Gas-discharge starting of hollow cathode operation in self-heating mode

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Gas-discharge starting of hollow cathode operation in self-heating mode

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Abstract. The conditions of a gas-discharge starting of the massive metal cathode with remote anode at small gas flows (Ar, 20-100 sccm) through the cathode cavity have been investigated. Optimization of geometry of the arc-discharge electrodes and the use of repetitively-pulsed power input mode (1 kW) during starting of the cathode provide reliable ignition of a glow discharge, accelerated starting of the cathode in distributed thermal emission mode (10 A, 15-20 s), reduction of energy and frequency of local cathode spots during starting process.

1. Introduction
Start of the hollow cathode operating in self-heating mode can be accessed by external heating or excitation of gas discharge in a cathode cavity. Heater in the form of coil made of high-resistance material mounted on the outer surface of the hollow cathode passes a current and heats the cathode up to temperatures providing the required thermionic current on the cathode. Gas-discharge starting of the cathode has following mechanism: first, a glow discharge (GD) is initiated, and then it is smoothly transferred into abnormal discharge mode, then into an arc with distributed thermal emission [1]. Coil heater is easy to operate, but it complicates design of the cathode assembly, reduces its reliability and requires considerable time for heating up the entire mass of the cathode. For example, functional run time of Hall engines SPD-70 and SPD-100 determined by thermal inertia of cathode-compensators in case of gas-discharge starting is 160-180 s [2]. Starting of the self-heated high-emission hollow cathode in SPD-100 engine (2-5 A, 1000 °C) requires 3-5 s [3]. However, heating via gas discharge requires the determined by Paschen law conditions [4] for initiation of a GD, and the rate of that current growth must be limited to avoid local arc spots resulting in a significant starting cathode erosion.

The authors [5] have developed procedure of gas-discharge starting of massive metal cathode for vacuum plasmatrones with diameter up to 60 mm and a several kA of working current, which allows to start a cathode of almost any design and mass within 40-100 s. Starting mode algorithm is based on changing the heating power depending on the current temperature. Power supply provides current interruption in the cathode circuit for a time necessary to eliminate emerging arcs with local spots. Quick starting of massive cathodes requires increased input power, which increases the probability of arc spots formation, that is why in such cases the methods based on localization of the primary heating zone are used, for example, the cathode with tapered narrowing or small starting cathode [5].
Along with the regulation of the growth rate of discharge current, the present work suggests an approach based on prevention of arc spots formation even at relatively large average discharge currents. If we assume that the probability of formation of the cathode spot on cathode warm-up stage obeys known laws, i.e. increases with increasing product of ion current density at the cathode by pulse duration [6], then the heating rate can be increased at the starting stage using repetitively-pulsed mode (RPM) of discharge burning with high amplitude and average current at short pulses. Strictly dosed energy supply during pulse and a pause, during which the surface charge drains from the surface of the dielectric inclusions or micropoints cool down, provide stabilization of the discharge.

This work presents the results of a study on initiation of a glow discharge with hollow cathode and its transition into arc mode with distributed thermal emission in electrode system with remotely located anode at small flows of argon through cathode cavity. It also offers an approach that includes the optimization of an ignitor electrode form, using of cathodic cavity with narrow input channel and repetitively-pulsed mode of power input that together provide reliable ignition of the discharge, an accelerated start of the cathode and decrease of its starting erosion.

2. Experimental technique

We have used cathode assembly layout presented in the figure 1 for the experiments. Pilot hollow cathode 1 was made of molybdenum due to easy mechanical processing and relatively low price of this material. A channel with diameter of 8 mm was drilled in a rod with diameter 16 mm and length 105 mm, the channel was divided into two parts by an insert with a narrow channel 2x10 mm. The right part of the rod with the channel with length of 60 mm and a wall thickness of 4 mm served as the hollow cathode. The left part of the channel was densely filled with pieces of tungsten wire, which prevented discharge burning in this area. Molybdenum cathode assembly was fitted to the water-cooled flange via screw connection through copper gasket and was placed inside a water-cooled housing 2 coaxial with the heat screen 3 made of graphite or niobium. The ring permanent magnets 4 from SmCo alloy with sizes 36x50x8 mm were installed on the outer surface of the housing 2. These magnets created a magnetic field with a maximum induction ~50 mT on the cathode axis.

The described cathode assembly design provides reliable contact for current of tens of amperes, ignition of glow discharge in the area of high-pressure gas near the narrowing, local heating of the cathode and subsequent formation of the active zone in the working area of the hollow cathode and eliminates gas leakage outside the hollow cathode. However, low melting point Mo (2620°C) and high pressure of saturated vapor prevent its using as a cathode material, so the Mo cathode was used only at the stage of testing the gas-discharge starting system. In the working version, the cathode is made from tantalum rod, the internal cavity of which contains emission insert from TiN [7].

Disk-shaped anode 5 from stainless steel (Ø200×h 15 mm) was placed at a distance of ~350 mm from the output aperture of the cathode 1. Argon flow through the cathode cavity was regulated in the range 20–110 sccm, gas pressure in the vacuum chamber was ~0.04–0.3 Pa. Discharge ignition in such a system with remotely located anode is difficult because of the small gas flow through the cathode cavity and low pressure in the anode area, so the ignitor electrode 6 was installed opposite the output aperture and connected to the positive output of the starter power supply 7 through the ballast resistor.

Ignition of the glow discharge in a system with a flat ignitor electrode requires relatively high voltage (U~10 kV) in combination with short-term pressure increase up to p~0.5 Pa. In order to reduce voltage of the discharge ignition and reduce the required argon flow through the cavity in the experiment, we have used hollow cylindrical ignitor electrode (Ø40 mm, l=40 mm) with holes Ø12 mm in the inlet and outlet apertures.

Voltage pulses with amplitudes up to 10 kV, duration 300 μs and frequency 7 Hz were applied to the ignitor electrode. Discharge gap breakdown ended with the emergence of a short-term (~300 μs) arc discharge with current up to 5 A, its plasma filled the main discharge gap “cathode-anode”, whose electrodes were connected to the starting power supply. The supply generated unidirectional voltage pulses up to 1.2 kV with a frequency of 40 kHz, duration of 5-12.5 μs, adjustable average current in a steady arc mode (3-10 A). After initiation of glow discharge the starting power supply provided
smooth increase of the average current up to preset current value during 10-15 s and decreasing of the constant component of the discharge current from 0.5 to 0 A during this time.

Discharge current and discharge voltage were recorded on oscilloscope “Rigol” DS1042C.

3. Experimental results
Dependencies of static breakdown voltage of the gap “cathode – ignitor electrode” on the gas flow through the cathode cavity are shown in figure 2. The curve 1 indicates that the working point is located on the left branch of the Paschen curve [4]. Application of the hollow ignitor electrode leads to significant reduction of the ignition voltage values $U_i$ (curve 2). Assuming that the pressure $p$ in the expanding gas flow varies with distance as $d^{-2}$, then the product of $pd^{-1}$. Therefore, the ignitor electrode should be as close as possible to the cathode aperture, and the existence of cavity preventing the free gas flow increases both the effective gap length and the gas pressure inside it. Low direct current discharge in the circuit “cathode – ignitor electrode” did not provide stable discharge ignition in the main gap, so we used pulse breakout with transition into the short-term arc mode with limited current. Dependencies of ignition voltage and breakout delay time on the gas flow at pulse breakdown are shown in figure 3. In a system with a hollow ignitor electrode at voltage growth rate $5 \times 10^8$ V/s and argon flow through the cavity 60 sccm, breakdown occurs at the pulse front, the breakdown voltage amounts to 7.5 kV.

![Figure 1. Diagram of the electrode system. 1 – cathode, 2 – housing, 3 – screen, 4 – magnet, 5 – anode, 6 – ignitor electrode, 7 – power supply.](image)

![Figure 2. Dependency of static ignition voltage on the gas flow. Ignitor electrode 1 – flat, 2 – cylinder-shaped.](image)

Figure 4 shows the current-voltage characteristic (CVC) of the direct current glow discharge in a cavity with a narrow (Ø2 mm) input channel. With increased current the discharge voltage initially rises to 380 V, then sharply decreases and continues to decrease monotonically with further increase in current. The behavior of the glow discharge CVC after formation of hollow cathode effect differs from the one observed in a system with cold hollow cathode and reflective discharge in a magnetic field [8]. It can be explained through local heating of the cathode and its transition into thermal emission mode. In repetitively-pulsed mode (PRM) of the discharge operation the current monotonically increases up to a given amplitude value, the glow discharge voltage remains approximately constant during heating and drops by 100-200 V after transition into the arc mode (figure 5). Voltage of abnormal GD burning at amplitude currents 5-20 A is 350-400 V. High voltage of the discharge after transition into the arc mode (~150-200 V) is characteristic of repetitively-pulsed arc discharge and arises from the need to compensate for heat loss during the pause between the pulses [9].
Duration of the starting process depends on the cathode surface condition. Starting a new cathode with surface containing exterior inclusions, films and microedges leads to formation of arc pulse packets, the current amplitude of which is limited by a power supply (figure 6). After self-quenching of the arc, the ignition pulse is initiated and heating process continues. The cathode temperature decreases during low-voltage arc with cathode spot and pause preceding the breakdown and re-ignition of the discharge that is why the total duration of starting for cathode with non-conditioned surface increases.

Inspection of the cathode after many starts (~100) has revealed that the erosion of the cathode (~ $10^{-6}$ g/C) occurs mainly at the entrance to the narrow input channel. Thus, we can conclude that the start heating of the cathode occurs locally.
Discharge concentration in a narrow channel with increased gas pressure provides fast local heating of this cathode part. After reaching the specified average current 5-10 A in PRM discharge, the DC power supply is connected and discharge current smoothly increases up to required value 30-50 A. The active zone is formed in the working part of the cathode cavity in DC mode. The active zone (AZ) is the area of the cathode surface, where electron emission current density is maximum.

The position of the active zone is significantly influenced by a permanent magnet field. Figure 7 (profiles 1-3) illustrates the effect of the permanent magnet location on the erosion profiles of the cathode surface manufactured from Mo tube with an inner diameter of 9 mm and wall thickness of 1 mm. In the discharge current range 5-50 A and argon flow 20-100 sccm, AZ exists in the area of the maximum magnetic field, so the regular movement of the magnet relative to the hollow cathode allows to increase a shared resource of the hollow cathode limited by its erosion in the AZ area to a wall thickness (figure 7, profile 4). It is difficult to control the position of the discharge active zone through non-uniform magnetic field due to the growth of thermal conductivity along the walls when increasing the wall thickness of Mo cathode up to 4 mm. Lower thermal conductivity of the TiN insert compared to Mo allows controlling the position of AZ using permanent magnets.

**Figure 7.** Erosion profiles of Mo cathode surface at different magnet positions: 1 - «5»; 2 – «6»; 3 – «7»; 4–serial shifts in positions «8». 9 – cathode edge. \( Q_{\text{Ar}} = 60 \text{ sccm}. \) DC mode, \( I = 25 \text{ A}. \)

### 4. Discussion

Power input rate during heating of the cathode is limited by the emergence of local arc spots. According to [6], the transition of glow discharge into arc occurs due to the charging of the surface of dielectric inclusions and films and their breakdown when reaching breakdown field intensity in the inclusion volume. Another reason for arc formation is the explosion of microedges [10]. Low-erosion starting of the cathode can be achieved through elimination of such surface irregularities by ion sputtering under conditions that do not lead to breakdown.

Assuming that all inclusions are of the same size and the sputtering rate is proportional to the ion current density \( j \), then elimination of inclusion during time \( T \) requires a certain ion irradiation fluence at \( jT = \text{const} \). According to [6], breakdown of the inclusion within a pulse also occurs at a critical value of the product of ion current density \( j_i \) by the time \( t_i \), which depends on the cathode material and the state of its surface, and \( j_i \cdot t_i = \text{const} \). Here \( t_i \) is the time before the breakdown. Proceeding from the above, it is possible to estimate the number of current pulses \( N \) required to atomize the irregularities in PRM discharge with average current density \( j = j_m f \tau \) on the cathode, where \( j_m \) is pulse repetition frequency, \( \tau \) – duration of pulses, as \( N = jT/(j_m\cdot\tau) = j_m f \tau T/(j_m\cdot\tau) = \text{const} \). Hence \( T = N f \), that is, the time for cathode conditioning with constant \( j_m \tau \) parameter varies inversely with pulse repetition frequency, which is obvious. Of course, under real conditions inclusion have different sizes and shapes, and \( j_i \cdot t_i \) depends on the duration of training, therefore, the completed assessment are purely qualitative and are meant to demonstrate the possibility of sharp reduction of the cathode start time using PRM discharge. Even if irregularities are not completely eliminated through ion sputtering, their controlled removal through arc formation under limited energy supply during the pulse and rapid quenching of the arc allows reducing starting erosion and time of cathode heating.
The start time of the cathode is defined by the time of energy input providing heating of the cathode working surface with a given mass and thermal and physical characteristic up to a temperature, at which significant thermal emission occurs from the cathode surface. For the assessment of energy consumed for heating of the cathode in glow discharge mode we use the starting mode that is characterized by a GD voltage 450 V, with a constant maximum current of ~20 A and with pulse duration 4 μs and time of transition into arc mode 15 s. When the energy in a single pulse is \( w = U_d I_d \sim 36 \text{ mJ} \), the energy, spent on heating of the cathode will be \( \sim 20 \text{ kJ} \). Here \( U_d, I_d, \tau \) – amplitude of the voltage, current and pulse duration.

In order to determine the energy \( W \) required for heating of the working part of the cathode (\( L < \sim 3 \text{ cm} \)) with \( M = 45 \text{ g} \) forcibly cooled to ~2200°C, we use simplified relation

\[
Q \sim M \left( T_1 - T_2 \right) \left( c_1 + c_2 \right) / 2 + \left( 1 / 4 \right) \left( \lambda_1 + \lambda_2 \right) S \left( T_1 - T_2 \right) t / l
\]

As energy being supplied to the cathode, its material (Mo) is heated from room temperature \( T_1 \) to thermal emission temperature \( T_2 \sim 2500 \text{ K} \). Part of the heat will be transferred to the radiator through the rod with length \( l \) and section \( S \) during time of heating \( t \). Specific heat capacity of Mo in this temperature range increases from \( c_1 = 250 \) to \( c_2 = 400 \text{ J/(kg·K)} \), and thermal conductivity \( \lambda \) decreases from \( \sim 130 \) to 100 \text{ W/m/K} \ [11, 12]. An estimated energy amount required for heating of the working cathode part is \( \sim 34 \text{ kJ} \), which is significantly higher than energy expense, for gas-discharge starting.

Thus, we can conclude that the use of repetitively-pulsed discharge allows to heat the cathodes at high average power ~1-1.3 kW, which provides quick starting of the metal cathode with mass ~45 g (15-20 s).

5. Conclusion

Application of hollow ignitor electrode lowers static breakdown voltage for electrode system with a hollow cathode at low gas flows (Ar, 60 sccm) by an order of magnitude (up to 1 kV).

While gas is being supplied to the cathode cavity through the channel of small diameter (1.5-2 mm), glow discharge is localized in the channel area, which provides fast local heating of the cathode and the transition of GD into arc mode. Repetitively-pulsed discharge operation mode at the heating stage helps to increase heating power up to 1 kW and reduces time required for starting of the cathode with average current ~15 A to 15-20 s without significantly erosive damaging of the cathode.

Small thickness of the cathode walls (1-2 mm) or using of the cathode material with low thermal conductivity (TiN) allows to use strongly inhomogeneous axisymmetric magnetic field in the cathode cavity created by permanent magnets and control by this way the position of active zone in a wide range of discharge current (1-50 A) and gas flow rates (30-110 sccm).

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