LITERATURE CITED

1. P. A. Bernhard, R. A. Roussel-Dupre, M. B. Pongratz, et al., "Observations and theory of the AMTE magnetotail barium releases," J. Geophys. Res., 92, No. A6 (1987).
2. O. B. Anan'in, Yu. A. Bykovskii, B. V. Zamyshlyaev, et al., "Spectroscopic investigations of a laser carbon plasma expanding into a background medium," Fiz. Plazmy, 9, No. 2 (1983).
3. O. B. Anan'in, Yu. A. Bykovskii, V. V. Mlynskii, and E. A. Stupitskii, "Spectroscopic and mass-spectral studies of the expansion of a laser plasma into a rarefied gas," Kvantovaya Elektron. (Moscow), 16, No. 11 (1989).
4. Yu. P. Zakharov, A. M. Orishich, and A. G. Ponomarenko, Laser Plasma and Laboratory Modeling of Transient Cosmic Processes [in Russian], Inst. Teor. Prikl. Mekh., Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1988).
5. F. E. Irons and N. S. Peacock, "A spectroscopic study of the recombination of C^{+6} to C^{+5} in an expanding laser-produced plasma," J. Phys. B, 7, No. 15 (1974).
6. Yu. P. Zakharov, A. M. Orishich, A. G. Ponomarenko, and V. G. Posukh, "Experimental investigation of the efficiency of deceleration of an expanding cloud of diamagnetic plasma by a magnetic field," Fiz. Plazmy, 12, No. 10 (1986).
7. S. Takagi, S. Ohtani, K. Kadota, and J. Fujita, "Cross section for one-electron capture by highly stripped ions of Be, B and C from H and AR below 10 keV," J. Phys. Soc. Jpn., 52, No. 11 (1983).
8. L. M. Biberman, V. S. Vorob'ev, and I. T. Yakubov, Kinetics of Nonequilibrium Low-Temperature Plasmas [in Russian], Nauka, Moscow (1982).
9. S. R. Pottasch, Planetary Nebulae, D. Reidel, Dordrecht-Lancaster (1984).

STABLE REGIMES FOR A NONEQUILIBRIUM PULSED-PERIODIC DISCHARGE IN A STREAM OF MOLECULAR NITROGEN AT HIGH PRESSURE

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1. The requirements of laser technology and plasma chemistry have determined for a long time the increase in interest in studying nonequilibrium, high-pressure gas discharges in rapidly flowing systems. Now these studies are particularly important in view of development of the possibility of exciting the internal degrees of freedom of particles in electrodeless self-sustaining UHF discharges [1]. However, experiments show that with high specific energy contribution the electric strength of weakly ionized molecular gases is markedly reduced [2-4]. Applied to a nitrogen plasma this phenomenon may be caused by processes of associative ionization of electron-excited metastables $A^3\Sigma_u^+$ and $a'^1\Sigma_u^-$ (gas breakdown conditions taking account of these ionization processes and rapidly occurring reaction of extinction of the electron-excited state of molecules by unexcited molecules are found in [7]). It is assumed [3, 7] that processes of associative ionization stimulate development of ionization-heating instability with contraction of the plasma. According to [8] illumination of a gas by UV radiation (in order to maintain a self-sustaining discharge) may also lead to a marked reduction in the electric strength of a medium. In studying pumping regimes of oscillating levels of molecules apart from these reasons for instability of discharges "burning" in a stream, it is necessary to consider the possibility of arrival in the discharge region of gas dynamic disturbances which arise down the flow in an oscillating-excited gas (in the case of forming disturbances of the impact type under conditions of strong oscillating nonequilibrium this phenomenon may play a destabilizing role even in supersonic streams [9]). In the present work a theoretical study is made of the effect of excitation and deactivation processes for electron and oscillating levels of

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gas particles on the parameters of an electrodeless pulsed periodic UHF discharge in a stream of dense molecular nitrogen, and also the most stable pumping regimes are discussed for molecule oscillating degrees of freedom.

2. We consider unidimensional gas flow of N_2 molecules and impurity particles which occurs along axis x with velocity D. Let in the initial instant of time the gas throughout the whole space be in an equilibrium condition with temperature T_0 and pressure p_0. Then in the region $0 \leq x \leq x_1$ a uniform amplitude-modulated UHF field is switched on with intensity $E_m(t)\sin \omega t$ ($E_m(t)$ and ω are field amplitude and frequency). If at boundary x = 0 low nitrogen preionization is provided constantly, then in this region with $t > 0$ a nonequilibrium low-temperature plasma starts to form. For time $\Delta t \approx x_1/D$ passage of a macroscopic gas particle through the discharge region as a result of interaction of the field with the plasma provides the contribution of energy to heating the electron component and exciting the internal degrees of freedom of molecules. After interaction the nonequilibrium medium relaxes in region $x > x_1$.

Consideration of discharge phenomena will be carried out under conditions that $\nu_\varepsilon \ll \omega \ll \nu_p$ (ν_ε and ν_p are frequencies of energy realization and the pulse of electrons on collision with neutrons). Then kinetic coefficients of electrons are determined by the parameter E/n_2, where $E(t) = E_m(t)/\sqrt{2}$ and n_2 is concentration of N_2 molecules [10]. As a basis for the kinetic scheme of interaction of the electric field with preionized gas we take a kinetic scheme provided in [7] in which apart from processes of direct ionization of molecules by electrons there are processes of associative ionization caused by paired interactions of metastable electron-excited molecules N_2 ($A^3\Sigma_u^+$) and $N_2(a'^1\Sigma_u^-)$. Occupation of metastable levels occurs not only as a result of direct excitation of molecules by electrons, but also as a result of extinction processes for higher levels by nonexcited molecules. Complex ions N_4^+ play the main role in recombined breakdown of the plasma.

The kinetic discharge scheme supplemented by processes of excitation of oscillating levels and dissociation of molecules by electron shock is determined by the reactions:

$$N_2 + e \to N_2^+ + e + e; \tag{2.1}$$

$$N_2(A) + N_2(a') \begin{cases} \to N_4^+ + e \\ \to N_2^+ + N_2 + e; \end{cases} \tag{2.2}$$

$$N_2(a') + N_2(a') \begin{cases} \to N_4^+ + e \\ \to N_2^+ + N_2 + e; \end{cases} \tag{2.3}$$

$$N_4^+ + e \to N_2 + N_2; \tag{2.4}$$

$$N_2(X) + e \begin{cases} \to N_2(A) + e \\ \to N_2(B, W^3, B') + e; \\ \quad \overset{st}{\dashrightarrow} N_2(A) \end{cases} \tag{2.5}$$

$$N_2(a') + N_2(X) \to N_2(A) + N_2(X); \tag{2.6}$$

$$N_2(A) + N \to N_2(X) + N; \tag{2.7}$$

$$N_2(X) + e \begin{cases} \to N_2(a') + e \\ \to N_2(a, W^1, C, \ldots) + e; \\ \quad \overset{st}{\dashrightarrow} N_2(a') \end{cases} \tag{2.8}$$

$$N_2 + e \to N + N; \tag{2.9}$$

$$N + N + N_2 \to N_2 + N_2,$$

$$N_2(X, i) + e \rightleftarrows N_2(X, i') + e. \tag{2.10}$$

In order to reduce the entry for reactions electron states of molecules are labelled with a single letter. The content of N_2^+ and N_4^+ ions in the plasma is controlled by the processes $N_2^+ + N_2 + N_2 \rightleftarrows N_4^+ + N_2$, which with high gas pressure and low temperature occur more rapidly in the forward direction [11]. Therefore in our case N_2^+ ions in the plasma are almost absent and its ion composition is governed mainly by N_4^+ particles.

In stating the problem, introduction of an impurity component into the gas stream was specified. The necessity of its presence is dictated by the fact that in a number of cases it should prevent or slow down rapid production of electrons into the discharge which may start due to processes of associative ionization. As a stabilizing gas component CO molecules were taken which are hardly subject to destruction by electron impact. They do not affect the dynamics of the electron component of the plasma connected with processes of direct ionization; they comparatively and effectively extinguish excitation of $N_2(A^3\Sigma_u^+)$ (the extinction rate factor for the A level of a CO molecule is $K_e = 2.4 \times 10^{-11}$ cm^3/sec [12]), and consequently they reduce the role of reaction (2.2). Another advantage of using this impurity is the possibility of observing experimentally relaxation of nitrogen molecule oscillations [13] from its IR-radiation.

Pumping and relaxation of N_2 molecule oscillations will be considered within the scope of a model for level-by-level kinetics of anharmonic oscillators [14, Chap. 4]. Then taking this into account equations which describe discharge dynamics are presented in the form

$$\frac{\partial n_e}{\partial t} + \frac{\partial (n_e v)}{\partial x} = K_1 n_2 n_e + K_2 n_A n_{a'} + K_3 n_{a'}^2 - K_4 n_e^2, \tag{2.11}$$

$$\frac{\partial n_A}{\partial t} + \frac{\partial (n_A v)}{\partial x} = (K_5 n_e + K_6 n_{a'}) n_2 - (K_7 n + K_e n_{CO} + K_2 n_{a'}) n_A,$$

$$\frac{\partial n_{a'}}{\partial t} + \frac{\partial (n_{a'} v)}{\partial x} = K_8 n_2 n_e - (K_6 n_2 + K_2 n_A + 2K_3 n_{a'}) n_{a'},$$

$$\frac{\partial n}{\partial t} + \frac{\partial (nv)}{\partial x} = 2n_2 (K_9 n_e - K_{10} n^2),$$

$$\frac{\partial n_{CO}}{\partial t} + \frac{\partial (n_{CO} v)}{\partial x} = 0,$$

$$\frac{\partial n_{(i)}}{\partial t} + \frac{\partial (n_{(i)} v)}{\partial x} = \pi_{i(e)} + n_2 (\pi_{i+1} - \pi_i), \; i = 0, 1, \ldots, i_*,$$

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial}{\partial x}[(\varepsilon + p) v] = \eta_T \sigma E^2 - n_2 \sum_{i=1}^{i_*} E_i (\pi_{i+1} - \pi_i),$$

$$\frac{\partial (n_2 v)}{\partial t} + \frac{\partial}{\partial x}\left[\frac{p}{m} + n_2 v^2\right] = 0.$$

Here n_e, n_{CO}, n are concentration of electrons, CO molecules, and N atoms; n_A, $n_{a'}$ are concentrations of A- and a'-metastables; n(i) is concentration of nitrogen molecules in the i-th oscillating level of the main electron state; v is gas velocity; K_1, K_2, ..., K_{10} are rate constants for reactions (2.1)-(2.10);

$$\pi_{i(e)} = \begin{cases} -n_e \left(n_{(0)} \sum_{j=1}^{8} K_{0j} - \sum_{j=1}^{8} K_{j0} n_{(j)} \right), & i = 0, \\ n_e (K_{0i} n_{(0)} - K_{i0} n_{(i)}), & i = 1, 2, \ldots, 8, \\ 0, & i > 8; \end{cases}$$

K_{0i}, K_{i0} are rate constants for excitation and deexcitation of the i-th oscillating level by electron impact;

$$\pi_{i+1} = Z \left[P_{i+1,i} f_{i+1} - P_{i,i+1} f_i + \sum_{j=0}^{i_*} (Q_{i+1,i}^{j,j+1} f_{i+1} f_j - Q_{i,i+1}^{j+1,j} f_i f_{j+1}) \right];$$

Z is collision frequency of N_2 molecules; $f_i = n_{(i)}/n_2$; $P_{i,i+1}$, $P_{i+1,i}$ are the possibilities of molecule transitions $(i \to i+1)$ and $(i+1 \to i)$ on collision with another molecule; $Q_{i+1,i}^{j,j+1}$ and $Q_{i,i+1}^{j+1,j}$ are probabilities of VV exchanges $\binom{j \to j+1}{i+1 \to i}$ and $\binom{j+1 \to j}{i \to i+1}$ with collision of

two molecules, i_* is the number of the last considered oscillation level (determined from the condition of knowingly ignoring the VV and VT processes which relate to the region of oscillating quantum numbers $i > i_*$); E_i is excitation energy of the i-th oscillation level $\varepsilon = 0.5n_2(5kT + mv^2)$; m is mass of N_2 molecules; $p = n_2kT$; η_T is fraction of total energy contribution to the discharge going into direct heating of the gas by electrons; and σ is plasma conductivity.

The set of Eqs. (2.11) is intended not only for studying kinetic and gas dynamic phenomena in the discharge region, but also for relaxation characteristics of a nonequilibrium medium in the region $x > x_1$. Here to use it in the relaxation zone makes sense in the section $x_1 < x \leq x_2$, where oscillatory distribution of molecules forms mainly due to VV processes and transition of gas into a state with a quasistationary distribution of particles with respect to oscillation levels is accomplished. In region $x > x_2$ a study of oscillatory relaxation of anharmonic oscillators should be carried out within the scope of a simple and quite reliable model of quasistationary relaxation [14] (the question of its suitability for solving gas-dynamic problems is considered in [15], and corrections of its analytical equations are made there).

If now we consider that in the region $x < 0$ gas movement is adiabatic, then together with conditions $f_i(0, t) = f_0\exp[-E_i/kT(0, t)]$ and $S(x_2 + 0, t) = \frac{1}{\hbar\omega_0}\sum_{i=1}^{i_*} E_i f_i(x_2 - 0, t)$ relationships (2.11) and gas-dynamic equations for the quasistationary relaxation model [15] form a closed set of equations which make it possible to describe self-consistently an electric discharge in nonstationary streams of molecular nitrogen. They are solved by means of the method of numerical integration of hydrodynamic equations on Lagrangian coordinates, and also with the use of an algorithm for solving rigid systems of normal differential equations provided respectively in [16, 17].

According to [7] occupation of metastable levels $A^3\Sigma_u^+$ and $a'^1\Sigma_u^-$ by electron impact in dense gases occurs with effective rate factors: $K_5 = \sum_m K_m$ and $K_8 = \sum_l K_l$, where K_m are constants for excitation of a molecule by electrons of the main state in the states $A^3\Sigma_u^+$, $B^3\Pi_g$, $W^3\Delta_u$, $B'^3\Sigma_u^-$; K_ℓ are excitation constants for molecules by electrons in electron states $a'^1\Sigma_u^-$, $a^1\Pi_g$, $W^1\Delta_u$, etc. In order to determine the dependence K_1, K_5 and K_8 on parameters S and E/n_2 results in [18] are used, and for K_9 results in [19] are used. It is noted that with $E/n_2 \geq 4\cdot10^{-16}$ V·cm^2 and $S \lesssim 1.5$ the nature of oscillatory distribution of gas molecules has a weak effect on these dependences (for discussion of this question see [20]). Data for rate constants of reactions (2.4) and (2.10) are provided in [12, 21]. In solving the problem it was assumed that $K_3 = 4K_2 = 2\cdot10^{-10}$ cm^3/sec [6], $K_6 = 2\cdot10^{-13}$ cm^3/sec [22] and $K_7 = 5\cdot10^{-11}$ cm^3/sec [11]. Due to the smallness of extinction factors for level $A^3\Sigma_u^+$ by unexcited molecules [23] the corresponding losses of A metastables in Eqs. (2.11) were ignored. Expressions for probabilities of VV and VT transitions were taken from [14], and temperature dependences $P_{10}(T)$ and $Q_{10}^{01}(T)$ were taken respectively from [1 and 24]. Values of K_{0i} were found from approximations plotted on the basis of the calculated results in [5]. The dependence $\eta_T(E/n_2)$ was taken from [25].

3. According to [7] the increase in electron avalanche connected with associative ionization reactions (2.2) and (2.3) cannot be prevented by processes of electron–ion recombination. Calculations also showed that the rate of electron multiplication due to processes (2.2) and (2.3) is much higher in an oscillating-excited gas. This is explained by a marked increase in frequencies of occupation for levels $A^3\Sigma_u^+$ and $a'^1\Sigma_u^-$ with an increase in number S which characterizes the degree of oscillatory nonequilibrium of the gas [5]. As a rule an increase in the number of electrons coincides in time with the main energy contribution to the oscillatory degrees of freedom for nitrogen. Therefore transition of a discharge into an unstable state in certain cases (which relate for example to a UHF discharge maintained by electromagnetic waves) may lead to disruption of spatially uniform pumping regime of an oscillatory gas reservoir (due to displacement of the electric field from the greater part of the discharge volume).

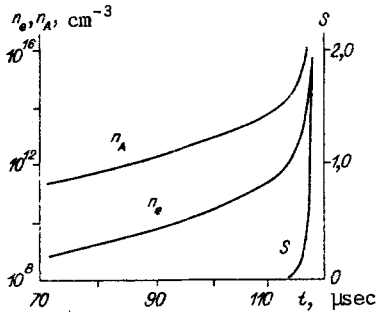

Fig. 1

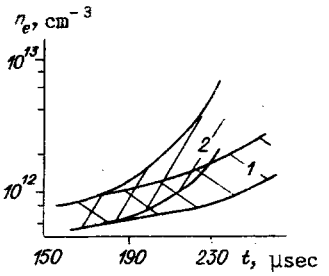

Fig. 2

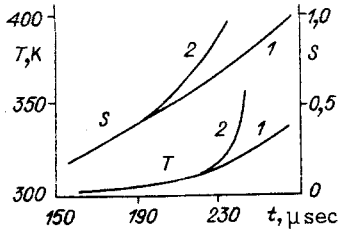

Fig. 3

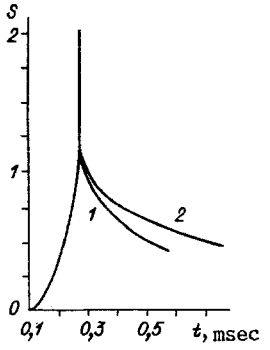

Fig. 4

In order to stabilize the process an addition of CO molecules is made to the gas. Here in all cases the value of n_{CO}/n_2 is assumed to be 10^{-2} (calculations showed that if $n_{CO}/n_2 \lesssim 10^{-2}$, then the effect of the addition on gas heating may be ignored). Shown in Fig. 1 is a typical picture of development of a single discharge in a field of constant amplitude. Equations (2.11) were solved with the conditions $n_2 = 10^{19}$ cm^{-3}, $E/n_2 = 7 \cdot 10^{-16}$ V·cm^2, $n_e(0) = 10^5$ cm^{-3}, $n_A(0) = n_{a'}(0) = 0$, $T(0) = 300$ K. It can be seen from the curves that up to the instant of time $t_0 \approx 100$ μsec the main mechanism for multiplication of electrons is an ionization for N_2 molecules by electron impact. In parallel there is accumulation of A metastables and an increase in the concentration of a'-metastables (by the rule $n_{a'} \approx K_8 n_e/K_6$). From instant $t_* \approx 115$ μsec an explosive increase starts in electron concentration. Investment of the energy field in oscillatory degrees of freedom occurs mainly in the associative-ionization phase of electron avalanche development. In illustrating this it is noted that the change-over of the system from a state with $S = 0.1$ to a state with $S = 1.0$ is accomplished after 115 μsec for about 1 μsec without gas heating ($\Delta T \approx 5$ K). This calculation (together with other calculations carried out for a broad range of values of parameter E/n_2) shows the impossibility of achieving a high degree of oscillatory gas in equilibrium with a constant electric field in the stable phase of the discharge.

We turn to a description of a discharge created by alternating pulses of a constant field with high and low amplitude. This field structure provides maintenance of the optimum average concentration of electrons by short pulses of high amplitude E_1 (lasting τ_1) and pumping of molecule oscillations in the recombined drop in electron concentration in a pulse of lower amplitude E_2 and lasting longer τ_2. In the calculation parameters of the periodic field were selected from the condition of greatest contribution of energy to oscillation in the stable phase of the discharge. Presented in Figs. 2 and 3 are the dependences $n_e(t)$, $S(t)$ and $T(t)$ found in isochoric and isobaric (lines 1 and 2) approximations for $E_1 = 9.5$ kV/cm, $\tau_1 = 100$ msec. $E_2 = 4.1$ kV/cm, $\tau_2 = 3$ μsec (solution of the equations was performed with the initial conditions adopted previously). The boundaries of the hatched regions in Fig. 2 are envelopes for function $n_e(t)$ which pass through points relating to values of electron concentration at instants of time for the end of short ionization pulses (upper boundaries) and values of electron concentration at instants of time for the end of long pumping pulses (lower boundaries).

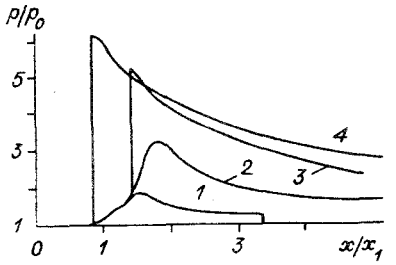

Fig. 5

It can be seen from Figs. 2 and 3 that in the case of isochoric discharge the value of S increases with time almost linearly, and in the range $0 \leq S \leq 1.5$ the increase in S accompanies a gradual increase in electron concentration to $\sim 10^{13}$ cm^{-3}. Thus, the strongly nonequilibrium pulsed-periodic discharge in question remains stable over a long period in relation to associative-ionization breakdown of the gas. In this case the main mechanism for breakaway of the stable pumping process for molecule oscillations becomes ionization-heating instability. According to Figs. 2 and 3 in an isobaric discharge this instability develops at instant $\tau_* \approx 230$ μsec when $S \approx 0.85$.

4. We analyze the stability of pumping regimes for nitrogen molecule oscillations by a pulsed-periodic discharge in uniform gas streams. In the initial instant of time parameters of the medium are as follows: $n_2(x, 0) = 10^{19}$ cm^{-3}, $T(x, 0) \equiv T_0 = 300$ K, $n_{CO}(x, 0) = 10^{17}$ cm^{-3}, $n_e(x, 0) \equiv n_{e0} = 10^5$ cm^{-3}. Parameters of the electric field operating in region $0 \leq x \leq x_1$ were taken the same as in the example broken down above. The size of the discharge region is selected so that macroscopic particles of uniform flow with different gas pumping rates occurs over the whole region of time τ close to τ_*. Apart from this in solving Eqs. (2.11) it was also considered that $n_e(0, t) = n_{e0}$ and $\tau = 255$ μsec.

Given in Fig. 4 for two pumping regimes with $D_1 = 0.5c_0$ and $D_2 = 1.1c_0$ (lines 1 and 2, c_0 is speed of sound in undisturbed flow) are dependences $S(x_1, t)$ which specify the dynamics of the pumping process for an oscillatory gas reservoir in the discharge. As can be seen, they are not uniform and they have clear maxima. Appearance of clear maxima is connected with development of ionization-heating instability of macroscopic gas particles which in the initial instant of time are close to the boundary $x = 0$. These maxima relate to a "fiber-like" spatial formation which carries the stream from the discharge region. It is noted that ultraviolet radiation of a "fiber" may lead to occurrence of a "supersonic" ionization wave propagating counter to the flow in a discharge region and transferring the discharge into a strongly nonuniform state [1].

Now cases are discussed when the intensity of the ultraviolet illumination is insufficient for stimulation of an ionization wave in the discharge region. If it is considered that with flow rates of $0.5c_0$ and $1.1c_0$ the relationship $v(x_1, t) < c(x_1, t)$ ($c(c_1, t)$ is speed of sound in the gas at the boundary $x = x_1$) is fulfilled, then the effect of a marked reduction in the level of pumping oscillations after transfer of a fiber from the discharge region becomes understandable (see Fig. 4). This reduction occurs due to gradual gas compression in the discharge region (and more accurately as a result of a reduction in parameter E/n_2) by disturbances which develop in the relaxation zone $x > x_1$.

The results of the calculation carried out for a stream moving with velocity $D_3 = 2c_0$ ($\tau = 270$ μsec) are of interest. In this version of the problem after transfer of the fiber from the discharge region at the exit steady-state flow is established with $S(x_1, t) = 0.9$. The possibility of realizing a stable steady-state regime of effective pumping of oscillations is governed here by the fact that small gas disturbances which arise in the relaxation zone are carried away by the flow. However, in region $x > x_1$ as a result of relaxation heating on the medium there is formation of a gas dynamic response in the form of a shock wave. By rapidly moving against the flow over an oscillating-excited gas (physics of the phenomenon are described in [9, 15]) the shock wave at instant of time $\tilde{t} = 3.32$ msec reaches boundary $x = x_1$ and then it starts to "extinguish" the discharge. Shown in Fig. 5 is the evolution of the gas dynamic response (pressure profiles 1-4 are given for $t = 0.86$; 1.56; 2.87; 3.7 msec respectively).

In conclusion it is noted that according to [26] in the example in question with $D \geq D_{c+} \cong 3.7c_0$ (D_{c+} is minimum steady-state weak-detonation flow rate) in a stream there should be formation of a steady-state pumping regime for molecule oscillations with $S(x_1, t) = 0.9$ and a relaxation zone of the impactless type.

LITERATURE CITED

1. G. M. Batanov, S. I. Gritsinin, et al., "UHF discharge of high pressure," Trudy FIAN SSSR, 160, 174 (1985).
2. N. A. Bogatov, S. V. Golubev, and V. G. Zorin, "Non-self-sustaining UHF discharge in a beam of electromagnetic waves," Lett. Zh. Tekh. Fiz., 10, No. 5 (1984).
3. S. I. Gritsinin, I. A. Kossyi, et al., "Non-self-sustaining UHF discharge in nitrogen at high pressure," Zh. Tekh. Fiz., 57, No. 4 (1987).
4. N. A. Bogatov, M. S. Gitlin, et al., "Experimental study of the stability of a non-self-sustaining UHF discharge," Zh. Tekh. Fiz., 57, No. 1 (1987).
5. H. Brunet, P. Vincent, and J. Rocca-Serra, "Ionization mechanism in a nitrogen glow discharge," J. Appl. Phys., 54, No. 9 (1983).
6. H. Brunet and J. Rocca-Serra, "Model for a glow discharge in flowing nitrogen," J. Appl. Phys., 57, No. 5 (1985).
7. B. P. Silakov, "Effect of processes of associative ionization of electron-excited metastables on the electric strength of weakly ionized molecular nitrogen at high pressure," Fiz. Plazmy, 14, No. 10 (1988).
8. M. G. Zhabitskii and V. P. Silakov, "Effect of ultraviolet radiation on the dynamics of a pulsed electric discharge in high pressure molecular nitrogen," Fiz. Plazmy, 15, No. 10 (1989).
9. A. A. Rukhadze, V. P. Silakov, and A. V. Chebotarev, "Spatial nonstationary shock waves in oscillating-excited nitrogen," Ktratk. Soobshch. Fiz., No. 6 (1983).
10. N. A. Dyatko, I. V. Kochetov, and A. P. Napartovich, "Effect of inertia of the energy distribution of electrons on the ionization frequency in weakly ionized plasma of an HF discharge," Fiz. Plazmy, 11, No. 6 (1985).
11. L. S. Polak, P. A. Sergeev, and D. I. Slovetskii, "Formation of complex atomic ions in a glow discharge in nitrogen," in: Plasma Chemistry Reactions and Processes [in Russian], INKhS, Akad. Nauk SSSR, Moscow (1977).
12. D. I. Slovetskii, Mechanisms of Chemical Reactions in a Nonequilibrium Plasma [in Russian], Nauka (1980).
13. S. I. Gritsinin, I. A. Kossyi, et al., "Dynamics of oscillatory excitation and heating of nitrogen during and after a pulsed UHF discharge," Teplofiz. Vys. Temp., 22, No. 4 (1984).
14. B. F. Gordiets, A. I. Osipov, and L. A. Shelepin, Kinetic Processes in Gases and Molecular Lasers [in Russian], Nauka, Moscow (1980).
15. V. P. Silakov and A. V. Chebotarev, "Quasistationary relaxation and gas dynamic phenomena in a single component system of excited anharmonic oscillators," Zh. Prikl. Fiz., No. 6 (1987).
16. A. A. Samarskii, Computation Methods in Mathematical Physics [in Russian], Izd. Mosk. Gos. Univ., Moscow (1986).
17. A. Yu. Zakharov and V. I. Turchaninov, "STIFF-program for solving rigid systems of normal differential equations," Istruktsiya IPM Akad. Nauk SSSR (1977).
18. I. V. Kochetov, V. G. Pevkov, et al., "Rates of processes initiated by electron impact in a nonequilibrium plasma. Molecular nitrogen and carbon dioxide," in: Plasma Chemistry Processes [in Russian], INKhS Akad. Nauk SSSR, Moscow (1979).
19. N. L. Aleksandrov, A. M. Konchakov, and É. E. Son, "Functions of electron distribution and kinetic coefficients for a nitrogen plasma," Fiz. Plazmy, 4, No. 5 (1978).
20. M. G. Zhabitskii and V. P. Silakov, "Dependence of kinetic electron coefficients in a low-temperature nitrogen plasma on the degree of oscillatory instability of the molecular component," Khim. Vys. Énerg., 24, No. 2 (1990).
21. B. M. Smirnov, Complex Ions [in Russian], Nauka, Moscow (1983).
22. J. W. Dreyer and D. Perner, "The deactivation of $N_2(B^3\Pi_g)$," J. Phys. Chem., 84, No. 18 (1980).
23. W. G. Clark and D. W. Setser, "Energy transfer reactions of $Na(A^3\Sigma_u+)$," J. Phys. Chem., 84, No. 18 (1980).
24. S. I. Valyanskii, K. E. Vereshchagin, et al., "Measurement of velocity constants for a VV volume in nitrogen with biharmonic excitation," Kvantovaya Élektron., 11, No. 9 (1984).

25. N. A. Dyatko, I. V. Kochetov, et al., "Effect of the ionization proess on kinetic coefficients in a low-temperature plasma," Preprint IAE No. 3842/12, Moscow (1983).
26. V. P. Silakov and A. V. Chebotarev, "Steady-state flow of an oscillating-excited gas of biatomic molecules," Prikl. Mekh. Tekh. Fiz., No. 5 (1986).

CONTRACTED DISCHARGE IN THE PRESENCE OF BOUNDARY LAYERS IN A SUPERSONIC PLASMA FLOW IN A CHANNEL

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This paper reports the results of an experimental study of the processes near the electrodes when a contracted discharge occurs in a pulsed supersonic channel. An analysis of the current-voltage characteristics and photoscans of the glow of the electrodes surfaces showed that in a pulsed supersonic argon plasma flow the resistance of the regions near the electrodes for divisible spots is lower than in the case of peripheral arc clamping. Then a decrease in the Mach number M_1 and the approach to a shock wave (in the zone of ionization relaxation) cause the current-voltage characteristics to shift to the right, i.e., to the region of a higher voltage drop between electrodes.

One of the simplest and most universal methods of studying the properties of an electric discharge in boundary layers is that of determining the current-voltage characteristics. When used in conjunction with a photoscan study of the discharge glow at the electrodes, depending on the state of the electrode surfaces and on the gasdynamic and thermophysical properties of the plasma in the channel, this method makes it possible to find more optimum operating conditions for the electrode walls of a pulsed cold-electrode MHD generator. The studies are complicated by the following: the existence of a boundary layer which moves relative to the electrodes and a longitudinal inhomogeneity of the initial portions of the gasdynamic plug because of ionization relaxation and the variation of the effective cross section of the gas flow behind the shock wave as boundary layers grow on the channel walls. The boundary layer can shorten the ionization relaxation to different degrees for laminar and turbulent layers [1, 2]. By the criteria of [2] the boundary layer is completely laminar provided that $p_1 d \leq 1.63 \cdot 10^3$ Pa·cm (d is the gasdynamic diameter of the tube and p_1 is the initial pressure in the chamber), while at $p_1 d \geq 16.3 \cdot 10^3$ Pa·cm the boundary layer becomes virtually turbulent along the entire length of the plug. In all other cases the nature of the boundary layer is determined only experimentally because of the lack of any theoretical model. The coordinates of the laminar-turbulent transition of the boundary layer depends on the critical Reynolds number [3]

$$\mathrm{Re}_{cr} = \rho \frac{(u_s - u_2)^2 X}{u_2 \mu_2},$$

where ρ, μ_2, and u_2 are the density, dynamic viscosity, and velocity of the flow in the coordinate system bound to the shock front, and u_s is the velocity of the shock-wave front in the laboratory coordinate system.

The time of the laminar-turbulent transition of the boundary layer is determined with a short-lag thermal resistance sensor, consisting of a thin metal film (platinum) deposited on a glass substrate [4].

Knowledge of the ionization relaxation zone makes it possible to isolate the region of shock-heated gas with an equilibrium electron concentration. The zone was calculated in the one-dimensional and quasi-one-dimensional (in the case of a turbulent boundary layer) approximations in the range of shock-wave Mach numbers M_1 = 8-12 over a wide range of p_1. The

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