Diffuse arc discharge with a hot cathode in a magnetic field as a plasma source of lead and silver mixture for the problem of spent nuclear fuel reprocessing

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Abstract. Conversion of a solid substance mixture into a low-energy (≈ 10 eV) plasma stream with stable parameters is a one of the important tasks for the developing nowadays method of plasma separation. The study of plasma stream characteristics of Pb and Ag mixture was carried out. The evaporation of the substances was realized using induction crucible heating. The discharge was initiated by an electron beam. A variation of the thermionic cathode (LaB$_6$) temperature and the crucible heater power allowed us to control the parameters of the discharge. It was shown, that maintaining a constant potential difference in the cathode-anode gap, in spite of the substantial difference in the saturated vapor pressure of model substances, is possible due to control of the thermionic current from the cathode and constant voltage power supply parameters. Measurements of the spectral composition of plasma radiation made it possible to determine the discharge burning regimes in which ions of multiplicity 2 were absent. The obtained results indicate a possibility of using this type of discharge for testing the method of plasma separation of spent nuclear fuel.

1. Introduction
Today, nuclear energy needs to update approaches and improve technologies related to processing, transportation and storage of spent nuclear fuel (SNF). A production capacity of existing technologies can carry out processing of all fuel removing from reactors, but only extensively with the production of additional liquid wastes of varying radioactivity. For this reason, a problem of SNF processing alternative methods development is relevant. Nowadays among the processing methods under development can be distinguished gas-fluoride, pyroelectrochemical and plasma separation [1–4]. The plasma separation concept can be divided into 3 main stages: a transfer of solid substance into a plasma stream, a separation of elements by groups of masses in a special configuration of the electric and magnetic fields in a buffer plasma, a collection of separated substances into collectors. The method implies that the plasma flow should consist of low-energy (≈ 10 eV) singly ionized ions and the degree of ionization should be close to 100% [4–6]. An important feature of the method under development is the compensation of the separated stream space charge in the buffer plasma of the high-frequency discharge (frequency is about 5 MHz, residual gas pressure from $1 \times 10^{-3}$ to $1 \times 10^{-5}$ Torr, magnetic field induction up to 2 kG) [7].
2. Experimental setup and results
The scheme of the investigated plasma source is shown in figure 1. The powder mixture of model substances was placed in a crucible, which was heated by electromagnetic induction. Silver and lead were mixed in the same mass ratio. During the experiments, cathode was grounded and a potential up to 200 V was maintained on the cooled annular anode. Variation of the cathode heating power allowed us to change quantity of the electrons injected into the discharge gap, and variation of the crucible heating power allowed changing number of the injected atoms of the model substances. The experiment was carried out as follows. Thermionic cathode and model substances (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 dc voltage source were fixed). On the way of the plasma stream propagation a collector (potential is of about $-80$ V) was placed. The results of the studies of the plasma source current-voltage characteristics and the parameters of the directed streams of a single-component silver and lead plasma are presented in [12].

The first series of experiments demonstrated that when the crucible is heated steadily, the evaporation of the substances occurs sequentially, according to the dependence of the saturated vapor pressure on temperature (Ag—100 Pa at 1569 K; Pb—100 Pa at 1229 K) [13]. Figure 2 shows the dependencies of the potential difference between electrodes, the ion current coming
Figure 2. Experiment with a smooth increase of the crucible heating power, where the plasma-forming substance is a mixture of silver and lead.

Figure 3. Experiment with an abrupt increase of the crucible heating power, where the plasma-forming substance is a mixture of silver and lead: the increase of the potential difference of the dc voltage source \( t \approx 450 \) s; the increase of the discharge voltage due to the vapor concentration reduction \( t \approx 450–900 \) s; control of the discharge voltage by the thermal emission of the cathode \( t \approx 900–1400 \) s.

to the collector, and the crucible heating power on the time of the experiment. This graph shows that to maintain the constant potential difference between the cathode and the anode
(using a multicomponent plasma-forming substance), it is necessary to make a selection of the appropriate mixture heating regimes, the incandescence thermionic cathode heating regimes, and to manage the potential difference in a dc voltage source that supports the arc discharge.

Figure 3 presents the results of the experiment in which heating of the mixture was carried out in a complex way. The presented graph emphasizes the possibility of controlling the potential difference of the arc discharge by varying of 3 parameters: the potential difference of the dc voltage source, the crucible temperature (saturated vapor pressure) and the temperature of the thermionic cathode (injection of additional electrons). An abrupt increase of the discharge voltage ($t \approx 450$ s in figure 3) is caused by deliberate increase in the potential difference at the dc voltage source, supporting the discharge. In the next time interval ($t \approx 450–900$ s in figure 3), a smooth increase in the potential difference between the cathode and the anode is caused by a lead vapor concentration decrease in the discharge gap. At $t \approx 900$ s of the experiment, the crucible heating power was abruptly increased to 2 kW. This led to a significant decrease of the discharge voltage. Further ($t \approx 900–1400$ s in figure 3), the voltage was kept constant by controlling the heating power of the thermionic cathode (additional injection of thermoelectrons). It should be noted that varying the number of additional electrons injected into the discharge gap allows us to change an atom-electron ratio. Influence of this parameter on the diffuse arc-discharge properties was shown in [14, 15].

The results from measurements of spectral lines intensity of silver Ag I (328.2, 521.1 nm), Ag II (462.1, 540.1 nm) and lead Pb I (357.3, 374.1 nm), Pb II (371.4, 504.4 nm), Pb III (385.5, 476.3 nm) (experiment in figure 3) near the anode (denoted by 8 in figure 1) are shown in figures 4 and 5, respectively.

It is seen from the presented graphs (see figures 4 and 5) that there are discharge burning regimes in which only the spectral lines of atomic and singly ionized silver and lead particles were detected in the formed plasma stream. The obtained data allow us to determine the upper boundary of the discharge voltage from the point of view of satisfying the requirement of the charge composition of the plasma stream.

Figure 4. The results of spectral lines intensity measurement (silver).
3. Conclusion
The results of the study of the plasma source operation modes based on a non-self-sustaining arc discharge with incandescent cathode in a magnetic field were presented. Mixture of silver and lead was used as a plasma-forming medium. The mechanisms of maintaining a constant potential difference between the cathode and the anode, in spite of significant difference in the dependence of the saturated vapor pressure on temperature and atom-electron ratio of one component of the mixture from another, are proposed and presented in this paper. The ability to control the discharge parameters and their weak dependence on the composition of the plasma-forming medium is a key feature of the created plasma source, since the developed method of plasma separation implies the conversion of a multicomponent mixture into a plasma stream. Measurements of the spectral composition of plasma radiation made it possible to determine the discharge burning regimes in which ions of multiplicity 2 were absent. The obtained results indicate the possibility of using this type of discharge for testing the method of plasma separation.

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References
[1] Zhiltsov V A, Kulygin V M, Semashko N N, Skvorodona A A, Smirnov V P, Timofeev A V, Kudryavtsev E G, Rakhkov V I and Orlov V V 2006 At. Energy 101 755–9
[2] Litvak A et al 2003 Archimedes plasma mass filter 30th EPS Conf. on Controlled Fusion and Plasma Physics. Book of Abstracts ed Koch R and Lebedev S (St Petersburg: European Physical Society) pp O–1.6A
[3] Bardakov V M, Kichigin G N, Strokin N A and Tsaregorodtsev E O 2010 Tech. Phys. 55 1504–8
[4] Samokhin A A, Smirnov V P, Gavrikov A V and Vorona N A 2016 Tech. Phys. 61 283–9
[5] Gavrikov A V, Sidorov V S, Smirnov V P and Tarakanov V P 2018 J. Phys.: Conf. Ser. 946 012172
[6] Amirov R Kh, Vorona N A, Gavrikov A V, Liziakin G D, Polistchook V P, Samoylov I S, Smirnov V P, Usmanov R A and Yartsev I M 2015 Phys. At. Nucl. 78 1631–4
[7] Gavrikov A, Kuzmichev S, Lizyakin G, Smirnov V, Timirkanov R, Usmanov R and Vorona N 2017 EPJ Web Conf. 157 03062
[8] Amirov R Kh, Vorona N A, Gavrikov A V, Lizyakin G D, Polishchuk V P, Samoilov I S, Smirnov V P, Usmanov R A and Yartsev I M 2015 Plasma Phys. Rep. 41 808–13
[9] Antonov N N, Gavrikov A V, Samokhin A A and Smirnov V P 2016 Phys. At. Nucl. 79 1625–31
[10] Musa G S, Ehrich H and Schuhmann J 1997 IEEE Trans. Plasma Sci. 25 386–91
[11] Borisenko A G, Saenko V A and Rudnickij V A 1999 Teplofiz. Vys. Temp. 37 5–12
[12] Antonov N N, Gavrikov A V, Smirnov V P, Usmanov R A, Lizyakin G D, Vorona N A and Timirkhanov R A 2018 J. Phys.: Conf. Ser. 946 012171
[13] Grigor’ev I S and Melikhov E Z 1991 Physical Quantities: Reference Book (Moscow: Energoatomizdat)
[14] Polistchouk V P, Serdyukova O K and Yartsev I M 1993 Zh. Tekh. Fiz. 63 66–74
[15] Amirov R Kh et al 2017 IEEE Trans. Plasma Sci. 45 1407