doi: 10.56761/EFRE2022.C1-O-043402

# Diffuse vacuum arc discharge with heated cathode made of mixture of ceramic and metal powders

*R.A. Usmanov*, A.D. Melnikov, V.P. Polistchook, S.B. Vetrova*

*Joint Institute for High Temperatures RAS, Moscow, Russia*
**usmanov.r@ihed.ras.ru*

**Abstract.** The paper present results of an experimental study of a plasma flow parameters generated by a vacuum arc discharge with heated cathode made of mixture of ceramic and metal powders. The discharge existed in a diffuse mode of cathode current attachment. The diffuse mode was characterized by relatively low values of cathode current density (10–100 A/cm$^2$), absence of significant voltage oscillations and stable glow of plasma formation. The data on mean charge of the arc plasma flux, ion energies and ion composition measured by time-of-flight mass spectroscopy method were obtained. It was shown that chromium is a main source of the plasma forming medium when cerium dioxide is a main source of electrons of thermionic emission. Obtained results can be useful in designing of stable plasma sources of multi-component condensed substances for wide range of applications from deposition of composite coatings to plasma mass separation.

**Keywords:** arc discharge, ceramic powder, metal powder.

## 1. Introduction

The problem of creating a source of multi-component plasma flux is rather relevant from the fundamental and applied points of view. Especially critical issues raise in the area of plasma-surface interaction, for example in tasks of the thermonuclear reactors development, deposition of functional coatings and films, as well as during elaboration of plasma mass separation methods [1]. In the framework of the above directions, it is especially important to develop methods for generating plasma of dielectric or semiconductor ceramic materials.

The paper is devoted to the study of a diffuse vacuum arc with a hot cathode containing a mixture of an oxide component with a metal (cerium dioxide and chromium). Due to the high temperature of the cathode (~2000 K), it is possible to provide conditions for the arc current conduction, to stabilize the discharge voltage fluctuations, and to decrease droplet fraction in the plasma flow. Previously, such a discharge has already been studied partially on a cathode made of a mixture of cerium dioxide powder and chromium flakes [2], and its promise as an efficient plasma generator was shown.

In this work, mixtures of powders were used as a cathode in order to organize a more uniform evaporation of the cathode material during the arcing process. A series of experiments was carried out with different mass fractions of the components of the cathode. The results of a complex study of the parameters of the resulting plasma flux, including the electron temperature, the mean charge of the flux, and the energy of the ions, are presented. The ionic component composition of the flux was also studied.

## 2. Experimental setup

The scheme according to which the experiments were carried out is shown in Fig.1. The cathode of the arc discharge was placed in a molybdenum crucible. The cathode was represented by a sintered "tablet" from a mixture of $CeO_2$ and Cr powders. An electron-beam heater (EBH) was located under the crucible, which made it possible to change the temperature of the crucible during the experiment at a fixed arc current. The anode was a molybdenum plate with a central hole. The diameters of the holes in the crucible and the anode coincided and were equal to 14 mm. The distance between the cathode and the anode was about 30 mm.

The rectifier with an output voltage of 380 V was used as an arc power source. The arc current was set by a water-cooled rheostat connected in series with the discharge gap. The arc discharge electrodes were located in a vacuum chamber evacuated to a residual gas pressure of less than 10 mPa. Voltage was applied to the anode at a crucible temperature of about 2100 K, when the mixture vapor pressure was sufficient to initiate a breakdown of the discharge gap. The temperature of the crucible was measured by a brightness pyrometer. The current, discharge voltage, and EBH power were measured.

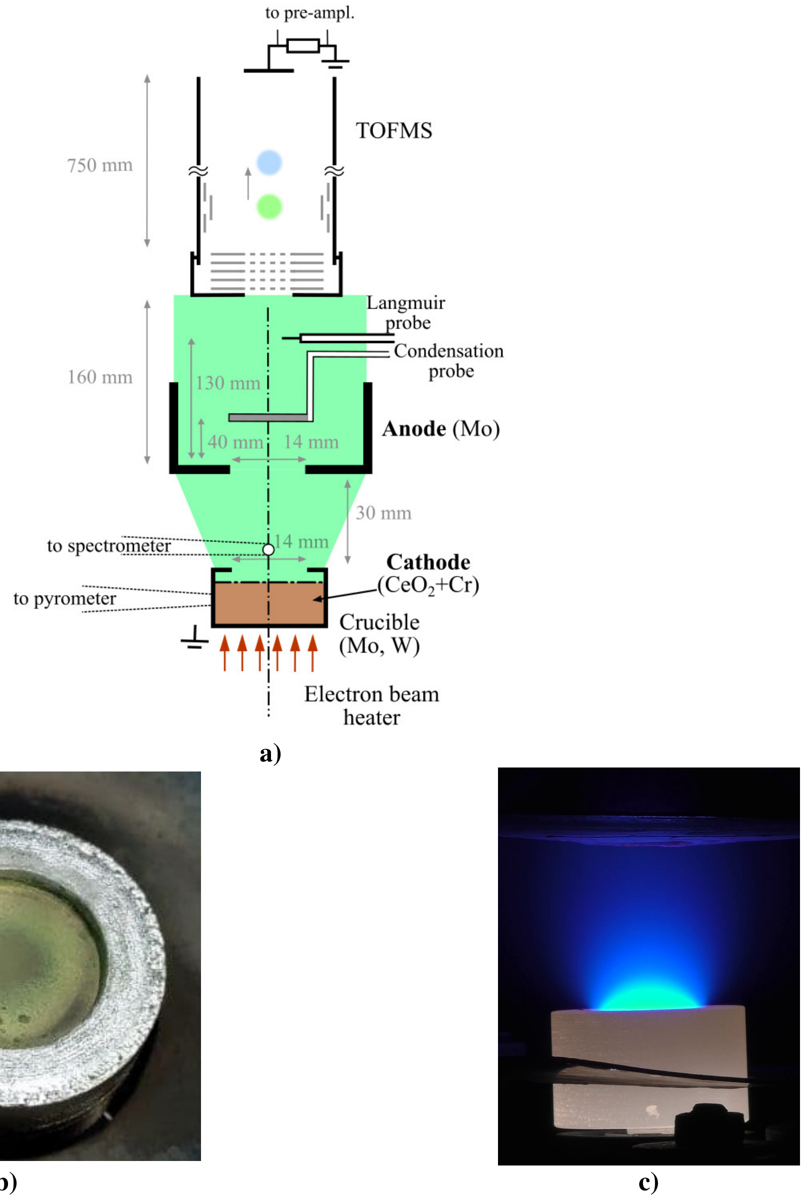


Fig.1. Experimental apparatus: a) the scheme of the experiment, b) appearance of the cathode after sintering, c) picture of the diffuse vacuum arc.

Several probe methods were used to diagnose the parameters of the discharge plasma. A single cylindrical Langmuir probe was used. It was located in the space behind the anode at a distance of about 130 mm. Processing of the recorded current-voltage characteristics of the probe was carried out according to the standard procedure [3]. To estimate the degree of ionization of the plasma escaping from the anode, the condensation probe method was used. The idea of the method is to measure the ratio of the charge passed through the probe to the mass of particles (neutrals and ions) deposited on its surface during the exposure time of the probe in the plasma flux. The measured ratio makes it possible to determine the mean charge of the particles settled on it. The probe was introduced into the plasma flux behind the anode at a height of about 40 mm above it. A multigrid probe was used to measure the ion energy of the flux. The probe was located in the space behind the anode at a distance of about 160 mm.

For qualitative control of the composition of the plasma flux formed in the arc, the discharge radiation spectra were recorded. To study the ionic composition of the resulting plasma, we used a time-of-flight mass spectrometer (TOFMS) of our own design with a drift zone length of 750 mm and a diameter of 40 mm. The spectrometer was located along the direction of propagation of the generated plasma flux at a distance of about 160 mm above the arc anode.

## 3. Results

The cathode was prepared from a mixture of $CeO_2$ and Cr powders, which were placed in a molybdenum crucible in different mass ratios. The particle size of powders was 10–100 μm. The experiments were carried out with the mass ratio of the powders 4:1, 1:1 and 1:4. The total mass of the cathode was about 6–8 g, depending on the experiment. The mixture of powders was pressed manually and sintered for an hour before the discharge was ignited in a vacuum at a temperature of about 1750 K. A typical view of the cathode after sintering is shown in Fig.1b.

A series of experiments was carried out in which the influence of the mass ratio of the components in the cathode composition on the crucible temperature at which the gap breakdown occurs was studied. The temperature of the crucible at which it was possible to initiate the arc on the mixed cathode was lower than on the cerium dioxide cathode [4]. Moreover, the more chromium was placed in the composition of the cathode, the lower the breakdown temperature was. With a ratio of chromium to cerium oxide of 4:1, it was possible to decrease the temperature of the crucible required for gap breakdown by more than 100 K. A more uniform discharge glow was also observed, which was more stable and spatially uniform (Fig.1c). With a ratio of chromium to cerium oxide of 1:4, the breakdown occurred at temperatures typical to oxide cathode, that is ~2200 K.

A series of experiments was carried out in which the dependence of the mean charge of the plasma flux on the discharge current was studied. The mean charge was determined by the condensation probe method at three currents: 42, 66, and 93 A. The data on the mean charge are given in Table 1. The data from the analysis of the plasma emission spectra indicated that the radiation contained mainly spectral lines of chromium particles. Therefore, when calculating the mean charge, it was assumed that mainly chromium was deposited on the condensation probe. In these experiments, the discharge current and voltage were maintained unchanged for 15 minutes. Due to the consumption of the cathode material, the discharge voltage increased with time, and for its stability it was necessary to increase the temperature of the crucible to keep the flux of particles evaporating from the cathode at the same level. A typical temperature adjustment was about 50 K. Under these conditions, the erosion rate of the cathode material was measured by weighing the crucible before and after the experiment. The data in Table 1 show that the increase in the arc current makes it possible to increase the mean charge of the plasma flux, and, accordingly, the degree of its ionization. The maximum mean charge achieved in the experiments was about 0.6*e* (*e* – elementary charge).

According to the data on the cathode erosion rate, the electrotransfer coefficient was estimated. It is equal to the ratio of the number of evaporated atoms from the cathode surface to the number of elementary charges that passed through it. Thus, at all measured currents, the electrotransfer coefficient was in the range of 0.024–0.035 atom/electron. Such a value of the parameter is rather typical to the arc on a $CeO_2$ cathode (0.02–0.06) than for a Cr cathode (0.08–0.12) [5], despite the fact that spectral lines of atoms and ions of chromium were mainly detected in the plasma radiation spectrum.

**Table 1**. Mean charge of the plasma flux

| | Arc current, A | | |
|---|---|---|---|
| | **42** | **66** | **93** |
| Arc voltage, *V* | 7.5 | 7.2 | 8 |
| Mean charge of the plasma flux, e | 0.29 | 0.46 | 0.57 |
| Cathode evaporation rate mg/s | 0.8 | 0.84 | 1.5 |
| Electrotransfer coeff., atom/electron | 0.035 | 0.024 | 0.03 |

Evaporation rate data also make it possible to estimate the vapor pressure of the cathode material near its surface. Given the crucible outlet area $S$ and assuming that the particles do not return to the cathode, we can assume that the rate of evaporation of the substance from the cathode $Q$ is determined by the expression $Q = S \cdot m \cdot n \cdot v$, where $m$ is the mass of chromium atoms, $v$ is the atomic velocity, $n$ is the concentration of atoms in the outlet of the crucible opening ($S \approx 1.5$ cm$^2$). Assuming that the speed of atoms is determined by the cathode temperature ~2200 K, it was calculated that the vapor concentration n in these experiments was at the level of $10^{14}$ cm$^{-3}$, which corresponds to a pressure of 3 Pa. This is two orders of magnitude lower than the saturation vapor pressure of Cr at a given temperature [6]. Based on the assessment and the values of electrotransfer coefficient, it can be concluded that the mixed cathode in the experiments rather operated in the thermionic mode [5], i.e., the flux of evaporating atoms from the surface was less than the flux of thermionic electrons. The main source of thermionic electrons was $CeO_2$ due to the lower work function (≈3.5 eV) than that of chromium (4.6 eV). A direct estimation of the atom-electron ratio is not possible, since the relationship between the emission surfaces of atoms and electrons is unknown.

When using a mixture of $CeO_2$ and Cr powders, it was possible to vary the discharge voltage by changing the heating power of the cathode crucible. Fig.2 shows the measured dependences of the discharge voltage on the EBH power at different arc currents for a cathode mixture with a mass ratio of 4:1 (Cr and $CeO_2$, respectively). According to observations, the range of voltage variation was the wider, the lower the discharge current was. So, at a current of 90 A, it was possible to change the arc voltage within 2 V, while at a current of 40 A, the range of variation was already 12 V.

The parameters of the plasma in after-anode space were studied. The electron temperature was measured depending on the discharge voltage at different currents. The experiments were carried out on a cathode with the ratio of $CeO_2$ and Cr fractions of 1:4. Experiments indicated that it is possible to control both the discharge voltage and the temperature of plasma electrons at a mixed cathode. So, it was possible to vary the electron temperature in the range of 0.8–1.4 eV at a current of 40 A and in the range of 0.4–0.8 eV at a current of 63 A. To answer the question about the ion composition being realized, a TOFMS was used.

Fig.3 shows a typical measured mass spectrum of ions in plasma flux propagating in after-anode space. Measurements show that only $Cr^+$ ($m/z = 52$) and $Ce^+$ ($m/z = 140$) ions are presented in the composition. Molecular ions were not observed in the composition. The ratio of the areas under the mass peaks shows that chromium ions exceed 90% of the composition of the flux. A similar ratio between the intensities of ion peaks is maintained when the discharge current varies in the range of 40–90 A and when the arc voltage varies from 6 to 12 V. The proportion of cerium ions in the flux increases towards the end of the experiment, when the amount of chromium in the cathode decreases as a result of its evaporation.

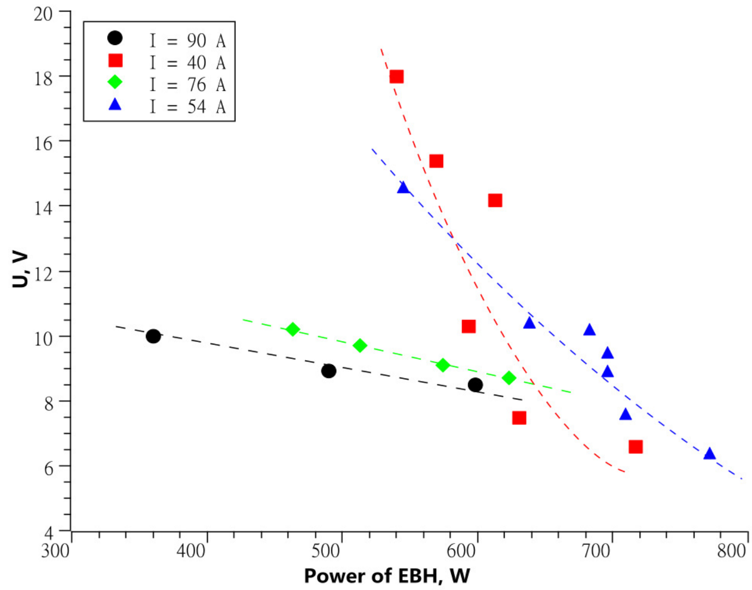


Fig.2. The dependencies of arc voltage on power of EBH at different arc currents.

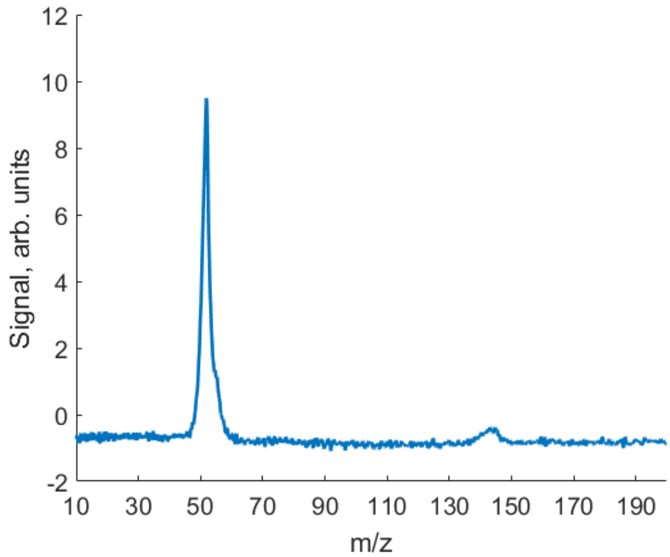


Fig.3. Typical mass spectrum of plasma flux.

The energy spectra of plasma ions were studied. The ion energies were determined relative to the electric potential of the cathode. The width of the spectra at half-height was about 2 eV, and the most probable ion energy significantly exceeded the corresponding arc voltage. The most probable energy is 11.5 eV at an arc voltage of 7.9 V. The latter is typical for vacuum arcs. When the arc voltage was varied by changing the cathode heating power, a corresponding shift of the most probable ion energy was observed. As the voltage increased, the ion energies also increased.

## 4. Conclusion

A diffuse vacuum arc on a cathode made of a mixture of $CeO_2$ and Cr powders with different mass ratios of components was studied, the main parameters of the resulting plasma flux were measured. The average erosion rate of the mixed cathode in the arc was measured at a crucible temperature of ~2200 K, it was at the level of 1 mg/s. The main evaporating material in the experiments was chromium. Using data on the erosion rate, the electrotransfer coefficient at the discharge cathode and the pressure of the plasma-forming medium at its surface were estimated. In the course of the study, the possibility of varying the arc voltage and the electron temperature of the resulting plasma by changing the cathode temperature is demonstrated. It was possible to vary the electron temperature from 0.4 to 1.5 eV. The dependence of the mean charge of the resulting plasma flux on the arc current is measured. Mean charge values of ~0.6*e* have been reached. It has shown that the ionic composition of plasma is mainly represented by $Cr^+$ particles, the proportion of which exceeds 90%. The energy spectra of the ions formed in the plasma are measured. The ion energy spread is at the level of 2 eV, and the most probable ion energy was about 11.5 eV.

**Acknowledgments**

The work was supported by the Russian Science Foundation under grant No. 21-72-00077 (https://rscf.ru/en/project/21-72-00077/).

## 5. References

[1] Liziakin G.D., Antonov N.N., Smirnov V.S., Timirkhanov R.A., Oiler A.P., Usmanov R.A., Melnikov A.D., Vorona N.A., Kislenko S.A., Gavrikov A.V., Smirnov V.P., *J. Phys. D: Appl. Phys.,* **54**, 414005, 2021; doi: 10.1088/1361-6463/ac128e

[2] Usmanov R.A., Amirov R.Kh., Gavrikov A.V., Liziakin G.D., Melnikov A.D., Polistchook V.P., Samoylov I.S., Smirnov V.P., Vorona N.A., Yartsev I.M., *Plasma Sources Sci. Technol.*, **29**, 015004, 2020; doi: 10.1088/1361-6595/ab5f33

[3] Chen F.F., *Phys. Plasmas*, **8**, 3029, 2001; doi: 10.1063/1.1368874

[4] Usmanov R.A., Amirov R.Kh., Gavrikov A.V., Liziakin G.D., Polistchook V.P., Samoylov I.S., Smirnov V.P., Vorona N.A., Yartsev I.M., *Phys. Plasmas*, **25**, 063524, 2018; doi: 10.1063/1.5037674

[5] Polishchuk V.P., Usmanov R.A., Melnikov A.D., Vorona N.A., Yartsev I.M., Amirov R.Kh., Gavrikov A.V., Liziakin G.D., Samoylov I.S., Smirnov V.P., Antonov N.N., *High Temp.*, **58**, 476, 2020; doi: 10.1134/S0018151X20040124

[6] Grigoriev I.S., Meilichov E.Z., *Physical Values, Reference Handbook*. (Moscow: Energoatomizdat, 1991).