CIV FENOMEN IN GAS-METAL PLASMA

Yu.V. Kovtun
National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
E-mail: Ykovtun@kipt.kharkov.ua

The paper deals with limitation of the rotational velocity of multicomponent gas-metal plasma, and also, with the effect of this phenomenon on mass separation in the rotating plasma. The measured data on the rotational velocity of the gas-metal multicomponent plasma are presented and analyzed.

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INTRODUCTION

Possible physico-technical approaches to the realization of the magnetoplasma method of substance separation for spent nuclear fuel (SNF) reprocessing are widely discussed in the current literature [1 - 9] as an alternative to the radiochemical method of SNF reprocessing. With this method, the plasma ions, and accordingly, the SNF substance, are supposed to be separated into light and heavy mass groups (so-called "partial separation"), or be separated element by element ("complete separation").

Consideration was given to the feasibility of creating a magnetoplasma device based of the beam-plasma discharge [1, 2], and also, with the use of the ion-cyclotron resonance [3].

Much attention of the investigators has been given to the possibility of separating the substance, including SNF, into mass groups and elements using the devices with plasma rotating in crossed $\boldsymbol{E}\times\boldsymbol{B}$ fields. Various versions of rotating-plasma devices for SNF separation have been proposed [2, 4 - 9], among them the ones based on the reflective discharge [2, 8, 9].

The realization of the SNF-separating magnetoplasma method implies the creation of facilities and complexes of capacities comparable in the order of magnitude with the radiochemical reprocessors of the same profile. For this purpose, consideration is given to a well-ionized dense plasma with a particle concentration of up to 10^{20} m^{-3} (10^{14} cm^{-3}). For plasma rotation-based magnetoplasma facilities, the separation coefficient is dependent on the rate of rotation and the difference of separated masses. In view of this and the separation device capacity requirements, the rate of plasma rotation should be of about 10^4 m/s.

In spite of the intensive studies into magnetoplasma separation techniques, no or little consideration has been given to some problems still not clearly understood. Among them, we may mention the limitation of the rotational velocity of multicomponent gas-metal plasma and the effect of this phenomenon on mass separation in the rotating plasma. The present work is the continuation of our previous studies (see refs. [10 - 12]).

1. MASS SEPARATION IN THE ROTATING PLASMA

The possibility of using centrifugal effects for substance separation in the rotating multicomponent plasma has been indicated in ref. [13]. As noted in [14], the centrifugal effect of separation is not the only mechanism, which may take place in the rotating plasma. The radial separation coefficient for the two-component plasma is determined as:

$$\alpha_0 = \frac{\left(N_i^A(r) / N_i^B(r)\right)}{\left(N_i^A(0) / N_i^B(0)\right)}, \tag{1}$$

where $N_i^A(0)$, $N_i^B(0)$ and $N_i^A(r)$, $N_i^B(r)$ denote the density of ions of species A and B on the axis and at a distance of r from the axis, respectively. For the case of a fully ionized isothermal plasma at $Z_i^A = Z_i^B = 1$, $v_\varphi^A = v_\varphi^B = v_\varphi = \omega_\varphi r$ the separation coefficient α_0 can be estimated by the relation [15]:

$$\alpha_0 = \exp\left[\frac{\Delta m v_\varphi^2}{2kT}\right], \tag{2}$$

where v_φ is the rate of plasma rotation, T is the plasma temperature, k is the Boltzmann constant; $\Delta m = m_i^A - m_i^B$, m_i^A and m_i^B denote the masses of ions of species A and B. The estimation shows that at T = 2 eV, Δm = 25, $v_\varphi = 10^3$ m/s and $v_\varphi = 10^4$ m/s the separation coefficient α_0 is equal to 1.1 and $1.78\cdot10^4$, respectively. So, by increasing the rate of rotation it is possible to increase the separation coefficient. However, as is evident from the experiments with plasma in the crossed $\boldsymbol{E}\times\boldsymbol{B}$ fields, the rate of rotation v_φ is limited by the critical velocity v_c.

2. LIMITATION OF PLASMA ROTATIONAL VELOCITY

The notion of the critical ionization velocity (*CIV*) was first introduced by H. Alfven as a part of his theory of solar system evolution [16]. Alfven has postulated a strong interaction between the plasma in the magnetic field and the neutral gas, which results in the ionization of neutral atoms as the relative velocity between the plasma and the neutral gas exceeds the critical ionization velocity v_c:

$$v_c = \sqrt{\frac{2e\phi_i}{m_n}}, \tag{3}$$

where ϕ_i is the ionization potential, m_n is the mass of the neutral atom or the molecule. The *CIV* hypothesis was first tested with experiment in the device known as a homopolar device [17], where the neutral gas and plasma filled in the space between two cylinders. Further experimental studies were carried out in space and laboratory environments [18, 19]. In a laboratory environment, a great number of experiments were performed in electric discharges with crossed $\boldsymbol{E}\times\boldsymbol{B}$ fields for different conditions [18 - 21], including such as the discharge gap geometry; the neutral gas pressure; the kind of gas; magnetic field, discharge current, plasma density values. The studies have shown that the experimentally observed rotational velocity is limited within 50% of v_c given by formula (1). Fig. 1 shows the v_c values calculated by eq. (1) versus the atomic number of the elements. Table 1 lists the calculated v_c values for the UO_2

molecule and its dissociation products. The estimation shows that at T = 2 eV, $v_\varphi = 2.2\cdot10^3$ m/s (equal to v_c for U), Δm=25 and Δm=50 the separation coefficient α_0 is equal to 1.6 and 2.58, respectively. As is obvious, the limitation of the plasma rotational velocity may substantially decrease the separating capacities of rotating-plasma devices.

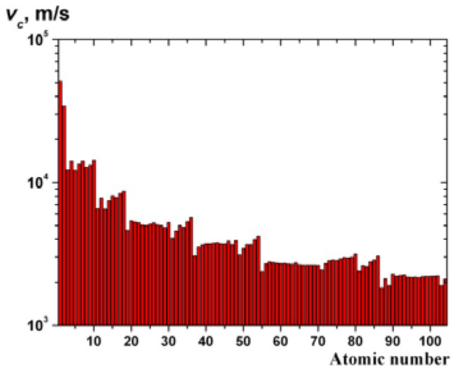

Fig. 1. Critical ionization velocities of the elements. (Atomic weights and ionization potentials of elements with atomic numbers 1 to 99 are taken from [22], with 100 to 104 – from [23], ionization potential At [24])

When postulating the *CIV*, Alfven has indicated two necessary conditions: i) presence of plasma in the magnetic field, and ii) neutral gas presence. In his review [18], Brenning has summed up the results of *CIV* phenomenon studies over two empirical criteria, the fulfillment of which leads to the *CIV*.

Table 1

Gas Species	Atomic (molecular) weight, amu	v_c, m/s
O	16	$12.8\cdot10^3$
O_2	32	$8.5\cdot10^3$
U	238	$2.2\cdot10^3$
UO	254	$2.06\cdot10^3$
UO_2	270	$1.96\cdot10^3$

The first criterion that characterizes the desired magnetic field value is the Alfven Mach number [18]:

$$M_A = \frac{V_0}{V_A} = \left(\frac{m_i N_i V_0^2/2}{B^2/2\mu_0}\right)^{1/2}, \qquad (4)$$

where $V_A = B/(\mu_0 m_i N_i)^{1/2}$ is the Alfven velocity, N_i – ion density; m_i – ion mass; μ_0 – magnetic constant; B – magnetic induction; V_0 – velocity. The analysis of the experimental results, carried out in [18], has shown that the CIV is observed in strong magnetic fields ($V_A > 10\ V_0$), while in the range from V_A=V_0 up to V_A =10 V_0 the CIV be observed, but not always. In weak magnetic fields at $V_A < V_0$ the CIV is virtually never observed. As indicated in [18], in terms of the magnetic field, the value of $V_A > 3\ V_0$ ($V_A > 3\ v_c$) may be considered to be a sufficient condition for the CIV. From the above it follows that $1 \geq M_A$. For example, for the uranium plasma of density $N_i = 10^{18}\ldots10^{20}$ m^{-3} at the magnetic field inductions $B > 5\cdot10^{-3}$ T (for 10^{18} m^{-3}) and $B > 0.05$ T (for 10^{20} m^{-3}), the condition $V_A > 3\ v_c$ will be fulfilled. In the magnetoplasma devices with crossed $\boldsymbol{E}\times\boldsymbol{B}$ fields under development, the expected magnetic field value generally exceeds the above-estimated magnetic field induction values. So, the magnetic field criterion for the *CIV* in the magnetoplasma devices will be in many cases fulfilled.

The second criterion characterizing the required neutral gas density is the Townsend criterion [18]:

$$\int N_n dz > \frac{v_c}{\langle \sigma_e V_e \rangle_{\max}}, \qquad (5)$$

where N_n is the density of neutral atoms (molecules); V_e – electron velocity; σ_e – electron-impact ionization cross section; $<\sigma_e V_e>_{max} = K_{e,max}$ – maximum rate constant of electron-impact ionization. In accordance with the data of ref. [25], taking the $K_{e,max}$ values to be $3.3\cdot10^{-13}$ m^3/s for U, $3.6\cdot10^{-13}$ m^3/s for UO, $3.8\cdot10^{-13}$ m^3/s for UO_2, we obtain, respectively, $v_c/K_{e,max} \approx 6.7\cdot10^{15}$ m^{-2} (U), $5.7\cdot10^{15}$ m^{-2} (UO), $5.2\cdot10^{15}$ m^{-2} (UO_2). For the O_2 molecule, we have $v_c/K_{e,max} \approx 5.7\cdot10^{16}$ m^{-2} at $K_{e,max} \approx 1.5\cdot10^{-13}$ m^3/s [26], this being an order of magnitude higher than the estimated values for uranium and its oxides. Correspondingly, for the monatomic O at $K_{e,max} \approx 7.9\cdot10^{-14}$ m^3/s [27] we have $v_c/K_{e,max} \approx 1.6\cdot10^{17}$ m^{-2}. Naturally, the $K_{e,max}$ values taken for the estimations may differ by order of magnitude from the $K_{e,max}$ value under real experiment conditions. Thus, the $v_c/K_{e,max}$ value may vary in a rather wide range.

In completely ionized plasma, the *CIV* effect will not be observed. However, in laboratory conditions the plasma is always bounded, and its interaction with the surface will result in the production of neutral atoms, e.g., in the surfaces of the vacuum chamber. As a result, the rotational velocity will be limited to v_c. In the magnetoplasma devices, the mass separation of substance calls for a constant supply of the feed stock to the plasma volume; that will eventually lead to the *CIV* and to the velocity v_c limitation. In refs. [28 - 30], Lehnert has put forward several ideas as to the possibility of increasing the rate limit of plasma rotation. One of his proposals was confirmed experimentally. In the magnetic field of mirror configuration with limitation of plasma rotation velocity in the chamber ends $v_\varphi = v_c$, giving due consideration to isorotation [28], the maximum rotational velocity in the center body section (middle part) will be described by the expression (see [21]):

$$v_{\max} = v_c R^{1/2}, \qquad (6)$$

where R is the mirror ratio. As is seen from eq. (6), the maximum rotational velocity can be increased by a factor of $R^{1/2}$. So, the introduction of the substance to be separated to the magnetoplasma device in the region behind the mirrors, where v_φ will be limited to v_c, will make it possible to increase the rate limit of plasma rotation in the middle part. However, as estimations show [12], a substantial increase is possible at high mirror ratios.

3. LIMITATION OF MULTICOMPONENT PLASMA ROTATIONAL VELOCITY

The *CIV* phenomenon was investigated by experiment not only in molecular and atomic gases, but in their mixtures, too [18, 19, 31]. Besides, the *CIV* was observed in the gas-metal plasma produced in the pulsed magnetron discharge, where the metal component entered the discharge due to sputtering of the cathode material [32, 33].

Based on eq. (3), the authors of ref. [31] have derived a semiempirical relation for a two-component gas mixture:

$$v_c^* = \sqrt{\frac{2\left(\alpha_i e\phi_i^A + (1-\alpha_i)e\phi_i^B\right)}{\alpha_i m_n^A + (1-\alpha_i)m_n^B}}\,, \quad (7)$$

where m_n^A, m_n^B and ϕ_i^A, ϕ_i^B denote, respectively, the mass of a neutral atom or a molecule of species *A* and *B*, and their ionization potentials; α_i is the fractional ion production rate of component *A* equal to $\alpha_i = (\nu_i^A / \nu_i^A + \nu_i^B)$; ν_i^A and ν_i^B – ionization frequency of particles of species *A* and *B*, respectively. Since $\nu_i^A = N_n^A K_e^A$ ($\nu_i^B = N_n^B K_e^B$), then at $K_e^A = K_e^B$ the fractional ion production rate α_i will take on the form $\alpha_i = (N_n^A / N_n^A + N_n^B)$. The comparison in [31] between the calculated and experimentally measured v_c^* values for a number of gas mixtures has shown in some cases a satisfactory agreement between the experimental data and the values calculated by formula (7). In refs. [12, 32], evaluations of v_c^* were made for a number of gas-metal mixtures. We give here the v_c* estimates for the case of UO_2 dissociation into atoms and molecules. For complete dissociation of the UO_2 molecule into 2*O* and *U*, we obtain α_i = 0.667 ($K_e^O = K_e^U$) and α_i = 0.324 ($K_e^O \approx 7.9\cdot10^{-14}$ m³/s, $K_e^U \approx 3.3\cdot10^{-13}$ m³/s), respectively, $v_c^* = 4.87\cdot10^3$ m/s and $3.15\cdot10^3$ m/s. For the case of O_2 and *U*, we obtain α_i = 0.5 ($K_e^{O_2} = K_e^U$) and α_i = 0.313 ($K_e^{O_2} \approx 1.5\cdot10^{-13}$ m³/s, $K_e^U \approx 3.3\cdot10^{-13}$ m³/s), respectively, and hence v_c^* = $3.6\cdot10^3$ and $2.98\cdot10^3$ m/s. For *O* and *UO* we obtain α_i = 0.5 ($K_e^O = K_e^{UO}$) and α_i = 0.18 ($K_e^O \approx 7.9\cdot10^{-14}$ m³/s, $K_e^{UO} \approx 3.6\cdot10^{-13}$ m³/s), respectively, and hence $v_c^* = 3.7\cdot10^3$ and $2.54\cdot10^3$ m/s.

A somewhat different approach to the *CIV* problem in the multicomponent mixture has been considered in [34], according to which the *CIV* may be observed on condition that the following energy equilibrium equation is fulfilled:

$$\Delta E = \frac{\sum \nu_{i,j}\left[(1/2)m_{n,j}V_0^2 - e\phi_{i,j}\right]}{\sum \nu_{i,j}} \geq 0\,, \quad (8)$$

where $\phi_{i,j}$, $m_{n,j}$, $\nu_{i,j}$ are, respectively, the ionization potential, the neutral atom (molecule) mass, and the ionization frequency of the *j-th* component in the mixture. At the electron-impact ionization cross-section $\sigma_{e,max}$ for all the mixture components, eq. (8) is asymptotically reduced to the form [34]:

$$v_\infty = \sqrt{\frac{\sum_j x_j 2e\phi_{i,j}}{\sum_j x_j m_{n,j}}}\,, \quad (9)$$

where x_j is the mole fraction of the component *j*. For the two-component mixture eq. (9) is similar to eq. (7) at $K_e^A = K_e^B$. To estimate v_∞ for the multicomponent mixture, we put the temperature of UO_2 to be 3500 K, and in this case, according to the data of ref. [35], the vapor composition would be: x = 0.59782 (UO_2); $x = 8.30306\cdot10^{-4}$ (O_2); x = 0.36284 (UO_3); x = 0.00922 (*UO*); $x = 2.10898\cdot10^{-5}$ (*U*); x = 0.02927 (*O*). The estimation gives $v_\infty = 2.32\cdot10^3$ m/s, this being close to the v_c value for *U* (see Table 1).

It should be noted that in the case of multicomponent mixtures, the criteria required for the *CIV* occurrence should also take into account the multicomponent composition. For the two-component plasma, the criterion $V_A > 3\, v_c$ may have the form $V_A > 3\, v_c^*$, and, correspondingly, for the multicomponent mixture we have $V_A > 3\, v_\infty$. However, in this case there is some uncertainty in the choice of the V_A value. For example, at $N_i = 10^{18}$ m⁻³ and $B = 5\cdot10^{-3}$ T the Alfven velocity is equal to $7.07\cdot10^3$ m/s and $2.7\cdot10^4$ m/s for *U* and *O*, respectively. As a result, at $v_c^* = 4.87\cdot10^3$ m/s (2*O* and *U*) and $N_i = 10^{18}$ m⁻³, the condition $V_A > 3\, v_c^*$ is fulfilled at B > $1\cdot10^{-2}$ T (Alfven velocity for *U*) and B > $2.7\cdot10^{-3}$ T (Alfven velocity for *O*). According to ref. [36], in case of several ion species in the plasma, the Alfven wave has two modes: R – the right-hand circularly polarized mode, and L – left-hand circularly polarized mode. At frequencies $\omega << \Omega_2$, where Ω_2 is the cyclotron frequency of the large-mass ion, the dispersion relationship is written as $\omega \approx V_{AT} k_z$. Correspondingly, the Alfven velocity is equal to $V_{AT} = V_A^1 \big/ \sqrt{1+(\rho_2/\rho_1)}$, where V_A^1 is the Alfven velocity of the smaller-mass component, ρ_1 and ρ_2 are the respective densities of the components of lower and higher masses, $m_1<m_2$. In view of the above, the criterion $V_A > 3\, v_c^*$ can be represented as $V_{AT} > 3\, v_c^*$. Taking $v_c^* = 4.87\cdot10^3$ m/s (2*O* and *U*) and $N_i = 10^{18}$ m⁻³, the condition $V_{AT} > 3\, v_c^*$ will be fulfilled at the magnetic induction $B > 6.4\cdot10^{-3}$ T, this being somewhat higher than for *U* ($B > 5\cdot10^{-3}$ T). In the case of the two-component (multicomponent) plasma, the Townsend criterion will be written as $v_c^* \big/ K_{e,\max}^{eff}$ ($v_\infty \big/ K_{e,\max}^{eff}$), where $K_{e,\max}^{eff}$ is the maximum effective electron-impact ionization rate constant of the mixture. The estimation of this criterion gives $v_c^* \big/ K_{e,\max}^{eff} \approx 1.9\cdot10^{16}$ m⁻² ($v_c^* = 3.15\cdot10^3$ m/s) for the two-component mixture (2*O*, *U*), and $v_\infty \big/ K_{e,\max}^{eff} \approx 6.8\cdot10^{15}$ m⁻² ($v_\infty = 2.32\cdot10^3$ m/s) for the multicomponent mixture, which is close in value to $v_c/K_{e,max} \approx 6.7\cdot10^{15}$ m⁻² for *U*.

4. EXPERIMENTAL SETUP

The rotational velocity of the gas-metal plasma in crossed $\boldsymbol{E}\times\boldsymbol{B}$ fields was investigated by experiment at the **MAKET** setup [10]. The setup provides a high-current pulsed reflective discharge in the magnetic field of mirror configuration, *R*=1.25. The detailed description of electrophysical parameters of both the setup and the discharge can be found in refs. [10 - 12]. The gas-metal plasma was produced in the working environments of gases (H_2, *Ar*, 88.9% *Kr*-7% *Xe*-4% N_2-0.1% O_2) and the sputtered cathode material (*Ti*). The discharge resulted in the production of a dense ($N_e \leq 2\cdot10^{14}$ cm⁻³), highly ionized (≤ 100%) gas-metal plasma with *Ti* amounting to 40…50% [12]. The results of the investigations on the gas-metal plasma parameters have been summarized in [12].

The rotation of multicomponent gas-metal plasma was investigated by the method of microwave correlation reflectometry (MCR) [11, 37]. The MCR technique rests on the definition of the autocorrelation function (*ACF*) and cross-correlation function (*CCF*) of two poloidally spaced microwave signals reflected from the layer of same-density plasma. The microwaves are reflected from the plasma layer of critical density N_{cr}, i.e., at the plasma electron density $N_e \geq N_{cr}$. So, unlike the optical Doppler spectrometry, the MCR method can be used to determine the rotational velocity v_φ of the reflecting layer having $N_e \geq N_{cr}$. To a first approximation, its value is found to be $\approx E_r/B_z$ [11]. The plasma rotational velocity for the case of circular symmetry profile is given by the relation $v_\varphi = \omega_\varphi r_{cr} = \Delta\varphi\, r/\Delta t$, where $\Delta\varphi$ is the angular distance between the reflected-wave receiving points; r_{cr} is the reflecting layer position determined from the phase shift of the reflected wave; Δt is either the time shift of the CCF maximum, or the *ACF* period, ω_φ is the angular rate of rotation. Some possible errors of rotational velocity measurements by the MCR technique were analyzed in ref. [37]. According to the estimations in [37], the measurement errors may vary from several percent's up to 30% and more.

Simultaneously with the reflectometry measurements, the maximum $N_c = N_{cr}$ and the average density were also measured by means of a microwave interferometer that permitted the determination of the time interval of the existence of the critical density layer.

5. EXPERIMENTAL RESULTS AND DISCUSSION

The use of the MCR technique has made it possible to measure the plasma rotational velocity in the reflective discharge in time. The plasma dynamics in time can be arbitrarily divided into several stages [11]. At the first stage, plasma layers with $N_e=N_{cr}$, of radius equal to the sensing wavelength $r = \lambda$, are formed; at the second stage the radial dimensions of the plasma layers with $N_e=N_{cr}$ increase up to a certain value, $r = r_{max}$, upon reaching which the radius of the layers remains practically the same for the time Δt (~ hundreds of μs); at the third stage the radial dimensions of plasma layers start decreasing, the density falls off and the plasma decays. It has been demonstrated experimentally in [11] that the increase in B caused the increase in r_{max}, ω_φ, and, correspondingly, the plasma rotational velocity v_φ in the reflective discharge.

The measured data on the rotational velocity v_φ of the gas-metal plasma produced in the reflective discharge are generalized in Fig. 2. The data spread is indicated for sampling from n>5 measurements of the maximum rate of rotation; for the n<5 sampling the mean values of $\bar{v}_\varphi$ are indicated. The solid and dotted lines in Fig. 2 also show the v_c values for the elements entering into the composition of the gas-metal plasma. From the data given in Fig. 2 it follows: first, the rotational velocity v_φ is dependent on the magnetic induction value, at least, up to $B \approx 0.15$ T (see Figs. 2,b,c); secondly, v_φ is dependent on the atomic weight of ions present in the plasma (see Figs. 2,b,c). As mentioned earlier in [10, 11], the dependence of v_φ on B and m_i is qualitatively described by the one-fluid MHD plasma model. For example, the estimation in [10] for pure H_2 gives $v_\varphi > 10^5$ m/s, which is not observed in the experiment (see Fig. 2,a), whereas for the 50%H_2+50%Ti mixture the estimate $v_\varphi = (2.8\ldots5.6)\cdot10^4$ m/s is close to the experimental value (see Fig. 2,a).

We now consider the limitation of the plasma rotational velocity. As is seen from Fig. 2, at the magnetic induction B less than ≈ 0.1 T the rotational velocity is $v_\varphi < v_c$(Ti), but with the B increase up to $B > 0.1$ T, the rotational velocity becomes $v_\varphi > v_c$ (Ti).

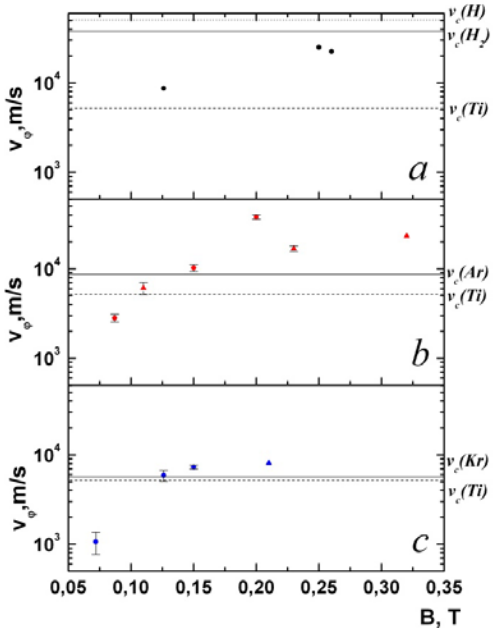

Fig. 2. Maximum rotational velocity of the plasma layer with $N_e \geq 1.7\cdot10^{19}$ m^{-3} versus magnetic induction: a – H_2+Ti, ● – p = 0,267 Pa, $U_{dis.}$ = 3.6 kV ($I_{max} \approx$ 1.66 kA); b – Ar + Ti : ● – p = 0,8 Pa, $U_{dis.}$ = 3.8 kV ($I_{max} \approx$ 1,7 kA); ▲ – p = 0.133 Pa, $U_{dis.}$ = 3,2 kV ($I_{max} \approx$ 1.53 kA); c – (Kr - Xe - N_2 - O_2)+ Ti: ● – p = 0.8 Pa, $U_{dis.}$ = 3.8 kV ($I_{max} \approx$ 1.7 kA); ▲ – p = 0.133 Pa, $U_{dis.}$ = 3.4 kV ($I_{max} \approx$ 1,56 kA)

Actually, an excess of the critical velocity takes place, but since in the given case the multicomponent gas-metal plasma is investigated, a more detailed consideration will be given here to the rotational velocity limitation. Table 2 lists the v_c values calculated for the elements entering into the plasma composition, and also the v_c^* (v_∞) values for their mixtures. As is seen from Table 2, the condition $V_A > 3\, v_c$ ($V_{AT} > 3\, v_c^*$) is fulfilled at $B > 0.02\ldots0.03$ T ($1.7\cdot10^{19}$ m^{-3}), and hence, in the given experiments, too (see Fig. 2). At given experimental conditions, the neutral atoms come to the plasma in longitudinal and radial directions relative to the plasma column. In the process, Ti atoms come to the plasma in the longitudinal direction. The calculations carried out in [12] have shown the content of neutral titanium atoms in the basic plasma column to be insignificant. Both, the working gas atoms and the atoms (molecules) desorbed from the discharge chamber wall come to the plasma radially; their quantity can amount to several percent's [10].

The mass separation of the neutral component takes place in the weakly ionized rotating plasma in the same manner as in gas centrifuges [14, 29]. In this case, according to [29], the radial concentration of the neutral particles can be calculated from the relation:

$$N_n(r) = N_n(0)\exp\left[\frac{m_n\omega_\varphi^2 r^2}{2kT}\right]. \qquad (10)$$

In view of this, the concentration of neutral particles and the percentage of the particles coming radially into the plasma may substantially differ from the initial value. For illustration, Fig. 3 shows the radial distribution of neutral particles calculated by formula (10) as the N_n^p / N_{n0}^{Σ} ratio, where N_n^p and N_{n0}^{Σ} are, respectively, the partial and total concentrations of the particles. The calculation was performed for the mixture of 88.9% *Kr*-7% *Xe*-4% N_2-0.1% O_2 at the conditions close to the ones of gas centrifuges [14]: $\omega_\varphi = 7{\cdot}10^3$ rad/s (v_φ = 700 m/s at $r=r_{max}$) T = 600 K. So, in this case for $r/r_{max} = 0.5$ the concentration will be 87.35% *Kr*-2.02% *Xe*-10.38% N_2-0.25% O_2, and hence, $v_\infty = 5.9{\cdot}10^3$ m/s will be somewhat higher than at the initial concentration (see Table 2). At $\omega_\varphi = 1{\cdot}10^4$ rad/s ($v_\varphi = 10^3$ m/s at $r=r_{max}$) T = 600 K, and with $r/r_{max} = 0.5$, the estimation gives the concentration 52.54% *Kr*-0.19% *Xe*-46.28% N_2-0.99% O_2, and accordingly, $v_\infty \approx 7{\cdot}10^3$ m/s. Therefore, this effect should apparently be taken into account when considering the limitation of plasma rotational velocity. A more detailed consideration calls for construction of the multifluid MHD model with due regard for a variety of atomic processes occurring in the plasma.

Table 2

Gas Species	v_c, m/s	v_c^* (v_∞), m/s	*B, T* (*V* > 3 *v*)
H	$51{\cdot}10^3$	–	0.029
H_2	$38{\cdot}10^3$	–	0.031
Ti	$5.2{\cdot}10^3$	–	0.021
50%*H*+50%Ti	–	$8.9{\cdot}10^3$	0.025
50%H_2+50%Ti	–	$9.2{\cdot}10^3$	0.026
Ar	$8.7{\cdot}10^3$	–	0.031
50%*Ar*+50%Ti	-	$7{\cdot}10^3$	0.026
Kr	$5.7{\cdot}10^3$	–	0.029
50%*Kr*+50%Ti	–	$5.5{\cdot}10^3$	0.025
Xe	$4.2{\cdot}10^3$	–	0.027
88,9% *Kr*-7% *Xe* - 4% N_2-0,1% O_2	–	($5.6{\cdot}10^3$)	

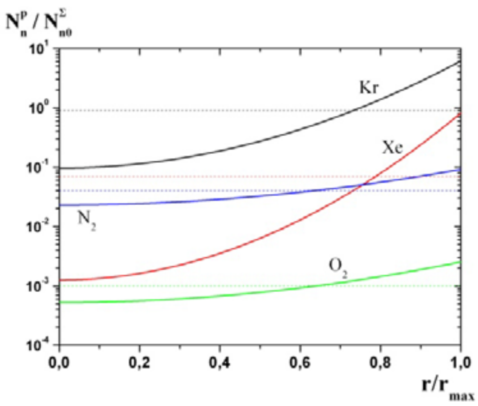

Fig. 3. Radial distribution of neutral particle concentrations. The dotted lines show the initial concentration; solid lines are for the concentration at $\omega_\varphi = 7{\cdot}10^3$ rad/s

Summarizing the results, it can be stated the following: i) at *B*>0.1 T the plasma rotational velocity in the mixtures under consideration is $v_\varphi > v_c(Ti)$, this being evidently due to an insignificant content of neutral *Ti* in the plasma column; ii) the rotational velocity in the H_2+*Ti* plasma does not exceed v_c of the *H*, H_2 gas components; for the *(Kr - Xe -* N_2 *-* O_2*)+ Ti* mixture the rotational velocity is no more than 50% of $v_c(Kr)$; iii) the same is the case for *Ar* + *Ti* at $B \le 0.15$ T, i.e., we have $v_\varphi < 1.5\, v_c\,(Ar)$, and the excess of this value is apparently due to the entry of lighter impurities. Thus, the chosen method of metal component delivery to the plasma permits one to extend the limiting range of plasma rotational velocity.

CONCLUSIONS

We note finally:

1. Consideration has been given to the rotational velocity limitation, including the case of multicomponent gas-metal plasma, which is related to the critical ionization velocity effect. It has been shown that the plasma rotation velocity limitation can substantially reduce the separative power of the rotating-plasma devices.

2. Measurements have been made and experimental findings have been generalized for the rotational velocity of the gas-metal multicomponent plasma produced in the reflective discharge. It has been shown that the rotational velocity of the gas-metal multicomponent plasma correlates with the critical rate of gas component ionization.

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КРИТИЧЕСКАЯ СКОРОСТЬ ИОНИЗАЦИИ В ГАЗОМЕТАЛЛИЧЕСКОЙ ПЛАЗМЕ

Ю.В. Ковтун

Рассмотрено ограничение скорости вращения многокомпонентной газо-металлической плазмы и влияние этого эффекта на разделение по массам во вращающейся плазме. Проведены и обобщены результаты экспериментальных измерений скорости вращения газометаллической многокомпонентной плазмы.

КРИТИЧНА ШВИДКІСТЬ ІОНІЗАЦІЇ В ГАЗОМЕТАЛЕВІЙ ПЛАЗМІ

Ю.В. Ковтун

Розглянуто обмеження швидкості обертання багатокомпонентної газо-металевої плазми і вплив цього ефекту на розділення за масами в плазмі, що обертається. Проведені і узагальнені результати експериментальних вимірювань швидкості обертання газометалевої багатокомпонентної плазми.