PLASMA PHYSICS AND PLASMA METHODS

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Studying emission of the short high current vacuum arc with copper electrodes

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The work provides for the measurement of emitted power of the high current vacuum arc burning on copper electrodes. The emission measurement range was 100 nm ≤ λ ≤ 1.100 nm. The developed measurement method allowed for analyzing the change of the emitted power depending on the arc current in visible and ultraviolet spectrum parts and in the vacuum ultraviolet region. Analysis of the obtained results demonstrated that the emitted power spectrum redistributes in the vacuum arc with a high anode activity. The obtained results allowed the possibility to evaluate the emission fraction in the arc power balance.

Keywords: vacuum arc; emitted power; low temperature plasma; electromagnetic emission; electric arc.

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Introduction

The high current vacuum arcs studies are foremost related to development of the vacuum arc-damping equipment. Therewith, the electromagnetic emission means a lot in the vacuum arc power balance. With the increasing arc current and relatively increasing plasma density, the emission role becomes more significant [1]. It is quite a difficult task to determine the arc power balance considering the emission.

The electromagnetic emission is generally not considered under mathematical simulation of the vacuum arc. However, some approximate calculations were made considering the arc emission [2–4]. When studying the plasma emission experimentally, the spectroscopic methods are mainly used [5]. In our works [6–8] we measured the

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emission flow created by the entire plasma volume. These works provide for the results of emission measurement of the high current vacuum arc with the copper chromium composition (CuCr30) electrodes used in the advanced arc-damping chambers. In the previous works, the authors studied $200\ \text{nm} \le \lambda \le 1100\ \text{nm}$ spectrum range. It emerged that a major part of emission was concentrated within $\lambda < 400$ nm range, and the emitted power fraction in the arc with the anode activity was nearly 25 % of the total arc power. These measurements along with the measurements of discharge current and arc voltage can be used to determine the basic plasma parameters [9].

Upon achievement of a certain current density, the developed high current arc demonstrates the anode activity, and there are quite large areas of a material fusion on both electrodes. Such fusion temperature reaches 2.000 K [10]. Therewith, the copper melting point is 1.356.55 K, and the chromium one is 2.130 K. At such temperatures, evaporation from the copper electrodes surface would be significant, which means the basic material in the interelectrode gap would be copper vapors. Within the vacuum ultraviolet range (100–200 nm), there are quite many intensive lines of copper atoms and ions. Thus, it can be suggested that the power emitted from the arc within this range would be significant. To assess contribution of each electrode component (Cu, Cr) to emission, we have measured emitted power of the vacuum arc burning on copper electrodes at this stage of the study.

Experimental procedure

The high current vacuum arc emission was measured within $100\ \text{nm} \le \lambda \le 1.100\ \text{nm}$ range, this range also includes the vacuum ultraviolet (VUV) region. The arc was ignited in the cathode center by an auxiliary discharge between an electrode and a needle with current withdrawn from it. The arc was fed by the rectangular current pulse with the duration of 9 ms. The interelectrode gap was 4 mm. The current varied within 10–25 kA, which provides the average current density variation of $1.5\ \text{kA/cm}^2 \le j \le 3.5\ \text{kA/cm}^2$ in the completely developed arc. The end electrodes diameter was 30 mm. The electrodes material was oxygen-free copper (OFC Cu).

The experimental plant layout was previously described in [6]. Assessment of the high current vacuum arc emitted power based on the emission flow intensity registered with the photo receiver has been based on [11]. We will mention the basic plant parameters and critical auxiliary modifications here. The electrodes were located in the vacuum chamber under continuous exhaust ($\sim 10^{-4}$ Pa). To stabilize the discharge, a uniform axial magnetic field (AMF) was applied, the AMF induction was ~ 10 mT/kA. Thus, arching in diffusion mode was ensured. To register emission, three photodiodes FDUK8-UVS with the active area size of 3.5 mm were used. The typical sensitivity $S(\lambda)$ of the photodiode within $100\ \text{nm} \le \lambda \le 1.100\ \text{nm}$ range is shown in Figure 1.

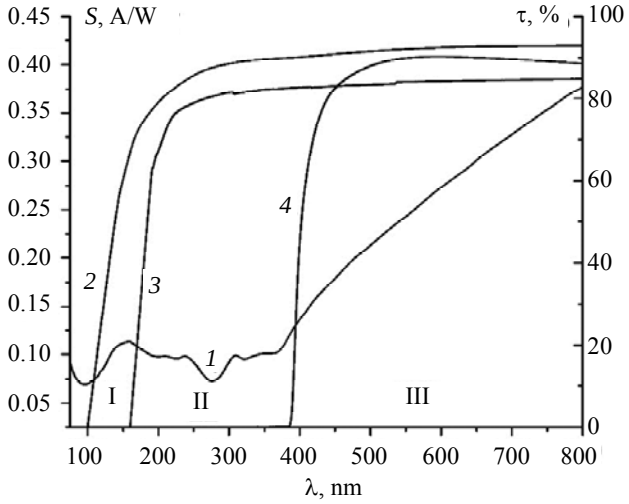

Fig. 1. Dependency of the photodiode sensitivity – 1 and filters transmission coefficients: 2 – MgF_2; 3 – KU-1; 4 – ZhS-10

All three photodiodes were located inside the vacuum chamber, which allowed us for registering emission in the vacuum

ultraviolet. To divide the range registered by the photodiodes into regions (marked as I, II, III in Fig. 1), the light filters were used. MgF_2 glass transmits emission with $\lambda \geq 100$ nm, KU1 quartz glass transmits light with $\lambda \geq 175$ nm, and Zh-10 color glass (GOST 9411-91) transmits $\lambda \geq 400$ nm. Figure 1 shows the light filters transmission coefficients $\tau(\lambda)$ in addition to the photodiodes sensitivity. Within 100–400 nm range, the spectrum sensitivity characteristic of the photodiode changes insignificantly, so the emitted power in this region can be assessed quite easily within the narrow spectrum regions: 100–175 nm (Region I) 175–400 nm (Region II). The photodiode sensitivity characteristic in $\lambda > 400$ nm region (Region III) increases with the increasing wavelength, while the arc emission in the long wave region has a low sensitivity. Therefore, the authors calculated Region III sensitivity as an average within the range, which would not result in large error of the emitted power assessment. To limit the maximum signals registered by the photodiodes, the diaphragms of different diameters (from 1 mm for ZhS-10 filter to 0.5 mm for the others) were used.

Experiment results and discussion

At the relatively small current $I_a \approx 10$ kA, when the arc burns in the diffusion mode without anode activity, the shape of the registered signals from the photodiodes approximately follows the discharge current shape. The registered signal is low, especially through ZhS-10 filter. Examples of the electrical measurement results under two large currents are shown in Figures 2 and 3. It can be observed that with the increasing current pulse amplitude, the photodiode pulse value and shape (and the emitted plasma power respectively) change significantly.

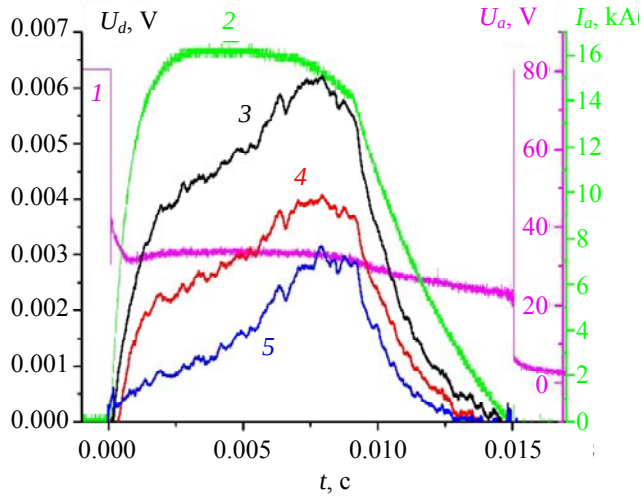

Fig. 2. Measurement results. $I_a \approx 16$ kA. 1 – arc voltage; 2 – arc current; signals from photodiodes with filters: 3 – MgF_2; 4 – KU1; 5 – ZhS-10

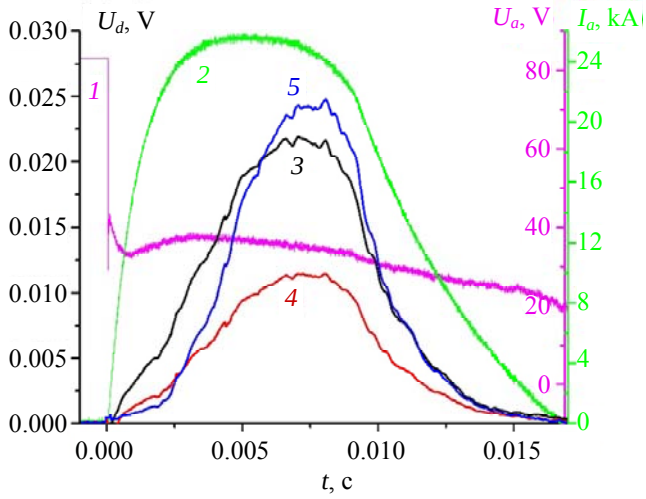

Fig. 3. Measurement results. $I_a \approx 25$ kA. 1 – arc voltage; 2 – arc current; signals from photodiodes with filters: 3 – MgF2; 4 – KU1; 5 – ZhS-10

When the current reaches $I_a \approx 16$ kA (Fig. 2), and the first signs of anode activity occur on the electrodes, the signals from the diodes increase respectively. Regardless of the current pulse having a long-standing plateau, the signals from the diodes increase linearly, and become at least twice higher by the pulse end, and for ZhS-10 filters, the triple increase is observed. Further current increase results in significant change of the diodes signals shape. At the pulse end, the signals emerge to increase rapidly, and at the currents of $I_a \approx 18$ kA (at such currents, significant fusion of surfaces is observed on

both electrodes), they increase at least fourfold by the pulse end. Therewith the signal received through MgF_2 filter starts increasing earlier than the others, but increase of the signal on the photodiode received through ZhS-10 filter is much higher than increase of the signals on other photodiodes.

Further current increase up to $I_a \approx 25$ kA (Fig. 3) does not result in change of the diode signals shape, but causes their significant increase. At the maximum current, both electrodes surfaces are melted completely.

Significant change of the shape of the signal from a photodiode at the currents significantly exceeding 15 kA correlates with occurrence of the anode activity. The anode activity results in increase of the plasma density and thereby in increase of the emission role significance.

By virtue of simultaneous emission registration with three photodiodes through different filters we can observe the dependency of emitted power P on discharge current within spectrum Region I (~ 100–175 nm), Region II (~ 175–400 nm) and Region III ($\lambda \geq 400$ nm) at different time after the arc ignition. These dependencies are shown in Figure 4.

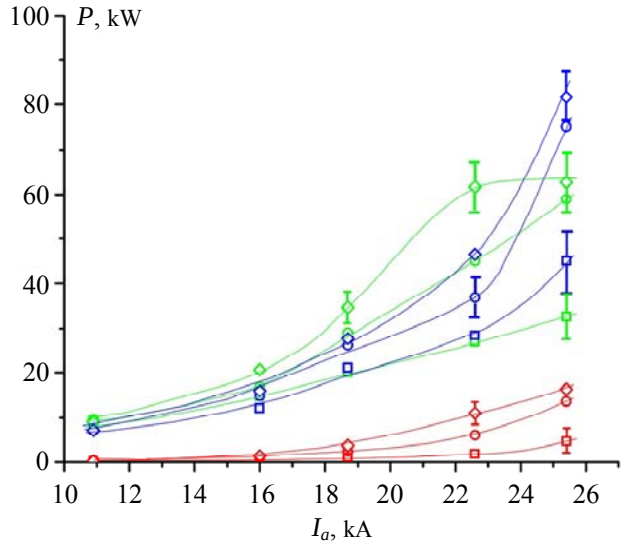

Fig. 4. Dependency of emitted power on current in different spectrum regions: blue - Region I; green – Region II; red – Region III. Time instants: square – 3.5 ms; round – 5.5 ms; diamond – 7.5 ms

Based on the shown dependencies, it can be observed that the emitted power in all observed spectrum regions reaches the maximum by the pulse end (7.5 ms). However, the change of the emitted power with the increasing current upon achievement of the limit currents, when activity on the anode is already high enough ($I_a > 20$ kA), is not the same for different regions of the spectrum.

In Region III, the emitted power in the arc with the developed anode activity increases by an order of magnitude, as compared to the arc in the diffusion mode without anode activity. In addition, the emitted power increases significantly with the increasing current in the vacuum ultraviolet region (Region I). Therewith, at the limit currents, the increase speeds up and achievement of the maximum emission is observed faster.

There is a different story in the medium spectrum region (Region II). Before occurrence of the anode activity, the emitted power increases in step with the vacuum ultraviolet region, but at the current of ~ 22.5 kA, the power increases rapidly and reaches the value above the power in the vacuum ultraviolet region, although at the current pulse end (7.5 ms). While at a higher current (~ 25 kA) the emitted power magnitude in Region II nearly does not increase, as compared to emission in Region I. Therewith emission to Region II reaches its saturation as early as in the middle of the current pulse.

Emission in Region I is generally determined by ionic, also resonance, copper lines. The significant part of emission in Region II would be determined by atomic lines so far (two resonance lines of the copper atom are located there as well). At the currents of $I_a > 20$ kA, the authors observe the both electrodes completely fused, which means that copper is evaporated from the surface intensively. With increasing current, the atoms evaporated from the surface would

be ionized actively, and emission would increase respectively.

Conclusion

Emission plays a substantial role in the developed vacuum arc. At 25 kA arc current, about 900 kW power would be emitted in the discharge. Based on our assessment, about 150 kW would escape from the arc at the emission within ~ 100–1.100 nm, that is up to 15 % of the total discharge power would be emitted by the end of arcing at the high current densities. Therefore, calculation of power balance in high current vacuum arcs should consider emission. Therewith the emitted power increases faster with the increasing current in the vacuum ultraviolet region. At the current of 25 kA (current density $j \leq 3.5$ kA/cm^2), emission in the vacuum ultraviolet reaches 80 kW by the pulse end. In 175–400 nm spectrum region, the maximum is achieved at the lower current ($I_a = 22$ kA) and amounts to -60 kW. The analysis demonstrates that the emitted power is redistributed to the vacuum ultraviolet in the developed vacuum arc with anode activity. It means that the measurements should be also taken in the shorter waves region ($\lambda \leq 100$ nm).

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