LITERATURE CITED

1. V. M. Ievlev, "Some results on investigation of a gas-phase, cavity-type nuclear reactor," Izv. Akad. Nauk SSSR, Energ. Transp., No. 6 (1977).
2. V. M. Ievlev (ed.), Thermophysical Properties of the Working Media of a Gas-Phase Nuclear Reactor [in Russian], Atomizdat, Moscow (1980).
3. G. A. Pavlov, "Transfer coefficients of a plasma with strong Coulomb interaction," Zh. Tekh. Fiz., No. 5 (1984).
4. V. I. Kucherenko and G. A. Pavlov, "Calculation of the effective coefficients of thermodiffusion of a nonideal multielement plasma," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1978).
5. G. A. Korn and T. M. Korn, Manual of Mathematics, McGraw-Hill, New York (1967).
6. A. A. Shiryaev and G. A. Pavlov, "Hypersonic flow over a spherical probe in the atmosphere of Jupiter," Preprint Ob'ed. Inst. Khim. Fiz. Akad. Nauk SSSR (1982).
7. G. A. Pavlov and A. A. Shiryaev, "Dissipative structures in a plasma with volumetric heat release," Pis'ma Zh. Tekh. Fiz., 9, No. 21 (1983).
8. A. I. Vol'pert and R. S. Tishakova, "Positive solutions of the second boundary-value Problem for quasilinear parabolic equations," Preprint Ob'ed. Inst. Khim. Fiz. Akad. Nauk SSSR (1981).
9. P. K. Gupta and A. R. Cooper, "The [D]-matrix for multicomponent diffusion," Physica, 54, No. 1 (1971).

SUPERHEATED-IONIZATION INSTABILITY OF AN EXTERNALLY MAINTAINED DISCHARGE

N. M. Maslennikov

UDC 537.525

A large number of papers have been devoted to instabilities of an externally maintained discharge, which is quite proper, since they limit the maximum current and voltage on the discharge gap. Instabilities are initiated by processes both in the cathode region and in the volume of the discharge gap. The experimental results presented in [1-3] can serve as an example of the latter case. Typical current oscillograms illustrating the development of instability in nitrogen in a pulsed regime are presented in Fig. 1, based on data of these papers. The higher the voltage U on the discharge gap, the greater the current density j of the discharge and the smaller the time τ of development of instability. The interpretation of these experiments has undergone considerable changes in recent years. The authors of [1-3] initially eliminated the possibility of gas heating during the action of the voltage pulse, since it was assumed that the Joule energy released in the volume of the discharge gap goes almost entirely into the excitation of vibrational degrees of freedom of nitrogen molecules, while the observed instability was explained by step-by-step ionization. After the publication of [4, 5], it was recognized in [6] that a certain fraction of the Joule energy is indeed expended on heating of the nitrogen.

The authors of [7] also came to the conclusion that under the experimental conditions of [1] instability can develop only through step-by-step ionization, and the calculated and measured times of development of instability are close for $E/N > 3.5 \cdot 10^{-16}$ V·cm^2. The considerable discrepancies at lower values of the ratio E/N were explained by neglect of the field nonuniformity.

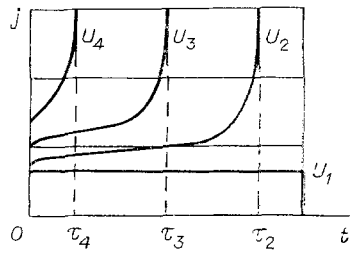

Fig. 1

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 25-28, May-June, 1985. Original article submitted February 28, 1984.

 0021-8944/85/2603-0322$09.50

TABLE 1

U, kV	5	7	9	11	5	7	9	11	3,7	6,5
j_b, $\mu A/cm^2$		13,5				31,5			900	
q_e, $cm^{-3} \cdot sec^{-1}$		$1,3 \cdot 10^{16}$				$3 \cdot 10^{16}$			$8,6 \cdot 10^{17}$	
j_{av}, A/cm^2	0,24	0,31	0,33	0,41	0,4	0,6	0,8	0,8	3,2	4,8
E/N_0, 10^{-16} V·cm^2	1,0	1,5	2	2,5	1,1	1,6	2,1	2,6	0,7	1,2
E/N_1, 10^{-16} V·cm^2	4,5	4,5	4,5	4,4	5,1	4,5	4,5	4,5	5,9	5,7
τ_{exp}, μsec	975	320	205	65	650	245	100	55	300	100
τ_{cal}, μsec, $\eta_T = 1,0$	900	340	170	80	610	155	65	35	145	45
τ_{cal}, μsec, $\eta_T = 0,7$	1300	500	240	120	800	215	90	50	215	55
t_g, °C	1000	600	400	250	1000	600	370	250	2050	1150

In [8] a large number of elementary processes were taken into account, and the authors made up for the absence of experimental data on the values of many constants by varying them within wide limits. For the coefficient of recombination they took a value 10 times smaller than that usually adopted in calculations. As a result of very laborious calculations it was concluded that the proposed model agrees well with experimental data and that the time of development of instability can be determined by either associative or step-by-step ionization, depending on the concrete conditions.

It should be noted that associative ionization was observed at pressures of 80-800 Pa in [9]. It is risky to transfer these results to the region of higher pressures, especially since its action was not manifested at all in [10].

Such a variety of views on the interpretation of the same results can be explained by the inconsistency of data on the rate constant of vibrational–translational (VT) relaxation. Thus, according to [11, 12], at T = 300°K this constant equals $1.02 \cdot 10^{-20}$ and $1.5 \cdot 10^{-18}$ cm^3/sec, respectively. In [11] the measurement chamber and the piping system were heated to 100°C, evacuated to a pressure of $7 \cdot 10^{-3}$ Pa, and only then filled with nitrogen from which the water vapor was preliminarily frozen out. The optical pumping and the high nitrogen pressure, exceeding 1000 kPa, assured a water vapor content of less than 10^{-5}%. As a result, the rate constant was measured under ideally pure conditions. A pulsed discharge at a pressure of 30 kPa was used for pumping in [12]. The flow of the discharge current was evidently accompanied by gas release from the electrodes, as a result of which the rate constant proved to be almost two orders of magnitude higher than in [11]. Unusually rapid heating of nitrogen in a gas stream at atmospheric pressure was noted in a quasisteady discharge [13].

It is well known that impurities, especially water vapor, have a major influence on the rate of relaxation processes in nitrogen. On the basis of the data of [14, 15] it can be concluded that the addition of 0.05% water vapor to pure nitrogen increases the rate constant by five orders of magnitude.

In [1-3] no measures were taken to eliminate the entry of water vapor and reduce gas release from the equipment. Both extra pure [1, 2] and technically pure nitrogen [3] were used. Under such conditions the rate of VT relaxation can be rather high, and the fraction of Joule energy η_T expended on gas heating is close to one.

The most complicated theoretical constructs were developed in the papers cited above to explain the observed phenomena, while due attention was not paid to a relatively simple one, which is connected primarily with underestimating the possibility of nitrogen heating in the actual installations of the type of [1-3].

According to [16], the superheated-ionization instability is the most widespread, one can say universal. Therefore, we made the calculation with allowance for heating of the gas, the decrease in its density and the rate of externally maintained ionization, and the increase in the velocity of electron drift and the rate of self-maintained (direct) ionization.

From the relation

$$j/j_0 = \frac{n_e}{n_{e0}} \frac{v_e}{v_{e0}} = \sqrt{\frac{q}{q_0} \frac{\beta_0}{\beta}} \frac{v_e}{v_{e0}}$$

we determined the variation of the relative current density.

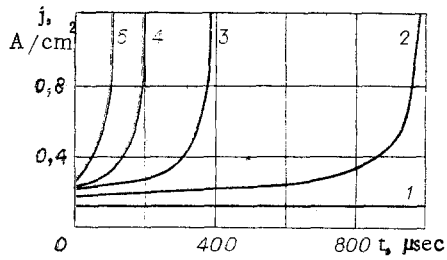

Fig. 2

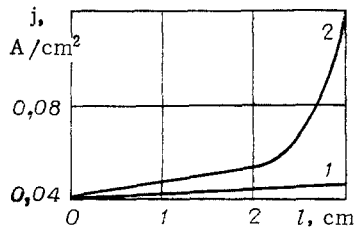

Fig. 3

Here n_e and v_e are the electron density and drift velocity; q is the total rate of externally maintained (q_e) and self-maintained (q_s) ionization; β is the coefficient of recombination; the index 0 denotes the initial value of the respective parameters; $\beta_0/\beta \approx 1$, since the coefficient of recombination in nitrogen hardly varies in the investigated range of values of the ratio E/N [17].

The gas temperature and the electron density were calculated from the usual equations

$$\frac{1}{T}\frac{dT}{dt} = \frac{\gamma - 1}{\gamma}\frac{jE}{p}\eta_T, \quad \frac{dn_e}{dt} = q - \beta n_e^2,$$

where E is the electric field strength; p is the gas pressure; γ is the adiabatic index; η_T is the fraction of Joule energy expended on gas heating. The initial value of the current density was taken from the experimental data of [1, 3].

The Townsend ionization coefficient, required to calculate the rate of self-maintained ionization, was determined from the equation [18]

$$\alpha/N = 1.17 \cdot 10^{10} \exp\left(+7.5 \cdot 10^{-18} E/N\right).$$

As the calculated time of development of instability we took the time during which the initial current density increased by a factor of e. As was shown in [2], during this time the current density grows uniformly over the entire cross section of the discharge gap, i.e., the instability has a volumetric character.

The results of the calculation are presented in Table 1, where j_{av} is the discharge current density averaged over a pulse; E/N_0 and E/N_1 are the ratio E/N at the start of action of the voltage pulse and at the time of development of instability; τ is the time of development of instability; t_g is the calculated gas temperature corresponding to the time τ. The calculated time dependence of the discharge current density in nitrogen at a pressure of 100 kPa and an electron-beam current density j_b = 13.5 μA/cm² is plotted in Fig. 2 for voltages of 3, 5, 7, 9, and 11 kV (curves 1-5, respectively).

The calculation was made for η_T = 1.0 and 0.7, when the calculated data are in satisfactory agreement with the experimental data for j_b = 13.5 and 31.5 μA/cm², respectively. In [19] it is also assumed that η_T = 1.0.

The calculation and the functions presented in Fig. 2 showed the following. For U = 3 kV the power released is small, and during the action of a voltage pulse t_p = 1000 μsec the gas is heated to only 200°C. As the gas is heated the rate of externally maintained ionization and the electron density decreases, while the electron drift velocity increases, compensating for the decrease in n_e. Therefore, the current density hardly changes.

For U = 5 kV the gas is heated more strongly, the ratio E/N grows, and the action of self-maintained ionization starts to be felt. This results in the fact that the current density gradually increases over 700 μsec. By the time t = 800 μsec, q_s starts to exceed q_e and the current grows sharply. By the time t = 900 μsec, q_s exceeds q_e about threefold.

The higher the voltage, the larger q_s, the more steeply the current grows, and the earlier the instability sets in.

For $\eta_T < 0.4$ the rise of the calculated discharge current proves to be insignificant and differs considerably from the corresponding experimental data.

These data correspond to the condition for the development of instability formulated in [16]: at the current when the externally maintained discharge approaches a self-maintained discharge.

The conformity of the calculated functions and the oscillograms of the discharge current and the conformity of the experimentally measured and calculated times of development of instability in a wide range of variation of the parameters indicates that such a mechanism is possible under actual conditions.

A superheated-ionization instability can also occur in a steady discharge. In Fig. 3, for the experimental conditions of [20], we show the calculated variation of the discharge current density in the direction of the gas stream with $\eta_T = 1$ for the central region (curve 1), where the stream velocity equals the average-mass velocity, and for the peripheral region (the boundary layer along the insulated wall), where the velocity is taken as one third the average-mass velocity (curve 2). In the central region the gas is little heated, the ratio E/N is small, $q_s \ll q_e$, and the current density varies insignificantly in the direction of the gas stream. In the peripheral region the gas is heated so much that the action of self-maintained ionization is felt, as a result of which the current density grows sharply at the end of the discharge gap and instability develops. The increased energy release in the boundary layer leads to the fact that the stream velocity grows more slowly in it than in the main volume of the discharge gap. Therefore, the specific applied energy decreases with an overall increase in the stream velocity.

Increased energy release can also occur due to the higher discharge current density where the local current density of electron emission from the cathode is greater.

The author thanks E. K. Eroshchenkov and V. V. Chulkov for useful discussions.

LITERATURE CITED

1. L. P. Menakhin, E. K. Eroshchenkov, and K. N. Ul'yanov, "Current instability in molecular gases," Zh. Tekh. Fiz., 45, No. 6 (1975).
2. E. K. Eroshchenkov, I. O. Sibiryak, and K. N. Ul'yanov, "Instability of an externally maintained glow discharge," Pis'ma Zh. Tekh. Fiz., 2, No. 10 (1976).
3. A. A. Kostylev, Ya. I. Londer, et al., "An experimental investigation of the electrical and power characteristics of a pulsed, externally maintained flow discharge," Zh. Tekh. Fiz., 47, No. 11 (1977).
4. A. P. Napartovich, V. G. Naumov, and V. M. Shashkov, "Gas heating in a combined discharge in a nitrogen stream," Dokl. Akad. Nauk SSSR, 232, No. 3 (1977).
5. V. Yu. Baranov, F. I. Vysikailo, et al., "Contraction of the decaying plasma of a discharge in nitrogen," Fiz. Plazmy, 4, No. 2 (1978).
6. Ya. I. Londer, L. P. Menakhin, et al., "Efficiency of excitation of rotational states of the nitrogen molecule," Zh. Tekh. Fiz., 49, No. 11 (1979).
7. F. I. Vysikailo, A. P. Napartovich, and É. E. Son, "Stability of an externally maintained glow discharge in pure nitrogen," Fiz. Plazmy, 4, No. 6 (1978).
8. K. V. Baiadze, V. M. Vetsko, et al., "Influence of vibrationally excited particles on the stability of an externally maintained discharge in molecular gases," Dokl. Akad. Nauk SSSR, 249, No. 4 (1979).
9. L. S. Polak, P. A. Sergeev, and D. I. Slovetskii, "Mechanism of nitrogen ionization in a glow discharge," Teplofiz. Vys. Temp., 15, No. 1 (1977).
10. S. M. Kurkin and V. M. Shashkov, "Role of associative ionization in the mechanism of instability of a glow discharge in nitrogen," Zh. Tekh. Fiz., 53, No. 5 (1983).
11. M. A. Kovacs and M. E. Mack, "Vibrational relaxation measurements using "transient" stimulated Raman scattering," Appl. Phys. Lett., 20, No. 12 (1972).
12. Yu. S. Akishev, A. V. Dem'yanov, et al., "Determination of the constants of vibrational exchange in N_2 from gas heating," Teplofiz. Vys. Temp., 20, No. 5 (1982).
13. I. G. Persiantsev, "A quasisteady gas discharge at atmospheric pressure with ionization by an electron beam," Author's abstract of dissertation for degree of physicomathematical sciences, Nauchno-Issled. Inst. Yad. Fiz., Mosk. Gos. Univ., Moscow (1974).
14. P. W. Huber and A. Kantrowitz, "Heat-capacity lag measurements in various gases," J. Chem. Phys., 15, No. 5 (1947).
15. R. L. Taylor and S. Bitterman, "Survey of vibrational relaxation data for processes important in the CO_2–N_2 laser system," Rev. Mod. Phys., 41, No. 1 (1969).
16. Yu. P. Raizer, Principles of the Modern Physics of Gas-Discharge Processes [in Russian], Nauka, Moscow (1979).
17. V. Yu. Baranov, R. K. Bevov, et al., "Influence of water vapor on an externally maintained gas discharge," Teplofiz. Vys. Temp., 20, No. 6 (1982).

18. V. L. Granovskii, Electric Current in a Gas [in Russian], Nauka, Moscow (1971).
19. I. P. Koroleva, A. P. Napartovich, and A. N. Starostin, "Peculiarities of the spatial–temporal evolution of a superheated-ionization instability," Fiz. Plazmy, 8, No. 3 (1982).
20. N. M. Maslennikov, "An externally maintained discharge in a nitrogen stream," Zh. Tekh. Fiz., 48, No. 4 (1978).

NONEQUILIBRIUM ROTATIONAL DISTRIBUTION FUNCTION FOR D_2O MOLECULES IN A RAREFIED SUPERSONIC JET

S. S. Bakastov, V. K. Konyukhov, and V. I. Tikhonov

UDC 533.6.011.8

An ever increasing interest in the study of rotational relaxation of polar molecules in a gaseous medium has recently been observed. For example, chemical lasers have elicited a series of theoretical and experimental papers on the rotational relaxation of HF molecules [1, 2]. For polyatomic molecules there also exist interesting and important problems, the solution of which requires an understanding of the laws of rotational relaxation. They include the behavior of water vapor in the upper layers of the atmosphere, the creation of gas-dynamic lasers (GDL) based on rotational transitions of molecules in the submillimeter range, clarification of the mechanism of action of masers, etc. The complexity of the rotational spectra of polyatomic molecules hinders the theoretical description of relaxation processes and the interpretation of experimental results, so that there are far fewer papers on rotational relaxation of polyatomic molecules than for diatomic molecules. There now exist models permitting a satisfactory description of the processes connected with rotational relaxation of molecules, such as the Polany–Woodall model [3]. There is an absence of such simple and convenient models for polyatomic molecules of the asymmetric-top type.

Rotational relaxation of the D_2O molecule in a rarefied supersonic argon jet was investigated in the present work. This was done earlier for diatomic, polyatomic, and linear molecules and molecules of the symmetric-top type [4, 5], while for molecules of the asymmetric-top type it is being done for the first time. The purpose of the work was to investigate the nonequilibrium distribution of molecules over the rotational levels during rapid cooling in a supersonic argon jet by the spectroscopic method and to construct a simple model permitting a satisfactory description of the populations of the rotational levels.

As the subject of observation we used a plane, supersonic argon jet with a small (less than 1%) admixture of D_2O vapor (Fig. 1). At such a concentration one can assume that relaxation takes place mainly due to D_2O–Ar collisions, and neglect D_2O–D_2O collisions. The difference in the populations of rotational levels connected with a radiative transition was measured by the method of submillimeter spectroscopy. A backward-wave tube (BWT) served as the radiation source. The probe beam was formed with Teflon lenses L_1 and L_2, passed through a polaroid P and a modulator M, intersected the jet, confined by Teflon walls, and was picked up by a gallium receiver through the lens L_3.

The initial gas pressure and temperature were 266 Pa and 293°K, respectively. The parameters of gas flow in the supersonic region were calculated by Skovorodko by the method of natural coordinates described in [6] for the case of the flow of a monatomic gas from a plane slot with a height of 0.72 cm. The calculated gas temperature in the measurement region was 65 ± 5°K. Conformity between the calculated and actual parameters of the gas stream was verified by measuring the pressure with a Pitot tube. The departure of the measured from the calculated pressure was 4% for the central streamline.

Teflon walls were set up to avoid expansion along the coordinate parallel to the slot. Boundary layers developed in the gas flow at the walls, and absorption in them could result in errors in the measurements. However, the temperature in the boundary layer is close to the stagnation temperature, and hence five times higher than the temperature of the main stream, so that the density in it is five times lower. The measurements were made for low rotational transitions, for which absorption decreases strongly with an increase in tempera-

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 28-36, May-June, 1985. Original article submitted March 15, 1984.

 0021-8944/85/2603-0326$09.50