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INFLUENCE OF THE GAS MIXTURE COMPOSITION ON THE CO_2 LASER PLASMA PARAMETERS

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Abstract. Gas mixtures widely used in CO_2 lasers are investigated by the Boltzmann equation analysis. The optimal conditions for the vibrational excitation of the antisymmetric mode of CO_2 are found.

1. Introduction

The development of high efficiency CO_2 lasers requires the electron transport coefficients and molecular excitation rates in order to predict the laser characteristics thereby permitting the optimization of the laser performance. In these studies the accurate values of the electron parameters in the gas mixture with various concentration ratios of the components CO_2, N_2 and He for a wide range of ratios of electric field E to number gas density N (E/N values) are necessary.

Calculations predicting the fractional energy transfer from an electron to the vibrational levels 10^00, 01^10 and 00^01 of the CO_2 molecule have been carried out [1–5]. The electron swarm parameters and excitation rates in several CO_2, N_2 and He mixtures have been obtained [4, 5] using the Boltzmann equation. The assumption that the first two terms of the expansion are sufficient to represent the distribution function is made. It seems to be adequate in the case of CO_2 laser mixtures [4] although some analysis [6, 7] showed that this approximation is of limited validity in several cases of practical interest.

Recently many authors report new cross section data [8–10, 12]. Most of them are found in such a way that calculated swarm parameters are in very good agreement with their experimentally measured values. Because of that the problem of calculating the distribution functions, transport coefficients and excitation rates is of current interest.

The present work deals with an investigation of a large number of CO_2 laser mixtures on the basis of the Boltzmann equation using a projection method [6] and new collision cross section data. We have calculated the electron drift velocity, mean energy, and relative parts of energy transferred to the vibrational levels of CO_2 and N_2 molecules at various E/N values. We have found the values for which the energy transfer to the antisymmetric vibrational mode of CO_2 and the first vibrational N_2 level is maximal. The results obtained show that this energy transfer for the corresponding optimal E/N value depends slightly on the gas mixture composition.

2. Theoretical Preliminaries

Collisions with electrons responsible for population and depopulation of the vibrational modes in CO_2 and N_2 molecules excited in CO_2 laser plasmas are written as follows:

$$\begin{aligned} CO_2\,(00^00) + e &\Longleftrightarrow CO_2\,(10^00) + e \\ CO_2\,(00^00) + e &\Longleftrightarrow CO_2\,(01^00) + e \\ CO_2\,(00^00) + e &\Longleftrightarrow CO_2\,(00^01) + e \\ N_2\,(V_N) + e &\Longleftrightarrow N_2\,(V_N+1) + e \end{aligned} \tag{1}$$

where $(V_1 V_2^1 V_3)$ notes the respective vibrational modes of CO_2 molecules and V_N is the quantum number of the N_2 vibrational levels.

To calculate the rate coefficients for forward and backward reactions (1) and also the drift velocity and the electron mean energy the electron energy distribution function should be known. It can be obtained by solving the Boltzmann equation, which for a stationary homogeneous plasma in a steady electric field E has the form [1]:

$$-\frac{e}{m} E \nabla_V f(V) = \left(\frac{\partial f}{\partial t}\right)_c \tag{2}$$

where ∇_V denotes a gradient in the velocity space and the right hand side term is the collisional integral.

The method of numerical solution of Eq. (2) is based on an expansion of $f(V)$ [6]

$$f(V) = \sum_{j=0}^{n=1} f_j(u) P_j(\cos\theta) \tag{3}$$

where u is the electron energy, $u = \dfrac{mV^2}{2e}$, $P_j(\cos\theta)$ are zero-order Legendre polynomials. Substitution of Eq. (3) into Eq. (2) leads to a system of coupled differential equations for the expansion coefficients which is solved using the Galerkin method. The electron mean energy u_e and the drift velocity V_{dr} are defined by the formulae:

$$u_e = \frac{2}{3}\int_0^\infty u^{\frac{3}{2}} f_0(u)du\,; \qquad V_{dr} = -\frac{1}{3}\sqrt{\frac{2e}{m}}\int_0^\infty u f_1(u)du$$

The rate coefficients for various collision processes such as excitation, ionization and attachment are given by

$$K_{ij} = \sqrt{\frac{2e}{m}}\int_0^\infty u Q_{ij}(u) f_0(u)du$$

where K_{ij} denotes the rate coefficient for a process i concerning the j-th gas mixture component, and $Q_{ij}(u)$ is the corresponding cross section in Å^2. The relative parts of energy δ_{ij} for excitation of vibrational modes are defined as follows:

$$\delta_{ij} = \frac{\psi_j u_{ij} K_{ij}}{V_{dr}\frac{E}{N}}$$

where u_{ij} is the activation (deactivation) energy in eV for the respective vibrational mode, ψ_j is the molar fraction of the j-th component of the gas mixture, and E/N is in 10^{-16} Vcm^2.

For CO_2 laser plasma the following collision processes have been considered: elastic scattering, excitation of vibrational and electronic levels, ionization, dissociation and the respective super elastic vibrational and electronic collisions.

Recently reported cross section data for these processes are used in the present work. Momentum transfer cross sections for CO_2 and N_2 are taken from [8] and for He — from [9]. The cross section data set for excitation of vibrational and electronic levels and ionization are from [10] and the cross section of dissociative attachment is from [11]. Data for excitation of vibrational and electronic levels in N_2 are from [12].

3. Results and Discussion

We have considered eighty one laser mixtures with various ratios of the gas components CO_2, N_2 and He used in CO_2 lasers both in pulsed and in cw laser operation. Number densities for N_2 and He molecules per CO_2 number density (ψ_{N_2}/ψ_{CO_2} and ψ_{He}/ψ_{CO_2}) are 0, 0.5, 1, 2, 4, 6, 8, 10 and 20.

Values of E/N ratios for which the power transfer to the upper laser level 00^01 of CO_2 and to vibrational excitation of N_2 has a maximum value are of great importance in the optimization of laser performance. For every gas mixture we have found this optimal E/N value. In order to establish this value we investigated the dependence of $\delta_{000,001}$ (the part of energy transferred to the upper laser level by direct electron collisions) on E/N. Calculated characteristics at optimal conditions are presented in Table 1 in the following order: $(E/N)_{opt}$ in 10^{-16} Vcm^2, V_{dr} in 10^{-6} cm/s, u_e in eV, $\delta_{000,010}, \delta_{000,100}, \delta_{000,001}, \delta_{0,1}$.

Table 1 shows that the relative part of energy $\delta_{000,001}$ for excitation of the upper laser level by collisions between CO_2 molecule and electrons at the optimal E/N value essentially does not depend on the ratio of gas components in practice.

Table 1. Calculated characteristics for CO_2:N_2:He mixtures. Order of the quantities: $(E/N)_{opt}$ in 10^{-16} Vcm^2; V_{dr} in 10^{-6} cm/s; u_e in eV; $\delta_{000,010}$; $\delta_{000,100}$; $\delta_{000,001}$; $\delta_{0,1}$

ψ_{N_2}/ψ_{CO_2}	ψ_{He}/ψ_{CO_2} = 0	1	2	4	8	20
	2.62	1.69	1.39	1.08	0.70	0.47
	6.91	5.69	5.02	4.15	3.10	2.19
	0.47	0.50	0.55	0.57	0.49	0.49
0	0.22	0.21	0.20	0.19	0.22	0.20
	0.22	0.21	0.21	0.21	0.21	0.20
	0.47	0.48	0.49	0.49	0.50	0.48
	0.0	0.0	0.0	0.0	0.0	0.0
	1.75	1.30	1.08	0.84	0.63	0.41
	5.09	4.50	4.10	3.56	2.91	2.08
	0.38	0.37	0.37	0.38	0.38	0.38
1	0.23	0.23	0.23	0.21	0.23	0.22
	0.19	0.19	0.19	0.19	0.19	0.19
	0.46	0.46	0.46	0.46	0.46	0.45
	0.12	0.11	0.10	0.10	0.09	0.08
	1.44	1.13	0.99	0.80	0.60	0.41
	4.33	3.93	3.68	3.25	2.74	2.02
	0.39	0.37	0.38	0.38	0.37	0.37
2	0.22	0.23	0.23	0.23	0.23	0.23
	0.19	0.19	0.19	0.19	0.19	0.19
	0.46	0.46	0.46	0.46	0.46	0.44
	0.13	0.11	0.11	0.11	0.10	0.09
	1.06	0.94	0.84	0.74	0.58	0.40
	3.44	3.26	3.08	2.94	2.50	1.93
	0.37	0.38	0.37	0.37	0.37	0.37
4	0.23	0.23	0.23	0.23	0.23	0.22
	0.19	0.19	0.19	0.19	0.19	0.18
	0.46	0.46	0.46	0.46	0.45	0.44
	0.11	0.12	0.11	0.11	0.11	0.10
	0.78	0.73	0.69	0.62	0.52	0.38
	2.65	2.57	2.50	2.37	2.15	1.76
	0.37	0.37	0.37	0.37	0.36	0.36
8	0.23	0.23	0.23	0.22	0.23	0.22
	0.19	0.19	0.19	0.18	0.19	0.18
	0.45	0.45	0.45	0.45	0.44	0.43
	0.13	0.13	0.13	0.13	0.12	0.12
	0.51	0.48	0.47	0.45	0.40	0.30
	1.85	1.78	1.77	1.72	1.64	1.34
	0.34	0.35	0.35	0.35	0.34	0.34
20	0.23	0.23	0.23	0.22	0.23	0.22
	0.18	0.18	0.18	0.18	0.18	0.17
	0.43	0.42	0.42	0.42	0.42	0.39
	0.15	0.15	0.15	0.16	0.14	0.15

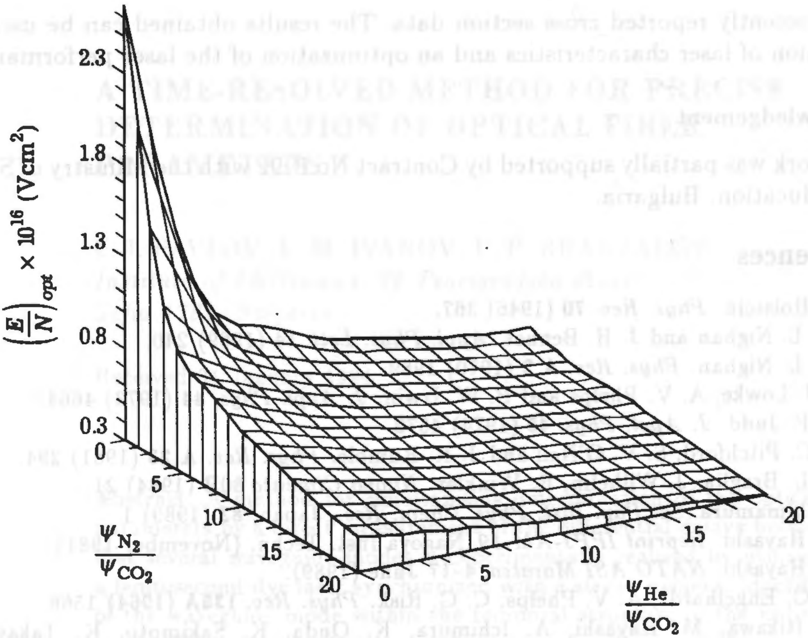

Fig. 1. **Optimal E/N value plotted versus the fractions of N_2 and He molecules in CO_2:N_2:He mixtures**

For a given E/N value the vibrational excitation rates for the antisymmetric mode of the CO_2 molecule and the first vibrational level of N_2 increase when the ratio ψ_{N_2}/ψ_{CO_2} is increased. This can be explained by the decrease of losses for excitation of modes 10^00 and 01^10 of the CO_2 molecule. Also, the electron drift velocity decreases with a growth of the ratio ψ_{N_2}/ψ_{CO_2}. That results from the larger value of momentum transfer cross section for N_2 molecules in the electron energy region (0–10) eV in comparison with that for CO_2 molecules.

The results indicate that for various gas mixtures $(E/N)_{opt}$ changes in the range of $(0.3\text{–}2.6)\times10^{-16}$ V.cm^2 whereas the electron mean energy varies slightly in the (0.34–0.57) eV region.

Figure 1 shows the optimal E/N values as a function of ψ_{N_2}/ψ_{CO_2} and ψ_{He}/ψ_{CO_2}. It is clear that a rise of ψ_{N_2}/ψ_{CO_2} and ψ_{He}/ψ_{CO_2} in the (0–4) range results in a rapid decrease of $(E/N)_{opt}$ followed by an almost linear decrease. For a given ratio of ψ_{N_2}/ψ_{CO_2} an addition of He in the gas mixture decreases the optimal E/N value. These curves are usable for a choice of $(E/N)_{opt}$ for energy gas mixture CO_2:N_2:He in practical applications.

4. Conclusions

A large number of gas mixtures used in CO_2 lasers has been investigated in the present work. The electron energy distribution functions were obtained by numerical solution of the Boltzmann equation using a projection method and incorporating recently reported cross section data. The results obtained can be used in a prediction of laser characteristics and an optimization of the laser performance.

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