Letter to the Editor

SELFCONSISTENT STATIONARY SOLUTION OF THE ELECTRON BOLTZMANN EQUATION AND OF THE VIBRATIONAL STATE RATE EQUATION IN A NITROGEN DC DISCHARGE[1]

САМОСОГЛАСОВАННОЕ СТАЦИОНАРНОЕ РЕШЕНИЕ УРАВНЕНИЯ БОЛЬЦМАНА ДЛЯ ЭЛЕКТРОНОВ И УРАВНЕНИЯ СКОРОСТИ ОБРАЗОВАНИЯ КОЛЕБАТЕЛЬНЫХ СОСТОЯНИЙ ДЛЯ РАЗРЯДА ПОСТОЯННОГО ТОКА В АЗОТЕ

K. ROHLENA[2], K. MAŠEK[2], Praha

The Boltzmann equation was solved simultaneously with the set of 48 rate equations governing the vibrational levels of the nitrogen ground state. The 7 lowest vibrational levels are fed by electron collisions. The wall recombination returning the molecules to the lowest vibrational level helps to establish a stationary distribution.

In a wide region of the self-sustained discharge operation the similarity laws [1] guarantee the full description of the discharge plasma (in a monocomponent gas) by means of two independent parameters only (e.g. $n_g R$, I/R in a cylindrical tube). If thus more parameters enter the electron Boltzmann equation the distribution function can no longer be made independent of the unknown quantities (e.g. particle concentrations) and the problem of the discharge analysis must be solved simultaneously. This is, in particular, the case of molecular gases, where the population of the vibrational levels may essentially influence the electron distribution itself. The first calculations in this direction have been performed by Capitelli and co-workers [2—9], who solved the time problem: time evolution of the vibrationally excited state populations with the simultaneous solution of the (stationary) Boltzmann equation. In the present contribution the discharge steady state is examined on the basis of a simultaneous solution of the electron Boltzmann equation and of the vibrational rate equations of the N_2 electronic ground state.

The electron Boltzmann equation is taken in its usual two-component form and it is simplified for the case of one-dimensional homogeneous plasma. It, however, includes the inelastic and superelastic transitions between the 7 lowest vibrational levels together with 7 electronic inelastic transitions. The cross-section scheme and the denotation is identical with that presented in [10].

$$E_z^2 \frac{d}{dU}\left(U \frac{df_0/dU}{n_g Q_d + \sum_i n_i Q_{il}}\right) - n_g \frac{6m}{M_g}\frac{d}{dU}(U^2 Q_d f_0) +$$

$$+ \sum_f 3n_i [UQ_{if}(U) f_0(U) - (U + U_f - U_i) Q_{fi}(U + U_f - U_i) \times$$
$$\times f_0(U + U_f - U_i)] = 0. \quad (1)$$

The 49 vibrational rate equations have the same structure as used, e.g., in [11] or [12], with the electronic source term (collisional excitation of the vibrational levels) now given by the pertinent integrals over the electron distribution function, which is found as a solution of (1). The vibrational rate equations are thus of the type

$$n_u [P_{v+1u, v}^{V-T} n_{u+1} - (P_{vu+1}^{V-T} + P_{vu-1}^{V-T}) n_u + P_{v-1u}^{V-T} n_{u-1}] +$$

$$+ \sum_{w=0}^{v} [P_{v+1u, w-1u, w}^{V-V} n_{u+1} n_{w-1} - (P_{vu+1, ww'}^{V-V} + P_{vu-1, ww+1}^{V-V}) n_u n_w + P_{v-1u, w+1u, w}^{V-V} n_{u-1} n_{w+1}]$$

$$+ \sum_{w=0}^{v} n (S_{wv}^{EI} n_w - S_{vv}^{EI} n_v) = 0. \quad (2)$$

The principal terms are the electronic excitation (and depopulation) of the examined vibrational level v (S_{vw}^{EI} collisional integrals), the $V - T$ transitions (P_{vu}^{V-T} is the transitional probability) and finally the $V - V$ transitions ($P_{vw, vw'}^{V-V}$). The last process, owing to the convergence of the vibrational levels for high
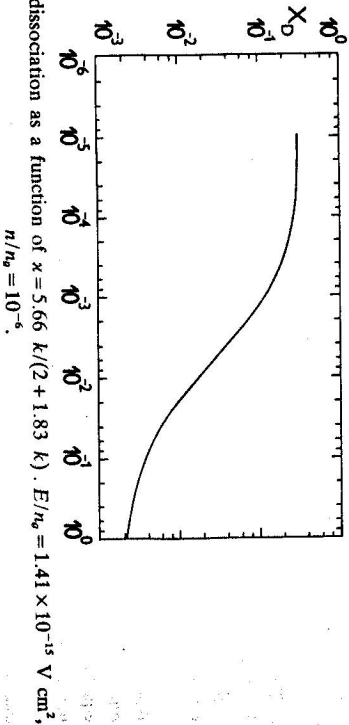
Fig. 1. Fractional dissociation as a function of $x = 5.66 \, k/(2 + 1.83 \, k)$. $E/n_g = 1.41 \times 10^{-15}$ V cm², $n/n_g = 10^{-6}$.
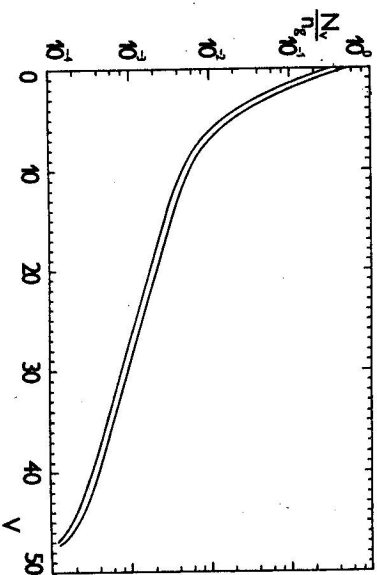
Fig. 2. Distribution of the vibrational levels in dependence on two values of the wall reflection coefficient: upper curve $k = 5.22 \times 10^{-1}$, lower curve $k = 3.54 \times 10^{-5}$, $E/n_g = 1.41 \times 10^{-15}$ V cm², $n/n_g = 10^{-6}$.

vibrational quantum numbers v, is responsible for the "ladder mechanism" of the dissociation, which in case of N_2 is the leading one, as opposed to the direct collisional dissociation [4]. The correctness of the system (2) was tested in the following two ways: firstly the electronic terms were omitted and the solution was then found to be a Boltzmann distribution of the excited molecules over the entire vibrational states at the neutral gas temperature. The second test consisted in the solution of the rate equations (2) with the "ladder mechanism". As the dissociation is then irreversible (no recombination mechanism has so far been included) the steady state solution is represented by a fully dissociated gas, which results from the model irreversibility. To obtain a more realistic steady state solution the rate equations (2) were supplemented by a wall recombination term, which returns the N_2 molecules in the lowest vibrational level. The wall recombination rate depends on the quality of the wall surface. We therefore regarded the recombination coefficient k as an independent quantity and produced the curves of the dissociation degree in dependence on that parameter. In the present version the rate equation system still entails a parametrical dependence on the reduced field E/n_g, ionization degree n/n_g, the neutral gas temperature T_g and the $n_g R$ (discharge tube radius). The curves of the dissociation degree are thus for fixed $n_g R = 3.54 \times 10^{16}$ cm^{-2} and $T_g = 300$ K still parametrized by E/n_g and n/n_g. The dissociation degree increases with decreasing wall recombination, the steepest dependence occurring in the interval corresponding to a transition from the reflection limited to the diffusion limited recombination rate, Fig. 1. As by-products of the calculations the distribution of the vibrational levels (Fig. 2) and the electron distribution function (Fig. 3) are obtained. While it is understandable that especially for the high field values the dependence of the electron distribution function on the vibrational population is weak as most of the energy is pumped into the electronic levels [10], it is rather remarkable, as a preliminary mapping of the parametric dependence suggests, that the field value influences the vibrational level distribution only slightly.
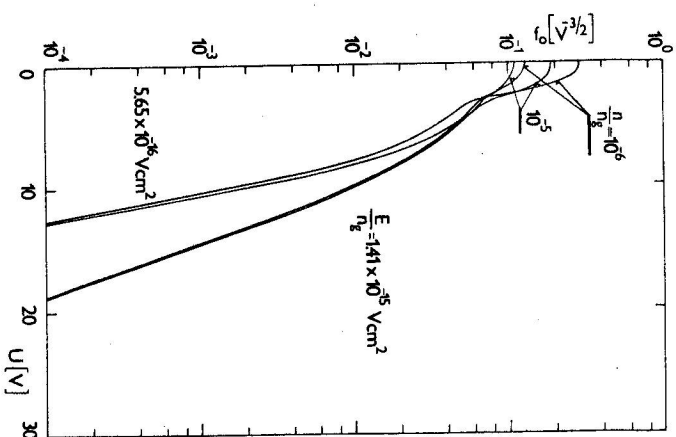
Fig. 3. Electron energy distribution function calculated selfconsistently for the indicated parameters, $k = 3.54 \times 10^{-5}$.

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