EXPANSION OF PARTIALLY IONIZED ARGON THROUGH A SUPERSONIC NOZZLE

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The results of calculations of equilibrium, frozen, and relaxing flows of partially ionized argon through a hypersonic nozzle are presented. Calculated values of the flow Mach number and the electron density and temperature are compared with the experimental values obtained by the gas-dynamic and probe methods in a shock tunnel. An analysis of the data leads to the following conclusions:

1) The theoretical value of the recombination rate in three-body collisions is in accordance with the experimental results.

2) There is a clearly expressed ionization "freezing" effect.

3) As a rule, the experimental values of the electron temperature considerably exceed the calculated values.

There have been several theoretical studies of plasma flows in expanding nozzles, notably that of Talbot, Chou, and Robben [1], in which the expansion of partially ionized hydrogen and argon through a supersonic nozzle was calculated on the basis of the recombination model proposed by Bates et al. [2]. Unfortunately, this calculation was made for very small densities and only two values of the degree of ionization and, accordingly, does not provide exhaustive information. However, it showed that in the presence of large degrees of ionization of the gas at the nozzle inlet the laws of electron-ion recombination have an important influence on the flow characteristics.

1. Calculation of ionized gas flow through a hypersonic nozzle. We assume that the flow is quasi-one-dimensional. Disregarding friction, we can describe the flow of a partially ionized gas through a nozzle by means of the following system of equations [1]:

$$\frac{d}{dx}(\rho u A) = 0, \qquad \rho u \frac{du}{dx} = -\frac{dp}{dx}$$

$$u \frac{d}{dx}\left(i + \frac{1}{2} u^2\right) = -\frac{R}{\rho}, \qquad p = \frac{\rho}{m_a} k (T + \alpha T_e)$$

$$\frac{d\alpha}{dx} = -[(\delta + \beta)\alpha - \beta] \frac{\rho\alpha}{m_a u}$$

$$\frac{dT_e}{dx} = \frac{2}{3} \frac{T_e}{\rho} \frac{d\rho}{dx} - \frac{1}{\alpha}\left(T_e + \frac{2}{3} \frac{I}{k}\right) \frac{d\alpha}{dx} - \frac{2}{3} \frac{m_a R}{\rho \alpha u k}$$
$$- \frac{\rho}{u}\left[D_1 \alpha T^{-3/2} \ln\left(\frac{D_2 T^3}{\rho\alpha}\right) + (1 - \alpha) D_3\right](T_e - T)$$

$$i = \frac{5}{2} \frac{k}{m_a}(T + \alpha T_e) + \frac{\alpha}{m_a} I, \qquad \alpha = \frac{N_e}{N_e + N_a}$$

$$D_1 = \frac{2e^4}{3 m_a^2 k}\left(\frac{8\pi m_e}{k}\right)^{1/2}, \quad D_2 = \frac{9k^3 m_a}{8\pi e^6}, \quad D_3 = \frac{5\pi (m_e B)^{1/2}}{3 m_a^2} \tag{1.1}$$

Here, ρ, p, T, and i are density, pressure, temperature, and enthalpy, respectively; u is the flow velocity; A the nozzle cross section; R the radiation power losses per unit volume; α the degree of ionization; m_a and m_e are the atom and electron masses; e is the electron charge; T_e the electron temperature; δ and β are the ionization and recombination rate constants; k is Boltzmann's constant; I the ionization potential; N_e and N_a are the numbers of electrons and atoms per unit volume; B is the intermolecular force constant.

In the equation for the electron temperature the terms on the right-hand side, respectively, characterize the changes in electron temperature caused by the change in density during expansion, kinetic processes, and the energy losses due to radiation and collision processes involving ions and atoms (terms in brackets).

Let us now examine the problem of frozen, equilibrium, and relaxing adiabatic flows through hypersonic nozzles.

2. Frozen flow. We make the following assumptions: 1) the degree of ionization is constant and equal to the value at the nozzle inlet, $\alpha = \alpha_0$ = const; 2) the electron temperature is equal to the temperature of the heavy particles; 3) there is no dissipation of energy, including radiative, i.e., R = 0.

Then, introducing the following characteristic quantities:

$$\bar{T} = \frac{I}{k}, \ \bar{\rho}, \quad \bar{p} = \frac{\bar{\rho} I}{m_a}, \quad \bar{u} = \left(\frac{I}{m_a}\right)^{1/2}, \quad \bar{i} = \frac{I}{m}, \quad \bar{A} = A_*$$

we reduce the system of equations to dimensionless form:

$$\rho u A = \rho_* u_*, \qquad \rho u \, du = -dp$$
$$i + {}^1/_2 u^2 = i_0, \qquad p = \rho T (1 + \alpha_0), \qquad i = {}^5/_2 \ T (1 + \alpha_0) + \alpha_0 \tag{2.1}$$

Here, the subscripts 0 and * denote values of the parameters at the nozzle inlet and in the throat section, respectively. To solve this system it is necessary to determine the mass flow rate $\rho_* u_*$ in the throat section.

From (2.1) we obtain

$$d\,[\sqrt{2(i_0 - i)}] = -\frac{2}{5} A d\left(\frac{i - \alpha_0}{A \sqrt{2(i_0 - i)}}\right) \tag{2.2}$$

After differentiation with respect to the length η of the nozzle this gives

$$\left\{\frac{2}{5} \frac{2(i_0 - i) + (i - \alpha_0)}{[2(i_0 - i)]^{3/2}} - \frac{}{\sqrt{2(i_0 - i)}}\right\} \frac{di}{d\eta} = \frac{2}{5A} \frac{i - \alpha_0}{\sqrt{2(i_0 - i)}} \frac{dA}{d\eta}$$

In the throat section the expression in braces should be equal to zero, since $dA/d\eta = 0$, and $di/d\eta \neq 0$ (supersonic flow regime beyond throat). Hence we obtain the values of the parameters in the throat section:

$$i_* = {}^1/_4 (3i_0 + \alpha_0), \qquad T_* = {}^3/_4 T_0, \qquad u_* = \sqrt{{}^5/_3 T_* (1 + \alpha_0)} \tag{2.3}$$

Now, integrating system (2.1), we find

$$\rho = \rho_0 (T / T_0)^{3/2}, \qquad u = \sqrt{5(1 + \alpha_0)(T_0 - T)}$$

Substituting ρ and u in the first of Eqs. (2.1), we have

$$\rho_0 \left(\frac{T}{T_0}\right)^{3/2} \sqrt{5(1 + \alpha_0)(T_0 - T)} = \frac{\rho_* u_*}{A} \tag{2.4}$$

Determining $\rho_* u_* = 0.726 \ \rho_0 \sqrt{T_0(1 + \alpha_0)}$ and substituting in (2.4), we obtain the temperature as a function of the cross-sectional area of the nozzle,

$$\left(\frac{T}{T_0}\right)^{3/2} \left(1 - \frac{T}{T_0}\right)^{1/2} = \frac{0.324}{A} \tag{2.5}$$

Equation (2.5) was used to determine the distribution of the parameters along the length of the nozzle. In this case as the variable we took the ratio T/T_0, since this made iteration unnecessary. After finding the temperature dependence of A we determined the values of all the other parameters.

3. Equilibrium flow. For equilibrium flow the following assumptions are valid: 1) the degree of ionization α is related with temperature by the Saha equations; 2) the electron temperature is equal to the temperature of the heavy particles; 3) we assume that energy is not radiated, i.e.,

$$R = 0$$

The equilibrium flow is described by the same system of equations (2.1) supplemented by the Saha ionization equation

$$\frac{\alpha^2}{1 - \alpha} = \frac{T^{3/2}}{\rho} \exp\left(-\frac{1}{T}\right) \tag{3.1}$$

Here the characteristic quantity for $\bar{\rho}$ is taken to be

$$\rho = 2\left(\frac{2\pi m_e k}{h^2}\right)^{3/2} m_a \frac{g_i}{g_a} \left(\frac{I}{k}\right)^{3/2}$$

where h is Planck's constant and g_a and g_i are the statistical weights for atoms and ions.

System (2.1), (3.1) can be integrated. In fact, differentiating (3.1), we obtain

$$\frac{2-\alpha}{\alpha(1-\alpha)}\,d\alpha=\frac{3}{2}\frac{dT}{T}-\frac{d\rho}{\rho}+\frac{dT}{T^2} \tag{3.2}$$

Eliminating the velocity u from the second and third of Eqs. (2.1), we have

$$^5/_2\,(1+\alpha)dT+{}^5/_2 T d\alpha+d\alpha-\rho^{-1}\,dp=0 \tag{3.3}$$

Then, differentiating the equation of state in system (2.1) and eliminating the pressure by substituting it into Eq. (3.3), we obtain

$$^3/_2\,(1+\alpha)dT+(1+{}^3/_2 T)d\alpha-T\,(1+\alpha)\rho^{-1}d\rho=0 \tag{3.4}$$

Solving this equation together with (3.2), we obtain

$$\left[\frac{3}{2}+\frac{(2-\alpha)(1+\alpha)}{\alpha(1-\alpha)}\right]d\alpha+d\left(\frac{1+\alpha}{T}\right)=0$$

After integration we have

$$\frac{5}{2}\alpha+\frac{1+\alpha}{T}+2\ln\frac{\alpha}{1-\alpha}=\text{const}=C_0 \tag{3.5}$$

The constant C_0 is determined by the values of the parameters for the frozen flow.

Thus, system of equations (2.1), (3.1) has been reduced to a system of algebraic equations, where Eq. (3.5) is taken instead of the second equation in system (2.1). To obtain a solution it is necessary to find the values of the flow parameters in the throat section. As distinct from the case of a frozen flow, where we obtained an expression for T_* starting only from Eq. (2.2), for equilibrium flow, where $\alpha = \alpha(A)$, Eq. (2.2) is supplemented by Eq. (3.5), and it can be transformed as follows:

$$\left\{1-\left[\frac{^5/_4\,T(1+\alpha)}{i_0-{}^5/_2 T(1+\alpha)-\alpha}-\frac{3}{2}\right]\left[\frac{5T}{2}+1+\frac{5(1+\alpha)}{2}\frac{dT}{d\alpha}\right]\right\}\frac{d\alpha}{d\eta}=\frac{5T(1+\alpha)}{2A}\frac{dA}{d\eta} \tag{3.6}$$

In the throat section $dA/d\eta = 0$ and $d\alpha/d\eta \neq 0$; consequently, the expression in braces is equal to zero. Thus, for the point $\eta = \eta_*$ we obtain the following system of two equations in T_* and α_*:

$$\alpha_*-\alpha_*^2+5T_*^2\left[\frac{(i_0-\alpha_*)-{}^5/_2 T_*(1+\alpha_*)}{^3/_2(i_0-\alpha_*)-5T_*(1+\alpha_*)}+\left(1+\frac{5}{2}T_*\right)^2\right]^{-1}=0$$
$$T_*=\frac{1+\alpha_*}{C_0-{}^5/_2\alpha_*-2\ln[\alpha_*/(1-\alpha_*)]} \tag{3.7}$$

System of equations (3.7) was solved by an iterative method. Then the product $\rho_* u_*$ was found and all the remaining parameters of the equilibrium flow were calculated. For simplicity the degree of ionization α was taken as the independent variable.

4. **Relaxing flow.** In calculating a relaxing flow of partially ionized argon we used the expression for the recombination rate coefficient in three-body collisions [3]

$$\beta=5.2\cdot10^{-23}\,N_e T_e^{-9/2},\ \text{cm}^{-3}/\text{sec}$$

which is consistent with the quantum-mechanical calculations of Bates et al. [2]. Generally speaking, this formula is valid for low temperatures, when electron capture proceeds to high levels. At high temperatures it leads to exaggerated values of the recombination rate, but the exaggeration corresponds to a factor of not more than 5–10 even at a temperature on the order of 10,000°K. With this indeterminacy in mind, we made calculations for three values of the recombination rate coefficient, $10^{-1}\beta$, β, and 10β, which made it possible to estimate the sensitivity of the results to that coefficient.

Ionization was assumed to take place in stages, the controlling stage being the process of excitation of the atoms from the ground state. Therefore in calculating the ionization coefficient δ we used the cross section for the excitation of argon atoms [3]

$$\delta=5\cdot10^{-11}\sqrt{T_e}\exp(-133{,}000T^{-1}),\ \text{cm}^3/\text{sec}$$

We note that it is important to take ionization into account only in the subsonic region, where conditions are close to equilibrium. In the supersonic region, on the other hand, ionization can be neglected.

As the calculations showed, the pressure distribution along the nozzle changes only slightly on transition from equilibrium to frozen flow; therefore, the relaxing flow was calculated on BÉSM-2M computer by a difference method for a given pressure distribution corresponding to equilibrium flow.

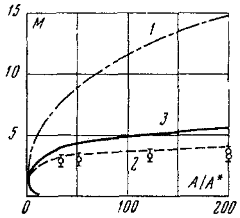

Fig. 1

In the calculations the independent parameter A was varied on two intervals: subsonic ($9 \geq A \geq 1$) and supersonic ($1 \leq A \leq 220$). It should be noted that in the calculations at the nozzle inlet point parameters slightly different from the stagnation parameters are obtained, since the gas velocity in the inlet section is not equal to zero.

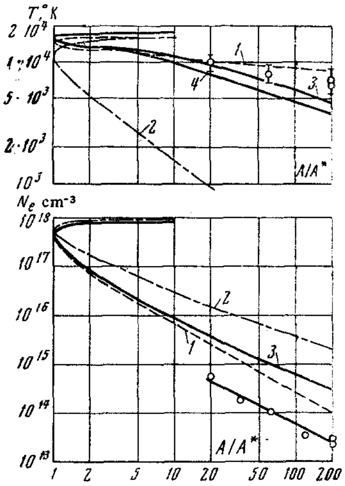

Fig. 2

The calculations were made for a nozzle whose convergent section is rounded at a radius equal to the throat diameter, while the variation of the area in the divergent part of the nozzle is described by the function

$$A = A_* + k(x - x_*)^2$$

where x_* is the distance from the inlet to the throat; $k = \pi \operatorname{tg}^2 \theta$. The asymptote of the divergent section of the nozzle is a cone with vertex half-angle θ. The calculations were made for a nozzle with throat diameter 8 mm and $\theta = 15^\circ$. As the values of the stagnation flow parameters we selected values corresponding to equilibrium conditions behind the reflected shock fronts in argon at incident shock Mach numbers 7, 10, and 17 and initial pressures 1 and 10 mm Hg. These values corresponded to the conditions of our experiments.

Some of the more interesting results of the calculations are presented in Figs. 1–4, which show graphs of the gasdynamic and thermodynamic parameters of argon as functions of the expansion ratio (in Fig. 1 the numerals 1 and 2 denote the frozen and equilibrium flows, respectively; in Figs. 2–4 the notation is as follows: 1 — equilibrium flow, 2 — frozen flow, 3a,b — electron temperature and density corresponding to values of the recombination rate coefficient β, 10β, $10^{-1}\beta$ for the case of a relaxing flow, 4 — atomic temperature for a relaxing flow).

From an analysis of the results of the calculations it follows that the values of a series of parameters depend importantly on the nature of the flow. The difference is particularly great for the electron temperature and density. The Mach number of the flow is also a very sensitive function that depends on the flow regime, but only at large initial degrees of ionization. As the degree of ionization decreases, for most parameters the differences rapidly decrease, remaining important only for the electron density and temperature. This was taken into account in selecting the method of experimental investigation.

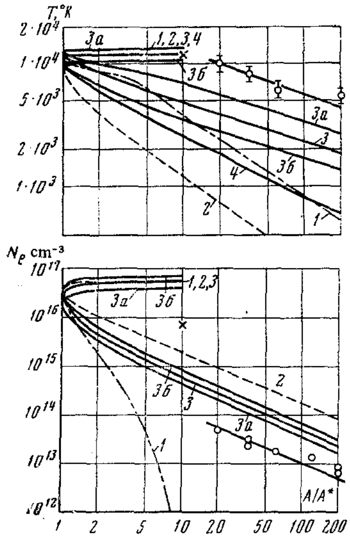

Fig. 3

5. Experimental apparatus. The flow of partially ionized argon was investigated in a shock tunnel consisting of a shock tube with a nozzle, vacuum chamber, and measuring instrumentation.

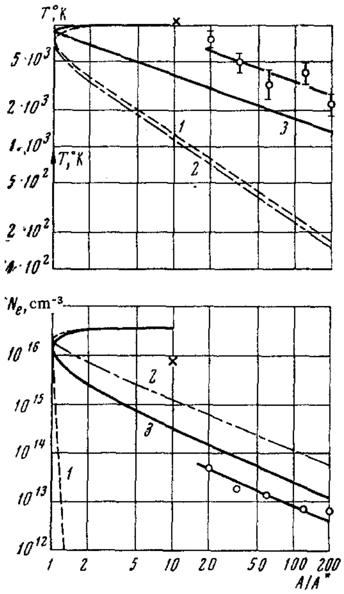

Fig. 4

The shock tube, described in detail in [4], has a high-pressure stage 3 m long designed for a maximum working pressure of 2000 atm and a low-pressure stage 9.1 m long and 80 mm in diameter designed for a pressure of 700 atm. The low-pressure stage ends in the working section, along which three barium titanate pressure transducers are installed. These serve to measure the propagation velocity of the incident shock and to trigger the oscillographs and a flash lamp via the synchronization unit.

In order to generate strong shocks a hydrogen-oxygen mixture was burned in the high-pressure chamber.

The shock tube ended in a nozzle situated in a vacuum chamber. This chamber, with a volume of 0.8 m^3, had inspection windows 200 mm in diameter, through which it was possible to view the exit section of the nozzle and a half-wedge with a sharp leading edge. This made it possible to obtain a picture of the flow over the half-wedge of gas from the region behind the reflected shock. The shock and Mach lines were visualized by means of schilieren photography using an IAB-451 instrument. As the pulsed light source we used a one-shot spark system with a flash lasting approximately 5 μsec. The flash was synchronized with the flow process by means of a special circuit with a variable delay, the synchronization unit being triggered by an electric probe at the nozzle exit.

The experiments were conducted according to the two-diaphragm scheme; the channel of the low-pressure stage of the shock tube was separated from the nozzle by a thin cellophane diaphragm, which made it possible to pump out the shock tube and the vacuum chamber containing the nozzle to various initial pressures.

The vacuum chamber was evacuated to a pressure of 10^{-4} mm Hg, the low-pressure state to 10^{-3} mm Hg, the inleakage into the latter being 10^{-3} mm Hg in 30 min.

In the experiments we used stainless-steel nozzles, the convergent sections of all the nozzles being the same, while the divergent sections varied in length and hence in the diameter of the exit section. We used a set of nozzles with exit-to-throat area ratios of 20, 35, 60, 120, and 200.

6. **Results of an investigation of ionized argon flows by the gasdynamic method.** An important question relating to the shock tunnel method is that of the duration of steady-state flow in the nozzle unifrom with respect to the plasma parameters. This time was determined experimentally by means of a special probe mounted at the nozzle exit. It was shown that for an initial argon pressure of 1 mm Hg the duration of steady-state flow varies approximately from 100 to 200 μsec as the incident shock Mach number varies from 18 to 10. As the initial pressure increased, the duration of steady-state flow rose correspondingly.

We noted above that at large degrees of ionization the M number of a plasma flow expanding through a hypersonic nozzle depends to a considerable extent on the flow regime. The calculations for equilibrium and frozen flows essentially determine the possible limits of variation of the M number of the flow as a function of the electron recombination rate.

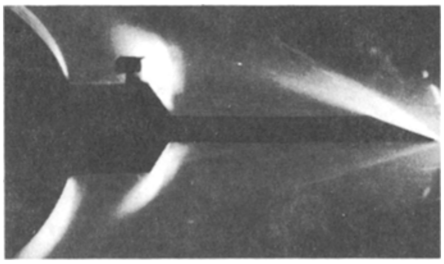

Fig. 5

In our experiments the M number of the flow was determined from the angle of inclination of the Mach lines propagating, for example, from the edge of the half-wedge. A schilieren photograph of the flow over the half-wedge for an incident shock Mach number of 17 is shown in Fig. 5. The Mach line and the oblique shock are distinctly visible. The Mach number of the flow was determined from the Mach angle in accordance with the expression $\sin\alpha = 1/M$.

This method was used to investigate the flow of ionized argon through an expanding nozzle for the most favorable conditions from the standpoint of the effect of electron-ion recombination on the plasma dynamics. These conditions corresponded to low density and a high value of the degree of ionization behind the reflected shock front. In these experiments the initial pressure was 1 mm Hg. For shock waves with $M = 17$ the temperature behind the reflected shock was 15,580°K, and the degree of ionization was approximately 0.5.

In Fig. 1 the results of these experiments are compared with the results of the above-mentioned calculations for the dependence of the M number of the flow on the expansion ratio. The points are grouped close to the curve corresponding to the equilibrium flow regime. A certain discrepancy between the experimental data and the calculated curve is attributable to possible errors. Apart from the errors in measuring the Mach angle, which are reflected in the graph by the vertical lines, the method is affected by errors associated with the non-one-dimensionality of the flow, inaccuracies in the positioning of the half-wedge, and boundary layer formation. However, as an analysis showed, taking these errors into account does not lead to any substantial change in the results obtained.

Thus, the experimental data presented above indicate that the flow of partially ionized argon through the nozzles was close to equilibrium, i.e., at large degrees of ionization the electron-ion recombination rate is quite high and is able to "follow" the changes in the state of the gas during expansion. However, it is natural to assume that at large expansion ratios and relatively small degrees of ionization the ionization equilibrium will be disturbed, but this can no longer lead to significant changes in the flow Mach number and under these conditions the gasdynamic method employed above is unsuitable. Therefore in order to investigate the behavior of the electron component during the expansion of ionized argon through nozzles we subsequently employed the probe method.

7. Probe measurements of the parameters of a plasma expanding through a nozzle. The probe method has been widely used in plasma diagnostics since in principle it makes it possible to determine the electron temperature and the density. Its advantages consist of its simplicity and the localization of the measurements, its disadvantages in the contact nature of the method and the complexity of the theory in the case of a dense plasma.

The theory of electrostatic probes has been examined by a number of authors, whose work is carefully analyzed in [5].

In [5] the electron temperature was determined from the beginning of the rise in electron current in the current-voltage characteristic of the probe. In this region for the case of a repulsive potential the probe current is given by the expression

$$j = j_i - j_e \exp\left[\frac{-e(V - V_0)}{kT_e}\right]$$

Here, j, j_i, j_e are the total, ionic, and electronic probe current densities, respectively; V and V_0 are the probe potential and the plasma ground potential.

Assuming that in the region of the electron current rise the variation of the ion current can be neglected, we easily obtain the following expression:

$$\frac{d}{dV} \ln \frac{dj}{dV} = \frac{1.16 \cdot 10^4}{T_e}$$

which was used to determine the electron temperature in analyzing the experimental data.

The electron concentration in the nozzle was determined from the ionic saturation current. The calculation was based on the improved formula proposed by Hohm and taking into account the penetration of the probe field beyond the space charge region, which leads to an increase in the collected ion current:

$$j_i = 0.61 n_i e S \left(\frac{kT_e}{M}\right)^{1/2}$$

Here n_i is the ion density, equal to the electron density; M is the ion mass; and S the surface area of the probe.

This formula is applicable only to a rarefied plasma, in which the ion mean free path is greater than the space charge thickness; this condition was satisfied in making the nozzle measurements.

In determining the electron concentration in the dense plasma behind the reflected shock we used the expression obtained in [6], which relates the ionic saturation current with the electron temperature and the ion concentration in the undisturbed plasma:

$$n_i T_e = 2 \cdot 10^{12} \frac{a}{\lambda} \sqrt{AT}\, j_i \ln \frac{l}{a x_0}$$

Here a and l are the radius and length of the probe, x_0 is the ratio of the space charge radius to the probe radius, A is the atomic weight, T is the atom temperature, and λ is the ion mean free path.

The ion mean free path was calculated from the charge exchange cross section Q for small particle velocities, an expression for which is given in [7]; for atomic gases

$$Q = \left[\frac{10^{-13}}{\sqrt{\pi I}} \ln\left(\frac{\sqrt{\pi I}}{v} e^{31}\right)\right]^2$$

Here I is the ionization potential in ergs; v is the relative ion velocity averaged over the Maxwell distribution, which in the first approximation is equal to

$$\sqrt{2}V \quad (V\text{—arithmetical mean velocity})$$

In the experiments we employed a single flat probe consisting of a rectangular steel plate measuring 1.4 × 3.3 × × 0.8 mm. The probe was installed at the nozzle exit in such a way that its current-collecting surfaces were strictly parallel to the flow. This made it possible to eliminate the effect of the flow velocity on the current collected by the probe.

The intermittent action of the shock tunnel made it necessary to develop a special method of recording the current-voltage characteristic of the probe during an interval on the order of 10–20 μsec. For this purpose we designed a generator capable of producing pulses of a particular shape, including a portion falling linearly from +13 V to −13 V in a time of the order of 10–12 μsec. A pulse of the necessary shape was obtained by using two synchronized sawtooth-voltage generators and amplified by a push-pull power amplifier with a transformer output shunted by a 2-ohm resistance. The generator pulse power was 25 W.

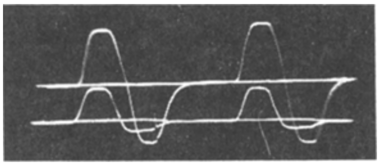

Fig. 6

A load resistance, the voltage drop at which was fed to a differential amplifier and registered by an OK-17 oscillograph, was connected in series with the probe. The second beam of the same oscillograph recorded the signal at the generator output. The difference between these voltages determines the voltage drop directly at the probe. A typical probe current oscillogram is shown in Fig. 6. From the oscillograms thus obtained we constructed the current-voltage characteristic, which was then analyzed in accordance with the above-mentioned method.

Two series of experiments were performed at an initial argon pressure of 1 mm Hg for incident shock Mach numbers of 17 and 10 and one series for a Mach number of 7 at an initial pressure of 10 mm Hg. The results of the experiments are represented by the points in Figs. 2–4.

From the data obtained for M = 17 it follows that the electron temperature is close to the equilibrium value, whereas the experimental values of the electron density lie outside the range of possible values and are approximately five times less than the values corresponding even to the equilibrium flow regime. This result apparently indicates that radiative cooling has an important influence on the plasma parameters behind the reflected shock. Owing to radiative losses the true values of the temperature and the electron density decrease as compared with the calculated equilibrium values. It was not possible to determine them by the probe method, since for so dense a plasma it was difficult to obtain the ionic saturation current. In view of these difficulties and the fact that for this regime there is a relatively small difference between the values of the electron density for the equilibrium and frozen flows, we will turn to weaker shocks for which the difference is much greater.

The results of the experiments at M = 10 and p = 1 mm Hg are presented in Fig. 3 (in this case the temperature behind the reflected shock was equal to 11,300°K, and the degree of ionization, to 0.10). For this regime, using the probe method, we determined the electron temperature and density behind the reflected shock (the experimental values are represented by crosses). From the data obtained it follows, first, that the electron concentration behind the reflected shock is almost six times less than the calculated equilibrium values, which is probably associated with radiative cooling of the gas, while, secondly, the experimental values of the electron density along the length of the nozzle are closer to the parameters of the frozen than to those of the equilibrium flow. Thus, there is a sharply expressed "freezing" effect. Moreover, the experimental values of the electron density are located below the calculated curve for a relaxing flow. However, if the change in the initial state due to radiative cooling is taken into account, the agreement between the calculated and the experimental data is good. In this case the experimental values correspond most closely with the calculated curve for a relaxing flow obtained for a value of the recombination rate coefficient 0.1β. Thirdly, the experimental values of the electron temperature considerably exceed the calculated values over the entire length of the nozzle.

Similar results (Fig. 4) were obtained in the other series of experiments of $M = 7$ and $p = 10$ mm Hg (temperature behind reflected shock 9800° K, degree of ionization 0.02). However, in this case there was better agreement between the calculated and experimental values of the electron density both in the stagnation flow and along the length of the nozzle.

In conclusion it should be emphasized that for the experimental conditions, as follows from a comparison of the experimental and calculated data, the recombination rate coefficient is approximately an order less than the theoretical values [2]. This is because, as previously noted, under the experimental conditions recombination proceeds to lower levels.

Ionization "freezing" was actually observed in all the operating regimes, and the frozen degree of ionization was of the order of 10^{-2}.

The fact that the experimentally determined values of the electron temperature exceeded the calculated values apparently indicates that insufficient allowance was made for all the processes affecting the behavior of the electron temperature. Incidentally, this is consistent with the data of [8], in which it was noted that the electron temperature for gas flow through a nozzle was frozen at values corresponding to the values of the electron temperature in the nozzle throat. Here, it should probably be taken into account that in the course of recombination in three-body collisions an electron is captured by one of the upper levels of the atom, and then as a result of electron impacts of the second kind, the excited atom gradually goes over into one of the lower states. Thus, the process of deactivation of excited atoms has an important influence on the behavior of the electron temperature. Estimates show that for the conditions of our experiments the characteristic deactivation time for electron impacts of the second kind is approximately an order less than the dwell time of the gas in the nozzle and the energy transfer time for electrons and heavy particles.

However, before proceeding to refine the starting system of equations and supplement it with the kinetic equations for the atomic level populations, it would be desirable to check our probe measurements by one of the spectroscopic methods.

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