Argon plasma cathode binding in arc discharge

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Pyrometric investigation tungsten cathode in argon arc plasma discharge at atmospheric pressure is repoted. The distribution of temperature on current removal surface of the cathode was measured. The analysis of electron emission current density on the cathode is compared to experimental data. Discussed possible reasons for discrepancy between the experimental and theoretical values of the electron emission current.

1. The object of study

Thermionic cathode from tungsten is widely used in practice, in particular in the plasma torches. In this regard, the study of near-electrode processes are still under investigation [1-7].

Our experimental setup consists of expanding anode channel and tungsten cathode. Plasma torch is produced by high-current arc (200A) in argon at atmospheric pressure. Cathode soldered into a massive copper water-cooled holder ending in a cone with an apex angle of 70 °. The investigation of the cathode and the binding plasma region of the arc near cathode were made through the observation windows in the nozzle (Figure 1).

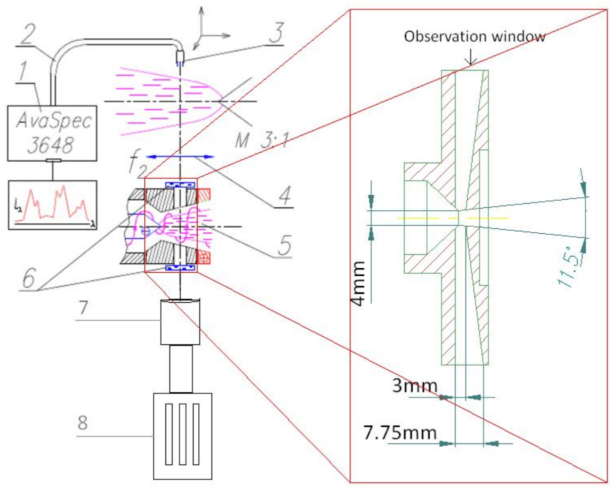

Fig.1. Experimental setup. 1) Spectrometer Avaspec 2048 2) Fibre optics 3) Focusing lens 4) Lens 5) Argon plasma 6) Quartz observation windows 7) Focusing lens "Helios-40-2" 8) Coloured camera "Phantom".

The sharp image of cathode was projected on a coloured camera's 'Phantom Miro M110' with the use of focusing lens 'Helios-40-2' From one of the observation windows. Spectrum was recorded by a 3-channel spectrograph Avaspec 2048 (wavelength interval is 200÷1100 nm) from the opposite window.

2. Typical time and length scales

Typical values for electron temperature and electron concentration for argon plasma in high-current arc (200A) are about $T_e \sim 2\,\text{eV}$ and $n_e \sim 10^{17}\,\text{cm}^{-3}$. The Debye radius of this plasma is $r_D \sim 10^{-6}\,\text{cm}$.

The diffusion coefficient for the fully ionized and quasi-neutral plasma can be estimated as

$$D_i \sim 1/3\lambda u_i \sim \frac{u_i}{3n_i\sigma_{tr}}$$
$$\sigma_{tr} \approx \frac{2.87\cdot 10^{-14}\ln\Lambda}{\left(T\left[eV\right]\right)^2} \qquad (1)$$

where σ_{tr} - the transport scattering cross section of ions and $\ln\Lambda$ - Coulomb logarithm [8].

Thus, we have value for the diffusion coefficient $D_i \sim 100\,\text{cm}^2/\text{s}$. In the studied plasma radius of the plasma column is $r \sim 0.1\,\text{cm}$, which gives value for the diffusion time $\tau_{dif} \sim \frac{r^2}{D_i} \sim 10^{-5}\,\text{s}$. We will not consider the effect of diffusion on the population of the excited level do to $\tau_{dif} >> \tau_* \sim 10^{-8}\,\text{s}$, where τ_* the lifetime of the excited ions of argon.

The characteristic time of energy exchange between the electron-electron, ion-electro and ion-ions systems are about $\tau_{ee} \sim 10^{-12}$ s, $\tau_{ii} \sim \tau_{ee}\left(\frac{M_i}{m_e}\right)^{1/2} \sim 5\cdot 10^{-10}$ s, $\tau_{ei} \sim \tau_{ee}\left(\frac{M_i}{m_e}\right) \sim 10^{-7}$ s, where M_i - mass of the ion, m_e - electron mass.

A settling time of the ionization and recombination equilibrium $\tau_{ion} \sim 1/(k_{ion}n_e) \sim 10^{-7}$ s and $\tau_{rec} \sim 1/(k_{rec}n_e) \sim 10^{-7}$ s respectively ($k_{ion} \sim 10^{-10}$ cm^3/s, $k_{rec} \sim 10^{-10}$ cm^3/s [5]).

Length of establishing electronic, ionic and ion-electron systems are of the order $l_{ee} \sim 10^{-10}$ cm, $l_{ii} \sim u_i\tau_{ii} \sim 10^{-4}$ cm, $l_{ei} \sim \sqrt{D_i\tau_{ei}} \sim 10^{-2}$ cm, $l_{ion} \sim \sqrt{D_i\tau_{ion}} \sim 10^{-2}$ cm.

Length of ionization and recombination $l_{ion} \sim l_{rec} \sim \sqrt{D_i\tau_{rec}} \sim \sqrt{D_i\tau_{ion}} \sim 10^{-2}$ cm.

The hydrodynamic time for plasma is about $\tau_p \sim r/u_p \sim 10^{-5}$ s where the plasma velocity is $u_p \sim 10^4$ m/s.

We have the following hierarchy of times and length scales:

$$\begin{aligned} &\tau_{ee} << \tau_{ii} << \tau_* < \tau_{ei} \sim \tau_{ion} \sim \tau_{rec} << \tau_{dif} \sim \tau_p \\ &r_D << l_{ee} \sim l_{ii} << l_{ei} \sim l_{ion} \sim l_{rec} < r \end{aligned} \quad (2)$$

which lets to say about LTE (local thermodynamic equilibrium) for the studied plasma.

3. Concentration and temperature of electrons

The spectrum recorded along the axis of the plasma jet from the tip of the cathode in increments of 0.2mm. Spectral lines Ar II and Ar III in 327 ÷ 332nm was used for the electron temperature calculating on basis of the method of relative intensities of particles with different degree of ionization. The electron temperature is close to $T_e = 2.5$ eV.

The electron density was found by Stark broadening of the spectral lines of argon ions Ar II 373,79nm and Ar II 329,36nm. Obtained values are in good agreement with the modulation of argon plasma composition from the Saha equation.

4. Cathode surface temperature.

The cathode surface temperature determined by using the three-colour matrix video recordings through the high-speed Phantom camera with a spatial resolution of 25 microns. standard brightness - tungsten ribbon lamp with brightness temperature of 2400 K was used for the calibration of radiation fluxes from the cathode surface. Obtained the maximum cathode surface temperature is about 2800 K.

5. Theory and experiment for the current density at the cathode

Density of the electron emission current from hot surface in accordance with the law of Murphy-Goode:

$$\begin{aligned} &j_{em} = AT_k^2\frac{f}{\sin(f)}\exp\left(-\frac{e}{kT_k}\left(\varphi - \sqrt{\frac{eE_k}{4\pi\varepsilon_0}}\right)\right) \\ &f = 1.64\cdot 10^{-2}E_k^{3/4}/T_k \end{aligned} \quad (3)$$

where φ - for the work function of tungsten, E_k in V/cm; gives the value of $j_{em} = 2.9\cdot 10^3$ A / cm^2 for anomalous large $E_k = 5.6\cdot 10^6$ V/cm.

The resulting calculations show that in realizable case the electron emission current value can not compensate for the missing part between the ion current and the total current $j - j_{ion} >> j_{em}$.

Acknowledgments

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3. References

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