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INITIAL DISEQUILIBRIUM IN SUPERSONIC FLOW OF LOW-DENSITY ARC PLASMA

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UDC 933.95:533.9

Much attention is currently being given to nonequilibrium processes in supersonic flows of supercooled plasma. Particular interest attaches to the conditions for nonequilibrium population of excited atomic and ionic states in the plasma-forming body. The working bodies are usually gases in experiments, while in theoretical calculations they are the vapors of readily ionized metals, which are recognized as promising working bodies for plasma-dynamic lasers, particularly lithium vapor. For example, population inversions have been observed in supersonic plasma flows for the levels of hydrogen [1] and helium [2], and lasing has been obtained in supersonic plasma jets of argon [3] and hydrogen [4]. In all the experiments, the plasma flow was from an electric-arc source into a low-density medium under stationary conditions [1, 2] or quasistationary ones [3, 4].

Studies on the parameters of the plasma in low-density supersonic jets produced by electric-arc sources have also shown that there is marked thermal and ionization disequilibrium in the flow beginning with the end of the nozzle [5] and in the plasma-source arc chamber [6].

The substantial initial disequilibrium in the plasma produced by an arc discharge (an arc plasma) complicates examining the variation in parameters during the subsequent expansion. At present, in spite of extensive studies such as [7], methods of estimating arc-plasma parameters remain very complicated.

Here we present an engineering method of estimating the parameters of a thermal plasma formed by a dc arc discharge at a pressure in the source chamber not exceeding 10^5 Pa and a temperature T_0 of $2\text{-}20 \times 10^3$°K. The estimates are compared with experimental data.

The method involves the following assumptions:

1) The plasma is assumed to be ideal and of two-temperature type and consisting of electrons, ions, and atoms with Maxwellian velocity distributions and with temperatures T_e for the electrons and T_0 for the heavy particles (atoms and ions);

2) the plasma parameters are homogeneous in the arc-discharge region;

3) the ionization equilibrium in the plasma corresponds to the electron temperature T_e; and

4) the difference between T_e and T_0 is due only to the electric field.

In this formulation, the state of the plasma in the electric field of the arc can be described by a system of equations for a thermodynamically equilibrium plasma together with a relation specifying the nonisothermal nature of the plasma as determined by the electric field strength E. Finkelnburg's equation [8] is used for this purpose, which reflects the balance of the energy acquired by the electrons in the electric field and the energy they lose in elastic collisions with heavy particles.

Leningrad. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 39-44, July-August 1983. Original article submitted July 13, 1982.

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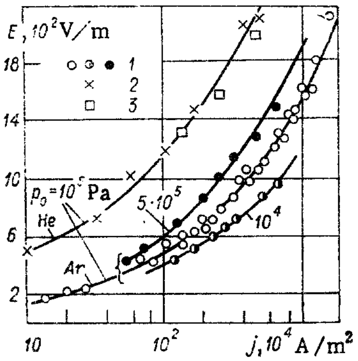

Fig. 1

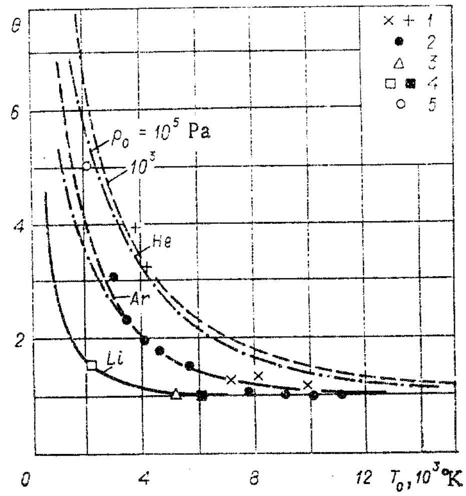

Fig. 2

The dependence of the field E on the plasma parameters was determined in empirical form as obtained by processing data on the electric fields in dc arcs.

The following is a system of equations describing the state of the arc plasma with these assumptions:

$$p_0 = kT_0 n_g(1 + \alpha\Theta); \tag{1}$$

$$\frac{n_e n_{z+1}}{n_z} = \frac{2g_{z+1}}{g_z} = \left(\frac{2\pi m_e}{h^2} kT_e\right)^{3/2} \exp\left(-\frac{I_z}{kT_e}\right); \tag{2}$$

$$n_e = \sum_{z=1}^{n} z n_z; \tag{3}$$

$$H_0 = \frac{1}{m_g}\left[\frac{5}{2} kT_0(1 + \alpha\Theta) + \sum_{z=1}^{n} \frac{n_z}{n_g} I_{z-1}\right]; \tag{4}$$

$$\frac{\Theta - 1}{\Theta} = \left(\frac{e\lambda_e E}{\frac{3}{2} kT_e}\right)^2 \frac{m_g}{4m_e}; \tag{5}$$

$$E = E(j,\ p_0),\ j = \sigma E, \tag{6}$$

where z is ionic charge, an atom corresponds to z =0, $n_g = \sum_{z=0}^{n} n_z$ is the overall concentration of the heavy particles, $\Theta = T_e/T_0$ is the plasma nonisothermicity, $\alpha = n_e/n_g$ is the degree of ionization, and j is the current density through the plasmotron channel of diameter d. The other symbols are those generally used.

System (1)-(4) with $\Theta = 1$ describes the equilibrium plasma composition. The mean-mass enthalpy of the plasma H_0 and the pressure in the arc chamber p_0 are taken as known characteristics of the source and are input quantities for determining the other parameters.

With the degree of ionization $\alpha \leqslant 10^{-4}$ characteristic of an arc plasma, the electron mean free path λ_e is determined by the Coulomb interactions for virtually all working bodies and is dependent only on the plasma electron parameters [7]:

$$\lambda_e = (n_e Q_{ee})^{-1} \simeq 1{,}7 \cdot 10^{10} \frac{T_e^2}{n_e},\ \text{м}. \tag{7}$$

Under these conditions, the electrical conductivity σ may be determined by Spitzer's method in terms of the electron parameters alone [7]:

$$\sigma = \frac{0{,}6\,(kT_e)^{3/2}}{e^2 m_e^{0,5} \ln\Lambda},\quad (\Omega\cdot\text{m})^{-1}, \tag{8}$$

where $\ln\Lambda = 6$–8 for $n_e \leqslant 10^{22}$ m^{-3}.

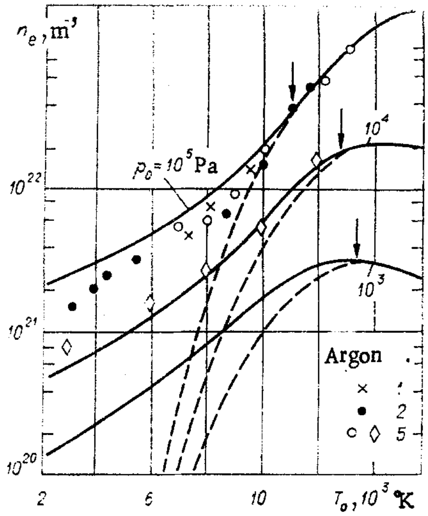

Fig. 3

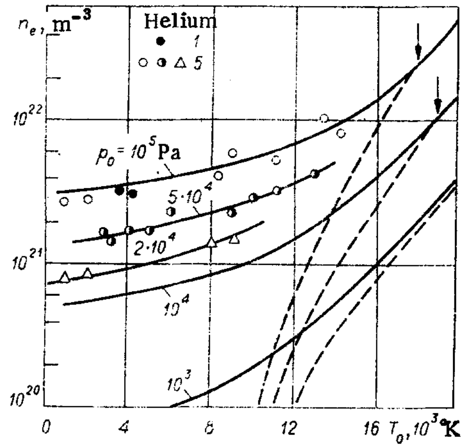

Fig. 4

As (6) we used empirical relations obtained by generalizing the results of [9] for an argon plasma:

$$E = 0.16 j^{0.5} p_0^{0.1}, \ \text{V/m}.$$

A similar relation was obtained for a helium plasma from the results of [10, 11]:

$$E = 3.2\cdot 10^{-2} j^{0.35} p_0^{0.5}, \ \text{V/m}$$

Figure 1 shows these results and the corresponding relationships, where points 1 are from [9], 2 from [10], and 3 from [11].

Independent interest attaches to disequilibrium in the arc plasmas provided by vapors of readily ionized metals, which are promising working bodies for plasma-dynamic lasers. However, virtually no information is available on the arc fields in plasmas of such metals at substantial electron-component densities $n_e \sim 10^{21}$–10^{22} m^{-3}. In [12] we find the voltage-current characteristics of an arc plasmotron working with lithium vapor. If we take the potential drop near the electrodes as about 2-7 V (as found in [12]) and use the voltage-current characteristics, we can derive a relationship of the type of (6) for a lithium plasma:

$$E = 8.5\cdot 10^{-2} j^{0.5} p_0^{0.15}, \ \text{V/m}.$$

These relationships of (6) apply for dc arcs under plasmotron conditions for arc currents in the range 100-800 A, plasmotron channel diameters d = 0.4-2 cm, and pressures in the arc chamber of $p_0 = (0.1$–$5)\cdot 10^5$ Pa for argon and helium and $p_0 = 10^3$–10^4 Pa for lithium.

Then (5) with (6) together with (7) and (8) determine the relationship between the plasma parameters and E.

This system of equations was solved with specified combinations of the plasma parameters in the ranges $p_0 = 10^3$–10^5 Pa and $T_0 = (2$–$20)\cdot 10^3$ °K.

Discussion of Calculated Results. The nonisothermicity of an arc plasma (Fig. 2) is determined by the nature of the gas and by T_0. In particular, as the ionization potential I increases (from lithium to helium), the nonisothermicity rises. In the pressure range used, with $T_0 \gtrsim (3$–$4)\cdot 10^3$ °K, Θ is almost independent of the pressure and can be expressed as a function of temperature:

$$\Theta = 0.44 I T_0^{-\varkappa} \pm 0{,}1, \qquad (9)$$

where the ionization potential is in electron volts and the temperature is in thousands of degrees Kelvin. For lithium $\varkappa = 0.5$, for argon $\varkappa = 0.85$, and for helium $\varkappa = 0.9$.

The nonisothermicity increases as T_0 decreases, while the effects of the pressure increase, and for $T_0 \sim 2\cdot 10^3$ °K the accuracy of the approximations of (9) is about 15-20%.

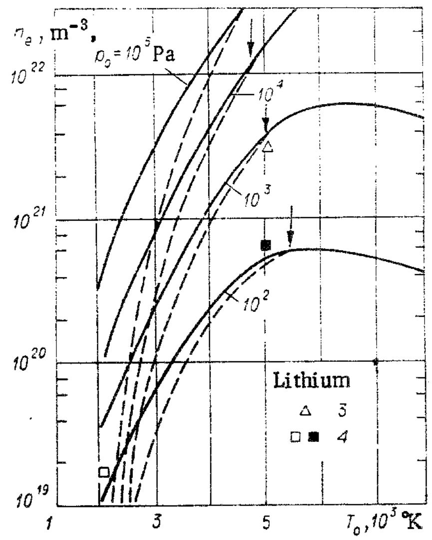

Fig. 5

The plasma becomes more isothermal as T_0 increases; this state sets in as the plasma goes over to the equilibrium state and corresponds to a temperature T_{0e}. For helium $T_{0e} \simeq 16 \cdot 10^3$ °K, for argon $\sim 12 \cdot 10^3$ °K, and for lithium $\sim 5 \cdot 10^3$ °K.

The arc-plasma composition (Figs. 3-5) indicates that T_{0e} actually corresponds to transition of the plasma to the equilibrium state (this is indicated by the arrow). The equilibrium plasma composition is obtained by solving system (1)-(4) and is shown by the broken line. The calculations on the equilibrium composition agree to within 10-15% with more accurate ones [13].

T_{0e} increases slightly as the pressure is reduced (the scale of Fig. 2 does not enable us to show this). At atmospheric pressure, the plasmas from all the working gases examined go over to the equilibrium state at $n_e \simeq 3 \cdot 10^{22}$ m^{-3}, which agrees qualitatively with the opinion widely held in the literature [8, 11] that at such electron concentrations the interaction with the heavy particles is so effective that the plasma in any gas discharge should certainly be in equilibrium.

As the pressure is reduced, the nonisothermicity results in marked composition disequilibrium. For example, the electron concentrations in the arc plasma at $T_0 \sim (2\text{-}3) \cdot 10^3$ °K exceed the equilibrium values by an order or more for these gases. The arc plasma becomes an equilibrium one at a mean mass temperature exceeding T_{0e}.

Comparison of Calculations and Experiment. In the experiments, we used probe methods to examine the electron-density distributions along the axes of supersonic plasma jets produced in argon and helium by a dc arc plasmotron in low-density gas with a pressure in the arc chamber of $p_0 = (0.1\text{-}1) \cdot 10^5$ Pa and various arc powers. The methods and the results are given in [5].

The main feature of these jet flow modes is the requirement that the plasma composition should be frozen in supersonic expansion into a low-density medium. This requirement is met if the characteristic plasma recombination time τ_r is greater than the characteristic time τ_g for change in the gas-dynamic parameters that determine the recombination rate, i.e., $\tau_r \geqslant \tau_g$. If this condition is obeyed, we can derive a relation [5] restricting the plasma density at the input to the nozzle:

$$n_{e*} \leqslant 4.5 \cdot 10^{10} T_0^{2,5} \left(\frac{\Theta}{\delta_*}\right)^{0,5}, \text{ m}^{-3}, \qquad (10)$$

where δ_* is the characteristic dimension (diameter) of the nozzle in the critical section.

If condition (10) is obeyed, it has been shown [5] that the electron-density distribution corresponds to the distribution of the density in an ideal gas escaping into vacuum from a sonic nozzle starting at the end of the nozzle and proceeding along the axis of the jet. This enables one to calculate the electron density in the arc chamber as the retardation density of the plasma flow on the assumption of supersonic flow for an ideal gas. The results are shown in Figs. 2-4 (points 5) in relation to the retardation pressure p_0. Here the points 1 show the results from [11], and points 2 show those of [14], which were obtained with freely burning arcs in argon and helium at atmospheric pressure.

Measurements on lithium plasma under arc-discharge conditions are shown in Figs. 2 and 5 of [15] for $p_0 = 7 \cdot 10^2$ Pa and are indicated by points 3, while those from [16] are indicated by points 4 for $p_0 = 1.5 \cdot 10^2$ Pa (filled symbols) and for $p_0 = 0.5 \cdot 10^2$ Pa.

The calculations and experiments on the initial disequilibrium in a supersonic arc-plasma flow at low densities show that in these cases the proposed method of estimating the parameters in the arc chamber is very effective.

An interesting point is that this method of calculating the arc-plasma parameters is not very critical as regards accuracy in determining the electric field in the arc. For example, as the nonisothermicity in the plasma decreases, (5) degenerates and the equation system becomes analogous to that in the equilibrium case. If there is marked disequilibrium (nonisothermicity), we get from (5) that $n_e \sim T_e E$. Estimates show that with an error by a factor of threefold in determining the electric field strength one gets 10% error in determining T_e and n_e.

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