ELECTRICAL PROPERTIES OF A DIFFUSION FLAME OF OPPOSITELY DIRECTED JETS

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UDC 536.46

The electrical properties of a diffusion flame of oppositely directed cylindrical jets of oxidant and fuel are analyzed. Spatial distributions of the concentrations of charged particles and electric field strength are obtained.

As a result of the chemical reactions taking place during the combustion of gases, charged particles — ions and electrons — are formed in the flame front. Experimental reports [1-4] indicate that in various fuel mixtures the maximum concentration of charged particles in the combustion zone varies from the equilibrium values corresponding to thermal equilibrium to superequilibrium values produced by chemical ionization.

The mechanism of formation of the intrinsic electric field arising because of the large difference in diffusion properties of the ions and electrons was analyzed in [5]. A flame with a low degree of ionization propagating through a mixture of already mixed gases was analyzed there.

The intrinsic electrical properties of a diffusion flame formed by opposing cylindrical jets of oxidant and fuel at high and low degrees of ionization are studied below.

A review of the experimental research on the electrical properties of diffusion flames is given in [4]. The basic concepts concerning the structure of a diffusion flame of oppositely directed jets which are used below are contained in [6-8]. A mathematical model for describing the action of an external electric field on a diffusion flame was proposed in [9].

Statement of the Problem

Let us consider a steady diffusion flame formed through the collision of oppositely directed cylindrical jets of oxidant and fuel (see Fig. 1). The diameters and velocities of the colliding jets, as well as the gas density and other physical parameters, are assumed to be the same. It is assumed that the oxidant and fuel are supplied in the stoichiometric ratio, and therefore the flame is located in the plane of symmetry. The oxidant and fuel are consumed in the chemical reaction zone (it is shaded in Fig. 1), which leads to the formation of the final and intermediate products as well as ions and electrons which diffuse into the unburned gas. The diffusion of charged particles into the unburned gas is restrained by the convective flow. In addition, the intrinsic electric field arising as a result of the separation of charges owing to the large difference in diffusabilities of ions and electrons has an important effect on the process of diffusion of the charged particles.

We introduce a cylindrical coordinate system (x, y) so that the x axis is directed along the axial line of the colliding jets, the origin of coordinates lies at the critical point, and y is the radial coordinate. The equations of diffusion of the ions and electrons with allowance for their interaction have the form

$$\mathbf{u}\nabla N_e = -\operatorname{div}\mathbf{J}_e + \Phi, \quad \mathbf{J}_e = -D_e\nabla N_e - \mu_e N_e\mathbf{E}, \tag{1}$$

$$\mathbf{u}\nabla N_i = -\operatorname{div}\mathbf{J}_i + \Phi, \quad \mathbf{J}_i = -D_i\nabla N_i + \mu_i N_i\mathbf{E}. \tag{2}$$

Here $\mathbf{u}(u_x, u_y)$ is the velocity vector of the gas flow, D and μ are the coefficient of diffusion and the mobility of the charged particles in the electric field, and Φ is the total rate of formation and loss of ions and electrons.

Since the ions generated in the flame are similar in their physical properties, we will assume that singly charged ions of a single kind, not differing in the model under consideration, and electrons are formed as a

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 32, No. 6, pp. 1034-1042, June, 1977. Original article submitted October 24, 1975.

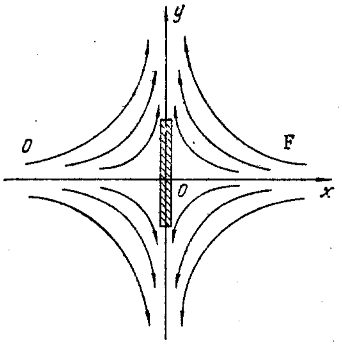

Fig. 1. Diagram of diffusion combustion in the collision of oppositely directed jets of oxidant (O) and fuel (F).

result of the chemical reactions, which are concentrated in a narrow zone near the maximum flame temperature.

The electric field strength satisfies the Poisson equation

$$\operatorname{div} \mathbf{E} = 4\pi e (N_i - N_e) \tag{3}$$

(e is the electron charge).

If the velocity distribution in the gas stream is known from a solution of the hydrodynamic problem of the collision of oppositely directed jets, then, by solving the system of equations (1)-(3), one can find the steady spatial distributions of the concentrations of charged particles and the electric field strength.

We distinguish the following characteristic scales of the problem: d is the diameter of an undisturbed jet, equal in order of magnitude to the characteristic size of distortion of the hydrodynamic field, i.e., the size of a region of significant curvature of the streamlines; $\bar{d}$ is the Debye radius of the plasma formed in the flame, characterizing the distance to which the separation of the charged particles takes place owing to their thermal motion; Δ is the size of the region in which the chemical ionization reaction takes place; $\sqrt{dD_i/u_0}$ and $\sqrt{dD_e/u_0}$ are the characteristic diffusion sizes over which significant variation occurs in the concentrations of ions and electrons in the absence of an electric field (u_0 is the velocity of an undisturbed jet).

The current Debye radius $\bar{d}$ has the smallest value in the chemical reaction zone in which the concentration of charged particles is maximal ($\bar{d}_0^2 = kT/4\pi e^2 N_i^0$, where k is Boltzmann's constant, T is the combustion temperature, and N_i^0 is the maximum ion concentration in the combustion zone).

If the number of charged particles formed in the flame is insignificant (thermal ionization, $N_i^0 \approx 10^6$-10^8 cm^{-3}), so that the Debye radius at the flame front is sufficiently large in comparison with the characteristic diffusion size of the ions, then the interaction of the charged particles can be neglected and one can consider the free diffusion of the electrons and ions; the distribution of electric field strength is then calculated from the Poisson equation. In this case in Eqs. (1) and (2) one can neglect terms describing the effect of the electric field on the transfer of charged particles. In addition, for the conditions usually used in experiments [6, 7] the diameter of the jet far exceeds the characteristic diffusion size for ions but is considerably smaller than the corresponding characteristic size for electrons ($D_i/D_e \sim 10^{-2}$-10^{-3}). One can then assume that the diffusion of ions takes place in the vicinity of the critical point, at which one can use one-dimensional equations [7, 8], while the electron concentration in this region can be taken as small in comparison with the ion concentration. In the potential flow of an incompressible fluid having axial symmetry about the y axis the velocity distribution near the critical point has the form [7,10]

$$u_x = -2\frac{u_0}{d}x, \quad u_y = \frac{u_0}{d}y. \tag{4}$$

In flames with a higher degree of ionization (chemical ionization, $N_i^0 \sim 10^9$-10^{12} cm^{-3}) the Coulomb interaction between charged particles leads to the combined ambipolar diffusion of ions and electrons, which changes into free diffusion upon departure from the flame front [11-13]. The characteristic size at which a considerable decrease in the concentration of charged particles in comparison with their concentration in the zone of chemical ionization occurs is equal in order of magnitude to the ion diffusion size and is far smaller than the diameter of an undisturbed jet, which allows one to consider the diffusion process in the vicinity of the critical point and to use the one-dimensional approximation.

We will neglect processes of recombination and the formation of negative ions, assuming that the particle distribution in the vicinity of the critical point is determined by diffusion processes. This assumption is satisfied if the characteristic time of diffusion of ions from the region of maximum temperature is far less than the characteristic reaction times of recombination and electron capture. With such a ratio of characteristic times the reactions leading to the loss of charged particles exert a considerable effect on their distribution only in the region of reaction products at larger y.

A Diffusion Flame with a High Degree of Ionization in the Chemical Reaction Zone

In flames with a high degree of ionization the charged particle density is rather high and the plasma remains quasineutral both in the chemical ionization zone and at a considerable distance from it, until the particle concentration decreases by several orders of magnitude. To calculate the charged particle fluxes and electric field strength we use the methods developed in the theory of a weakly ionized plasma [11-13].

In the mode of ambipolar diffusion the densities of the charged particles and their fluxes coincide, i.e., $N_i \simeq N_e = N$ and $\mathbf{J}_i \simeq \mathbf{J}_e = \mathbf{J}$. Using these relations, from (1) and (2) we obtain $\mathbf{J} = -D_a \nabla N$, where $D_a = (\mu_i D_e + \mu_e D_i)/(\mu_e + \mu_i) \simeq 2D_i$ is the coefficient of ambipolar diffusion. Then the charged particle concentration is determined from the equation

$$\mathbf{u} \nabla N = D_a \nabla N + \Phi, \tag{5}$$

which can be solved in the vicinity of the critical point with the velocity distribution (4). Moreover, in the vicinity of the critical point one can neglect the radial dependence in (5) [7, 8] and reduce the problem to the solution of the one-dimensional diffusion equation

$$-2 \frac{u_0}{d} x \frac{dN}{dx} = D_a \frac{d^2N}{dx^2} + \Phi. \tag{6}$$

Since the chemical reaction is concentrated in a narrow zone with $|x| < \Delta/2$ at the origin of coordinates, the term allowing for the creation of particles in Eq. (6) can be dropped, assigning as a boundary condition a flux of particles coming from the chemical ionization zone into the region of $x < 0$ (the solution is sought in the region of negative x). This condition can be obtained from Eq. (6) by integrating it over an interval including the chemical reaction zone and then making its extent approach zero and the intensity of the chemical reaction approach infinity so that $\int_{-\Delta/2}^{\Delta/2} \Phi dx$ is finite. As a result, we obtain

$$x = 0, \quad D_a \frac{dN}{dx} = \frac{1}{2} \int_{-\Delta/2}^{\Delta/2} \Phi dx = A. \tag{7}$$

At distances comparable with the diameter of a jet the concentration of charged particles is far less than their concentration at $x = 0$, so that one can set

$$x = -\infty, \quad N = 0. \tag{8}$$

The solution of Eq. (6) with the boundary conditions (7) and (8) has the form

$$N = \frac{1}{2} \sqrt{\frac{\pi d}{D_a u_0}} A \left[1 + \operatorname{erf}\left(\sqrt{\frac{u_0}{dD_a}} x\right)\right]. \tag{9}$$

At $x = 0$ we get from (9) the connection between the particle concentration N_i^0 in the chemical ionization zone and the intensity of the chemical reaction:

$$N_i^0 = \frac{1}{2} \sqrt{\frac{\pi d}{D_a u_0}} A = \frac{1}{4} \sqrt{\frac{\pi d}{D_a u_0}} \int_{-\Delta/2}^{\Delta/2} \Phi dx. \tag{10}$$

As mentioned in [5], as the boundary condition at $x = 0$ it is convenient to assign the charged particle concentration in the chemical ionization zone, which is known from experiment. Then the constant A can be taken as known from (10).

Now let us find the distribution of electric field strength. With ambipolar diffusion the strength of the self-consistent field arising due to the different mobilities of electrons and ions and providing for approximately equal concentrations and fluxes of charged particles can be calculated [11-13] from the expression for the fluxes of electrons and ions in (1) and (2), taking $\mathbf{J} = \mathbf{J}_e = \mathbf{J}_i = -D_a \nabla N$ and $N = N_e = N_i$. Then we have

$$E_s = -(D_i/\mu_i)\,(\nabla N/N).$$

Substituting the concentration distribution from (9) into this, we obtain

$$E_s = -\frac{D_i}{\mu_i}\sqrt{\frac{2u_0}{\pi d D_i}} \cdot \frac{\exp\left[-\left(\sqrt{\frac{u_0}{dD_a}}\,x\right)^2\right]}{1 + \operatorname{erf}\left(\sqrt{\frac{u_0}{dD_0}}\,x\right)}. \tag{11}$$

Since the particle distribution near the critical point does not depend on the y coordinate, the radial component of the field is equal to zero. At x = 0 we get from (11)

$$E_s(-0) = E_0 = -\frac{D_i}{\mu_i}\sqrt{\frac{2u_0}{\pi d D_i}}. \tag{12}$$

The jump in the strength of the self-consistent field $E_s \sim dN/dx$ at the surface x = 0 [at x = +0 from the conditions of symmetry of the problem we get $E_s(+0) = -E_0$] is explained by the introduction of a concentrated source of charged particles at this surface, which leads to a discontinuity in the fluxes of charged particles and to the formation of a surface charge at x = 0.

The reason for the formation of a jump in the electric field strength can be understood by approximately constructing a solution in the chemical ionization zone, assuming, for example, that in the region of $|x| < \Delta/2$ the rate of the chemical reaction leading to the formation of charged particles is constant and equal to Φ_0.

Such an analysis gives the following distributions of concentrations and electric field strength at $|x| < \Delta/2$:

$$N = N_i^0 - \frac{1}{4}\,\frac{\Phi_0}{D_i}\,x^2, \quad E_s = \frac{1}{2}\cdot\frac{\Phi_0}{\mu_i N_i^0}\,x.$$

At the boundary of the chemical ionization zone at $x = -\Delta/2$ we obtain the electric field strength

$$E_s\left(-\frac{\Delta}{2}\right) = E_0 = -\frac{1}{4}\cdot\frac{\Phi_0 \Delta}{\mu_i N_i^0},$$

which coincides with (12) if one allows for the relation (10).

The solutions (9) and (11) describing the mode of ambipolar diffusion are valid if the Debye radius is small enough in comparison with the characteristic sizes of the quasineutral plasma which forms. With departure from the flame front the charged particle concentration declines, and the Debye radius increases as $\sim N_i^{-1/2}$; in this case the region of ambipolar diffusion is replaced by some transition region, after which comes the region of free diffusion of ions and electrons. We note that the concentration of charged particles in the region of free diffusion is far lower than their concentration in the chemical ionization zone, so that the solutions (9) and (11) describe a region of considerable variation in the concentration of ions and electrons.

The criterion for the applicability of the solutions obtained can be represented in the form

$$N_i - N_e \ll N$$

or in the form of the equivalent condition $\bar{d} \ll l$, where l is the size of the region occupied by the quasineutral plasma, which, as seen from (9), is equal in order of magnitude to $\sqrt{dD_a/u_0}$.

Let us determine the size of the region of ambipolar diffusion. At the point x_*, up to which the solutions (9) and (11) are correct, the difference between the ion and electron concentrations becomes comparable with the total concentration of charged particles, i.e.,

$$N_i - N_e = \beta N, \tag{13}$$

where β is a constant less than unity.

Substituting the distribution N(x) from (9) into (13) and expressing the difference $N_i - N_e$ on the left side of (13) from the Poisson equation [12], in which one must substitute the distribution $E_s(x)$ from (11), we obtain the equation for determining x_*:

$$\frac{1}{\pi}\cdot\frac{u_0\bar{d}_0^2}{dD_i}\cdot\frac{\sqrt{\pi}\,\xi_*(1+\mathrm{erf}\,\xi_*)+\exp(-\xi_*^2)}{(1+\mathrm{erf}\,\xi_*)^2}=\beta(1+\mathrm{erf}\,\xi_*). \tag{14}$$

Here $\xi_* = x_*/\sqrt{dD_a/u_0}$. Since we are considering flames with a high degree of ionization ($u_0\bar{d}_0^2/dD_i \ll 1$), the solution of Eq. (14) exists for $x_* > \sqrt{dD_a/u_0}$, where it is simplified and takes the form

$$-\sqrt{\frac{\pi}{2}}\cdot\frac{u_0\bar{d}_0^2}{dD_i}\;\xi_*=\beta\exp(-\xi_*^2). \tag{15}$$

Since the solution describing the mode of ambipolar diffusion is valid only for large enough $x \gg \sqrt{dD_a/u_0}$, let us find the asymptotic distribution of electric field strength; from (11) with $x \gg \sqrt{dD_a/u_0}$ we have

$$E\simeq\frac{u_0x}{d\mu_i}=-\frac{u(x)}{2\mu_i}. \tag{16}$$

Thus, the strength of the self-consistent electric field which provides for equality of the fluxes of electrons and ions in the mode of ambipolar diffusion is determined by the velocity profile of the gas stream and the mobility of the ions, just as in a highly ionized flame propagating through a mixture of already mixed gases [14].

Let us turn to an estimate of the maximum value of the electric field strength. In the region of ambipolar diffusion $(0, x_*)$ the modulus of the electric field strength increases, approaching the value (16). In the region of free diffusion $|x| > |x_*|$ the field dies out, since in this region $N_e > N_i$ and it follows from the Poisson equation that $dE/dx < 0$. At some point lying in the transition region the concentrations of charged particles are equalized and $dE/dx = 0$, i.e., the field reaches the extremal value. The distributions of charged particle concentrations and electric field strength are represented qualitatively in Fig. 2. Assuming that the maximum is reached at a point close to x_*, we obtain

$$|E|_{\max}=-E_{\min}\simeq-\frac{u_0x_*}{d\mu_i}=\frac{u(x_*)}{2\mu_i}.$$

Let us make an estimate for concrete parameters. With $N_i^0 \sim 5\cdot10^{12}$ 1/cm^3 and $T = 2000$°K we obtain $\bar{d}_0 \approx 3.2\cdot10^{-4}$ cm. Let $\sqrt{dD_i/u_0} \sim 0.07$ cm ($d = 1$ cm, $D_i = 1$ cm^2/sec, $u_0 = 200$ cm/sec); then from (15) we have $\xi_* \simeq 3.2$ ($\beta = 1$) or $x_* \approx 0.22$ cm and $|E|_{\max} \sim 10$ V/cm. We note that the size of the coefficient β has an insignificant effect on the position of the point x_* (in the example under consideration $\xi_* \approx 3.2$ when $\beta = 1$ and $\xi_* \simeq 3.3$ when $\beta = 0.1$), and consequently, on the value of $|E|_{\max}$.

We emphasize that the solutions obtained are valid only for $\bar{d}_0^2 \ll dD_i/u_0$ and $d \gg D_i/u_0$, i.e., for flames with a high degree of ionization and "thick" enough jets.

In conclusion, we note that [9], in the part touching on the calculation of the distribution of charged particle concentrations in the absence of an electric field, contains a number of important defects caused by the fact that the authors did not allow for the effect of the intrinsic electric field on the diffusion of ions and electrons at larger particle concentrations. An estimate of the strength of the intrinsic electric field calculated from the charged particle distribution given in that report would give an extremely high value, exceeding the breakdown value of the field. We note also that a one-dimensional statement of the problem and the assumption of the superposition of the hydrodynamic velocity field and the velocity field of the ion wind, which does not occur in reality, are used without justification in [9].

A Diffusion Flame with a Low Degree of Ionization in the Chemical Reaction Zone

Let us find the distribution of the electric field strength in a diffusion flame of oppositely directed jets with low ionization in the chemical reaction zone. Since the number of charged particles formed in the flame is slight, in the first approximation we neglect the interaction of electrons and ions in the diffusion process ($(\sqrt{dD_i/u_0}/\bar{d}_0)^2 \ll 1$).

Because of radial symmetry $dN_i/dy|_0 = 0$, and the distribution of ion concentration does not depend on y [7, 8]. Then the diffusion is described by Eq. (6) in which D_a must be replaced by D_i. On the assumption that the zone of the reactions leading to the formation of charged particles is narrow and with allowance for the boundary conditions [see (7) and (8)] we obtain the ion distribution in the form

$$N_i=\frac{1}{2}\sqrt{\frac{\pi d}{D_iu_0}}\,A\left[1+\mathrm{erf}\left(\sqrt{\frac{u_0}{dD_i}}\,x\right)\right]. \tag{17}$$

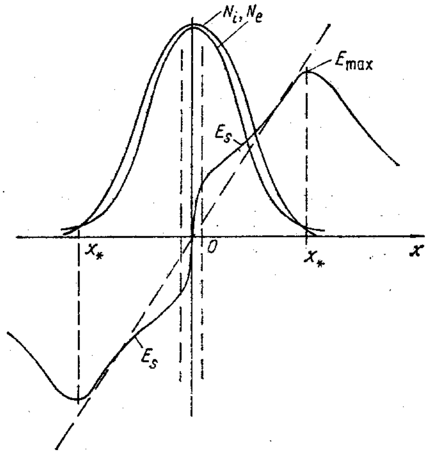

Fig. 2. Distributions of ion and electron concentrations and electric field strength.

The connection between the ion concentration in the chemical ionization zone and the intensity of the chemical reaction is obtained from (17) by setting x = 0 [see (10)]:

$$N_i^0 = \frac{1}{2}\sqrt{\frac{\pi d}{D_i u_0}}\,A = \frac{1}{4}\sqrt{\frac{\pi d}{D_i u_0}}\int\limits_{-\Delta/2}^{\Delta/2}\Phi dx.$$

Since usually $D_e/u_0 \gg d$ in experiments, one can assume that in the region of small x and y being considered here the electron concentration is constant and equal to the electron concentration N_e^0 in the flame.

The distribution of electric field strength is found from the one-dimensional Poisson equation taking E(0) = 0 (this condition can be obtained from an analysis of the structure of the chemical reaction zone analogous to that done in the preceding section):

$$E = 4\pi e\left\{(N_i^0 - N_e^0)x + N_i^0\left[x\,\mathrm{erf}\left(\sqrt{\frac{u_0}{dD_i}}\,x\right) + \sqrt{\frac{dD_i}{\pi u_0}}\left(e^{-\frac{u_0 x^2}{dD_i}} - 1\right)\right]\right\}. \tag{18}$$

The modulus of the electric field strength takes on the maximum value at the point x_*, at which $N_i(x_*) \simeq N_e$ and $dE/dx = 0$ [see Eq. (3)]. In the approximation under consideration the Coulomb interaction does not affect the diffusion of the charged particles. Since $D_e \gg D_i$, one can take $N_e^0 \ll N_i^0$. Then $x_* \gtrsim dD_i/u_0$ and from (18) we get

$$|E|_{\max} = -E(x_*) \simeq 4\sqrt{\pi}\,eN_i^0\sqrt{\frac{dD_i}{u_0}}.$$

Let us make an estimate. With $N_i^0 = 5\cdot 10^6$ cm^{-3} and T ~ 2000°K the Debye radius is $\bar{d}_0 \sim 0.26$ cm. With $\sqrt{dD_i/u_0} \sim 0.1$ cm we obtain $|E|_{\max} \sim 0.1$ V/cm. With $|x| > |x_*|$ and $N_e > N_i$ we have $dE/dx < 0$ and the field strength decreases to zero.

We note that the results presented in this section and applicable to flames with low ionization ($\bar{d}_0^2 \gg dD_i/u_0$) and for a jet which is "thin" to electrons ($d \ll \sqrt{dD_e/u_0}$) and "thick" to ions ($d \gg \sqrt{dD_i/u_0}$).

NOTATION

x, y, coordinates; $\mathbf{u}(u_x, u_y)$, velocity of gas stream; N, concentration of charged particles; e, i, indices pertaining to electrons and ions, respectively; D, diffusion coefficient; μ, mobility; **J**, flux; **E**, electric field strength; Φ, rate of chemical reactions of charged particle formation; e, electron charge; d, diameter of undisturbed jet; $\bar{d}$, Debye radius; $\bar{d}_0$, value of Debye radius at x = 0; u_0, velocity of undisturbed jet; Δ, width of chemical reaction zone; k, Boltzmann's constant; T, temperature; N_i^0, ion concentration at origin of coordinates; D_a, coefficient of ambipolar diffusion; A, constant; E_s, self-consistent electric field strength; E_0, electric field strength at x = +0; l, characteristic size of plasma; x_*, value of x up to which the ambipolar solution is correct; ξ_*, dimensionless value of x_*; β, constant.

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STUDY AND GENERALIZATION OF VOLT — AMPERE AND THERMAL CHARACTERISTICS OF A TWO-JET PLASMOTRON

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UDC 533.9

The construction of a two-jet plasmotron is worked out. Its thermal and electrical characteristics are studied. The volt — ampere characteristics and thermal efficiency are generalized.

Two-jet plasmotrons find application in plasma chemistry, in plasmathermy, and in processes of treatment of disperse materials [1-3]. A peculiarity of two-jet plasmotrons is the presence of an open semicompressed electric arc and two combining plasma streams directed at an angle to one another. The absence of engineering equations for the calculation of two-jet plasmotrons hinders their most rapid introduction into industry.

In the present report we begin comprehensive studies of the design of two-jet plasmotrons and the plasma streams produced by them for the development of industrial constructions.

The two-jet plasmotron studied is analogous in construction to that described in [4, 5]. The arc ignition system and the design of the electrode units are original. A diagram of the design of the two-jet plasmotron and the electric arc ignition system are presented in Fig. 1.

The length of the arc is limited by the construction of the anode unit of the two-jet plasmotron which permits only slight axial movement of the anode spot. The construction of the anode unit resembles the construction of the inner electrode of a one-chamber plasmotron; the anode itself is copper and water cooled. The cathode is of the end type, copper — zirconium, and water-cooled. To fasten the electrode units of the two-jet plasmotron we developed a device making it possible to vary the distance L between the electrode units of the two-jet plasmotron and their angles of inclination to the line of centers within wide limits during operation. In the course of operation the distance L between electrode units was varied in the range of $(2-7) \cdot 10^{-2}$ m and the angles of inclination α_1 and α_2 from 15 to 60°.

Ignition of the electric arc is accomplished with an oscillator; the ballast resistance R (Fig. 1) was used to limit the current strength at the moment of ignition of the arc.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 32, No. 6, pp. 1043-1052, June, 1977. Original article submitted May 21, 1976.