GAS-METAL PLASMA SOURCE PROJECT FOR THE SEPARATION TECHNOLOGY

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This scientific paper deals with the project related to the gas-metal plasma source design. It describes the structure and electric power supply circuit. The consideration has been given to a possibility of the use of this source for the separation technology, in particular for the reprocessing of spent nuclear fuel (SNF). The requirements set to the source and parameters of the generated plasma have been devised. The efficiency of magnetoplasma reprocessing of SNF has been evaluated and the selection of metals and their oxides as the simulation media for the experiments carried out to reprocess spent nuclear fuel have been substantiated.

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1. INTRODUCTION

Nuclear power stations generate 50% of electric power in Ukraine, and annually about $300\,t$ of spent nuclear waste are formed. At the moment $4000\,t$ of nuclear waste have been piled up and by the year 2050, when the number of the reactors will double, the quantity of spent NF will reach 40000 tons. The service life period of the dry storages of nuclear waste in Ukraine is considered to be 50 years. By the year of 2070, when the uranium ore reserves will be depleted, we inevitably will be forced to recycle spent nuclear waste into the fuel. Already today the world arranged the production of MOX-fuel using Purex technologies. However, the use of Purex technologies in Ukraine is hardly possible due to the need of huge consumption of fresh water. The spent nuclear fuel can be reprocessed using electromagnetic separators, but it is very energy-expensive $3.5{\cdot}10^6\,eV/ion$, in addition to reprocess $300\,t$ of NF ion currents of $4.5\,kA$ are required. To reprocess SNF of one reactor that discharges approximately $20\,t$, we need equivalent ion currents of about $300\,A$. It means that we need separators of a new generation of higher performance and lower power inputs. The magnetoplasmic method can be used as an alternative technique, which is very similar to the electromagnetic method as for the principles. The [1] proposes energy inputs for the nuclear waste reprocessing at the level of $500...1000\,eV/ion$. The values that were experimentally obtained at the level of $10^4\,eV/ion$ are given in [2].

2. PROBLEM OF STATEMENT

The SNF plasma is a physically complicated and expensive test object. Therefore, for the purpose of research the SNF is simulated with a different degree of approximation with regard to some properties. In scientific papers [3] the plasma of inert gases simulated SNF in terms of mass composition. Now we need to simulate the entire set of physical and chemical specific features of SNF including elemental composition and molecular composition, ionization potentials of elements and compounds and chemical bonds. The present stage includes the generation of metal plasma, its transportation, ion-plasma separation and deposition with further removal of the fallout. The degree of the separation of nuclear fuel (NF) and nuclear ash (NA), i.e. fission products, and also the relation of this value to the parameters of the separation plant is of essential value. The separator efficiency can be evaluated using the expression (1)

$$P = \sum_k M_k \Delta\mu_k V_k^{\parallel} n_k^i \alpha S t\,. \qquad (1)$$

The summation here is done in terms of separable elements, M_k is the atomic weight of the element or isotope, μ_k is its percentage, $V_k^{\parallel}$ is the longitudinal velocity of plasma ions, n_k^i is the concentration of plasma ions, S is the plasma section, α is the efficiency of ion separation, t is the operation time. The coefficient α is always less than unity and it is a combined ratio and depends on many parameters. The equation shows that the separator efficiency is mainly defined by the material flow, i.e. the values of n_k^i, $V_k^{\parallel}$, S that in their turn are defined by the flow of evaporated or sputtered material. The mass of material evaporated per time unit by the surface S: $G = \alpha q_{evp}$, where α is the coefficient that takes into consideration the reverse precipitation of evaporated material because of the scattering onto the surface vapor cloud, q_{evp} is the evaporation rate of substances with the atomic weight of A ($g\ cm^{-2}\ c^{-1}$), which obeys the Langmuir equation: $q_{evp} = 4.4 \cdot 10^{-4}(A/T)^{0.5} p_s$, where $p_s = K1 \cdot \exp(K2/T)$ is the vapor tension of the ma-

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terial. The coefficients $K1$ and $K2$ depend on the material and at similar values of q_{evp} for different A can differ greatly. In the general case the evaporation rate of the i–th component from the mixture is related to the partial pressure of its vapors at the surface p_i, and $p_i = \gamma_i p_{si} c_i / A_i$, where c_i is the weight concentration of the components, γ_i is the activity factor that takes into account the possibility of interaction of different components in the melt. For the two-component alloy, for example: $q_{evp1}/q_{evp2} = (A_2/A_1)^{0.5}\gamma_1 p_{s1} c_1/\gamma_2 p_{s2} c_2 - \alpha_{12} c_1/c_2$, where $\alpha_{12} = \gamma_1 p_{s1}(A2/A1)^{0.5}/\gamma_2 p_{s2}$ is the coefficient of the mixture evaporation.

The density of extracted ion current flowing to the negative probe placed into plasma can be given by the expression [4]

$$j_+ = 0.4 e n_+ \sqrt{\frac{2kT_e}{M}}\,[A/cm^2]\,. \qquad (2)$$

Where n^+ is the concentration of ions, T_e is the temperature of electrons; M is the element mass or isotope mass. It can be seen from the expression that the current density is decreased in inverse proportion to the square root as the mass increases. In the expression (1) the current density therefore in spite of diminishing ion current with an increase in the ion mass the separator efficiency will be increasing in direct proportion to the root of the atomic mass of the released element. Therefore, the design capacity of the plant DIS-1 [5, 6] (at $S = 10^3\,cm^2$, $n_i = 10^{11}\,cm^3$, $\alpha = 1$, $T_i = 3\,eV$) will make in terms of ${}^6Li$ – $21,5\,kg/year$, in terms of ${}^{132}Xe$ – $101,5\,kg/year$, and in terms of ${}^{\sim 240}U$, Pu – $137\,kg/year$.

3. SELECTION OF PARAMETERS

Most parameters included in the separator efficiency expression are the characteristics of the plasma flow tobe created and transported to the separation region. Therefore, the primary task is to create the plasma source (PS), which can generate the plasma flow that meets the requirements of the separation technology. The plasma source should:

1. efficiently ionize the broad spectrum of elements and compounds, in particular metals and their oxides;

2. create a heavy-current highly ionized plasma flow with and/or without minimum drop phase;

3. generate plasma with low electron temperature that will reduce the share of multicharged ions and it will also allow us to use the separation mechanism in terms of ionization potentials;

4. facilitate the formation of films that have low adhesion to the surface of gathering collectors and that of plasma source;

5. the source must operate in the external magnetic field of the separator;

6. withstand plasma and heat loads born by structural materials in stationary or pulse modes.

The selection of gases, metals or metal oxides as the simulation media is defined by the availability of appropriate plasma sources. While working with the gaseous working substance at partial gas ionization in the plasma source the degree of ionization is $\sim 15\%$. Due to the reprocessing process the role of ion-neutral collisions and the possibility of ionization in the separation region is increased during separation and transportation processes. Hence, it is reasonable to change for the metals with the recycling coefficient close to zero. Such metals will be condensed on the walls with the probability of about 100%. The creation of metal plasma requires an efficient evaporator that would provide the generation and transportation of metal vapor to the ionization area. Thereat the drops and clusters are not desirable due to the longer free path until the total ionization takes place in comparison with that of individual atoms. The efficient evaporation of the anode material can be carried out either as described in the scientific paper written by A.G. Borysenko [7] or out of the liquid phase obtained using the laser, inductive and E-beam heating. As simulation media we consider metals Ca, Al, Cu, Mo, Ba and oxides CaO, BaO, MoOn , where $n = 1, 2, 3$.

To create highly ionized plasma we need to generate plasma of such a size and density at which actually all the neutrals getting into it would ionize. The decay of the flow of neutral atoms N_0 in plasma of a length x can be evaluated using the ratio: $N = N_0 \exp(-x/\lambda)$, where λ is the free pass of an atom before the ionization. At plasma sizes of $r_p = \lambda$ the pass will be covered by 37% of injected atoms. The length 5λ will be covered only by $0,67\%$ of atoms, which corresponds to quasicomplete ionization of SNF in plasma sources with $2r_p \sim 30\,cm$, at plasma density level of $n_e \sim (3...4)\cdot 10^{14}\,cm^{-3}$. To meet the condition of the plasma collisionlessness in the separation region the required characteristic dimension of the separation area should be $2\,m$.

4. PLASMA SOURCE STRUCTURE

The requirements set to the plasma source can be met for the high-current, reflective and dense discharge with low electron temperature. To implement such a discharge we propose to use the source with the non-self-maintained arc discharge in anode vapors combined with reflective discharge in the mirror ratio magnetic field. To increase the plasma density we provided for the pulse operation mode of the source with the discharge current of approximately $1\,kA$. The source and test desk are schematically shown in Fig.1. The vacuum chamber 1 that was fabricated using nonmagnetic stainless steel of $30\,cm$ and $50\,cm$ long is cooled by water. The magnetic coils 6 create magnetic field of the mirror ratio configuration with the peak intensity of up to $300\,Oe$. The anode 2 is water-cooled with the replaceable head made of the evaporated substance. The electrodes of the reflective (Penning) discharge 4 are made of copper with diameter of $20\,cm$. The vacuum system maintains pressure at the level of $10^{-5}\,torr$. The working portion of the anode can be evaporated in several ways: a) laser; b) electron beam from the top; c) electron beam from the bottom; d) induction heating.

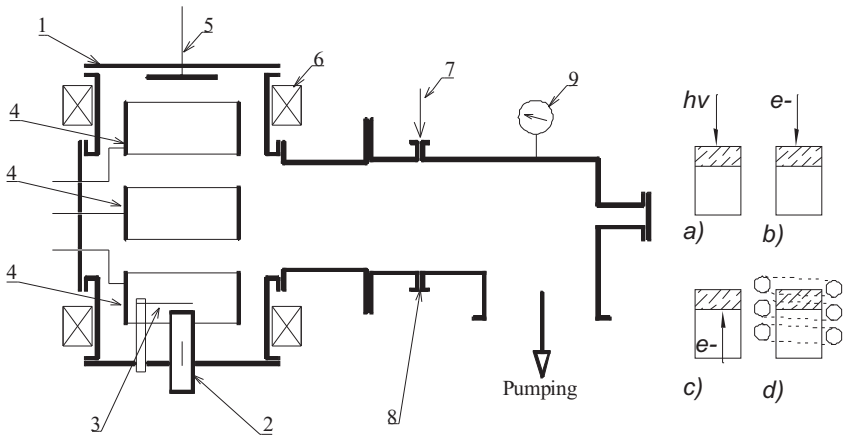

Fig.1. *The source and test desk: 1 is the vacuum chamber; 2 is the anode; 3 is the heated cathode; 4 are the electrodes of the reflective discharge; 5 is the collector; 6 is the magnetic system; 7, 8 is the diagnostic window; 9 is the vacuum meter. a) – d) are the options of the evaporation of the working medium of the anode*

The first stage of the source is presented by the dependent arc discharge with the heated cathode in anode vapors and it delivers metal vapors and provides primary ionization. The second stage is the reflective discharge that increases the ionization degree and plasma density. The plasma density at the level of $10^{11} - 10^{12}$ was obtained using the DIS-1 unit at discharge currents of about $10\,A$ [3]. To increase the plasma density we assumingly will use the reflective discharge in the mirror ratio magnetic field at a high-current pulse with the duration of $5\,ms$ and the current of about $1\,kA$.

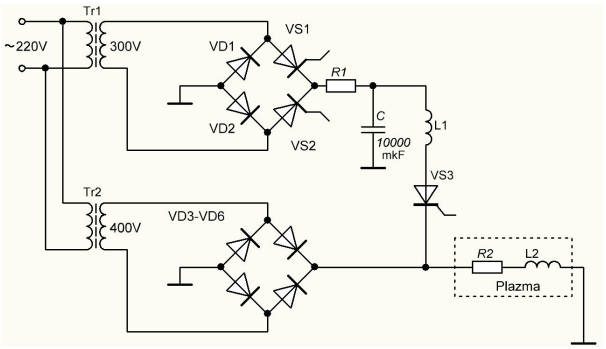

Fig.2. *Electric power circuit for the plasma source*

Electric power supply circuit of the plasma source (Fig.2) consists of two lines: one is for the direct voltage and the other is for the current pulse generator. The direct voltage source provides $400\,V$, $50\,A$. The current pulse generator consists of the charge circuit and discharge circuit and it shapes pulses with the current amplitude of $\sim 1\,kA$, voltage of $400\,V$ and duration of $5\,ms$. The capacitor bank C is charged through the current-limiting resistor $R1$. The discharge circuit is a decaying oscillating loop, in which the capacitor bank is discharged into the discharge gap having an active resistance $R2$ and induction $L2$. The discharge circuit and charge circuit are switched by the thyristors $VS1 - VS3$. The resulting current pulse has a constant component, which at the time of switching of the thyristor $VS3$ will be summed up with the pulse component shaped by the current pulse generator. The pulse component of the current in the discharge loop is defined by the expression $I = (U/\omega L)\sin(\omega t)\exp(-\alpha t)$, where ω is the cyclic frequency of the oscillating loop, $\alpha = R/2L$ is the decay coefficient, R and L are the resistance and induction of the oscillating loop, accordingly taking into account the discharge gap and t is the time. The resistance of the oscillating loop consists of the electric circuit and discharge gap resistance (plasma resistance). In the case of highly ionized hydrogen plasma the conductivity is described by the Spitzer formula: $\sigma = 1.4 \cdot 10^8 (T_e^{3/2}/\Lambda)$, where T_e is the temperature of electrons in kelvins, and Λ is the coulomb logarithms. In the range of T_e values peculiar for the high temperature plasma, the value $\Lambda = 15$ is selected and the formula can approximately be written as $\sigma \approx 10^7 T_e$. The point of principle for the Spitzer formula is that it actually depends just on temperature. The fully ionized hydrogen plasma has conductivity comparable with that of copper at $T = 10^7\,K$. In the case of partially ionized molecular plasma there is no simple analytical solution that describes its conductivity, however in many experiments [8,9], the specific conductivity of plasma was in the range of $(10^1 ... 10^2)\Omega^{-1}\,cm^{-1}$. Therefore in our case the discharge gap resistance won't exceed several Ohm hundredth and it will insignificantly influence the discharge pattern. For separation processes to proceed in amount sufficient for the analysis the plasma pulse duration should exceed the system transit time by the heaviest plasma ions at least 2 to 5 times, i.e. $\tau = x/v$ (where x is the system length, v is the heavy ion rate).Thus, the pulse duration should be at the level of 1 to $10\,ms$. Fig.3. shows the relationship of current pulse amplitude for $L = 300\,\mu H$, $R = 0.6\,Ohm$, $C = 10000\,\mu F$, as a function of time. In this case the current pulses is $5\,ms$ and it satisfies our requirements.

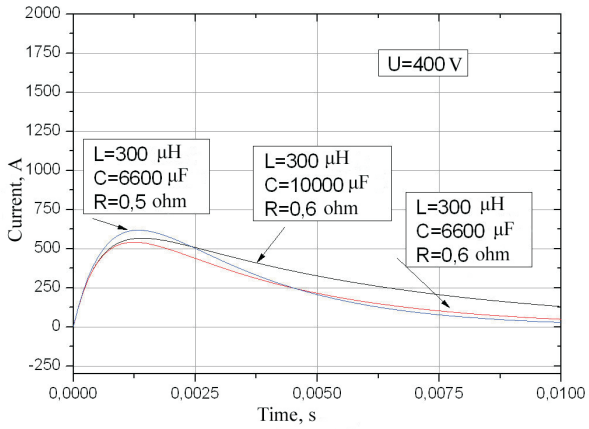

Fig.3. *The relationship of the current pulse value as a function of time for many parameters of the discharge circuit*

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ПРОЕКТ ИСТОЧНИКА ГАЗО-МЕТАЛЛИЧЕСКОЙ ПЛАЗМЫ ДЛЯ СЕПАРАЦИОННОЙ ТЕХНОЛОГИИ

В. Б. Юферов, С. В. Шарый, М. О. Швец, А. Н. Озеров

Представлен проект источника газо-металлической плазмы. Приведена конструкция и электрическая схема его питания. Рассмотрена возможность использования данного источника для сепарационной технологии, в частности для регенерации отработанного ядерного топлива (ОЯТ). Разработаны требования к источнику и параметрам создаваемой плазмы. Оценена производительность магнитоплазменной переработки ОЯТ и обоснован выбор металлов и их оксидов в качестве имитационных сред в экспериментах по регенерации ОЯТ.

ПРОЕКТ ДЖЕРЕЛА ГАЗО-МЕТАЛЕВОЇ ПЛАЗМИ ДЛЯ СЕПАРАЦІЙНОЇ ТЕХНОЛОГІЇ

В. Б. Юферов, С. В. Шарий, М. О. Швець, А. Н. Озеров

Представлено проект джерела газо-металевої плазми. Приведена конструкція та електрична схема його живлення. Розглянута можливість використання джерела для сепараціонної технології, зокрема для регенерації відпрацьованого ядерного палива (ВЯП). Розроблено вимоги до джерела та параметрам плазми, що створюється. Оцінена продуктивність магнітоплазмової переробки ВЯП та обгрунтовано вибір металів і їх оксидів в якості імітаційних середовищ в експериментах по регенерації ВЯП.