figure 6 correspondingly. The distributions are shown at the instant then the ion current is close to maximum (see figure 3). Mostly because of plasma compression by self-magnetic field, heat fluxes at the cathode center are considerably higher than those at the cathode edge. The main input for the heating is provided by ion fluxes and radiation fluxes from the plasma. It is seen (figure 5), that in the center of cathode the total current density provided by “active surface” is higher than the average current density provided by cathode spots. In other words, there is a TEA in the center of the cathode, while the cathode spots are displaced towards the periphery of the cathode. This is what we call the hybrid type of cathodic attachment.
Figure 7. Arc current ($I_{total}$, black curves); Cathode surface temperature in the centre ($T_c$, blue curves).

Figure 8. Plasma mass in calculation domain (M, black curves); Total cathode erosion (Er, blue curves).

Figure 7 shows three different current pulses for which calculations have been made. The temperature curves at the centre of the cathode surface are also shown there. It can be seen that for a current pulse with a maximum of about 11 kA, the temperature at the center of the cathode reaches 4 kK, which is significantly higher than the boiling point of copper. At this temperature, the cathode delivers matter to the plasma, the velocity of which is on the order of the thermal velocity. This velocity is much less than the velocity of plasma jet from the cathode spots. Therefore, even with a comparable integral erosion of cathode spots and TEA, the plasma density above the cathode increases sharply. The increase in the plasma mass in the calculated domain is shown in figure 8. The same figure shows the total (ions and atoms) specific erosion of the cathode. Erosion is calculated from the integral fluxes of matter crossing the outer boundaries of the computational domain. Therefore, at the beginning of the current pulse, erosion is zero.

In the case of a current pulse with an amplitude of 6 kA, the plasma mass changes relatively weakly (figure 8). In this case, the cathode surface temperature does not exceed 3 kK (figure 7). The total specific erosion from the cathode is practically the same as that specified for ion erosion through cathode spots. 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 instant, increases sharply (figure 8). As can be seen from figure 7, 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. Erosion does not increase as much as the mass of plasma in the gap. Erosion increases by about 8 times, while the mass of plasma is about 20 times. As already mentioned, an increase in mass, in addition to an increase in erosion, is strongly influenced by a decrease in the average plasma flow velocity. It is this effect that is observed when the interelectrode gap is pumped with arc plasma guns to create a plasma liner for the gas-puff Z-pinch implosion [12].

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