

MAGNETO-PLASMA SEPARATION AS A METHOD FOR REPROCESSING OF SPENT FUEL AND RADIOACTIVE WASTE

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A variant of a separating device based on the plasma-beam discharge is considered, including: processes of radioactive material (SF and RAW) ionization; evaluation of the mass-production capacity of the device with taking into account the atomic weight of the separated substance and the spatial-density characteristics of the plasma used and main power consumption. The consideration enables one to estimate more objectively the potentialities of magneto-plasma separating devices and to determine the method for controlling them.

PACS: 52.50.Dg; 28.41.Kw

The goal of this work is to carry out a comparative analysis of magneto-plasma separating devices, operating and under development, designed for research and industrial purposes, namely, for separation of radioactive waste (RAW) and spent fuel (SF). Analysis is based on the literature [1-5] and original authors' data [6,7].

A reason for this analysis proceeds, in particular, from the problematics of building a nuclear fuel cycle in Ukraine, in the part of developing the SF reprocessing technology designed for separation of uranium and plutonium [8].

The use of magneto-plasma separators (MPS) in the process of SF and RAW reprocessing is possible in the following cases: first – the use of MPS as a first stage of SF reprocessing, i.e. separation of uranium dioxide from the decay products that can permit to concentrate high-level radioactive wastes (HL RAW) the most compactly in the solid form on the receiving plates; second – reprocessing of RAW formed at radiochemical plants after chemical SF reprocessing. In the both cases the "partial separation" is under consideration [7].

Excitation in the plasma-beam discharge of different branches of high-frequency and low-frequency oscillations necessary for plasma particle heating results in that there is no need to use external radio-frequency oscillators for plasma heating and heating up [9-11].

The distinct features of this device, in comparison with existing analogs, are: the method of plasma formation and heating, opportunity to use the evaporating and sputtering mechanisms of working substance feeding into the discharge, design simplification due to the non-use of external rf oscillators and internal antenna setups for plasma formation and heating, as well as, decreased severity of requirements to magnetic system parameters and lowering the power consumption for plasma formation and heating.

In the plasma, formed and heated to the temperature T_i in the longitudinal magnetic field, ions with different masses have different Larmor radii. Using different Larmor radii it is possible to separate "light" and "heavy" ions i.e. "heavy ions" are depositing on the cylindrical parts of the tank, and "light ions" go out and are depositing on the edge electrodes.

Of an essential interest for separation technologies designed for RAW and SF reprocessing is the consideration of elementary processes taking place in the RAW and SF ionization. A nomenclature of particles,

participating and being formed as a result of elementary processes at the initial discharge stage, consists of the following molecules, atoms and ions: UO_2 , UO , U , O_2 , U^+ , O^+ , O_2^+ and others. Here it is necessary to distinguish the main elementary processes in the physics of atomic and electron collisions: ionization and excitation by electron impact, dissociation and dissociative ionization by electron impact.

The time for reaching the plasma density of $\sim 10^{11} \text{ cm}^{-3}$ at the expense of primary beam electrons is 1 ms. In the case of the ionization by plasma secondary electrons (exponential discharge stage) the time of reaching the plasma density of $\sim 2 \cdot 10^{11} \text{ cm}^{-3}$ is 28 μs at $T_e=100\text{eV}$ and 53 μs at $T_e=20\text{eV}$.

For the separation of a substance into elements the output of magneto-plasma separators can be written as follows:

$$\dot{m} = M \cdot \Delta\mu \cdot \pi \cdot n_{\max} \cdot r_{\max}^2 \cdot \frac{\gamma}{\gamma + 2} \cdot K_{\text{eff}} \cdot v_p, \quad (1)$$

where M is the atomic weight, g; $\Delta\mu$ is the element percentage in the substance; n_{\max} is the maximum plasma density; r_{\max} is the maximum radius of plasma formation (flux); γ is the index of a power; K_{eff} is the separator efficiency coefficient; v_p is the plasma flux velocity.

Using expression (1) we calculated the efficiency of the device OPN-1 [6,7] taking into account the service time taken as about 10% of the device operation time value (see Fig.1). The reprocessed fuel output can reach 12-18 t/year if the separator efficiency coefficient is 0.5 – 0.8.

As it follows from equations (1) the separator output can depend on the plasma density spatial distribution form being used in the separator. Investigation and comparison were carried out for three types of a discharge: rf discharge, plasma-beam discharge and reflection-type discharge (RD).

In the first case, the device APMF-DEMO [12], the plasma is formed using a 4-turn two rf antenna with an internal radius of 0.413 m, generation frequency $\omega/2\pi = 6 \text{ MHz}$, power of 3 MW. It has been established that the profile T_e has a uniform character in the range from 2 to 4 eV, and the plasma density profile has either one maximum in the peripheral region of the plasma column or once more additional maximum in its center

depending on the variant of rf power supply phasing of the antenna rings (Fig.2, curves 1 and 2).

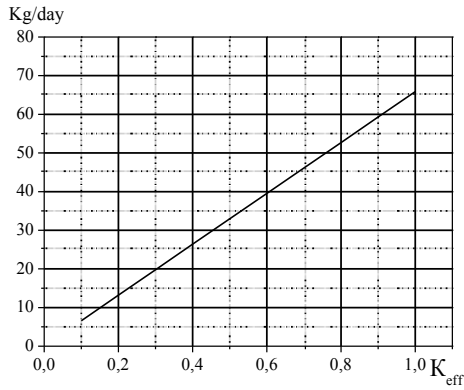


Fig. 1. Mass output of the separator for different values of the efficiency coefficient

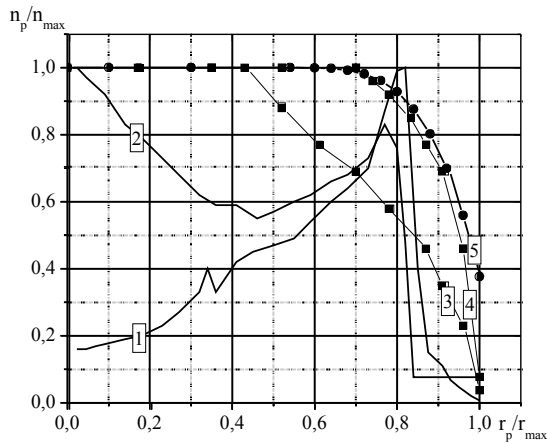


Fig. 2. Radial distribution of the argon plasma density distribution in the separating devices of a different class operating upon different principles of plasma formation and heating. 1 – Archimedes separator, $B_0=0.16T$, 0000 phase, $n_{max}=1.49 \cdot 10^{13} \text{ cm}^{-3}$, $r_{max}=0.44m$; 2 – Archimedes separator, $B_0=0.16T$, $0\pi0\pi$ phase, $n_{max}=1.49 \cdot 10^{13} \text{ cm}^{-3}$, $r_{max}=0.44m$; 3 – plasma-beam discharge, $B_0=0.2T$, $n_{max}=2.5 \cdot 10^{14} \text{ cm}^{-3}$, $r_{max}=0.024m$; 4 – plasma-beam discharge, $B_0=0.1T$, $n_{max}=1.2 \cdot 10^{14} \text{ cm}^{-3}$, $r_{max}=0.024m$; 5 – reflection-type discharge, $B_0=0.15T$, $n_{max}=1.7 \cdot 10^{13} \text{ cm}^{-3}$, $r_{max}=0.05m$

The experimental investigation of beam plasma spatial (BPS) characteristics was carried out at electron beam energy $E_e \leq 30\text{keV}$, current $I_e \leq 20A$ and injection duration $\sim 400\mu\text{s}$. The obtained experimental data were used to find the plasma density spatial distributions in the cross section of the plasma column (Fig.2, curves 3 and 4). At a low magnetic field strength ($B_0 < 0.3T$), that corresponds to the “partial separation” mode of separator operation, the plasma density distribution $n_p=f(r)$ is close to the uniform one (see Fig.2, curves 3 and 4) with a significant density gradient near the trap wall.

For the reflection discharge with dimensions $L=1.5m$, $\varnothing=0.2m$, the discharge and plasma parameters $I_p \sim 1kA$, $U_p \leq 4.5 \text{ kV}$, $B_0 \leq 0.6T$, $n_p \sim 2 \cdot 10^{13} \text{ cm}^{-3}$, $T_e \leq 50\text{eV}$,

$T_i \leq 10\text{eV}$ the profile of plasma density spatial distribution was obtained using the rf interferometer on the wave length $\lambda = 8 \text{ mm}$ (Fig.2, curve 5). One can see that the plasma density spatial distribution has a uniform character similar to the PBD distribution.

The plasma column cross-section areas for profiles 1 and 5 (Fig.2) differ by a factor of 2 - 2.5 that can essentially influence on the separator output. Therefore, it is reasonable to select a discharge type providing the distribution profile $n_p=f(r)$ close to the uniform one (curves 4,5 in Fig.2).

Let us estimate the power consumption for the device OPN-1 in the following channels: solid substance transformation in vapor W_{ph} ; working substance vapor ionization and plasma heating W_p ; magnetic field formation W_B ; maintenance of the working pressure in the MPS vacuum chamber W_v . The estimation of the minimum power consumption W_{ph} for plasma flux maintenance at a level of $2.2 \cdot 10^{21}$ uranium particle/s, provided that the vapor input into the ionization chamber occurs without losses and with 100% ionization, gives the power value of $\sim 70 \text{ kW}$ for the electron-ray evaporator. Taking into account the previous experimentally measured value of the ratio $r_p/r_b \sim 5 - 10$ (r_p is the plasma radius, r_b is the electron beam radius) we obtain that in the present project at $r_p = 50 \text{ cm}$ r_b should be no less than $10 - 5 \text{ cm}$. For this, one needs electron beams of a large aperture and, respectively, cathodes with a large emitting surface of $\sim 200 - 400 \text{ cm}^2$. For formation of an electron beam with a current density of $1-2 \text{ A/cm}^2$ the power can be from 1 to 4 MW. The creation of a uniform magnetic film with the strength of an order of 0.15 T in the volume of 3.14 m^3 will require the power W_B of an order of 0.2 MW .

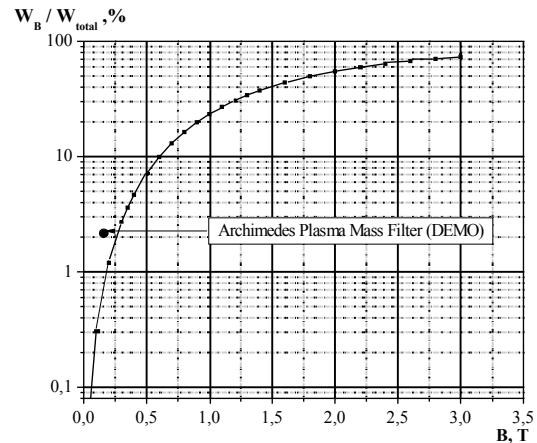


Fig.3. Specific fraction of power consumption for creation of the magnetic field in the total energy balance providing the operation of the separation device OPN-1 as a function of the magnetic field strength

The power consumption fraction for creation of the magnetic field W_B is not a constant value and depends on the experiment purpose, as well as, on the mode and objectives of device operation, see Fig.3. In the mode of RAW “partial separation” the fraction of power consumption by the B-field does not exceed 2-3 % of the

total power consumption, in the mode of heavy element “complete separation” it is of about 10%, in the mode of some heavy isotope enrichment it is to 50%. The high value of the magnetic field $B > 0.5-1$ T is also necessary to increase the efficiency of plasma formation and heating in the devices with large plasma volumes (> 0.5 m³). The power consumption W_v for maintenance of the working pressure in the MPS vacuum chamber using the cryogenic vacuum pumps with a pumping speed of 18000 l/s will be ~ 20 kW for a pump.

CONCLUSIONS

The results of tests on the possibility of using the magneto-plasma separation technologies for SF and RAW reprocessing show the following:

1. Among new developments of a certain interest is a separating device based on the plasma-beam discharge, which possesses a fairly effective mechanism of plasma formation and heating with given parameters and does not require the use of external rf-power oscillators and special antenna setups.

2. It has been established, that the output of the separating device depends in a considerable degree, on the plasma density spatial distribution profile in its cross-section. For the plasma-beam discharge and reflection-type discharge the distribution profiles $n_p=f(r)$ are optimum ones.

3. The total and specific power consumptions through the consumption channel were estimated. The power consumption for B-field creation depends on the mode of separator operation.

REFERENCES

1. P. Louvet, A.C. La Fontaine // *Proc. of Int. Conf. on Chem. Exchange and Uranium Enrichment. Tokyo. Japan/* Bulletin of the Research Lab. for Nucl. Reactors, Tokyo, Japan, 1990, p. 289.
2. A.I. Karchevsky, A.I. Laz'ko, Yu.A. Muromkin et al. Investigations on lithium isotope separation in the plasma by isotopic selective ICR heating. // *Fizika plazmy*. 1993, v.19, N 3, p. 411- 419 (in Russian).
3. V.I. Volosov, V.V. Demenyov, V.V. Dranichnikov et al. *Design of the device for isotope separation by the*

method of ICR heating: Preprint. Novosibirsk: INF 2001- 48, 2001 (in Russian).

4. A. Litvak, S. Agnew, F. Anderegg, B. Cluggish et al. Archimedes Plasma Mass Filter // *30th EPS Conference on Contr. Fusion and Plasma Phys., St. Petersburg, Russia. 2003*. V. 27A, O-1.6A.

5. V.A. Zhil'tsov, V.M. Kulygin, N.N. Semashko et al. Plasma separation of the elements applied to nuclear material handling // *Atomic Energy*. 2006, v. 101, N 4, p.755-759.

6. Patent of Ukraine 24729, WPC 2006, B01D 59/00. *The device for substance separation into elements/* Ye.I.Skibenko, Yu.V.Kovtun, V.B.Yuferov// *Bulletin No 10. Appl. 16.03.2007; Publ. 10.09.2007* (in Ukrainian).

7. E.I. Skibenko, V.B. Yuferov, Yu.V. Kovtun. Conceptual design of the plasma source based on the plasma-beam discharge for separation technologies// *Proc. of 8 International Conference "Equipment and technologies of thermal treatment of metals and alloys"/* - Kharkov: NSC KIPT, 2007, v.1, p. 232-238. (in Russian).

8. V.S. Krasnorutsky. On nuclear fuel cycle of Ukraine // *Yaderni ta radiatsijni tekhnologii*. 2006, v. 6, N 1 – 2, p. 7-14 (in Ukrainian).

9. Ya.B. Fainberg. Interaction of a charged particle beam with electron plasma // *Atomnaya energiya*. 1961, v.11, N 4, p. 313-335. (in Russian).

10. O.F. Kovpik, E.A. Kornilov, S.M. Krivoruchko, S.S. Moiseev, Ya.B. Fainberg. On the influence of different-type oscillations on the ion heating in plasma-beam discharges// *Pis'ma v ZhETF*, v.15, N 9, 1972, p.501-504. (in Russian).

11. O.F. Kovpik, Yu.E. Kolyda, E.A. Kornilov, E.V. Lifshits, S.A. Nekrashevich. Influence of the external high-frequency modulation on the ion heating during beam-plasma interaction // *Fizika plazmy i problemy upravlyaemogo termoyadernogo sinteza*. Kiev: "Naukova Dumka", 1972, N 3, p.15-23. (in Russian).

12. B.P. Cluggish, F.A. Anderegg, R.L. Freeman et al. Density profile control in a large diameter, helicon plasma// *Physics of plasmas*. 2005, v.12, N 5, p.057101-1.

Article received 30.09.08.

МАГНИТОПЛАЗМЕННАЯ СЕПАРАЦИЯ, КАК СРЕДСТВО ПЕРЕРАБОТКИ ОЯТ И РАО

А.М. Егоров, Е.И. Скибенко, Ю.В. Ковтун, В.Б. Юферов

Рассмотрен вариант сепарирующего устройства на основе пучково-плазменного разряда, в том числе: процессы ионизации вещества ОЯТ и РАО; оценка массовой производительности устройства с учетом атомного веса выделяемого вещества и пространственно-плотностных характеристик используемой плазмы; оценка основных энергозатрат. Проведенное рассмотрение позволяет более предметно оценить возможности магнито-плазменных сепарационных устройств и определить способ их регулирования.

МАГНИТОПЛАЗМОВА СЕПАРАЦІЯ, ЯК ЗАСІБ ПЕРЕРОБКИ ВЯП І РАВ

О.М. Єгоров, Є.І. Скібенко, Ю.В. Ковтун, В.Б. Юферов

Розглянуто варіант сепаруючого пристрою на основі пучково-плазмового розряду, у тому числі: процеси іонізації речовини ВЯП і РАВ; оцінка масової продуктивності пристрою з урахуванням атомної ваги виділюваної речовини і просторово-щільнісних характеристик використовуваної плазми; оцінка основних енерговитрат. Проведений розгляд дозволяє більш предметно оцінити можливості магніто-плазмових сепарационних пристроїв і визначити спосіб їхнього регулювання.