Investigation of service life characteristics of hot cathodes in arc plasmatrons

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Abstract. Among the applied challenges associated with the use of electric-arc plasma, the most urgent is the erosion of electrodes in plasmatrons, which determine the continuous operation of an electric-plasma device. Investigation results on the thermal state of hot cathodes and their erosion are presented depending on the main defining parameters, namely geometrical dimensions of electrodes, Joule heating, current of the arc discharge, and the gas medium. The conditions for the minimum specific erosion and long service life of tungsten thermionic cathodes are established experimentally.

1. Introduction

The service life of hot cathodes is determined by the rate of their destruction (erosion), electrophysical, and thermal processes in the near-electrode regions of the arc discharge, both on the surface, and inside the cathode. Therefore, the ways to solve the problem of the tungsten cathode life are varied and depend on operating conditions, the purpose of plasmatrons, and, therefore, technological process and type of plasma-forming gas, current strength, and pressure in the discharge chamber. It should be noted that due to the lack of a general theory of cathode processes, the results of experimental studies are of particular value.

Erosion of W-cathodes is caused by thermal loads at the contact point of the arc reference spot with the metal surface, which is directly related to the physical processes in the near-electrode regions of discharge. Playing an insignificant role in the general balance of heat, thermal and electrophysical processes in the areas of arc contact with the electrodes have a decisive effect on the rate of their destruction and service life.

The fundamental phenomenon, discovered in the 70s of the last century - recycling of tungsten atoms - allowed explaining many experimental results on the service life of tungsten cathodes. The essence of the phenomenon is that the atoms of tungsten, evaporated in the zone of the arc spot, falling into the arc column, are ionized and returned by the electric field in the form of ions to the end surface of the cathode. At that, the end of the rod cathode grows slightly, and the material is carried away from the lateral surface (Fig. 6, dashed line). The present research aims to study the processes of erosion of hot cathodes in various gases to determine the durability of their operation.

2. Thermal state of hot cathode

According to peculiarities of the near-cathode processes, arcs are divided into three types: with non-stationary fast-moving spots, with stationary spots, and without a spot (Fig. 1). The transition from one type of binding to another is always associated with the thermal regime of the hot cathode. It is mainly
characterized by the emission current density at the cathode, which is known to be determined by the Richardson-Dashman formula: \( j_e = A T^2 \exp(-\frac{\phi}{kT}) \). Here, the work function of the electron \( \phi \) is of great importance. For example, for pure tungsten \( \phi = 4.5 \) V, and for tungsten, activated with thorium oxide \( \phi = 2.63 \) V. A decrease in the work function leads to a noticeable decrease in the value of \( j_e \) and the thermal load on the cathode surface under the arc spot.

**Figure 1.** The temperature field of the working surface of the cathode in the arc referencing zone.

An experimental setup for measuring heat fluxes \( Q_s \) to a tungsten rod cathode is schematically shown in Fig. 2. Cathode 2 with length \( l_{rod} \) and diameter \( d_{rod} = 0.5 \) cm is embedded in a water-cooled copper holder 1 and installed coaxially with the calorie table diaphragm 3. The gap between the diaphragm and the rod forms narrow annular slot 4 with a width of 0.1 cm, through which the plasma-forming gas is fed at a flow rate \( G \).

**Figure 2.** Schematic diagram of the experimental setup.

The equation of energy balance for the scheme in Fig. 2 is written as:

\[
Q_s = Q_1 + Q_c + Q_r + Q_g - Q_J
\] (1)

Here \( Q_1 \) is the amount of heat removed by water through cross-section A-A; \( Q_c \) is the heat sent to the diaphragm via convection; \( Q_r \) is the radiant energy to the diaphragm; \( Q_g \) is the energy in gas at the slot outlet in cross-section B-B; \( Q_J \) is the Joule heat in the rod volume. The heat flux through the arc spot \( Q_s \) was calculated. The gas temperature at the slot outlet was measured using thermocouple 5. The heat fluxes to the cathode \( Q_s \) were studied at various lengths of a tungsten rod in argon, nitrogen, helium, and hydrogen. Typical data concerning the dependence of \( Q_s \) on the arc current in argon for various lengths of the protruding part of the rod \( l_{rod} \) are shown in Fig. 3 (the limiting currents at which the electrode melted under the arc spot are marked with a dashed line). Similar data were obtained for other gases. Heat fluxes to the W-cathode for \( l_{rod} = 0 \) almost coincide (\( Q_s \) for nitrogen and hydrogen are obtained by subtracting the recombination energy of these molecules).
Let us consider a tungsten rod, whose one end is heated by arc plasma $Q_s$, and the other end is in a water-cooled holder at temperature $T_0$. The model of the cathode assembly corresponds to Fig. 2.

The one-dimensional equation of thermal conductivity of the rod is written in the form:

$$\frac{d}{dz} \left( \lambda \frac{dT}{dz} \right) = \frac{2\alpha}{r_c} (T - T_0) + \frac{2\sigma_0 \epsilon}{r_c} (T^4 - T_0^4) - \frac{0.24 \rho I^2}{(\pi r_c^2)^2}$$

where $\lambda$ and $\alpha$ are the thermal conductivity of the rod and the coefficient of heat transfer from it to gas, respectively; $r_{rod}$ is the rod radius; $\rho$ and $\epsilon$ are specific electric resistance and integral radiant flux of the W-cathode; $\sigma_0$ is the Stefan-Boltzmann constant.

When gas flows in a narrow annular slot, the heat transfer coefficient $\alpha$ is calculated by the formula:

$$Nu = 1.5 \cdot 10^{-2} R e d 0.8 \ Pr 0.4 \ (D/d_{rod}) 0.25.$$  

The boundary conditions for solving equation (2) are set at the cooled end of the rod:

$$at \ z = 0 \quad \lambda \pi r_c^2 \frac{dT}{dz} = Q_1; \quad T = T_0 = 300 \ K.$$

The calculation took into account that the transfer coefficients $\lambda$, $\alpha$, $\rho$, and $\epsilon$ are functions of temperature. To determine the limiting values of heat fluxes and temperature fields in the rod, Eq. (2) was integrated up to the melting temperature $T_m$.

Typical temperature fields in a tungsten rod cathode are shown in Fig. 4. According to the analysis of the presented curves, it can be seen that the Joule heat, released in the rod volume affects significantly the temperature distribution profile along the cathode length. Calculation and experiment show that with an increase in $l_{rod}$, the heat flux to the cathode decreases due to Joule heating.
The problem of temperature field distribution in the composite cathode (the W-rod is embedded flush with the copper holder) was simulated by the method of electric grids and was solved using an EI-12 electric integrator. The W-cathode of a real plasmatron was selected for modeling. In this case, rectangular heat load $Q_s$ on the section of the W-cathode within arc spot $d_s$ is set. The values of heat fluxes and dimensions of arc referencing are taken from experiments. On the backside of the electrode, the temperature was taken to be $T_0 = 300$ K. The electrode surfaces, excluding the heating and cooling zones, were considered to be thermally insulated.

The typical distribution of equithermal surfaces in a composite cathode is shown in Fig. 5 (solid curves). According to the figure, the heat flux spreads mainly in the radial direction (dashed curves).

**Figure 4.** Temperature distribution along the rod cathode axis [2]
(drod = 0.5 cm; lrod = 6 cm): 1 – 4 are $I = 200; 400; 600; 800$ A, respectively.

**Figure 5.** Distribution of equithermal surfaces in a composite cathode.
As a result, the temperature regime of the electrode is strongly influenced by both geometric dimensions and the configuration of the copper holder.

3. Erosion of hot cathodes

Solid thermionic tungsten cathodes in an oxygen-free environment represent the research object. The schemes of cylindrical W-cathodes are shown in Fig. 6 (they are, as a rule, activated with thorium, yttrium, and lanthanum dioxides to reduce the work function of the electron output from the metal).

![Figure 6. Schematic diagrams of solid hot cathodes.](image)

Specific erosion of the electrode $\overline{G}$ is defined as the loss of the material mass $\Delta m$, referred to the current value $I$ per unit time $t$, i.e. $\overline{G} = \frac{\Delta m}{I \cdot t}$, kg/C. Knowing the values $\overline{G}$ and $\Delta m$, it is quite easy to estimate the continuous operation of the electrode at a given arc discharge current.

Under the influence of a powerful heat source from the near-electrode section of the arc, the processes of intense melting, evaporation, boiling, and explosive destruction occur on the cathode surface. They actually determine the life of the electrodes.

For W-cathodes (Fig. 6, a-c), specific erosion is $10^{-11} - 4 \cdot 10^{-12}$ kg/C (argon, hydrogen) and $2 \cdot 10^{-8} - 10^{-10}$ kg/C (nitrogen) at arc currents from 150 to 1000 A.

An effective way to reduce erosion of the W-cathode is to reduce the surface of tungsten entrainment. Experiments have shown [1, 2] that a decrease in the length of the rod electrode ($l_{rod} > 0$) leads to a decrease in $\overline{G}$ and its minimum value is achieved at $l_{rod} = 0$ (Fig. 6, d). The dimensions of the arc spot on the electrode are several times smaller than those when the arc burns without a spot. Due to this, metal evaporates from a small area. Besides, the process of tungsten atom recycling occurs there in full.

The thermal effect of the arc on the cathode is illustrated by a photograph of the eroded surface of a thoriated W-cathode (Fig. 7). Melted bumps with a diameter of less than 0.5 mm are clearly visible on the surface. Perhaps, several arc spots existed there simultaneously and moved chaotically over the surface.

Experimental data on specific erosion of thoriated and lanthanated W-cathodes depending on the arc current are shown in Fig. 8 [2]. The scatter in the measurement results is largely due to the purity of the plasma-forming gases. Indeed, as in [1], we can shade the region of $\overline{G}$ from $10^{-11}$ to $10^{-13}$ kg/C in the range of currents from 0 to 1000 A and obtain any necessary results. However, specific experimental data are more reliable and more important.
Figure 7. Photo of the working surface of the tungsten cathode: I = 500 A; drod = 4 mm; working gas – nitrogen.

The experimental data in Fig. 8 represent the results of long-term tests (from 100 to 200 h) and experimental-industrial operation (120-130 h) of thermionic cathodes at lrod = 0. Under industrial conditions, erosion of a yttrided W-cathode \( \bar{G} \) (drod = 1.3 cm; lrod ~ 5 calibres) at currents of 1.9 - 2.3 kA was \( 1.4 \cdot 10^{-12} \) kg/C.

Specific erosion of the W-cathode at lrod = 0 depends not only on the arc current but also on the diameter of the tungsten insert. At a certain value of the W-cathode diameter \( d_c \) and at I = const, minimum specific erosion is observed. Therefore, the value of the optimal drod is recommended to be selected 10-30% larger than the size of the cathode spot of the arc.

A similar dependence is typical of a rod cathode, depending on the arc current (Fig. 9), as it was noted in [1].

Figure 8. Specific erosion of the tungsten cathode vs. the arc current in different gases

Figure 9. Specific erosion of the tungsten rod cathode (drod = 0.2 cm, lrod = 25 cm) vs. the arc current in helium.

To maintain minimum erosion of the cathode, it is necessary always to provide a good thermal and electrical contact between the tungsten cathode and the cooled copper body because heat is mainly transferred through the side surface of the W-cathode (see Fig. 5). Therefore, the size, the configuration of the copper body, organization of its cooling, and the method of sealing the W-cathode play an essential role in ensuring the long service life of the cathode assembly in general.
Conclusions
1. It has been established that erosion of electrodes in general, and of a tungsten cathode, in particular, is primarily determined by thermal loads at the contact point between a stationary reference spot of the arc and a metal surface.
2. For the first time, calculated and experimental data on the thermal state of a hot cathode, which contribute to the optimization of parameters in terms of geometric dimensions, cooling, arc discharge current, and W-rod length, are presented.
3. The effect of Joule heat release in the rod and convective heat transfer on the temperature regime of the cathode is shown. The results of experimental studies of W-cathode erosion in argon, nitrogen, helium, and hydrogen, depending on the arc current and the electrode diameter, including long-term tests (100-200 h) have been presented and analyzed. The obtained results on the optimal parameters of W-cathodes provide the life of their operation in technological regimes of at least 1,000 hours.

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References
[1] Zhukov M F, Zasypkin I M, Timoshevsky A N 1999 Electric arc generators of thermal plasma (Novosibirsk: Nauka)
[2] Cherednichenko V S, Anshakov A S, Kuzmin M G 2011 Plasma Electrotechnical Installations (Novosibirsk: NSTU)