The study of the plasma jets of lead and silver simulating spent nuclear fuel components

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Abstract. One of the tasks that must be solved to develop a spent nuclear fuel (SNF) plasma separation method is a creation of plasma source of substances simulating SNF components. Plasma of the diffuse arc discharge in a magnetic field with an incandescent cathode was considered in this paper, as such source. The discharge was initiated in a model substances vapor (lead and silver). Evaporation was carried out by crucible induction heating. Current–voltage characteristics of the discharge were obtained. Spectral analysis of the plasma jets radiation and double probe characteristics measurements in the area behind the anode were carried out. The minimum potential difference between the anode and cathode reached a value of about 7 V at current of about 1 A. When the potential difference in the discharge gap was close to 30 V (4.5 A) and 10 V (5.2 A) electron temperature in the plasma jet was 5–7 eV and 1–3 eV, respectively. Plasma density in jets took the value from $10^{11}$ cm$^{-3}$ to $10^{12}$ cm$^{-3}$. The obtained results indicate the possibility of using this type of discharge for the SNF plasma separation method approbation.

1. Introduction

Plasma sources of model substances are needed for the experimental testing of the spent nuclear fuel (SNF) plasma reprocessing method [1,2]. The plasma separation concept, that was proposed in [3–5], can be divided into 3 main stages: the transfer of solid matter into the cold plasma flow, the separation of elements by groups of masses in a special configuration of the electric and magnetic fields, the collection of separated substances into collectors. The method implies that the plasma flow should consist of low-energy ($\leq 10$ eV) singly ionized ions and the degree of ionization should be close to 100%.

Within the framework of the one-particle approximation, the principal possibility of a spatial separation of fluxes with different masses during the injection along magnetic field lines of force (2 kG) into a special electric field configuration was demonstrated previously [6]. Arc discharge is the one of the most promising ways to create such flows.

Let us take notice, that for plasma sources, which operation principle is based on the use of a contracted arc discharge [7–9], the droplet phase [10] is inherent. This leads to the formation of a significant mass of non-ionized substance in the flow. Furthermore, in such discharges the potential difference oscillations, leading to the appearance of ions of different multiplicity [11,12], are observed. Both these factors are unacceptable within the framework of the SNF plasma separation concept.
Figure 1. Scheme of the experiment: 1—crucible; 2—inductor; 3—thermionic cathode; 4—vapor of the model substance; 5—annular anode; 6—collector; 7—double probe; 8—photo of a plasma jet near the anode.

A vacuum-arc discharge with diffuse cathodic binding is deprived of similar problems. In the work [13], the arc operation mode was demonstrated, where predominantly singly ionized plasma with degree of ionization close to 100% was observed (the working substance is gadolinium, the atom–electron ratio is \( \xi \approx 0.05 \) [14]). This was achieved due to the external cathode heating, allowing to increase thermionic current. It was shown [15] that it is not possible to achieve similar parameters using cathodes with low thermal emissivity with respect to the evaporation rate (lead \( \xi \approx 10^8 \)). Let us note that some investigation results of non-self-sustained discharge in lead vapor with injection of thermionic electrons were presented in [16].

The analysis of the given above studies allowed to select the plasma generation mechanism and the plasma source design for the SNF and radioactive wastes (RW) plasma separation method working off. The source was created on the basis of a diffuse arc discharge in a magnetic field with an incandescent cathode. The main feature of the created device is independence of the thermionic injection (thermocathode) and substance vapor injection (crucible induction heating). The lead (207 u), simulating the heavy component of SNF, and silver (108 u), simulating the fission products of actinides, were chosen as a plasma-forming substances. The results of the studies of the magnetized plasma jets parameters in the area behind the anode are presented in this paper.

2. Experiment and results

The scheme of the experiment is shown on the figure 1. The investigated model substance was placed in a crucible, which was heated by electromagnetic induction. Generator power was about 2.5 kW. Crucible volume was about 10 cm\(^3\). LaB\(_6\) (diameter is 6 mm) was used as thermionic cathode. Variation of the cathode heating power allowed to change quantity of the electrons injected into the discharge gap, and variation of the crucible heating power allowed to change number of the injected atoms of the model substance.

During the experiments, cathode was grounded and a potential up to 200 V was maintained on the cooled annular anode. The distance between the cathode and the anode was about 50 mm. The discharge current was limited by a ballast resistance of 26.5 \( \Omega \). In the area behind the
Figure 2. CVCs of the discharge in silver vapor at concentrations $n_1 > n_2$. Thermionic cathode heating power was fixed.

anode, a collector and a double probe were installed for the magnetized plasma jets diagnostics. The experiment was carried out as follows. Thermionic cathode and model substance (mass was near 20 g) were heated at the residual argon pressure at the level of $1 \times 10^{-5}$ Torr. Model substance concentration increase in discharge gap led to the discharge current increase and to potential difference reduction (thermionic cathode heating power and potential difference at the constant–voltage source were fixed). Current–voltage characteristics (CVC) of the discharge for the two concentrations ($n_1 > n_2$) are shown on the figure 2. Concentration $n_1$ corresponds to the crucible heater power of about 2.15 kW, and concentration $n_2$ corresponds to crucible heater power of about 2 kW. The potential difference at the constant–voltage source was varied from 30 V to 200 V. The magnetic field induction was 650 G.

In the next stage of the experiment, two stationary modes were set by varying the crucible heating power: the first one was the discharge with the potential difference 30 V (discharge current was 4.5 A), the second mode corresponded to a voltage of 13 V and current of 5.2 A. In each of these modes studies of the spectral, double probe and collector CVCs of the plasma jet were carried out. The plasma jet diameter was about 10 mm. The measurements were carried out at a distance of 200 mm behind the anode. A typical experimentally obtained double probe CVC corresponded to a potential difference in the discharge gap of 30 V is shown on the figure 3.

The experimental data processing showed that electron temperature in the plasma jet at a potential difference between cathode and anode of 30 V and 13 V was in the ranges of 5–6 eV and 1–2 eV, respectively. The plasma density in both modes was in the range from $10^{11}$ cm$^{-3}$ to $10^{12}$ cm$^{-3}$.

The results of the plasma jet radiation spectral study in the region behind the anode (see figure 4) showed the presence of atomic lines (AgI) and lines of singly charged ions (AgII).

The collector CVC is shown on the figure 5. Potential difference between the thermionic cathode and the anode was fixed (13 V). Figure 5 shows that the maximum collector ion current
Figure 3. Double probe CVC at the discharge potential difference about 30 V. Electron temperature was about 5 eV, and plasma density was at the level of $2 \times 10^{11} \text{ cm}^{-3}$.

Figure 4. Plasma jet radiation spectrum (blue curve). Discharge potential difference was about 30 V. The radiation spectrum was recorded near the anode close to the source outlet. The silver spectral lines (green and red dashed lines) were taken from the atomic spectra database of the National Institute of Standards and Technology (NIST).

was about 55 mA. The same series of the experiments were carried out with lead as a working substance. When the potential difference in the discharge gap was close to 30 V (4.5 A) and
Figure 5. Collector CVC. Discharge potential difference was about 13 V.

13 V (5.2 A), electron temperature in the plasma jet was 6–7 and 2–3 eV, respectively. At a potential difference of about 30 V, lead ions of multiplicity +2 (the ionization potential of 15 eV) were found near the anode in the plasma radiation spectrum.

3. Discussion

It is necessary to note that experimentally obtained plasma jets densities \(10^{11}–10^{12} \text{ cm}^{-3}\) are optimum for plasma separation method approbation.

Indeed, one of the stages of the SNF or RW plasma separation method, as mentioned earlier, implies the separation of equally charged ions by mass in a special configuration of electric and magnetic fields [5, 6, 17]. For this purpose, a plasma jet of the separated substances is supposed to be injected into the buffer plasma. The buffer plasma with magnetized electrons is significant in this process. Firstly, the space charge compensation problem of the separated ion flux can be solved, with its help, in contrast to electromagnetic methods [18]. In other words, buffer plasma allows to obtain productivity, of interest from an industrial point of view, with energy consumption at an acceptable level [5, 7, 19–21]. Secondly, the magnetized buffer plasma allows to create spatial potential distribution in its volume, required for the separation of substances. This possibility arises from the fact that the electrons mobility along the magnetic lines of force considerably surpasses their mobility across the magnetic field. If the electrodes under the same potentials are immersed in such plasma (symmetrically at the ends of cylindrical vacuum chamber), then the electrodes potential propagates into the buffer plasma volume along the magnetic lines of force [22–25]. Collisions absence between plasma particles is important for creation potential distribution and for the unobstructed motion of separated flows across the buffer plasma volume. The collisionlessness requirement gives a restriction on the buffer plasma density \(n < 10^{13} \text{ cm}^{-3}\) [5, 17] (a characteristic size of separation area is 1 m).

As a summary of the foregoing, it can be stated that the plasma jets of the separated substance must move in a magnetic field and electrostatic potential of a given shape through a buffer plasma with a concentration about \(10^{13} \text{ cm}^{-3}\). Without any doubt, electrostatic potential should not
be distorted by the plasma jets propagation. The fulfillment of this requirement should be expected in conditions when the plasma jet density is much less than the buffer plasma density. The plasma jets densities of separated substances at the level of $10^{11}–10^{12}$ cm$^{-3}$ are preferable.

4. Conclusions

The analysis carried out in this work allowed us to propose and study a diffuse arc discharge with a thermionic cathode in a magnetic field as a plasma source of model substances for testing the SNF plasma separation method.

The discharge CVCs were obtained, and the spectral analysis of the plasma jets radiation and double probe characteristics measurements in the area behind the anode were carried out. The mechanisms of controlling the discharge parameters (potential difference, discharge current, electrons temperature) were described and demonstrated.

Conditions were defined, under which ions of multiplicities greater than one are absent in the plasma jets. The obtained data on the diffuse arc discharge characteristics in a magnetic field in lead and silver vapor are as fundamental, as practical. They allowed drawing a conclusion about the possibility of using this plasma generation mechanism for the tasks of the experimental testing of the SNF plasma separation method.

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