THE CALCULATIONS OF URANIUM AND LANTHANUM OXIDES TRAJECTORIES AT MAGNETOPLASMA SEPARATION STAGE

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Trajectories of charged particles (UO_2 and La_2O_3) at magnetoplasma separation stage – in system of crossed electric and magnetic fields – are calculated. The possibilities of UO_2 separation from La_2O_3 by changes in magnetic and electric fields components are investigated. Adding of certain changes in magnetic field distribution does not lead to the solution of problem, while the addition of variable component to constant radial electric field allows to separate the nuclear fuel from lanthanides complex compounds at magnetoplasma separation stage.

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INTRODUCTION

The problem of handling with spent nuclear fuel (SNF) is currently being solved by SNF disposal in appropriate storages (that only leads to accumulation of SNF) and partly by radiochemical reprocessing method. The latter method has several disadvantages, including the need to use chemicals and accumulation of liquid secondary waste. At present, it is actively developed an alternative method of reprocessing – magnetoplasma (MP) separation method, which consists in separation of nuclear fuel (NF) from fission products (FPs) in three successive stages: thermal heating, ionization and magnetoplasma separation in crossed electric and magnetic fields [1]. This method is based on physical principles and does not require additional reagents. Furthermore, the method has advantages in terms of energy efficiency.

Since nuclear fuel, used in the majority of nuclear reactors, is oxide (i.e. uranium dioxide UO_2), it is advisable to consider SNF, received as a result of oxide fuel operation.

After unloading of fuel elements from the reactors they contain a variety of chemical elements formed after the disintegration of radioactive isotopes of uranium and plutonium. About 95% of elements are uranium-238 (or rather its oxide) and transuranium elements, 5% – fission products, which must be removed from the overall composition of SNF. It is estimated [2] that in investigated MP separation method about 1.5% of FPs remain in SNF after thermal heating and ionization stages. These FPs can be separated from NF at magnetoplasma separation stage in *E*x*B* fields. This will be elements with masses 106 a.m.u. (SrO), 160 a.m.u. (CeO), as well as complex compounds with mass 324 a.m.u. (La_2O_3). Trajectories of charged particles with masses 270 a.m.u. (UO_2) and 324 a.m.u. (La_2O_3) at the third stage of MP method of SNF separation are calculated and presented in paper.

1. MATHEMATICAL MODEL

It is known that the motion of charged particle in electromagnetic field in the case of axial symmetry is described by system of equations in cylindrical coordinates, which includes the components of electric and magnetic field [3]:

$$m\vec{a} = q\vec{E} + q\left[\vec{V},\vec{B}\right],$$

$$\begin{cases} m\ \ddot{r} - r\dot{\varphi}^2\ = q\ E_r + r\dot{\varphi}B_z - \dot{z}B_\varphi\ ; \\ m\ 2\dot{r}\dot{\varphi} + r\ddot{\varphi}\ = q\ E_\varphi + \dot{z}B_r - \dot{r}B_z\ ; \\ m\ddot{z} = q\ E_z + \dot{r}B_\varphi - r\dot{\varphi}B_r\ . \end{cases}$$

Initial conditions:

$$r(0) = r_0,\ \varphi(0) = \varphi_0,\ z(0) = z_0,$$

$$\dot{r}(0) = V_{r0},\ \dot{\varphi}(0) = V_{\varphi 0},\ \dot{z}(0) = V_{z0}.$$

Components V_{r0} and V_{z0} are represented as: $V_{r0} = V_0 \sin\alpha$, $V_{z0} = V_0 \cos\alpha$, where V_0 – initial velocity of particle (connected with initial energy $W_0 = mV_0^2/2 = qU$), α – angle, with which charged particle starts its motion in system.

The following initial conditions are accepted in paper: $r(0)=0.01$ m, $\varphi(0)=0$, $z(0)=0$, $W_0=5$ eV, $\alpha=45^o$. The calculations were carried out in single-particle approximation.

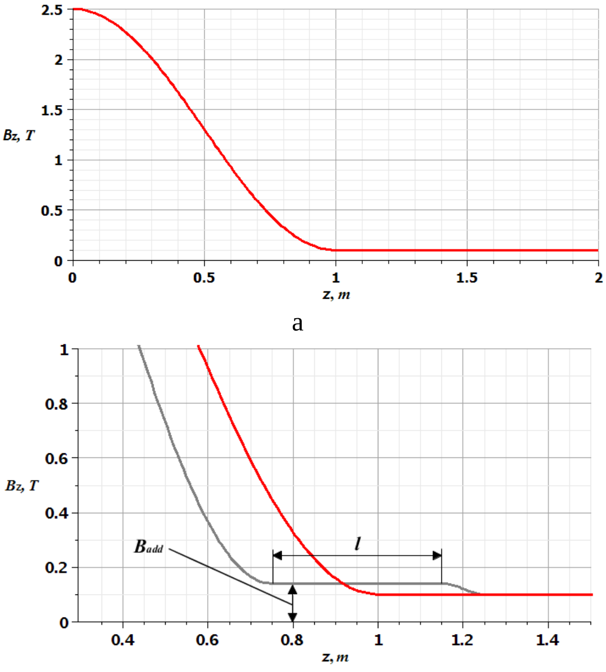
The induction of magnetic field has two nonzero components, B_r and B_z, which are related as $\mathrm{div}\vec{B} = 0$:

$$B_r = \begin{cases} 0,\ z < 0, \\ \dfrac{3\pi r B_0}{50L}\sin\left(\dfrac{\pi z}{4L}\right),\ 0 \le z < 4L, \\ 0,\ z \ge 4L; \end{cases}$$

$$B_\varphi = 0;$$

$$B_z = \begin{cases} 0,\ z < 0, \\ \dfrac{12}{25}B_0\sin\left(\dfrac{\pi z}{4L} + \dfrac{\pi}{2}\right) + \dfrac{13}{25}B_0,\ 0 \le z < 4L, \\ \dfrac{B_0}{25},\ z \ge 4L. \end{cases}$$

Induction of magnetic field along the *z*-axis is decreased in 25 times from value 2.5 T (B_0) up to 0.1 T ($B_{\mathrm{unif}} = B_0 / 25$) and then is not changed until the end of system (Fig. 1,a). There is ionization of working medium [2] in region of magnetic field maximum, in this region plasma is collisional. Further, the plasma from collisional turns into collisionless. The collisionless plasma mode allows to use mathematical model presented – movement of individual particles without collective phenomena. In such system of crossed *ExB* fields it is easy to separate NF from light FPs with masses 106 a.m.u. and 160 a.m.u. due to the difference of particles trajectories in incident magnetic field. Difficulties are with heavy compounds such as La_2O_3 (324 a.m.u.), since the mass of this molecule is greater than UO_2 one (270 a.m.u.), and collector for NF ions, except NF, will also get complex compounds of lanthanides. One of the possible solutions of this problem may be formation of additional section of uniform magnetic field with length *l* and induction B_{add} near B_{unif} (Fig. 1,b).



a

b

Fig. 1. The distribution of induction magnetic field along z-axis: a – without additional section; b – with additional section of uniform magnetic field

In calculations the values B_{add} and *l* are varied. Thus, the induction of additional section B_{add} was 20, 40 and 60 % of uniform magnetic field induction ($0.2B_{unif}$, $0.4B_{unif}$ и $0.6B_{unif}$). The value *l* was 20, 40 and 60 cm.

Another alternate solution of problem is adding of variable component to constant radial electric field:

$$E_r = E_0 + E_{add}\,, \quad E_{add} = kE_0 \sin \omega t \ .$$

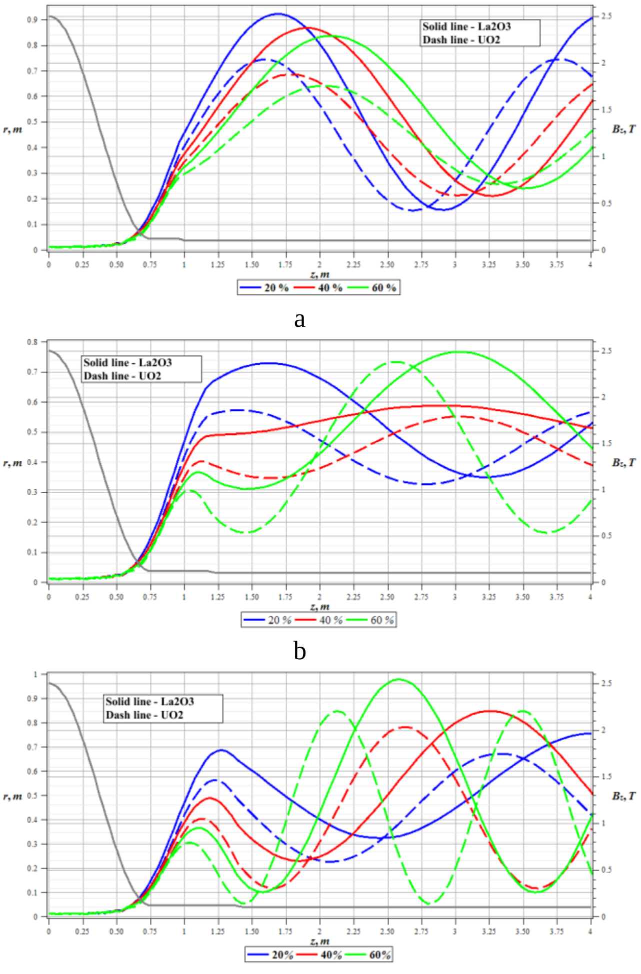
The value E_0 was taken equal to 400 V/m. In calculations parameter *k* was 0, 0.1, 0.3 and 0.6. The frequency *ω* is related to ion cyclotron frequency in uniform magnetic field B_{unif}:

$$\omega_{ci} = \frac{q}{m} \cdot \frac{B_0}{25}\,.$$

The following cases are considered: $\omega = \omega_{ci}$ (UO_2), $\omega = ½\,\omega_{ci}$ (UO_2), $\omega = \omega_{ci}$ (La_2O_3), $\omega = ½\,\omega_{ci}$ (La_2O_3).

2. INFLUENCE OF MAGNETIC FIELD ADDITIONAL SECTION ON PARTICLES TRAJECTORIES

Fig. 2, a,b,c shows trajectories of UO_2 (dash lines) and La_2O_3 (solid lines) ions for different values B_{add} and *l*.



a

b

c

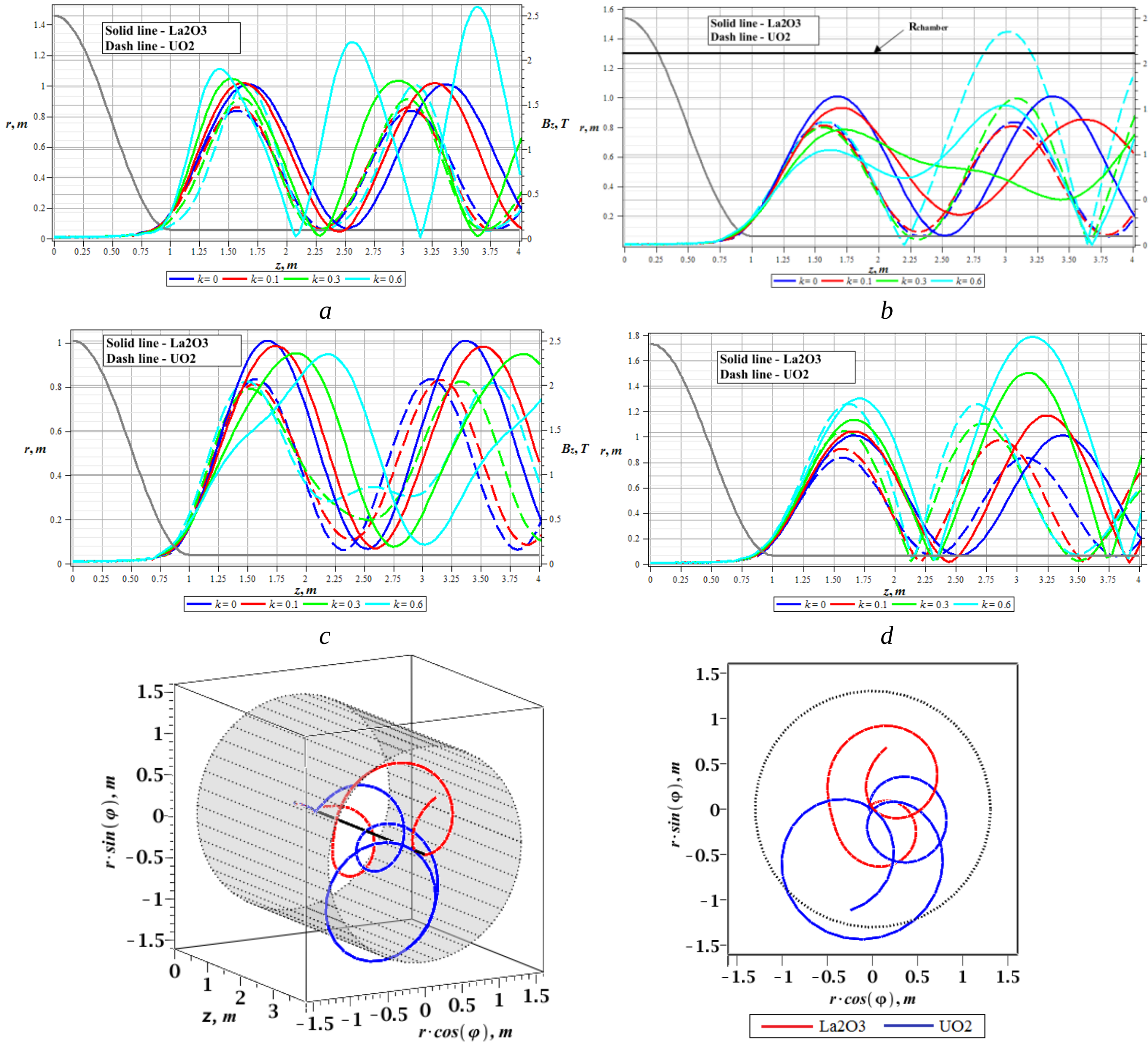
Fig. 2. Charged particles trajectories: a – l = 0.2 m; b – l = 0.4 m; c – l = 0.6 m

It is seen that with increase of length *l* the difference of Larmor radiuses UO_2 and La_2O_3 is risen, however, even at value *l* = 0.6 m and B_{add} = 0.6 B_{unif} this difference does not exceed 15 cm. Taking into account of initial parameters variety (energy, angle, start position of ions) would lead to "overlap" of NF and FP particles trajectories.

3. INFLUENCE OF ELECTRIC FIELD VARIABLE COMPONENT ON PARTICLES TRAJECTORIES

The trajectories of UO_2 (dash lines) and La_2O_3 (solid lines) ions for different values of parameters *k* and *ω* are presented in Fig. 3, a,b,c,d. Fig. 3,e,f shows three-dimensional view and cross section view of particles trajectories and vacuum chamber for case $\omega = ½\,\omega_{ci}$ (UO_2).

Calculations have shown that in the case of $\omega = ½\,\omega_{ci}$ (UO_2) (see Fig. 3,b) the trajectory of UO_2^+ ions exceeds radially trajectory of $La_2O_3^+$ ions at *k* = 0.6. This means that adding of variable component leads to the fact that the collector for NF (located at distance $R_{chamber}$ from z-axis) will get only particles with mass 270 a.m.u., while FPs as $La_2O_3^+$ ions, will move toward chamber end to appropriate collector.



a *b* *c* *d* *e* *f*

Fig. 3. Charged particles trajectories: a – $\omega = \omega_{ci}$ (UO_2); b – $\omega = ½\ \omega_{ci}$ (UO_2); c – $\omega = \omega_{ci}$ (La_2O_3); d – $\omega = ½\ \omega_{ci}$ (La_2O_3); e – three-dimensional view for case $\omega = ½\ \omega_{ci}$ (UO_2); f – cross section view for case $\omega = ½\ \omega_{ci}$ (UO_2)

CONCLUSIONS

Thus, formation of additional section of uniform magnetic field with parameters mentioned above (B_{add} and l) does not lead to significant differences in ions trajectories, while adding of variable component of electric field with amplitude $0.6E_r$ and frequency equal to half of ion cyclotron frequency of uranium dioxide, leads to movement of these ions along greater trajectories that allows to separate NF from complex compounds such as La_2O_3.

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РАСЧЁТ ТРАЕКТОРИЙ ДВИЖЕНИЯ ЗАРЯЖЕННЫХ ЧАСТИЦ ОЯТ НА СТАДИИ МАГНИТОПЛАЗМЕННОГО РАЗДЕЛЕНИЯ

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Рассчитаны траектории движения заряженных частиц (UO_2 и La_2O_3) на стадии магнитоплазменного разделения – в системе скрещенных электрического и магнитного полей. Исследованы возможности отделения UO_2 от La_2O_3 путём внесения изменений в компоненты магнитного и электрического поля. Внесение определённых изменений в распределение магнитного поля не даёт желаемых результатов, а добавление переменной компоненты к постоянному радиальному электрическому полю позволяет отделить ядерное топливо от сложных соединений лантаноидов на стадии магнитоплазменного разделения.

РОЗРАХУНОК ТРАЄКТОРІЙ РУХУ ЗАРЯДЖЕНИХ ЧАСТИНОК ВЯП НА СТАДІЇ МАГНІТОПЛАЗМОВОГО РОЗДІЛЕННЯ

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Розраховано траєкторії руху заряджених частинок (UO_2 і La_2O_3) на стадії магнітоплазмового розділення – в системі схрещених електричного і магнітного полів. Досліджено можливості відділення UO_2 від La_2O_3 шляхом внесення змін до компонент магнітного і електричного полів. Внесення певних змін у розподіл магнітного поля не дає бажаних результатів, а додавання змінної компоненти до постійного радіального електричного поля дозволяє відокремити ядерне паливо від складних з'єднань лантаноїдів на стадії магнітоплазмового розділення.