Plasma jet characteristics in vacuum arc with diffused cathode spot

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Abstract. Diffused vacuum arc, which is characterized by the absence of microparticles in cathode erosion products and by the irregular voltage oscillations, is considered to be a perspective plasma source for plasma reprocessing technology of spent nuclear fuel (SNF). The development of this technology requires data on ions energy in plasma jet. In this work parameters of plasma jet in diffused vacuum arc with a gadolinium cathode were studied by a retarding field analyzer, Langmuir and condensation probes. Gadolinium is regarded as a substance simulating SNF plasma. Ion energy spectrum was studied at arc currents of 30–75 A and voltages of 4–15 V at the distance of 20 cm above the arc anode. Dependencies of spectrum widths and most possible ion energies on arc voltages were obtained. The measured electron temperature was 2 eV, the maximum ion energy reached 70 eV. Experimental data were used to calculate adiabatic plasma expansion through the anode outlet.

1. Introduction

For the development of any plasma technology it is extremely important to have full information about parameters of used plasma. Nowadays a plasma reprocessing technology of spent nuclear fuel (SNF) is one of dynamically developing technologies. Conversion of condensed SNF in a plasma state with required parameters is one of the tasks that must be solved during the development of this technology. Vacuum arc with stationary diffuse cathode spot (DCS) is considered to be a perspective plasma source for plasma separation technology. This discharge can produce plasma with parameters required for plasma separation, such as high ionization degree (close to 100 %) and average charge of the ions close to unit [1]. The main distinction between a vacuum arc with DCS and contracted vacuum arcs on cold cathodes is a relatively low cathode current density (10–100 A/cm²) that is achieved by a high cathode temperature (up to 2 kK). In these conditions voltage oscillations and technically harmful cathode droplets are absent in the vacuum arc with DCS [2].

Experimental studies of the vacuum arc with DCS on the thermionic gadolinium cathode have demonstrated that plasma generated by this discharge generally satisfied the mentioned requirements for the plasma separation technology [3]. However, the lack of values of ion energies prevents further development of this technology. Calculations [4, 5] show that separation of heavy and light ion groups becomes possible with ion energy about one electron-Volt.

Ion kinetic energies in cathode jets of contracted vacuum arcs were studied for most of the conductive materials from lithium to uranium [6]; these energies varied in the range of 20–150 eV. In this discharge ion energy slightly depends on the arc current and geometry of the electrodes unit. In
the vacuum arc with DCS on a thermionic cathode there is a possibility of arc voltage control by changing of the cathode temperature and correspondingly saturated vapor pressure. Thus, ion energies behavior in vacuum arc with DCS is very attractive. The main purpose of our work was to study an after anode plasma characteristics on the gadolinium cathode, including the dependence of ion energies on arc current and voltage. Also, it should be noted that properties of vacuum arcs on gadolinium and uranium cathode are quite similar [3].

2. Experimental

The scheme of the experiment is shown in figure 1. The discharge was initiated in the vacuum chamber with residual gas pressure below 10 mPa. A rectifier with an output voltage of 380 V was used as an arc power supply. Gadolinium (arc cathode) was placed in a heat-insulated molybdenum crucible with the height of 14 mm and external diameter of 25 mm. The diameter of the crucible outlet was 14 mm. Under the crucible there was an electron-beam heater (EBH) which allowed cathode temperature alteration at fixed arc current. The increasing in EBH power caused the decrease in the arc voltage $U_a$ at the constant current $I$. A water-cooled steel disk, 26 mm thick with a centered 15 mm hole, was used as an arc anode. The diameter of the anode was 130 mm. The distance between electrodes was about 30 mm. The cathode temperature was measured by a brightness-temperature pyrometer. Estimated difference between measured and average temperature of the cathode surface was less than 3%. In experiments the cathode temperature was in a range of 1.9–2.0 kK. At these temperatures gadolinium saturated vapor density changes within the limits of $10^{14}$–5*10$^{14}$ cm$^{-3}$ [7].

After-anode plasma parameters (electron temperature, plasma potential and average charge of heavy particles) were measured by Langmuir and condensation probes. Ion energy spectrum was registered by a retarding field analyzer (RFA) that consists of a multi-grid probe with two 0.02x0.02 mm mesh size grids and a collector plate. The electron reflecting grid was biased at -60 V, and collector potential was varied from -30 to +30 V. The distance between both grids and collector was 0.5-1 mm. The diameter of the collector was about 30 mm. Note that in the described configuration this RFA could operate at plasma densities in the range of $10^9$–$10^{11}$ cm$^{-3}$.

RFA was placed at the distance of 20 cm above the anode along the discharge axis. A Langmuir probe was located close to the RFA outlet for plasma potential measurement. I-V curve for the Langmuir probe was processed using a standard method [8]. These data were used for RFA I-V curve processing and correction of ion energy spectrum shift on plasma potential where the analyzer was located.

![Figure 1. Experimental setup.](image)

3. Experimental results

Typical plasma potential and electron temperature dependencies on arc voltage measured by a Langmuir probe at arc current $I = 50$ A are shown in figure 2. Similar results were obtained for other
arc currents. At $I = 30$ A plasma potential monotonically rises from 4 to 6 V, and electron temperature increases from 0.5 to 1.7 eV. At $I = 75$ A the increase in the arc voltage from 5 to 12 V causes the plasma potential growth from 3 to 4 V and electron temperature increase from 0.5 eV to 1.3 eV.

**Figure 2.** Plasma potential and electron temperature dependencies on arc voltage at a distance of 20 cm above the anode at arc current $I = 50$ A.

Figure 3 shows the measured ion energy distributions at arc current $I = 50$ A. Figure 4 demonstrates the ion energies measurements (excluding ion charge state) in dependence on arc voltage at currents of 30, 50, 75 A. In different regimes values of most probable ion energies are in range of 3 – 20 eV, which significantly exceeds thermal energy of evaporated gadolinium atoms. Plasma density was determined from measured ion energy and ion saturation current of the Langmuir probe. At the distance of 20 cm above the anode at arc currents from 30 to 75 A the density of plasma was in a range of $3 \cdot 10^9 – 1.5 \cdot 10^{10}$ cm$^{-3}$.

**Figure 3.** Ion energy distribution functions, $I = 50$ A.

**Figure 4.** Most probable and maximum ion energies at the distance of 20 cm above the anode (excluding ion charge state).

**Figure 5.** True plasma ion energies at arc current of 50 A. Average ion charge of gadolinium plasma.

Energy values showed in figure 4 were obtained excluding the ion charge state. According to work [3] in the studied discharge the double charged gadolinium ions appear in plasma at arc voltages above 6 V. In figure 5 there is a true ion energy dependence considering its average charge at arc current of 50 A [3]. The approximation of average ion charge versus arc voltage from [3] is shown in the upper right corner of figure 5.
According to [9] ion kinetic energies in a contracted vacuum arc on a gadolinium cathode are higher than our mean values and reach 50 eV at arc voltage of 20 V and electron temperature of 1.7 eV. The same inequality in values of ion energies was observed in [10] where both arc regimes were studied on a carbon cathode – cathodic spot arc and cathodic distributed arc. By [10] most probable ion energy value in a cathodic spot arc was 25 eV (at arc voltage of 20 V) and in cathodic distributed arc it was 20 eV (at arc voltage of 30 V). Arc current in both cases was equal to 60 A and carbon ions remained mostly single charged.

4. Estimations of after anode arc plasma parameters
Calculation of plasma jet parameters is needed for practical application. The whole area of arc plasma flow can be divided into three regions. The first region covers a discharge gap where supersonic plasma jet is formed. The second region is an anode hole and the third region extends from the anode to a collector which receives a plasma jet. One of the important distinctions of plasma processes in these regions is a nature of current changing. In the first region it remains constant along the region length. In the second region current is consumed by the anode and therefore it decreases toward the anode outlet. In the third region current can be practically absent. Exactly such a case was realized in our experiments. The leakage current on chamber walls was less than 2 mA, and apparently its main part was formed between the cathode and anode where plasma density is high enough.

As current changing nature in described significantly different regions, they can be considered separately and obtained solutions can be connected on the borders. In [11] two-temperature flow the model of fully ionized gadolinium plasma with fixed ion charge \( z_i \) was described. A quasi-one-dimensional approach for averaged values over the flow cross section was used. The considered discharge geometry was close to the one used in our experiment. According to [11] as moving away from the cathode in plasma jet decreases faster than magnetic forces which contract it. After jet pinching its cross section \( F(x) \) is determined by discharge parameters. The cross section \( F(x) \) dependency on discharge parameters could be established as a result of jet pinching. Pinching of plasma jet leads to a qualitative change of plasma flow behavior. If the effect of magnetic forces is neglected the diffusive charge transfer dominates as moving away from the cathode – plasma potential decreases and electron temperature strives for zero. Pinching causes a weak rise of plasma potential and electron temperature.

In this work we used a model [11] for calculation and observed only after anode plasma. Boundary conditions for this region are specified by plasma parameters in the discharge gap and after anode area. After the anode current in plasma is absent, therefore adiabatic expansion of plasma cloud takes place, and ion kinetic energy increases on account of electron enthalpy.

Further it is considered that plasma stream after anode is supersonic (Mach number \( M_0 \) is greater than unit) and it expands in a channel with a specified cross section \( F(x) \). Ionization and recombination processes in plasma can be neglected, so ion charge \( z_i \) remains constant and the ratio of electron \( T_e \) and ion temperature \( T_i \) along the jet does not change.

Changing of Mach number along the channel length \( M \) can be found from the solution of the differential equation [11]:

\[
\frac{M^2 - 1}{M^2 (1 + M^2 / 3)} \frac{dM^2}{dx} = \frac{2}{F} \frac{dF}{dx}
\]  

(1)

Solution of (1) is:

\[
\frac{F(x)}{F_0} = \frac{M_0}{(1 + M_0^2 / 3)^2} \frac{(1 + M^2 / 3)^2}{M}
\]  

(2)

Relation \( F(x) = F_0 (1 + x^2 \tan^2 \alpha) \) was considered as a channel cross section where \( F_0 \) is an area of anode outlet and \( \alpha \) is a jet opening angle. From (2) using selected stream geometry a distribution of all main plasma parameters can be obtained.
Electron temperature along the stream is:

\[
T_e(x) = \frac{1 + M_0^2 / 3}{1 + M^2 / 3}
\]

(3)

Ion kinetic energy \(W_i\) [11] is:

\[
W_i = \frac{m_i u_i^2}{2} = \frac{5}{6} M^2 (T_i + z_i T_e)
\]

(4)

Its changing along the channel length is:

\[
\frac{W_i(x)}{W_i} = \frac{M^2 1 + M_0^2 / 3}{M_0^2 1 + M^2 / 3}
\]

(5)

Electron density is:

\[
\frac{n_e(x)}{n_e} = \frac{F_0}{F(x)} M \frac{1 + M^2 / 3}{1 + M_0^2 / 3}
\]

(6)

Plasma potential distribution along the jet length is:

\[
\varphi(x) = \varphi_0 - \frac{5}{2e} (T_{e0} - T_e(x)) = \varphi_0 - \frac{5}{6e} T_{e0} \frac{M^2 - M_0^2}{1 + M^2 / 3}
\]

(7)

where \(\varphi_0\) is plasma potential in anode outlet which is approximately equal to anode potential.

![Figure 6. Calculated distributions of plasma potential \(V(x)\) and ion kinetic energy \(W_i(x)\) in after anode area.](image)

After anode plasma parameter distributions obtained with the help of (1)-(7) are shown in figures 6 and 7. Values of free parameters \(M_0 = 1.5\), \(t g \alpha = 0.05\), \(T_{e0} = 0.2\) eV were selected to coincide with experimental data at the distance of 20 cm above the anode. Value \(\varphi_0 = 10\) В is selected for the corresponding arc regime, \(T_{e0} = 3\) eV is selected according to the measured electron temperature within the discharge gap from [3].

5. Conclusion

In conclusion let us list our main results. Ion energy distribution of after anode plasma in a vacuum arc with DCS on a gadolinium cathode was measured. It was concluded that external cathode heating allows to change ion energy in the range of 4-70 eV at arc voltage of 4-14 V, under arc current of 30-75 A. It was noted that in a vacuum arc with DCS ion energies are less than in a contracted arc.
Overall, obtained experimental results on plasma jet characteristics satisfy requirements of plasma separation technology at low arc voltages [1].

![Graph showing calculated distributions of electron density $n_e(x)$ and electron temperature $T_e(x)$ in after anode area.]

**Figure 7.** Calculated distributions of electron density $n_e(x)$ and electron temperature $T_e(x)$ in after anode area.

Experimental data were used to analyze adiabatic plasma expansion through the anode outlet. Calculated results allowed us to estimate distributions of plasma potential, plasma density, ion kinetic energy and electron temperature along the discharge axis in the whole area behind the anode. These data could be used in the development of plasma sources on the base of a vacuum arc with DCS.

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