TWO-TEMPERATURE MODEL OF A PLASMA UNDER CONDITIONS OF STATIONARY BLOWING OF A GAS THROUGH A PLASMOTRON

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UDC 533.9...1501

Results are given of a calculation conducted on the basis of a two-temperature plasma model for a cylindrical arc in a channel with the blowing through of a gas. It is shown that the gas venting leads to the appearance of a considerable separation between the electron and gas temperatures near the wall of the plasmotron and in the cathode zones. The possibilities of the two-temperature model are analyzed from the point of view of an approximate calculation of the electron temperature in arc and induction plasmotrons. It is shown that the electron temperature can be estimated from simple relationships with at least 10% accuracy for induction and 15-20% accuracy for arc plasmotrons.

1. Statement of Problem and Basic Equations

Calculations for arc and induction plasmotrons made on the basis of an equilibrium plasma model make it possible in a number of cases to obtain parameters rather close to the experimental values [1-5]. However, data which have been obtained recently indicate that at atmospheric pressure under conditions of forced blowing of cold gas through a plasmotron, the equality of the electron temperature T_e and the temperature T of the heavy plasma component (atoms and ions) can be significantly disturbed.

The data obtained in [6-8] for an argon plasma in the jet of an induction [8] and an arc plasmotron [6, 7] are examples of this.

The results of these works show that the quantity $T_e - T$ in a dense plasma depends on the flow rate G of the plasma-forming gas which is blown through the plasmotron.

The separation between the electron temperature and the gas temperature in a dense plasma cannot be explained within the framework of an equilibrium model in which the equality $T_e = T$ is postulated.

It is known that the transport effect, which pertains to forced venting in a stationary dense plasma, can lead to a disturbance in the local thermodynamic equilibrium [9], which is assumed to be undisturbed if the following conditions are satisfied (neglecting radiation): 1) equality of the temperatures of all the plasma components (thermal equilibrium) exists; 2) the principle of detailed equilibrium in reactions of the ionization–dissociation type (ionization equilibrium) is satisfied; 3) the Maxwellian velocity distribution and the Boltzmann equilibrium in excited levels are preserved.

Below we examine a particular case of a nonequilibrium problem, usually called the two-temperature model, in which it is assumed that the transport effect does not lead to a significant disturbance in ionization equilibrium, the velocity distribution function remains Maxwellian, and the distribution of excited levels remains a Boltzmann distribution.

However, it is assumed that the transport effect can lead to a disturbance in thermal equilibrium, i.e., give rise to a split between the temperature of the atomic–ionic gas and the electron temperature. The examination of this model will be conducted on the example of an argon plasma of p = 1 atm at temperatures up to 12,000°K, where ignoring radiation still does not introduce a serious error into the calculation. Of all the transfer effects leading to a disturbance in the thermal equilibrium, we will examine only

Leningrad. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 3-12, July-August, 1973. Original article submitted October 17, 1972.

forced convection (blowing of the gas along the axis of a cylindrical channel) and the thermal conduction of the plasma under the effect of radial temperature gradients.

This is a very important case in plasma technology, since the principal problem of almost any technological plasmotron is the effective heating of the greatest possible amount of supplied gas (gas arc heaters).

Let us adopt the following system of energy distribution in the plasma for the analysis of this case.

All the energy σE^2 of the electric field is transferred to the electron gas, which has a temperature T_e.

The electron gas transfers the fraction $3/2 \delta \nu n_e k(T_e - T)$ of the energy through collisions to the atoms and ions which have a temperature T, and the remaining energy is expended in radiation and is transferred to the walls through electron thermal conduction [U_r and div (λ_e grad T_e), respectively].

The energy given up by the atoms and ions is expended in heating the cold gas supplied to the channel ($\rho v_z c_p \partial T/dz$) and is transferred to the walls through atomic–ionic thermal conduction [div (λ_{ai} grad T)].

This two-temperature plasma model will be described by the following system of differential equations:

an energy balance equation for the electron gas,

$$\sigma E^2 = {}^3/_2 \delta \nu n_e k (T_e - T) - \frac{1}{r} \frac{d}{dr} \left(\lambda_e r \frac{dT_e}{dr} \right) + U_r \qquad (1.1)$$

an energy balance equation for the atoms and ions,

$$c_p \rho v_z \frac{\partial v_z}{\partial z} = \frac{1}{r} \frac{\partial}{\partial r} \left(r\lambda \frac{\partial v_z}{\partial r} \right) + {}^3/_2 \delta \nu n_e k (T_e - T) \qquad (1.2)$$

an equation of motion of the atomic–ionic gas,

$$\rho v_z \frac{\partial v_z}{\partial z} = \frac{1}{r} \frac{\partial}{\partial r} \left(r\mu \frac{\partial v_z}{\partial r} \right) - \frac{\partial p}{\partial z} \qquad (1.3)$$

Maxwell's equations

$$\text{rot } \mathbf{H} = \mathbf{j}, \ \text{rot } \mathbf{E} = - \mu_0 \partial \mathbf{H} / \partial t \qquad (1.4)$$

Keeping in mind the continuity equation and all the equations relating the nonlinear transport coefficients with the temperatures T_e and T, we obtain a closed system of equations which describe the proposed plasma model.

Here and below, n_e is the electron concentration, ν is the frequency of collisions of the electrons with atoms and ions, k is Boltzmann's constant, $\delta = 2m/M$ is the fraction of energy lost by an electron in an elastic collision, σ is the electrical conductivity of the plasma, E is the electric-field intensity, H is the magnetic-field strength, U_r is the fraction of radiant energy in W/cm^3, λ_e is the thermal conductivity of the electron gas of the plasma, ρ is the plasma density, v_z is the velocity of the plasma motion along the axis, μ is the plasma viscosity, p is the static pressure in the plasma, c_p is the heat capacity of the plasma, λ is the thermal conductivity of the atomic–ionic gas in the plasma, μ_0 is the magnetic permeability, j is the current density, I is the total arc current, R is the radius of the plasmotron, g is the static weight, m_e is the electron mass, and h is Planck's constant.

2. Properties of Nonequilibrium Plasma

Under the conditions of the problem being considered, when it is assumed that the transport effects do not lead to much disturbance in the ionization equilibrium, the plasma composition for the two-temperature system is usually computed on the basis of the Saha "unequal temperature" equation.

A somewhat different equation for the law of mass action as applied to the ionization reaction of the two-temperature system is obtained in [10]. For instance, for the ionization of a monatomic gas it has the form

$$n_e\left(\frac{n_i}{n_a}\right)^{T/T_e} = \frac{g_e g_i}{g_a}\left(\frac{2\pi m_e k T_e}{h^2}\right)^{3/2}\exp\left(-\frac{eV_i}{kT_e}\right) \tag{2.1}$$

In the derivation of (2.1) in [10] the plasma is considered to be an ideal gas consisting of two quasi-independent subsystems an electron and an atomic–ionic gas, which have different temperatures (T and T_e). The temperature-maintaining mechanism of each subsystem is not specified and the interaction energy of each subsystem with its own "thermostat" is assumed to be small on the average compared with the energy of the subsystem itself. It is shown in [10] that it is more convenient to use Eq. (2.1) than the Saha equation for a two-temperature system.

The heat content (enthalpy) of the plasma in the case of temperature nonequilibrium is calculated on the basis of the usual equations taking into account the difference between the temperatures of the electrons and the atomic–ionic gas. The calculation of the heat capacity $c_p = dH/dT$ of a nonequilibrium plasma must be conducted with allowance for the equation connecting the temperature of the atoms and ions with the temperature of the electrons, so the heat capacity must be calculated while solving a concrete individual problem, where the connection between T and T_e is established.

The thermal conductivity of the atomic–ionic gas $\lambda = \lambda_a + \lambda_i$ and the thermal conductivity of the electron gas λ_e enter separately into the energy balance equation for the different plasma components. Here λ_a, λ_i, and λ_e are the so-called contact thermal conductivities. The thermal conductivity λ_I caused by the transfer of ionization energy, starting with temperatures for which it plays a significant role, is added to the electron conductivity in the balance equation for the electrons (in diatomic gases the thermal conductivity of dissociation is added to λ). Using data on the composition of a two-temperature plasma one can calculate the thermal and electrical conductivity on the basis of the usual equations.

The results of the calculation of n_e for a two-temperature argon plasma for different T and T_e, calculated from the Saha equation and from (2.1), are presented in Fig. 1 [solid curves for Eq. (2.1), dashed curves for the Saha equation]. The values of n_e calculated from the Saha equation and from (2.1) can differ by more than two orders of magnitude.

3. Calculation for Argon Arc in Cylindrical Channel

To make it possible to compare the results obtained with experiment, Eqs. (1.1)-(1.4) were solved numerically for an electric arc in a channel for the conditions under which the measurements of the electron and gas temperatures, the mass flow rate, and the velocity over the cross section and the length of the arc column were conducted in [11].

The channel radius (R = 1 cm), the total arc current (I = 160 A), and the total argon flow rate (G = 1.2 g/sec), which corresponds to the flow rate averaged over the cross section ($\overline{\rho v}_z = G/\pi R^2 = 0.38$ g/cm^2 · sec), are given in the problem, and the distributions of electron temperature $T_e(z, r)$ and atomic–ionic temperature T(z, r) and of the voltage field E(z) along the length of the channel are determined.

In the system (1.1)-(1.4) we are confined to solving only two equations, (1.1) and (1.2), for which we make two assumptions plausible under the conditions of [11]: $\rho v(r)$ = const = 0.38 g/cm^2 · sec and E(r) = const. These assumptions do not introduce large errors into the analysis, while they greatly simplify the solution of the whole problem.

Equations (1.1) and (1.2) are first-order nonlinear differential equations, one of them in partial derivatives. To solve the system it is necessary to set four boundary conditions and one initial condition. Two of the boundary conditions

$$\left.\frac{\partial T_e}{\partial r}\right|_{r=0} = \left.\frac{\partial T}{\partial r}\right|_{r=0} = 0$$

are standard in problems of cylindrical symmetry, and we assign the gas temperature $T|_{r=R} = 300$°K at the water-cooled wall of the plasmotron as the third boundary condition. The initial condition (or boundary condition for the z coordinate) is $T(r)|_{z=0} = 300$°K. To determine the electron temperature at the wall (setting the fourth boundary condition) we make use of the assumption that all the energy σE^2 of the electric field in the zones near the walls is expended only on heating the heavy plasma component, i.e., Eq. (1.1) is converted into the algebraic equality

$$\sigma E^2 = {}^3/_2 \delta \nu n_e k\,(T_e - T) \tag{3.1}$$

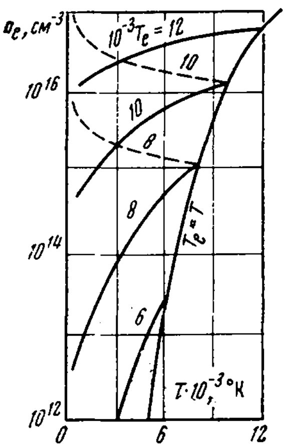

Fig. 1

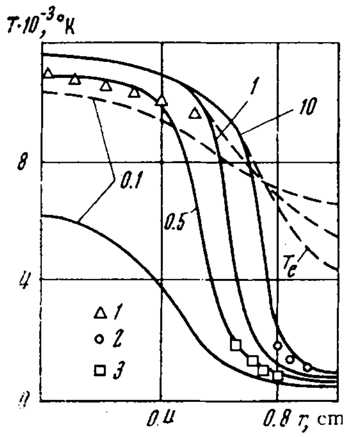

Fig. 2

from which one can determine $T_e(r)$ from the given T(R) and E. In this equation the electric-field intensity is found from the given total current I and the distribution $\sigma(r)$ from Ohm's law:

$$I = 2\pi E \int_0^R \sigma(r) r dr \tag{3.2}$$

The nonlinear coefficients of Eqs. (1.1) and (1.2) depend strongly on the values of T and T_e, which are unknown. Therefore, in order to begin solving the system, as well as setting up the fourth boundary condition [determining E from (3.2)], one must assign some distribution of $T_e(r)$, $\sigma(r)$, etc. The results of the distribution T(r) obtained from a solution of the equilibrium problem, identifying this distribution with T_e, are used as this zero approximation.

Equation (1.2) is solved by the grid method in accordance with (1.1). The value ρv_z is given beforehand and plays the role of a parameter. In each layer, with respect to z, Eqs. (1.1) and (1.2) are solved several times, which is connected with the nonlinearity of the coefficients and with the necessity of matching their values within a layer. The results of a calculation for an electric arc in a cylindrical channel are presented below for the case when the coefficients in Eqs. (1.1) and (1.2) and the plasma composition were calculated using Eq. (2.1).

The results of the arc calculation are presented in Fig. 2.

The radial distributions of the temperatures of the electron and atomic–ionic gas in the cross sections z = 0.1, 0.5, 1, and 10 cm are presented in Fig. 2; 1, 2, 3) experimental points from [11]; 1, 2) z = 2.8 cm, 3) z = 0.8 cm. Figure 2 shows how the gas entering the channel is heated. The equalization of T and T_e occurs in the central axial zone at a depth of ~0.3 cm, while in the region near the wall (r ≈ 0.9–0.8 cm), although an increase does occur in the gas temperature with its movement along the axis, its temperature is no higher than 1000°K even for z = 10 cm. The heating of atoms and ions is somewhat more significant in the mid-radius zone, where T_e ≈ 9500–8500°K. This shows up primarily in the variation in the T(r) profile along the z axis.

As the gas gets deeper into the channel the T(r) profile becomes broader, although the variation in the T(r) profile starting with the cross sections z = 1–2 cm is not great, and it occurs along the entire length of the plasmotron, which leads to a corresponding variation in all the other parameters. In this sense the arc in the nonequilibrium model for R = 1 cm has an established or weakly varying profile of $T_e(r)$ and T(r) only for z > 10 cm. The experimental points of the temperature of the atoms and ions measured in [11] are plotted in Fig. 2. The measurements confirm one conclusion of the nonequilibrium model: along the plasmotron wall (or near it) flows a gas whose temperature depends on G. The measured and calculated temperatures coincide at the axis of the channel.

For the section z = 0.1 cm there is a significant difference between T(r) and $T_e(r)$ in the entire measuring region. For the other sections, T and T_e coincide in the axial region, but near the wall T_e is 4000–5000°K higher than the temperature of the atomic–ionic gas. Such a significant difference between T_e and T in certain regions of the arc channel is an important result obtained from the two-temperature model and coincides with the conclusions of [12, 13]. Some decrease in T_e in the sections of $0 \le z \le 0.5$ cm compared with the farther (along z) regions does not agree with the experimental results, which always show an increase in T_e at the cathode. This disparity is explained by the fact that the conical geometry of the arc was not taken into account in the calculation.

The variation in the T(r) and $T_e(r)$ profiles along the z axis leads to a significant variation in the $\sigma(r)$ profile and the field voltage E(z). The magnitude of E(z) agrees well with the experimental points for the corresponding z in [11]. In the equilibrium model of the arc the increase in the field intensity in the direction of the cathode depends on the decrease in the diameter of the current channel, although, as follows from the calculations, at least part of the voltage drop near the cathode must be connected with intense heating of the cold gas entering the arc in the cathode region. This agrees particularly with the data of Stein and Watson obtained for an equilibrium arc. This circumstance should explain a certain increase in E in the regions of the arc near the wall where the heating of cold gas occurs most actively. The radial distribution E(r) differs from the distribution E(r) = const adopted in the calculation. The experiment shows that near the wall there is some increase in E. The shape of the E(r) curve resembles "cat's ears."

It must be noted that the cylindrical arc model considered differs from the experimental conical arc of [11], although the good agreement of the data obtained indicates, first, that the model is not based on erroneous assumptions and, second, that a large channel diameter (R = 1 cm) and a short length of the conical section ($z \le 0.8$ cm) make the conditions of [11] better approximate the model.

Summing up this calculation of the two-temperature model, the following principal results should be brought out.

In arc plasmotrons there are very significant spatial regions where T_e differs from T. The value of T(r) and the heat flux at the wall depend on the flow rate of the gas forming the plasma.

The T(r) and $T_e(r)$ profiles vary along the entire length of the channel (l = 10 cm), and in this sense the nonequilibrium arc (R = 1 cm) has a very large nonstationary section of >10 cm.

An increase in the field intensity in the cathode regions of the arc, among other reasons, must be connected with the intense heating of the fresh gas entering this region.

The blowing of cold gas into an arc plasmotron leads to considerable cooling of the atoms and ions near the plasmotron walls and a decrease in the heat flux to the wall. This effect assures the thermostability of the plasmotron arc cathode in those cases when the plasma-forming gas is blown into the cathode region.

4. Approximate Analysis of Possibilities of Two-Temperature Model of a Moving Plasma*

An exact numerical calculation and a comparative estimate of the terms entering into the energy balance equation show that a number of conclusions which are interesting and important can be obtained within the framework of the two-temperature model with a simpler writing of the equations by neglecting some of the terms.

For instance, in arc and induction plasmotrons (gas heaters) with a large flow of plasma-forming gases, reliable results on the electron and gas temperatures can often be obtained from an analysis of the approximate energy distribution pattern in the plasma.

According to this pattern all the energy σE^2 transferred from the electric field to the electrons is then transferred by collisions to the atoms and ions and is expended only in heating the newly supplied cold gas. In this case the energy balance equations for the electron and atomic–ionic gases can be written in the form

$$\sigma E^2 = {}^3/_2 \delta \nu n_e k (T_e - T) \tag{4.1}$$

$$\rho v_z c_p \frac{\partial T}{\partial z} = {}^3/_2 \delta \nu n_e k (T_e - T). \tag{4.2}$$

*All the conclusions and estimates made in this work are obtained for atmospheric pressure. They are valid only for a plasma whose composition and parameters are calculated on the basis of Eq. (2.1).

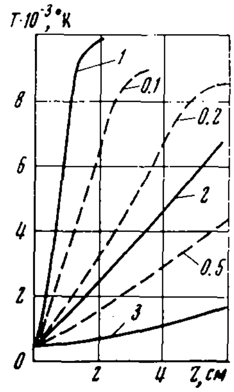

Fig. 3

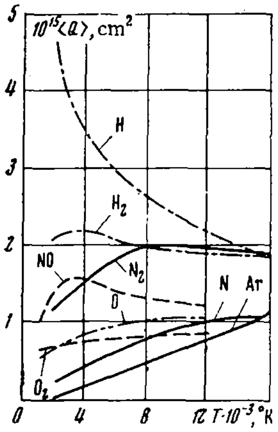

Fig. 4

The validity of this treatment is determined by the smallness of the divergence div (λ grad T) of heat fluxes at the wall and the radiation U_r compared with the other terms in Eqs. (1.1) and (1.2). If it is then considered that the specific energy σE^2 [W/cm²] inserted into the volume of the plasma and the mean specific flow rate $\rho v_z = G/\pi R^2$ of the plasma-forming gas through the plasmotron are known from experiment, the approximate calculation of T_e and T in induction and arc plasmotrons can be made on the basis of the simple equations (4.1) and (4.2) alone.

The radial distribution of T and T_e cannot be determined from Eqs. (4.1) and (4.2). Therefore the values obtained from (4.1) and (4.2) characterize the average plasmotron temperature over a cross section, pertaining to the average σE^2 and $\overline{\rho v}_z$.

Estimate of Depth of Equalization of Electron and Gas Temperatures in Plasma. When T_e and ρv are known from experiment, reliable data on the depth at which the temperature of the atoms and ions of the newly supplied gas approaches T_e can be obtained from an examination of the model case of the penetration of cold gas into a plasma occupying the half-space. In this case all the energy passed from the electrons to the atoms and ions is expended only on heating the newly supplied gas, and Eq. (4.2) is strictly obeyed.

Let us simplify the problem even more and examine how a cold gas penetrating into a plasma with constant T_e over the entire half-space is heated (this case can be realized in hf and microwave plasmotrons, where the plasma occupies a large volume and the gas flow rate is large):

$$T_e(z)|_{z\leqslant 1} = 0, \qquad T_e(z)|_{z\geqslant 0} = \text{const} \neq 0$$

Defining $\rho v z c_p = a$ and $^3/_2 \delta \nu n_e k = b$, we write Eq. (4.2) in the form

$$a\, dT/dz + bT = bT_e \tag{4.3}$$

The coefficients a and b are complicated functions of T and T_e, so that (4.3) can only be solved by numerical methods, such as the method of small sections with respect to z, in the limits of which a slight change occurs in T and T_e and a and b can be taken as constants. In addition, the constancy of b over a small section Δz does not introduce much error into the calculation because of its weak dependence on T. In this case the solution of the linear equation (4.3) in the small cross section $0 \leq z \leq \Delta z$ for the boundary condition $T_{z=0} = 0$ is

$$T = T_e\,[1 - \exp(-b/a\ z)] \tag{4.4}$$

and for the boundary condition $T|_{z=0} = T_0$ is

$$T = T_e\,[1 - \exp(-bz/a)] + T_0 \exp(-bz/a) \tag{4.5}$$

It follows from (4.4) and (4.5) that the temperature of the entering gas increases exponentially as it gets "deeper" into the plasma. The rate of increase dT/dz of the temperature depends on the ratio b/a. Equation (4.3) was solved numerically for an argon plasma at several temperatures by the method of linear sections for two cases (Fig. 3): 1) a given amount of gas (ρv = 0.3 g/sec·cm²) is blown into an argon plasma having different electron temperatures T_e = 8000, 9000, and 10,000°K (solid curves 3, 2, and 1). Different amounts of gas ρv = 0.1, 0.2, 0.3, 0.5 g/cm²·sec (dashed curves) are supplied to a plasma with a constant temperature T_e = 9000°K. The values of T_e and ρv were chosen on the basis of the operation of real induction plasmotrons. It follows from an analysis of the T(z) functions obtained that the specific flow rate of the gas and the electron temperature have a very strong influence on the rate of equalization of T and T_e. For example, at $T_e = 10{,}000$°K the temperatures T and T_e become equal at a depth of $\Delta z \approx 2$ cm, while at $T_e = 8000$°K the same amount of gas $\rho v = 0.3$ g/cm^2 · sec at a depth z = 10 cm is heated to only T ≈ 2000°K. At $T_e = 13{,}000$°K the "depth" at which the temperatures T and T_e become equal is $\Delta z \approx 0.4$ cm for a flow rate of 1 g/cm^2 · sec. Hence it follows that the most significant effect of the gas flow rate on the disturbance in thermal equilibrium is observed at low electron temperatures of $T_e \approx 9000$°K, which are realized in the zones near the walls of arc and high-frequency plasmatrons. An increase in the gas flow rate from 0.1 to 1 g/cm^2 · sec at $T_e = 9000$°K leads to a decrease in the temperature of the heavy component at a depth of z = 4 cm from 9000 to 1500°K.

This analysis can also be applied to an explanation of the high heating rate and low depth at which the temperatures T and T_e become equal in molecular gases. As follows from (4.4), dT/dz is proportional to the ratio

$$b/a = \frac{{}^3/_2 \delta \nu n_e k}{\rho v_z c_p} \tag{4.6}$$

Let us analyze the sizes of the individual terms in this equation for different gases. For the most common plasma-forming gases (Ar, N_2, H_2) δ is equal to $2.7 \cdot 10^{-5}$, $3.9 \cdot 10^{-5}$, and $5.5 \cdot 10^{-4}$, respectively. The collision frequency of the electrons is determined through the collision cross section Q by the equation

$$\nu = \bar{v}_e \left[n_a Q_{ea} + n_i Q_{ei} + n_m Q_{em} \right] \tag{4.7}$$

The dependence on the electron temperature of the plasma for Ar, N_2, N, O, O_2, H, H_2 is presented in Fig. 4. A comparison of δ, Q_{ea}, Q_{em}, and ν for molecular gases and for argon shows that in molecular gases $b = {}^3/_2\ \delta \nu n_e k$ is much greater for a given plasma temperature than in argon. This means that in molecular gases T and T_e for a gas supplied to the plasma at the same ρv become equal at much smaller depths than in argon, which is connected with the following causes: 1) the large interaction cross section between an electron and an atom (molecule) in nitrogen and hydrogen compared with argon; 2) the large fraction of energy transferred in elastic collisions in light molecular gases; and 3) the effect of inelastic collisions.

Estimate of Average Electron Temperature in Plasmotron. The temperatures of the electrons and atomic–ionic gas averaged over a cross section are determined in the framework of the case under consideration in a plasmotron through the joint solution of Eqs. (4.1) and (4.2). A graph of the dependence of the right side of Eq. (4.1) on the temperature of the atoms and ions,

$${}^3/_2 \delta \nu n_e k \,(T_e - T) = f\,(T, T_e) \tag{4.8}$$

constructed for different T_e, proves very useful for this purpose.

It is easy to give σE^2 for an induction plasma. In estimating T_e for arc plasmotrons it is easier to use the current density $j = I/\pi R^2$ averaged over the cross section (here I is the total current). Therefore Eq. (4.1) must be written somewhat differently. Using the expression

$$\sigma = \frac{e^2 n_e}{m_e \nu} K_\sigma$$

for the conductivity in the plasma (K_σ is a kinetic correction) and substituting it into (4.1), after several transformations one can obtain

$$j = 4 \cdot 10^{16}\ K_\sigma n_e \sqrt{T_e - T} \tag{4.9}$$

where j is in A/cm^2.

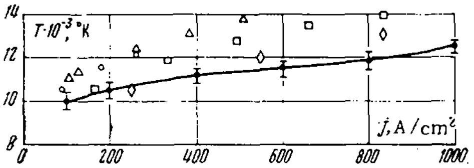

Fig. 5

The dependence of the right side of this equation on T at different values of T_e allows one to determine T_e if the average current density j and T are known. An analysis of the magnitudes of the right sides of Eqs. (4.1) and (4.9) shows that their dependence on the temperature of the atomic–ionic gas is weak. This in turn makes it possible to estimate the electron temperature T_e in the plasma, given only the average specific power σE^2 or the current density j. For instance, it follows from (4.1) that T_e = 10,000°K for $\overline{\sigma E^2}$ = 1.5 kW/cm^2 with a variation in T from 500 to 9500°K. For a current density j = 1000 A/cm^2 we

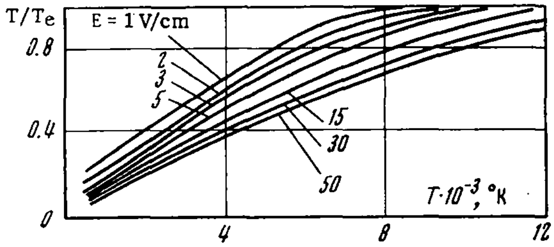

Fig. 6

have T_e = 12,500–11,500°K with a variation in T from 500 to 10,500°K. This weak dependence of (4.1) and (4.9) on T in a number of cases allows an estimate of T_e in the plasmotron on the basis of an ordinary algebraic equation like (4.1) and (4.9) from the given σE^2 or j without a joint solution of Eqs. (4.1) and (4.2), or (4.9) and (4.2). Let us compare the values of T_e obtained in this way with the experimental values. The values obtained from such an estimate are presented below

P, kW/cm^3	0.07	0.1	0.31	0.29	1.2	1.5
$T_m\cdot 10^{-3}$, °K	8.4	9.2	9.7	9.8	10.3	10.7
$T_c\cdot 10^{-3}$, °K	8.5	8.6	9.4	9.3	9.7	10

for the calculated electron temperature T_c corresponding to a certain specific power P, W/cm^3, in an induction argon plasma, and the T_m measured experimentally in [14] and corresponding to the same P. It is seen that the agreement of the results is unexpectedly good, and in some cases the disagreement is much less than the errors in the measurement and calculation. A very full survey of the dependence of the axial temperature of an argon arc on the ratio I/2R is given in [15] for arc plasmotrons. The data presented in [15] make it possible to relate the axial temperature T with the current density $\bar{j} = I/\pi R^2$ averaged over the cross section, with the help of which one can determine T_e on the basis of (4.9). The experimental axial temperatures $T_e(0)$ from the data of various authors [15] are plotted by points in Fig. 5. The calculated dependence $T_e = f(\bar{j})$ obtained from Eq. (4.9) is given by the curve. The calculated temperatures are too low because the calculation gives some average electron temperature (pertaining to the average current density), while the experimental values (Fig. 5) are given for the axial temperatures. A comparison of the experimental data and an approximate calculation shows that Eqs. (4.1) and (4.9) can be used to estimate the electron temperature in arc plasmotrons with an accuracy of no less than 20–25%, and of ~10% in induction plasmotrons.

The good agreement of the calculated and experimental dependences of the temperature on the power and current density indicates that the application of a two-temperature model correctly reflects the essence of the physical processes in plasmotrons.

The physical parameters σ, n_e, and ν of a plasma are determined by the two values T and T_e. Therefore each value of T and T_e corresponds to only a single value of the field intensity E, for which Eq. (4.1) should be used.

This made it possible to relate on the basis of the solution of (4.1) the three values (E, T, and T_e) for an argon plasma in the form of the nomogram Fig. 6, which can be used both in the exact solution of the whole system of equations of a moving plasma and for approximate estimates of the parameters of a nonequilibrium plasma.

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