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INVESTIGATION OF THE IONIZATION RATE IN A LOW-TEMPERATURE NONEQUILIBRIUM PLASMA FLUX

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Results are presented of a determination of the ionization rate constants of a low-temperature lithium plasma on the basis of measuring the plasma parameters in a longitudinal discharge and of numerical processing of the experimental data.

The flow of a low-temperature plasma in the channel of a magnetogasdynamic accelerator is characterized by an essential separation of the electron temperature from the heavy-particle temperature and by spoilage of the ionization equilibrium. Taking account of the ionization and recombination kinetics is a distinctive singularity of methods of computing plasma fluxes which yield the most confident information about the parameters of the working process. Progress in the development of such methods is slowed down because of the lack of information about the characteristics of the fundamental physical processes in a low-pressure nonequilibrium plasma and on the surface of the accelerator channel. Among these processes, a special place is occupied by volume ionization, since it is primarily one of the causes of ion generation. Evaluation of the volume ionization rate constant K in the formula for the change in charged particle concentration obtained in the ionization–recombination process

$$\frac{\partial n_e}{\partial t} = Kn_a n_e - \gamma n_e^3, \ (n_e = n_i), \tag{1}$$

is a very complex problem whose correct solution requires the presence of reliable data over the sections of the elementary processes in addition to the production of a correct theoretical model. Since information about these quantities is limited and of inadequate confidence at this time, an experimental determination of K acquires special value. The accumulation of appropriate experimental material is also the foundation for a critical analysis of existing theoretical developments on the question under consideration and of the selection of the logical physical model of the process. It should be noted that even an estimate of the coefficients to order-of-magnitude accuracy acquires great practical value in connection with the lack of experimental data on the plasma ionization rate constants for many substances.

A method of determining the coefficient K for ionized vapors of substances with a high boiling point, based on measurements of the partial profiles of the parameters and on the integrated discharge characteristics with a subsequent special numerical processing of these data, is elucidated briefly in this paper. The method is checked out in an example of a lithium plasma.

A coaxial plasmatron of the type in [3-4] with up to 10 kW power (Fig. 1) including a hollow tungsten cathode and a nozzle-anode separated by a boron carbonitride(BCN) insulator was used to obtain the plasma flux. The plasma jet is bounded by the wall of a thin-walled ($\delta \sim 2 \cdot 10^{-4}$ m) molybdenum tube 4 (Ø$3.2 \cdot 10^{-2}$ m) heated by direct heat, and joined to the nozzle-anode 2 through the insulator 3. The main purpose of the cylindrical tube ($L \approx 0.1$ m) is assurance of a steady plasma flow characterizing the preferred change in the parameters in the radial direction.

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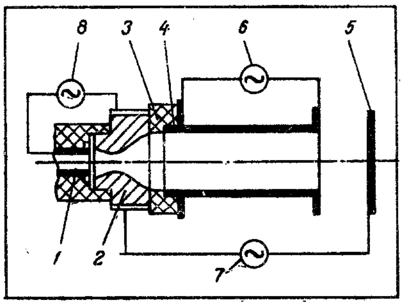

Fig. 1. Diagram of the experimental setup: 1, 2) cathode and anode of the plasma source; 3) insulator; 4, 5) tube and anode of the longitudinal discharge; 5, 7, 8) current generators.

Vapor condensation on its inner surface is prevented by heating the tube from the current source 6. A rise in the role of ion generation is achieved by triggering a longitudinal discharge between the nozzle 2 and a special auxiliary anode 5 which is a copper insulated plate mounted at a distance ∿0.2 m from the tube exit. The electrical supply for the discharge in the plasma source and for the longitudinal discharge is accomplished from the dc generators 8 and 7, respectively. Under definite conditions the plasma flow in such an apparatus has stationary radial profiles of the physical parameters which are described by a system of differential equations of the longitudinal discharge [1] and by boundary conditions [2] dependent on the kinetic gas coefficients, the plasma parameters, and the surface. According to the method, the profiles of the plasma parameters are measured in the exit section of the tube. The measurements were conducted both outside the tube at a distance ∿1 mm from the exit, and within it at a distance ∿8 mm from the exit by introducing a probe through a slot. Comparing the results did exhibit essential differences in the parameter distribution in the stream core. The following are the main theoretical hypotheses for processing the experimental results. A small change in the temperature, concentration, and mean mass flow rate of the plasma along the tube is assumed (a one-dimensional approximation). An equation for conservation of the charged particles in a given volume element is used and the charged particle losses because of motion are taken into account in this equation only by the process of their diffusion toward the wall. The assumption made is satisfied in the apparatus under consideration under the conditions of the experiment. For example, let us estimate the influence of the term $U(\partial n_e/\partial z)$ (U is the mean mass flow rate and z is the coordinate along the tube axis) in the conservation equation which is important for other conditions in application to the experiments conducted.

The ratio

$$\delta = \frac{U \frac{\partial n_e}{\partial z}}{n_e n_a K} \approx \frac{U}{n_a K L} \tag{2}$$

characterizes the fraction of the charged particles along the tube because of the combined effect of the factors U and $\partial n_e/\partial z$ as compared with their generation because of ionization. According to the average experimental results $U \sim 10^3$ m/sec, $n_a \sim 3 \cdot 10^{20}$ m^{-3}, hence $K \sim 5 \cdot 10^{-16}$ m^3/sec, $L = 0.1$ m, then $\delta \leqslant 0.06$, i.e., the contribution of the term under consideration for the conditions realized in the experimental apparatus described is negligible.

Therefore, the distribution of the electron concentration at the tube exit will be determined in large part by ambipolar diffusion of the charged particles to the wall under an attenuated influence of the effects associated with the longitudinal gradients of the plasma parameters.

Changes in the gasdynamic, as well as the magnetic, pressure due to the longitudinal current are taken into account in computing the radial profiles. For the case of an insulated wall $j_r = 0$ (j_r is the radial current density). The electron concentration n_e on the surface is determined as a result of simultaneous progress of the volume ionization, surface ionization, and surface recombination. The local concentration n_e in the volume is determined by the combined interaction between volume and diffusion processes. All the coefficients except K in the method used are assumed known. Then the solution of the above-mentioned system of equations depends on the coefficient K, which is approximated by a suitable three-parameter expression, for example,

$$K = AT_e^m \exp(-\beta/T_e). \quad (3)$$

The selection of the relationship (3) is due to the following reasoning. As is known from general physical representations and the strictest theoretical computations [9], the rate constant to step ionization K depends on the electron temperature T_e and the electron density n_e, where K is a function of just T_e for low values $n_e \leqslant 10^{18}$ m^{-3}.

The dependence $K(T_e)$ taken approximates well the theoretical computations of the ionization rate constant of a cesium plasma which agrees satisfactorily with experimental data [14]. Having a system of equations with a given expression for K and experimental temperature, concentration, and integrated characteristics (discharge current I_d, pressure p, longitudinal electrical field intensity E_z, mean mass flow rate $\dot{m}$, tube temperature T_w) by varying the parameters A, m, β in (3), those values can be found for which the numerical solution of the initial system of equations on an electronic computer will yield radial temperature and concentration profiles satisfying the experimental data best.

A probe and a spectroscopic method were used to record the experimental n_e, T_e profiles and to determine the mean atom temperature T_a in this paper.

The fundamental data on the radial n_e and T_e profiles in the experiments conducted were obtained by using the probe method [5-6], while the spectroscopic method was relied upon for a check and to obtain information about n_a (the concentration of neutrals) and T_a. The volt–ampere probe characteristics (VAPC) were recorded simultaneously at four points along the diameter by the remote high-speed insertion of a distribution of probes into the lithium plasma and by feeding a sawtooth voltage with a 10-15 Hz frequency. The shortness of the residency of the distributer block in the plasma prevented spoilage of the ceramic insulation of the cylindrical tungsten probes by the lithium. The probes were fabricated from $(2\text{-}3) \cdot 10^{-4}$-m diameter tungsten wire, which was imbedded, with the exception of the collecting surface, in a boron carbonitride dielectric tube. The pulse mode of operation permitted avoidance of substantial influence of contamination of the collecting surface on the VAPC. The sawtooth voltage and the current in the loop of each probe were recorded on an N004M loop oscilloscope. The electron and ion parts of the characteristic [5] were used in processing the VAPC to determine n_e and T_e. The error in measuring T_e was estimated at 20-25% and in measuring n_e as 20-30%.

The spectroscopic measurements were realized through special viewing windows of the vacuum chamber. An ISP-51 spectrograph with chambers having a 0.27 and 1.3 m focal length and an IT-51-30 Fabry-Perot interferometer were used to record the spectra. The spectra were photographed on panchromatic aerial photographic film of DK type with 1200 GOST (All-Union State Standard) units sensitivity. Deciphering the spectrograms was performed on an MF-4 microphotometer.

Its fine structure was taken into account when determining the neutral temperature T_a by means of the half-width of the spectrum line Li I 4972 Å (the transition $2p^2P_{1/2\ 3/2}-4s^2S_{1/2}$). According to the analysis, the accuracy of determining T_a is no worse than 20%. The mean value of the population of the lithium atom ground level (n_I) with respect to the section was determined by the method recommended in [7]. The line Li I 6707 Å (the transition $2s^2S_{1/2}-2p^2P_{1/2\ 3/2}$), observed in the form of a triplet because of self-inversion of the fine-structure components, was used. The oscillator strengths were taken from [8]. The resultant estimate of n_a was accomplished on the basis of the value of n_I found and on the mean mass flow rate $\dot{m}$ of the lithium. The error admitted is hence $\leqslant$40%. The E_z was determined both by measurement of the potential near the electrodes by the probes and by means of the volt–ampere characteristic of the discharge, and the electrode drops were hence estimated by means of the quantity Δu_p obtained by extrapolation of the characteristic to the value $I_d = 0$. The pressure p was estimated by means of the results of the probe and spectroscopic measurements

$$p = n_e kT_e + (n_i + n_a)\, kT_a.$$

The overwhelming part of the measurements was conducted at the tube exit and near the exit through a special hole for an $\dot{m} = 2.5 \cdot 10^{-5}$ kg/sec lithium discharge, an I_{source} = 150-A discharge current in the plasma source, and an I_d = 70-80-A longitu-

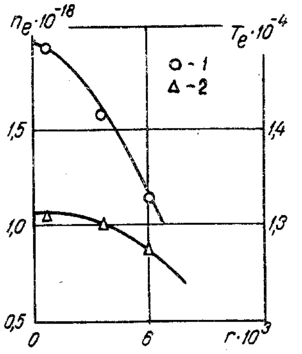

Fig. 2

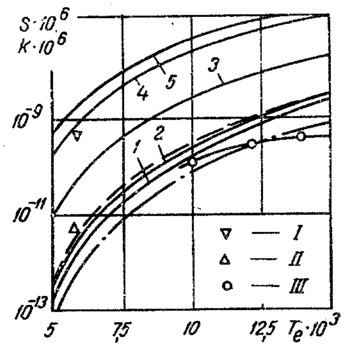

Fig. 3

Fig. 2. Radial n_e and T_e profiles: 1) T_e' 2) n_e; T_e, °K; n_e, m^{-3}; r, m.

Fig. 3. Data in S and K for a lithium plasma: solid line: S [9], 1) $n_e = 10^{14}$ m^{-3}, 2) 10^{18} m^{-3}, 3) 10^{19} m^{-3}, 4) 10^{20} m^{-3}, 5) 10^{21}, 10^{22} m^{-3}; dashed line: S [13]; dashed-dot line: S [11], I) S [10], $n_e = 10^{23}$ m^{-3}, II) S [10], $n_e = 10^{17}$ m^{-3}, III) K. S, K, m^3/sec; T_e, °K.

dinal discharge current. Typical central branches of the radial n_e and T_e radial profiles are shown in Fig. 2. Hence the maximum concentration $n_{e\ max}$ in the core was (2-3) · 10^{18} m^{-3}, and the temperature was $T_{e\ max} \approx (1.1\text{-}1.3) \cdot 10^4$°K. The pressure p has the value ∿13 N/m², the intensity was $E_z \approx 80$ V/m, and the wall temperature measured by using a thermocouple was $T_w \approx 1000$°K, $T_a = 2500 \pm 500$°K.

Presented in Fig. 3 are values of K for a lithium plasma computed by means of (3) on the basis of coefficients A, m, β determined from experimental results, and referred to the experimental profiles found and the mean values of the discharge parameters. Represented in this same figure are results of computing the ionization rate constant of lithium vapors by means of different theoretical models using the Maxwell electron distribution:

1) The ionization rate coefficients S [the quantity S differs from K in that n_I rather than n_a is present in the first member in the right side in (1)], found for an optically thin plasma by means of the stationary-sink hypothesis [9] in which step ionization taking account of the collision and radiation transitions is postulated and the Thomson formula is used for the ionization cross section and the Born–Bethe approximation for the excitation cross section; 16 discrete levels are hence taken into account and it is assumed that a Boltzmann distribution (solid curves) is valid for the higher levels;

2) The coefficients S determined in [10] under the assumption of an ionization model analogous to [9] but taking account of the first eight levels of the lithium atom and using the results of Drawin [11] and Vainshtein and Sobel'man [12] for the cross section of the collision acts (II and I in Fig. 3);

3) The coefficients S calculated taking account of shock ionization only from the ground level when using the semiempirical Drawin [11] ionization cross section (dashed-dot curve in Fig. 3);

4) The coefficients S determined taking account of shock ionization from the ground level when using the classical Thomson ionization cross section [13] (dashed curve in Fig. 3).

The following deductions can be made from a comparison of the data in Fig. 3.

Taking complete account of the collision-radiation processes results in the appearance of a dependence of the ionization rate constant on n_e and an approximately two-orders-of-magnitude reduction in its value for $n_e \leqslant 10^{18}$ m^{-3} compared with its values for $n_e \approx 10^{22}$ m^{-3}.

The results of computing S in [10] are in agreement with the values of S in [9] within the limits of the accuracy in determining the sections of the elementary processes.

The quantities S determined taking into account only ionization from the ground level adjoin the domain of low concentrations $n_e = 10^{14}\text{-}10^{18}$ m^{-3} of the computation

[9]. The difference between the S calculated using [11] and [13] is explained by the difference between the Drawin and Thomson ionization cross sections.

The values of K found from experiment in the domain $n_e(2\text{-}3)\cdot10^{18}$ m^{-3} are somewhat below the computed S obtained by means of the theoretical "stationary sink" model. In analyzing these results it should be kept in mind that a deviation of the free electron distribution function from the Maxwell distribution function can produce a tendency to diminution of the theoretical value of S.

NOTATION

n_e, electron concentration; n_a, atom concentration; n_I, atom concentration at the ground level; p, pressure; T_e, electron temperature; T_a, heavy particle temperature; T_w, wall temperature; v_r, radial velocity component; v_z, longitudinal velocity component; j_r, current density at the wall; I_{ld}, longitudinal discharge current; I_{source}, source discharge current; E_z, electrical field intensity; Δu_p, sum of drops near the electrode; K, ionization rate constant; γ, recombination rate constant; S, rate constant of the decrease in particles from the ground level; A, m, β, parameters in the expression for the rate of charged particle formation per unit volume; r, tube radius; L, tube length.

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