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CALCULATION OF THE VELOCITY OF A PLASMA FLOW IN THE NOZZLE EXIT SECTION OF A COAXIAL-ELECTRODE HALL ACCELERATOR

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The velocity of a plasma jet in the nozzle exit section and the pressure in the discharge zone of a coaxial-electrode Hall accelerator have been calculated on the basis of the experimentally measured enthalpy, temperature, and electron concentration near the indicated section within the framework of a model of the magnetic hydrodynamics of a plasma flow.

To experimentally reproduce the conditions of interaction of a plasma flow generated by a coaxial-electrode Hall accelerator (CEHA) with bodies found in this flow, it is necessary to know the physical characteristics of the indicated flow [1–6]. In practice, characteristics averaged over the physical volume of a plasma, such as the integral force F acting on the plasma and the velocity of a plasma flow v, are used. Correct calculation of the spatial distribution of these characteristics in the acceleration zone is a complex problem that has not been solved for the general case up till now.

The force F and the velocity v can be calculated only for concrete operating conditions with the use of available experimental data. In the present work, we propose a method of calculating the velocity of a plasma flow in the nozzle exit section of a CEHA with account for the design features of the CEHA and the physical processes occurring in it under concrete operating conditions.

A plasma is accelerated in a CEHA by three mechanisms depending on the power of the discharge in it: the gas-kinetic (thermal), Hall, and heavy-current mechanisms; in this case, the total velocity of a plasma flow in the CEHA represents the sum of the gas-dynamic, heavy-current, and Hall velocities. The possibility of the simultaneous use of different mechanisms of plasma acceleration in a CEHA allows one to improve its design and substantially widen the range of its operating parameters. However, this makes the analysis of the work of the CEHA much more difficult.

The equation of magnetic hydrodynamics of a steady plasma flow is as follows [7]:

$$\rho\,(\mathbf{v}\nabla)\,\mathbf{v} = -\,\nabla p + \mathbf{j}\times\mathbf{B}\,. \tag{1}$$

Figure 1 presents the scheme of work of a CEHA. Since the accelerator considered is coaxial, equations for it will be written in the cylindrical coordinate system $\{r, \varphi, x\}$, in which the current density $\mathbf{j}$ has components $\{-j_r, -j_\varphi, -j_x\}$ and the magnetic induction $\mathbf{B}$ has components $\{B_r, -B_\varphi, B_x\}$. In this case, the equation for a steady axisymmetric plasma flow is written in projections on the coordinate axes in the following form:

$$\rho\left(v_r\frac{\partial v_r}{\partial r} + v_x\frac{\partial v_r}{\partial x} - \frac{v_\varphi^2}{r}\right) = -\frac{\partial p}{\partial r} - j_\varphi B_x - j_x B_\varphi\,, \tag{2}$$

$$\rho\left(v_r\frac{\partial v_\varphi}{\partial r} + v_x\frac{\partial v_\varphi}{\partial x} + \frac{v_r v_\varphi}{r}\right) = j_r B_x - j_x B_r\,, \tag{3}$$

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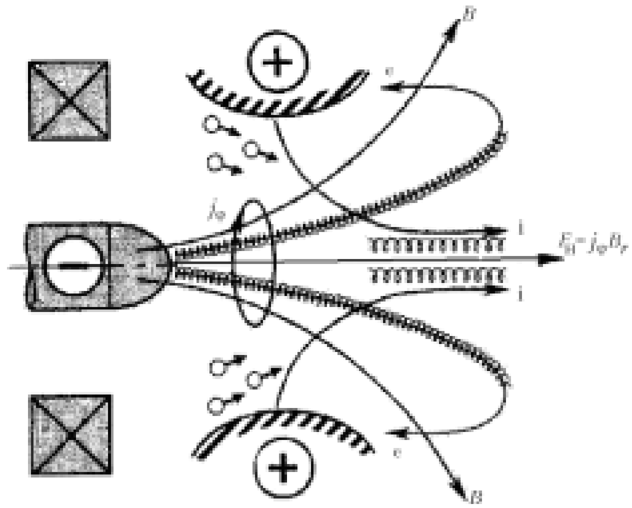

Fig. 1. Scheme of work of a CEHA: e) electrons; i) ions.

$$\rho\left(v_r \frac{\partial v_x}{\partial r} + v_x \frac{\partial v_x}{\partial x}\right) = -\frac{\partial p}{\partial x} + j_r B_\varphi + j_\varphi B_r . \quad (4)$$

Using Eqs. (2) and (4) and the continuity equation with corresponding boundary conditions, we obtain an expression for the force acting on the plasma in the axial direction [7]:

$$F = \int_S \rho v_x^2 \, dS = \sum_{i=1}^{3} F_i , \quad (5)$$

$$F_\mathrm{H} = \int_V j_\varphi B_r \, dSdx - \frac{1}{2} \int_{S_\mathrm{a}} j_\varphi B_x rdS , \quad (6)$$

$$F_\mathrm{h} = \int_V j_r B_\varphi \, dSdx - \frac{1}{2} \int_{S_\mathrm{a}} j_x B_\varphi rdS , \quad (7)$$

$$F_\mathrm{g} = p_0 S_\mathrm{c} + 2\pi \int_0^{r_\mathrm{a}} p\,(r)\, rdr . \quad (8)$$

The force component F_H (Hall component) is due to the interaction of the discharge current with an external magnetic field; it acts on the plasma on the side of the solenoid generating this field and on the side of the cathode. The force F_h (heavy-current) is due to the interaction of the discharge current with an intrinsic magnetic field; it acts on the plasma on the cathode side and the side of the current circuit. The force F_g is due to the response reaction to the pressure of the plasma inside the walls of the accelerator.

The velocity of a plasma flowing from the accelerator is equal to

$$v \approx F/G = (F_\mathrm{H} + F_\mathrm{h} + F_\mathrm{g})/G . \quad (9)$$

To estimate the contribution of each of the accelerating force components, it is necessary to investigate the work of the accelerator under concrete conditions. The following regimes were investigated in the present work: the

TABLE 1. Parameters of the CEHA (B_0 = 1 T, $G = 1\cdot 10^{-2}$ kg/sec, $r_a = 18.5\cdot 10^{-3}$ m, $r_c = 5.0\cdot 10^{-3}$ m, r = 0)

J, A	U, B	$H\cdot 10^{-6}$, J/kg	$n_e\cdot 10^{-21}$, m^{-3}	T_e, K	T_m, K	β	$p\cdot 10^{-5}$, Pa	v_H, m/sec	v_g, m/sec	v_Σ, m/sec	v_t, m/sec
200	270	3.6	—	—	2700	—	0.13	660	1300	1960	1800
300	254	5.3	—	—	3200	—	0.14	980	1350	2330	2200
400	245	7.1	—	—	3600	—	0.15	1300	1500	2800	2600
500	236	8.9	—	7000	4300	—	0.16	1650	1600	3250	2900
600	232	10.7	—	7200	4900	—	0.18	1970	1700	3670	3300
700	227	12.4	—	7200	5300	—	0.18	2300	1750	4050	3500
800	223	14.2	—	7400	5500	—	0.19	2650	1800	4450	3800
930	218	16.5	0.2	7400	5800	28	0.19	3100	1850	4950	4100
1100	215	20.1	0.2	7600	6200	28	0.20	3700	1900	5600	4600
1400	214	25.8	0.3	8300	6500	25	0.20	4700	1950	6650	5200
1600	214	27.7	0.4	8700	6600	28	0.20	5300	2000	7300	5400
1700	214	28.5	0.5	9400	6700	25	0.20	5600	2050	7650	5500
1900	215	34.3	0.7	9800	7000	25	0.21	6350	2100	8450	6000
2000	216	35.5	0.8	10,200	7400	25	0.21	6600	2150	8750	6200
2200	218	39.1	1.2	11,500	8000	25	0.22	7250	2200	9450	6600
2600	220	43.7	1.5	13,500	8400	27	0.23	8600	2250	10,850	7000
3000	224	46.2	2.3	16,000	9200	23	0.25	9900	2500	12,400	7200

magnetic-field induction in the discharge zone B_0 = 1 T, the discharge current J = 200–3000 A, the flow rate of a working gas (8.5 g of air and 1.5 g of nitrogen) G = 10 g/sec, and the pressure in the vacuum chamber $p_0 = 1.25\cdot 10^3$ Pa. We experimentally determined the volt-ampere characteristics of the CEHA [1] and the enthalpy H of the plasma in the discharge zone (see Table 1).

The conditions of realization of a concrete mechanism of plasma acceleration are determined first of all by the dynamics of the electron component. A plasma in a CEHA is mainly accelerated by the Ampere force $j_\varphi B_r$ arising as a result of the interaction of the azimuth Hall current j_φ with the radial component of the magnetic field B_r. This force acts on the electron component because a current in the accelerator is due to light electrons. At the same time, a major part of the kinetic energy is gained in the accelerated plasma by ions owing to their relatively large mass (the longitudinal velocities of electrons and ions should be equal in order that the quasi-neutrality condition be fulfilled); therefore the force acting on the electrons eventually increases the energy of the ion component. The neutral plasma component is accelerated because it is carried along by the ion flow and is acted on by the gas-dynamic forces. The direction of the discharge current in a large part of the plasma flow in the CEHA coincides with the force lines of the external magnetic field; the electric field in the plasma is comparatively weak and the electron temperature is low. As measurements of the electron temperature in a plasma jet showed [1–3], it falls within the range 8000–16,000 K. A flow of such a quasi-neutral plasma can be described in the approximation of magnetic hydrodynamics when the condition of magnetization of the electron component is fulfilled [8]:

$$\beta = \overline{\omega_e \tau_e} = \frac{\sigma B_0}{n_e e} > 1 \ . \tag{10}$$

The interaction between the electron and ion components is maintained in this case due to the self-consistent fields [9].

The Hall factor β was estimated by the temperature and concentration of the electrons in a plasma jet, measured at a distance of 130 mm from the nozzle exit section of the accelerator under different operating conditions [3–6]. The electron concentration was measured in regimes where this was possible. The length of the plasma jet, measured from the nozzle exit section, was ~500 mm and its diameter was ~120 mm. It was assumed that the concentration and temperature of the electrons at the jet axis in the cross sections considered are close to those in the nozzle exit section. The electric conductivity $\sigma(T)$ of the plasma along the force lines of a magnetic field is equal to that in the absence of this field [9]; therefore, as its values, we used the conductivity of air and nitrogen plasmas measured in [10]. Calculations have shown that, e.g., for the currents J = 930–3000 A, the Hall factor is equal to $\beta \approx$ 28–23.

Because of these assumptions, the Hall factor in the nozzle exit section of the accelerator was determined with an error, since both the concentration and temperature of the electrons in this section should be not lower than those in other cross sections. The highest electron temperature and concentration were obtained for heavy discharge currents, and the electron concentration at the temperatures considered increased much more rapidly than the electric conduction; therefore, the values of β should be smallest in this case. Nonetheless, because of the high magnetic induction (B_0 = 1 T), the ratio $\sigma/(n_e e)$ is deliberately larger than unity for the operating conditions of the CEHA considered. This is explained by the fact that, first, the electric conduction is equal to $\sigma(T) = (0.6–8)\cdot 10^3\ \Omega^{-1}\cdot m^{-1}$ in the temperature range investigated and, second, it follows from the equilibrium condition in the discharge zone that the maximum possible electron concentration at the indicated temperatures and pressures is equal to $n_e = 1\cdot 10^{20} - 1\cdot 10^{22}$ m^{-3}. Hence it follows that a minimum possible value of β ($\beta \geq 5$) can be realized at the highest discharge currents. In this case, the near-cathode plasma as a whole will not be accelerated in all probability since (10) is fulfilled for all the operating conditions of the CEHA studied.

The difference between the velocities of the ions and electrons is determined by the exchange parameter [11]

$$\xi = \frac{u_e}{v_i} = \frac{JM_i}{eG} . \tag{11}$$

Under the conditions where $\beta > 1$, the exchange parameter characterizes the relative independence of the ion and electron trajectories. For the regimes considered, the exchange parameter $\xi \leq 5\cdot 10^{-2}$, i.e., the electron trajectories differ insignificantly from the ion trajectories: the anisotropy of the conductivity practically does not distort the current distribution in the accelerator; therefore, there is no need to derive an individual equation of motion for electrons. In this quasi-one-dimensional case, the Hall component F_H of the plasma in the nozzle exit section of the CEHA can have the form [12]

$$F_H = \frac{3\beta}{8\pi x} S_a J B_0 , \tag{12}$$

where

$$x = z\sqrt{\beta^2 + 1} ; \tag{13}$$

$$z = \sqrt{\frac{\ln \frac{r_a}{r_c}}{2\pi\left(\frac{1}{S_a} + \frac{1}{S_c}\right)}} . \tag{14}$$

For the CEHA operating conditions studied, $\beta >> 1$ and, on condition that $\beta = \sqrt{\beta^2 + 1}$, Eq. (12) takes the form

$$F_H = \frac{3}{8\pi z} S_a J B_0 . \tag{15}$$

It follows from (15) that a characteristic feature of a CEHA, in which the Hall mechanism of acceleration is predominant, is a direct dependence of the accelerating force acting on the plasma on the value of the magnetic field in the acceleration zone, the discharge-current strength, and the geometric characteristics of the accelerator.

The role of the force F_h induced by a self-magnetic field is estimated from the condition [13]

$$F_h / F_H \approx J / B_0 \cong 1 , \tag{16}$$

where B_0 is expressed in gauss. Since the magnetic induction of the external magnetic field was high (B_0 = 10,000 G) in experiments on a CEHA, the critical current should be J = 10,000 A or higher in order that the above-indicated condition be fulfilled. In our experiments, the discharge current did not exceed 3000 A; this is why we did not consider effects arising in a plasma under the action of a self-magnetic field.

As for the gas-dynamic pressure gradients, they play a significant role at low discharge currents and large flow rates of a working gas in a dissociated or a weakly ionized plasma [14]. Nonetheless, the potential difference across the CEHA increased sharply with decrease in the discharge currents, which cannot be explained by only the gas-dynamic acceleration. This can be caused by the magnetic-field action because the ratio of the magnetic induction to the concentration of charged particles and the radius $B/(n_e r)$ in a high-velocity axisymmetric plasma jet remains unchanged, i.e., a magnetic field penetrates more easily into a plasma at small concentrations of charged particles. A decrease in the concentration of charged particles leads to an increase in the magnetic induction. This action of the magnetic field on the electron component of the plasma prevents its movement to the walls of the channel. The gas-dynamic mechanism of acceleration cannot be considered separately from the electromagnetic effects because the pressure in the space of the CEHA is also determined by the electromagnetic force that compresses the plasma. However, at low discharge currents and large flow rates of the working gas, the gas-dynamic mechanism, in which the gas rather than the plasma is the working substance, will make the main contribution to the acceleration of the plasma. On the other hand, at high discharge currents, the plasma in the CEHA is mainly accelerated by the Hall mechanism, where ions are accelerated by a self-consistent electric field without dissipation. Therefore, when the total velocity of the plasma flow was determined, these acceleration mechanisms were separated and the electromagnetic and gas-dynamic problems were considered separately.

For some regimes of operation of the CEHA we measured the pressure of the working gas upstream of the discharge zone; it was equal to $p_1 \cong 5\cdot 10^3$ Pa at a flow rate $G = 1\cdot 10^{-2}$ kg/sec. It is difficult to measure the pressure in the discharge zone, the more so the length of this zone is highly conditional. The pressure in the discharge zone can be determined from the equation of ideal-gas state

$$p\,(r_a) = nkT_m\,. \tag{17}$$

This formula is true for any gas having a fairly high temperature in which the concentration of particles is not very high [10].

The gas-dynamic component F_g in the nozzle exit section can be approximately written in the following form:

$$F_g \approx p_0 S_c + p\,(r_a)\,S_a\,. \tag{18}$$

The concentration of particles is estimated by the formula [13]

$$n = \frac{G}{M_i v_g S_a}\,. \tag{19}$$

The velocity of travel of particles in the discharge gap in the process of their thermal motion is related to the mean-mass temperature by the relation

$$\frac{M_i \overline{v_g^2}}{2} = \frac{3}{2}\,kT_m\,. \tag{20}$$

If a part of the plasma energy is expended for the dissipation, ionization, and radiation, the velocity of travel of particles v_g is approximately equal to

$$v_g \approx \sqrt{\frac{kT_m}{M_i}}\,. \tag{21}$$

In this case, $p(r_a)$ is calculated as

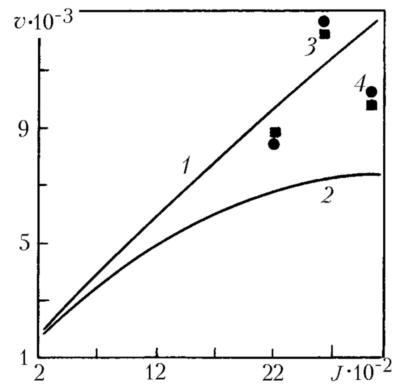

Fig. 2. Velocities of a plasma jet in the nozzle exit section of the CEHA: 1) v_Σ; 2) v_t; 3) v_{exp}, l = 130 mm; 4) v_{exp}, l = 160 mm.

$$p\,(r_a) \approx \frac{G}{S_a}\sqrt{\frac{kT_m}{M_i}}\ . \tag{22}$$

For the operating conditions of a CEHA, there is a lower boundary for the pressure in the discharge-zone because the degree of plasma ionization in the CEHA, determined by the Saha equation, is equal to ~2% [3]. The value of T_m in the discharge zone in different regimes of operation of the CEHA is determined by the mean-mass enthalpy H in this zone, which depends on the temperature and pressure in the discharge. If the pressure in the discharge falls within the range $(0.1–10)\cdot10^4$ Pa, the dependence of the enthalpy in the region considered on the temperature and pressure can be determined from the tables of thermodynamic functions presented in [14]. The enthalpy is mainly determined by the temperature; it changes insignificantly with change in the pressure. An increase in the enthalpy with increase in the pressure is within its measurement error, equal to ~12%. This facilitates determination of the mean-mass temperature. In the case where the dependence of the enthalpy on the pressure is significant, the pressure can be determined, in accordance with the method of successive approximations, by substituting the mean temperature in the region considered into (22). The pressures in the discharge zone $p(r_a)$ were calculated in this way for all operating conditions of the CEHA. The total pressure in the nozzle exit section was determined as

$$p = p_0 + p\,(r_a)\ . \tag{23}$$

The velocity of a plasma flow represents the sum of the Hall and gas-dynamic velocities. The velocity of the plasma flow increases significantly with increase in the discharge-current strength and reaches a value of $v_\Sigma \approx$ 12,000 m/sec for J = 3000 A. It is interesting to follow the contribution of each of the mechanisms considered to this velocity. As was expected, the gas-dynamic acceleration plays a significant role as long as the current reaches 2000 A; therefore, it cannot be disregarded at large flow rates of a working gas. The gas-dynamic acceleration will play an insignificant role at small flow rates, at which the plasma can be completely ionized. The Hall component makes the main contribution to the plasma acceleration at high discharge currents. To underline the role of the magnetic field in the plasma acceleration, especially at high discharge currents, we compared the calculated velocities and pressures with the velocities and pressures in the cross sections of a plasma flow l = 130 and 160 mm, measured earlier for a free jet and a compressed layer [5, 6, 15]. It was established that, in the cross section l = 130 mm, the velocity of a plasma jet v_{exp} = 8800 m/sec and the pressure upstream of an obstacle in a compressed layer $p_{exp} = 1\cdot10^4$ Pa for the current J = 2200 A, v_{exp} = 12,000 m/sec and $p_{exp} = 2.4\cdot10^4$ Pa for J = 2600 A, and v_{exp} = 9600 m/sec and $p_{exp} = 5\cdot10^4$ Pa for J = 3000 A, and, in the cross section l = 160 mm, v_{exp} = 8400 m/sec and $p_{exp} = 2.1\cdot10^4$ Pa for J = 2200 A, v_{exp} = 12,700 m/sec and $P_{exp} = 3.3\cdot10^4$ Pa for J = 2600 A, and v_{exp} = 9700 m/sec and $p_{exp} = 6.0\cdot10^4$ Pa for J = 3000 A. In other words, the method proposed for calculating the velocity and pressure in the discharge zone gives good results. It should be noted that the experimental data were obtained for cross sections of a plasma flow and not for the nozzle cross section, which introduces certain corrections into the parameters of the flow.

Figure 2 presents the velocities of a plasma flow v_Σ, determined for different operating conditions of the CEHA and, for comparison, the maximum velocity v_t of a plasma jet flowing to a vacuum through the nozzle in the absence of a magnetic field. Since, in the CEHA, the region of broadening of the jet experiences a part of the discharge current, v_t was estimated by the formula for an isothermal flow [7]

$$v_t = \sqrt{2 \frac{\gamma - 1}{\gamma} H \ln \frac{p_1}{p_0}} \ . \tag{24}$$

Comparison of these velocities has shown that, even at a low discharge current, the maximum possible velocity v_t is lower than the calculated total velocity v_Σ and the difference between these velocities increases with increase in the discharge current. This lends support to the fact that a magnetic field plays a crucial role in increasing the velocity of a plasma jet [13]. A divergent magnetic field not only confines the plasma but also represents the main source of momentum transfer realized through the acceleration of the plasma to the drift velocities and the turn of the vectors of these velocities in the longitudinal direction.

NOTATION

B, magnetic induction vector, T; B_0, magnetic induction in the discharge zone, T; B_r, B_x, B_φ, magnetic induction components, T; e, electron charge, K; F, force acting on the plasma, N; G, flow rate of a working gas, kg/sec; H, mean-mass enthalpy, J/kg; J, discharge current, A; **j**, current-density vector, A/m^2; j_r, j_x, j_φ, current-density components, A/m^2; k, Boltzmann constant, J/K; l, distance from the nozzle exit section along a jet, m; M_i, mass of a nitrogen ion, kg; n, concentration of particles, m^{-3}; n_e, concentration of electrons, m^{-3}; p, plasma pressure, Pa; p_0, pressure in the vacuum chamber, Pa; p_1, pressure upstream of the discharge zone, Pa; r, radius of a jet, m; r_a and r_c, radii of the anode and cathode, m; S, area, m^2; T, temperature, K; U, discharge voltage, V; u_e, drift velocity of electrons in the direction of an electric field, m/sec; V, volume occupied by a plasma, m^3; **v**, velocity vector of a flow, m/sec; v, velocity of a flow, m/sec; v_i, velocity of ions in the direction of magnetic-field lines, m/sec; x, characteristic length of the region experiencing a discharge current, m; β, Hall factor; φ, angular component, rad; γ, adiabatic index; ξ, exchange parameter; ρ, density of a plasma, kg/m^3; σ, electron conduction of a plasma, $\Omega^{-1}\cdot$m^{-1}; τ_e, average time of electron collisions, sec; ω_e, electron cyclotron frequency, sec^{-1}. Subscripts: a, anode; g, gas-dynamic; out, output; c, cathode; h, heavy-current; m, mean-mass; t, isothermal; H, Hall; exp, experiment; e, electron; i, ionic; r, radial; x, longitudinal; Σ and φ, total and azimuth; 0, conditions in a vacuum chamber; 1, conditions upstream of the discharge.

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