A COLD-CATHODE HALL PLASMA ACCELERATOR

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A high-speed plasma flux is produced in a plasma accelerator by means of Ampère forces while maintaining quasineutrality [1, 2]. This method of acceleration can produce a plasma flux with an ion energy $E_i \approx 1\text{-}10^4$ eV over a wide range in the mass flux density. Various types of stationary plasma accelerators have been developed and examined that operate with gaseous substances and metals of high vapor pressure. The range of working substances used in such plasma accelerators is restricted, which limits the efficient use in various areas of science and technology, in particularly in vacuum processes for producing materials and coatings by the condensation of such plasma fluxes (high-energy plasma technology) [3-5]. Here we consider a new type of Hall plasma accelerator that has a cold cathode working with the erosion products from the cathode, which substantially extends the range of working substances and enables one to produce plasma flows from refractory metals and metals of low vapor pressure.

1. Theoretical Scheme and Measurable Parameters. The accelerator (Fig. 1) is composed of coaxial force-cooled electrodes (1 cathode and 2 anode) and the magnetic coil 3, which produces an axially symmetrical and axially diverging magnetic field in the electrode gap. A difference from accelerators of this type with hot thermionic cathodes is that the cathode here is made of the working substance and has the end as the working surface. The working material is produced directly from the solid surface of the cathode under the action of mobile cathode spots produced by a vacuum arc burning between the electrodes. The number of these spots is proportional to the accelerator current, and the current density in a spot is $10^6\text{-}10^7$ A/cm^2 when the current in a spot varies up to hundreds of Ampères, in accordance with the thermophysical characteristics of the cathode material. The power density is then $10^7\text{-}10^8$ W/cm^2 in the spots, which provides for efficient production of the working substance while the evaporation surface as a whole remains cold. The cathode spots are prevented from migrating to the side surface by fitting the latter with the screen 4, which surrounds this surface with a small gap. The vacuum arc is excited either by breakdown in gas admitted to the electrode or by breaking a current contact between cathode and anode by means of a moving auxiliary electrode at the anode potential. The anode is force-cooled to prevent the working material from interacting with the anode.

The following are the characteristic parameters of this accelerator: input electrical power 1-10 kW; voltage on accelerator, $U = 30\text{-}60$ V; current, $I = 50\text{-}500$ A; external magnetic field, $B \leqslant 100$ G; consumption of cathode material, $\dot{m} \leqslant 0.04$ g/sec; and ion current density in the plasma jet, $j_i \leqslant 0.12$ A/cm^2.

The external characteristics of the accelerator were measured (voltage—current curve, flow rate, and efficiency η_m in the use of the mass), as well as the thermal losses at the electrodes Q_c and Q_a, from which we determine the effective voltage-equivalent energies supplied to the cathode $U_c^* = Q_c/I$ and the anode $U_a^* = Q_a/I$, as well as to the plasma $U_p^* = U - (U_c^* + U_a^*)$, which gives the energy efficiency $\eta_t = U_p^*/U$ of the accelerator, together with the total ion current and the distribution of the plasma parameters in the jet. The performance was evaluated by comparing the parameters of the accelerator with those of a plasma generator when the accelerator worked without the external magnetic field.

2. Plasma-Generator State. A vacuum arc was here excited between the electrodes, which burned in the vapor of the cathode material. The evaporation products from the cathode spots contained plasma, vapor, and microdroplet phases, whose relative proportions and velocity or energy distributions were dependent on the thermophysical parameters of the cathode material (the relationship is shown qualitatively in Fig. 2).

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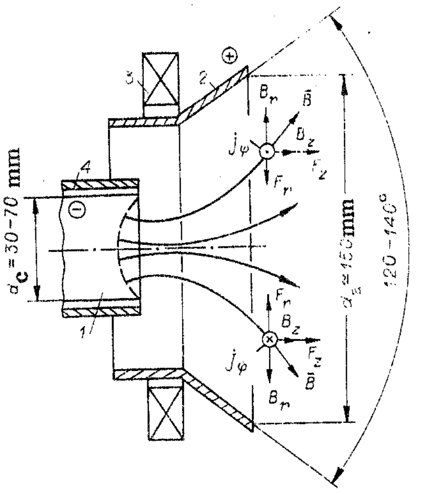

Fig. 1

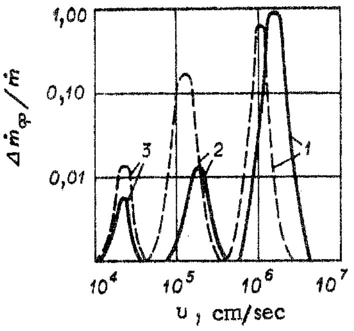

Fig. 2

Figure 2 also shows the typical distribution by phase composition and velocity v for the erosion products for a refractory metal (1 ions, 2 vapor, 3 microdroplets, where the broken curves are for the generator state and the solid lines are for the acceleration state). Refractory metal gives a high proportion of the plasma phase and only about 1% of the microdroplet phase. The proportion of microdroplet phase rises to 10% or more for a fusible metal. The degree of ionization in the evaporation products varies from 15 to 80% in accordance with the multiplicity of the ionization (the evaporation products contain singly, doubly, and triply charged ions), with high values applying for refractory metals, while the average ion energy was about 10-100 eV [6]. The proportion of droplet phase for a particular material is substantially dependent on the integral temperature of the evaporation surface as well as on features of the material such as gas inclusion, grain size, and so on. The proportion of microdroplet phase is minimized by reducing the grain size and the integral temperature of the surface, along with a high degree of surface finish. The erosion products escape isotropically within the angle of emission ω of the evaporation surface. The flow of working substance from the plasma generator is defined by

$$\dot{m}^* = \mu\eta_m I,$$

where μ is a coefficient of proportionality taking the value 10^{-4}-$4 \cdot 10^{-5}$ g/C in accordance with the material of the cathode and η_m is the efficiency in the use of the mass, which incorporates the mass loss to the anode arising from partial condensation on it.

The value of η_m in plasma-generator mode is almost independent of the current but is dependent on μ, which means that one can control the flow rate via the arc current.

The working-current range of the plasma generator has a lower bound set by the minimum current for long-term arc burning I_m, which in turn is dependent on the nature of the cathode material and on the parameters of the power supply. The minimum current decreases as the impedance of the supply increases. Table 1 gives basic data obtained with the accelerator working as a plasma generator, with I_m recorded for an impedance of about 1 Ω. Here we give data on the burning voltage of a stationary vacuum arc, which is almost independent of the arc current up to 500 A, together with the values of the coefficient μ, the electrical transport coefficient $\xi = I m_a \eta_m / \dot{m}^* e$ (where m_a is the mass of an atom in the cathode material and e is the electronic charge), and the energy performance of the generation per atom $\lambda = \bar{I} U m_a \eta_m / e\dot{m}^*$ and per unit mass $\varepsilon = UI\eta_m / \dot{m}^*$. The maximum current is restricted by the performance of the cathode cooling (design factor) and does not exceed 500 A for refractory metals and metals of high thermal conductivity (Cu and Ni).

When the accelerator works as a plasma generator, there is isotropic escape of the erosion products, whose phase composition and energy distribution are dependent on the nature of the cathode material. In that sense the operation as a plasma generator is analogous to that of the arc vacuum evaporators described in [7-10].

3. Plasma-Accelerator Mode. This mode occurs when an axially symmetrical and axially divergent magnetic field is imposed on the volume of the accelerator. The plasma is focused

TABLE 1

Metal	I_m, A	U, V	$\mu \cdot 10^4$, g/C	ξ, $\frac{\text{electron}}{\text{atom}}$	$\varepsilon \cdot 10^5$, J/g	λ, $\frac{\text{eV}}{\text{atom}}$
Al	60	16	1,25	2,26	1,28	36
Cu	80	20	1,165	5,77	1,72	115
Ni	90	19	1	5,87	1,9	111
W	350—400	26,8	0,6	29	4,47	775
Ti	80	22	0,53	9,9	4,15	218
Mo	200—250	28,4	0,47	20,4	6,05	580
Cr	90	20	0,42	13,8	4,76	276

into a directed flux and is accelerated along the axis of the system, and there are also various effects characteristic of this cold-cathode device. Experiments show that the field disrupts the random motion of the cathode spots and produces a directional motion, whose form is dependent on the field configuration at the evaporation surface. A qualitative description can be given of the stabilization in terms of the topology of the external field in the working volume and the character of the erosion wear.

A magnetic field parallel to the surface of the cathode displaces the spots at right angles to the vector of this field in a direction opposite to that due to the Ampère force. In the present case, the tangential field component B_r at the surface causes the spots to rotate around the axis of the cathode in this direction. As the spots rotate, they are displaced radially in the sense of the acute angle formed by the surface of the cathode and the field vector. The direction of this motion coincides with that of the Ampère force acting on the surface current formed by rotation of the spots and the normal component of the magnetic field B_z. Therefore, the evaporation surface takes a form close to orthogonal to the magnetic field lines (Fig. 1). When orthogonality is attained, the shape of the evaporation surface remains unchanged because of self-regulation, since any deviation from orthogonality due to deviation in the motion of the cathode spots accentuates such motion. Therefore, the speed of the cathode spots is low (B_r at the surface is low), viz., ≤ 1 m/sec. One consequence of this rotation around the axis is integral rotation of the plasma flow, whose speed is that of the rotation of the spots. These effects appear when the magnetic field at the axis of the accelerator is $\leqslant$40-50 G. In stronger fields, there is increased stabilization of the spots at the surface, which causes either accumulation of the spots at the center of the cathode or displacement to the periphery, in accordance with the topology of the field at the surface, and which is usually accompanied by extinction of the discharge. Therefore, the above fields are limiting ones for this design of accelerator. The fields may be made higher by stabilizing the spots with a stronger independent field of arched configuration [4].

Parts a-c of Fig. 3 (I = 200 A) show the characteristics of this cold-cathode device for this range in the magnetic field as obtained with a titanium cathode. The trends remain qualitatively the same for other working bodies. As the field strengthens at a constant current, there is displacement of the plasma from the anode and the formation of a rotating focused plasma flow, with increases in the voltage across the accelerator, the emerging ion current I_i, the consumption of working material, the energy content of the plasma jet, the energy and mass efficiencies, and the degree of ionization of the plasma α. Unchanged quantities are the consumption of the cathode material and the effective voltage equivalent of the energy loss in the cathode, which shows that the processes in the cathode spots are independent of the external magnetic field. In that case the effects of the magnetic field make themselves felt in the acceleration zone, where there is interaction between the radial electric field and the axial magnetic field, which produces an azimuthal Hall current j_φ that is $\omega_e\tau_e$ times the conduction current j_r (the Hall parameter is $\omega_e\tau_e \gg 1$ for a characteristic plasma concentration in the acceleration region of $n \simeq 10^{12}$ cm^{-3}, an electron temperature, $T_e \simeq 1$-10 eV, and B = 20-40 G). The occurrence of electron drift in the acceleration zone increases α (Fig. 3c) on account of ionization of the vapor component by electron collision and displacement of the plasma from the anode region, on account of focusing of the plasma jet by the bulk force $F_r = j_\varphi B_z$. The latter causes an increase in the mass efficiency (Fig. 3c) and an increase in the anode potential drop (increase in U_a^*), which is due to depletion of the plasma in the anode region of ions. Parts a and b of Fig. 4 also illustrate the

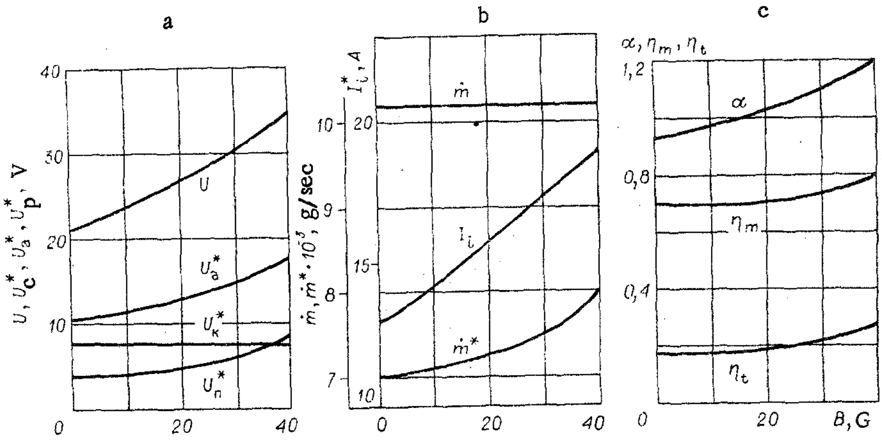

Fig. 3

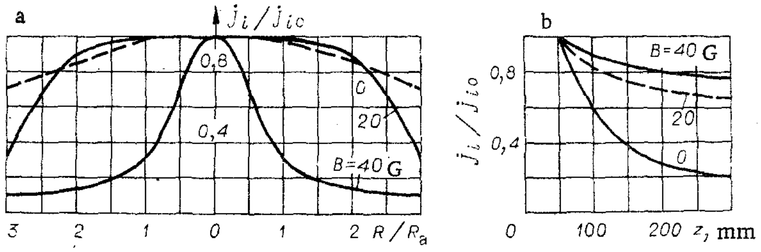

Fig. 4

focusing effect, which implies that there is appreciable focusing even for B ≈ 20 G. Parts a and b of Fig. 4 show also the distribution of the ion-current density over the radius and axis of the plasma jet in relation to the magnetic field at the axis (cathode material Ti, I = 200 A, radial distributions constructed for a distance z = 200 mm from the end of the cathode, R_a radius of the anode, R distance from the axis of the plasma jet, j_{i_0} ion current density at the axis of the plasma jet, j_i ion-current density at a distance R from the axis). There is relatively high uniformity in the ion-current density in the plasma jet. There is a certain fall in this density away from the end of the accelerator on account of thermal expansion of the plasma. Figure 3c shows α in relation to the magnetic field as calculated from the observed $\dot{m}^*$ and I_i for a singly ionized plasma. As α > 1, this must mean that there are highly charged ions in the plasma.

The plasma is accelerated in this system mainly by the force $F_z = j_\varphi B_r$, which is confirmed by the increase in the voltage equivalent of the energy deposited in the plasma U_p^* and also by direct measurements on the energy of the accelerated ions, which attains 100-150 eV for B = 30-50 G.

This cold-cathode device operated in accelerator mode has also shown another effect, viz., spontaneous separation of the microdroplet phase, with a reduction in the concentration of this phase in the plasma jet by an order of magnitude. The microdroplet phase is localized at the periphery of the jet and partly is deposited on the anode.

Therefore, this cold-cathode device produces focusing, acceleration, and integral rotation of the plasma flow, as well as equalization of the phase composition by ionization of the neutral component and separation of the microdroplets, which provides for smooth control of the flow speed at low energies (100-150 eV) by adjustment of the magnetic field in the volume of the accelerator.

This cold-cathode device provides focused dense plasma flows of particle energy 100-150 eV from a wide range of solid conducting materials, including refractory metals such as W, Mo, Nb. An accelerator of this type may find application in various areas of technology: in the creation of oil-free pumping systems involving the sorption of gases by the condensing flow of plasma from a getter material, in plasma chemistry to perform high-temperature reactions, and in research on the properties of plasma or the creation of radiation sources [1, 2]. The device provides good scope for producing materials and coatings by vacuum condensation from plasma flows at high and adjustable particle energies [4-6, 11].

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AN ELECTROSTATIC WALL PROBE IN A FLOW OF COOL PLASMA

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There are various difficulties in using an electrostatic wall probe with a flow of relatively dense plasma on account of convection and the formation of temperature and hydrodynamic boundary layers, as well as ambipolar diffusion, discrepancies between the electron temperature and the gas temperature, and nonequilibrium ionization and electron–ion recombination.

A major task in theoretical examination of the properties of wall probes is to construct voltage–current characteristics and determine the relation between the saturation ion current and the electrophysical parameters of the unperturbed plasma. The available data are conflicting. In [1-3], the saturation ion current was dependent on the profiles of the electron and gas temperatures near the probe. On the other hand, it follows from [4-6] that there is no appreciable effect on the saturation current from the distributions of these temperatures at the surface.

To resolve these conflicts and to provide a sound basis for the use of wall probes it is necessary to determine the theoretical distributions for the charged-particle concentrations, electric fields, and electronic and ionic components of the probe current together with the voltage–current characteristics, although it is extremely complicated to consider all the above factors [7]. For this reason, various simplifications and assumptions were made. For example, convection was neglected in [7-10], while the nonequilibrium ionization and recombination processes in the boundary layer were neglected in [11]. However, these simplifications are not always reasonably justified, and the limits of application are frequently not stated.

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