Operating modes of vacuum plasmatrons with hollow cathodes

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Abstract. Results of experimental studies of starting characteristics of vacuum plasma torches in glow discharge mode with switching to abnormal glow discharge and arc discharge are presented. It is demonstrated that if high-frequency current source is used parallel to direct current, ion current is increased and the time of starting mode is reduced. Experimental smelts of tantalum, tungsten, molybdenum, zirconium, and titan were carried out in operating modes with measurement of liquid metal surface temperature in relation to the supplied heating power.

1. Purpose of the study
Hollow cathode is normally executed as a cylindrical tube with inner diameter d, through which gas is delivered to a low-pressure chamber. Cathode temperature in working modes must be higher than temperature of intense thermionic emission development. In order to bring the plasma torch to working modes, linking of three consecutively developing gas discharges must be ensured: the ignition of independent glow discharge (normal mode, \( I \leq 0.5 \text{ A} \)), its switching to the abnormal mode for cathode heating (currents \( 0.5 \leq I \leq 50 \text{ A} \)), and after the heating – to arc mode (\( I \geq 100 \text{ A} \)). Arc mode is characterized by the ring-shaped arc anchor area on the cathode’s inner surface [1-3].

In order to optimize the starting modes of industrial plasma torches, experimental studies of current-voltage characteristics of various discharge burning modes presented in Figure 1 had to be conducted. Characteristic 1 relates to discharge with solid cylindrical cathode and cathode with cavity diameter \( d_2 = 20 \text{ mm} \) and no plasma forming gas supply. The conducted experiments found basically no substantial differences in current-voltage characteristics of solid and hollow cathodes without plasma forming gas supply with inner diameters larger than the doubled size of the dark glowing discharge area near the cathode \( (d_2 > 14 \text{ mm}) \).

Relations 2 and 3 characterize hollow cathode discharges with plasma forming gas supply \( 2 – (d_2 = 20 \text{ mm}, G = 5 \cdot 10^{-5} \text{ kg/s}) \) and \( 3 – (d_2 = 14 \text{ mm}, G = 3 \cdot 10^{-5} \text{ kg/s}) \). The shaded area is the area of current-voltage characteristics of discharge in cathodes of varying inner diameter (from 20 mm to 14 mm and less). Argon expenditure varied from \( G = 5 \cdot 10^{-5} \text{ kg/s} \) to \( G = 3 \cdot 10^{-5} \text{ kg/s} \).

The feature common to all three current-voltage characteristics is that the initial condition of independent discharge, i. e. ignition voltage, are the same [4, 5]. For characteristic 1 there is a noticeable horizontal section in this area, where the discharge only occurs from a part of the cathode surface.
This normal glow discharge is characterized by three features. Growth of current results in a proportionate increase of the cathode’s area engaged in the discharge according to Gail’s law. Visual observation of the same glow of growing arc anchor spots on the cathode allows concluding about the stability of current density up to the point where the cathode end area is fully covered with the arc anchor spot. The third trait of this area of current-voltage characteristic area (horizontal section) lies in the cathode voltage permanence as the current is increased up to the moment when all of the cathode surface is engaged in the discharge [6].

2. Study of plasma torch starting modes
Experiments show that the maximum temperature of cathode heating is established at some distance from the cathode end nearing the anode. It is obvious that the intensity of heating is linked to the ion current density in the cathode, which is spread quite unevenly over the axial coordinate of the cathode.

For the ignition of the glow discharge, the studied starting modes of cathode heating require power source idling voltage to be $U_{iv} \geq 250$ V. In order to decrease the starting voltage, studies of starting modes with additional high frequency range voltage on direct current voltage were conducted [7]. The scheme of high frequency generator connection and the scheme of the generator matching device are shown in Figure 2.

When the high-frequency generator is switched on, a high-frequency discharge emerges in the working space. The following switching-on of direct current source allows cathode heating modes to operate under voltages significantly lower than glow discharge ignition voltage under direct current. Figure 1 shows current-voltage characteristics of direct current discharges with simultaneous introduction of a high frequency power component (characteristic 4 – under high-frequency power 150 VA, characteristic 5 - under power 370 VA). Under direct current the high frequency discharge is concentrated in the inner space of the cathode.

The stream of plasma forming gas blows out the generated plasma as it happens in a plasma torch under atmospheric pressure. At the same time the likelihood of micro-arcs emerging on the cathode surface significantly decreases. The initial voltage of cathode heating mode with the power of high-frequency discharge 300 VA is equal to main power source idling voltage.
Figure 2. Scheme of high-frequency source connection and ion current measurement through a cylindrical screen.

The usage of starting power source becomes no longer necessary. The partially ionized plasma forming gas leaving the inner space of the cathode magnifies the glow sharply, which may be related to the increased degree of plasma ionization in the cathode. The stream of plasma forming gas pushes plasma out of the inner space of the cathode, forming the starting point of the discharge column near the cathode ending [8, 9].

In order to examine the occurring processes, a cylindrical probe is installed near the open end of the cathode. The probe is connected with adjustable resonance filter set to 13.56 MHz and a measurement system with a shift on the probe ($U = 100$ V). The measurement results are presented in Figure 3.

Figure 3. Relation between the ion current in the probe and the power of high-frequency source (explained in the text)

Characteristic 1 corresponds to the probe current with the direct current source off. It must be noted that high frequency discharge forms plasma inside the cathode and around it. From inside the cathode a glowing stream of plasma comes out along the cathode axis in the direction of the anode. Characteristic 2 shows the change of ion current after switching-on of direct current source with continuously decreasing voltage. In the starting mode current range ($I \leq 150$ A) the voltage of $U \approx 100$V is maintained. It is apparent that the combined work of two power sources magnifies the ion current in the probe, which designates increased plasma ionization inside and outside of the cathode. The same is indicated by the reduced cathode heating time. It should also be noted that the maximum temperature of the cathode occurs in the area where gas flow is shifting from ultrasonic to subsonic.
3. Experimental smelts of nonferrous metals

In order to evaluate the intensity of technological processes occurring during the processing of metals in vacuum plasma furnaces with hollow cathodes, it is necessary to determine the relations between metal surface heating temperatures and specific heating power.

In order to establish these relations, studies of the processes of tantalum, tungsten, molybdenum, zirconium and titan ingot melting in plasma vacuum furnaces were conducted. The experiments were carried out via laboratory facility with power of 20-120 kW and industrial electric furnace with power of 800 kW. The laboratory furnace allowed for the melting of compact scrap units, powder and tablet raw material and mixed scrap (compact units, powder, tablets). The industrial facility was used for the melting of tantalum powder of fraction up to 150 µm, produced via sodium thermal reduction. A special cathode construction helped ensure ion-electron heating of the powder in the plasma column with introduction of the powder to the smelt and its 100% technological processing. The crystallizer of the lab facility had the diameter of 100 mm; that of the industrial facility – 250 mm [1]. Both furnaces were equipped with magnetic systems of control over the maximum density of the energy emitted from the heating surface in the crystallizer. The furnaces were powered by thyristor power source [9].

All smelts aimed at producing ingots in the crystallizers were carried out in optimal modes, in which the cross-section size of anode area on the liquid metal bath was smaller than the inner diameter of the crystallizer. Radial sizes of the plasma column and anode area were regulated through altering the level of induction in the magnetic field.

The vacuum system of the furnace enabled to maintain a technologically advantageous pressure range from 0.1 to 100. The melting chamber of the lab facility had a diameter of 0.7 m and height 0.55 m. In order to stabilize the working pressures in the furnace chamber the vacuum system included the backing pump VN-6G, and the steam oil pump BN-4500 in a parallel-serial connection to the booster pump DVN-1500. The melting chamber was equipped with water-cooling facility, which allowed conducting measurements of energy balance of the smelting via calorimetry method, in addition to the water-cooling of the crystallizer, the cathode holder and the pallet. The cathode holder connected to a cylindrical cathode with inner diameter 2·10⁻² m was installed into the roof of the melting chamber on the same axis as the crystallizer. The cathodes were made of tantalum and tungsten. The smelts were carried out with the use of high purity argon. Argon expenditure varied within the range from 2.5·10⁻⁵ to 3.1·10⁻⁵ kg/s.

Measurement of liquid metal temperature in the crystallizer depending on the introduced power was conducted optically based on the radiation of the central part of the liquid metal bath in the crystallizer. As is known, an optical pyrometer, which measures radiance temperature, is liable to bigger systematic error due to the fact that the metal radiance coefficient depends on the surface quality and observed wave length. A pyrometer measuring color temperature also leads to big error as the scope of observed spectral interval depends on the wave length. Therefore in order to minimize errors, the liquid metal surface temperature was measured by the color temperature method with photoelectric registration system. A monochromator with diffraction grating producing the same spectral intervals on various wave lengths was used as a registration element. Assuming that radiation intensity is determined by Wien’s law, the ratio of intensities in different wave lengths λ₁ and λ₂ is:

\[
\frac{J_1}{J_2} = \frac{k_1}{k_2} \cdot \frac{\lambda_2^3}{\lambda_1^3} \exp \left( \frac{C_2}{T} \left( \frac{1}{\lambda_2} - \frac{1}{\lambda_1} \right) \right).
\]

In equation (1), \( J_1 \) and \( J_2 \) are the deflection of the recorder during the photoelectric registration of the radiation on wave lengths \( \lambda_1 \) and \( \lambda_2 \); \( C_2 = 1.438 \cdot 10^{-2} \) mK; \( k_1 \) and \( k_2 \) are the coefficients of the transformation of optical radiation into an electric signal.

Taking the logarithm of (1), we get:

\[
T = C_2 \left( \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \left( \ln \frac{J_1}{J_2} + 5 \ln \frac{\lambda_1}{\lambda_2} + \ln \frac{\varepsilon_2}{\varepsilon_1} + \ln \frac{k_2}{k_1} \right)^{-1}.
\]

(2)
Coefficients $k_1$ and $k_2$ were defined through the calibration of the measuring system by the radiation of standard incandescent lamp of the SI-2-10 type. The wave lengths $\lambda_1=5\cdot10^{-7}$ m, $\lambda_2=4\cdot10^{-7}$ m were chosen due to the fact that on these wave lengths $k_1=k_2$. The radiating properties of metals $\varepsilon_1$ and $\varepsilon_2$ were taken from the reference data. Since $\varepsilon_1$ and $\varepsilon_2$ depend on wave length and temperature, the problem was solved through iteration. Firstly, the color temperature was defined according to expression (2) with $\varepsilon_1=\varepsilon_2$. Secondly, with color temperature known the values $\varepsilon_1$ and $\varepsilon_2$ were determined and new temperature value was calculated which led to new values of $\varepsilon_1$ и $\varepsilon_2$ and so on. This procedure would reach the solution just after two iterations. The measurements were conducted via monochromator equipped with photoelectric registration system. In order to prevent the build-up of cathode material on the surface of optical glass, a vapor trap was installed, which consisted of a water-cooled tube and a diaphragm with an opening. Pure argon (expenditure $G <5\cdot10^{-6}$ kg/s) was supplied to this area, which prevented the metal vapors from contacting the glass.

The implemented measurement method is not sensitive to grey medium, whose capacity satisfies the condition $\tau(\lambda_1)=\tau(\lambda_2)$. Since the measurements for different wave lengths were conducted consecutively after short periods of time, this condition was fulfilled, so the effect of possible presence of dust and smoke on the results was excluded. The accuracy of temperature measurement in the system was verified at the measurement points during the conversion of metals from solid state into liquid state with breaks in the continuity of surface heating characteristics during compensation of latent melting heat. Temperature measurement error did not exceed 50 ºC.

The results of the measurements of liquid metal bath temperature are presented in fig. 4 in relation to average specific heating power. It is apparent that the level of heating of the metal depends on the input power, thermophysical properties of the heated metal and the heat losses from the liquid metal bath. Due to increased losses through radiation and heat transfer from the crystallizer, higher heating temperature requires disproportionately higher heating power [1]. Due to intense movement of liquid metal owing to the interaction of magnetic fields and spreading currents in the liquid metal, the equation of temperatures on the surface of the ingot occur temperatures on the surface of the ingot are made even, which is confirmed by temperature measurements in various spots on the surface of the metal. So the temperature measured in the center of the bath may be considered close to the average surface temperature of the liquid metal.

Figure 4. Relation of liquid metal surface temperature to the provided specific power.

The table 1 shows numerical values of specific and total power that lead to full melting of the metal surface in the crystallizer and heating temperature higher than melting temperature. The temperature measurement and building of relations $T=f(q)$ presented in the figure was carried out in established heating modes 10-12 minutes after the changes to the power of the plasma heating system. Thereby the temperature transition from the solid state of the metal surface to the liquid state has no breaks due to
spending of energy on melting. The temperature measurement experiments were conducted with the ingots gradually formed in the crystallizer without scrap loading during this period.

| Smelting material | $T_{pl}$, °C | $e_0$ | $P_{pl}$, kW | $p_0\cdot10^6$ W/m$^2$ | $\Delta T$, °C | Number of the characteristic in Figure 4 |
|-------------------|------------|------|-------------|----------------|-------------|---------------------------------|
| Tungsten          | 3420±50    | 0.461 / 0.447 | 60 | 5.3 | 270 | 6 |
| Tantalum          | 2996±50    | 0.498 / 0.460 | 52 | 4.6 | 280 | 5 |
| Molybdenum        | 2620±50    | 0.419 / 0.403 | 42 | 3.7 | 480 | 4 |
| Niobium           | 2469±15    | 0.368 / 0.348 | 38 | 3.3 | 580 | 3 |
| Zirconium         | 1852±40    | 0.450 / 0.403 | 32 | 2.8 | 690 | 2 |
| Titan             | 1608±20    | 0.503 / 0.444 | 26 | 2.3 | 400 | 1 |

* – variation range during the overheating of metals: numerator – for $\lambda_1$, denominator – for $\lambda_2$.

4. Conclusion

The determined relations between surface temperature of liquid metal bath and the supplied specific power can be used for the selection of the optimal melting mode and calculation of kinetic modes of metal refinement [10, 11]. Furthermore, the link between heating temperature and surface power determines the modes of operating the facilities for surface melting of industrial ingots aimed at their degassing and quality improvement.

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