Effect of gas concentration on the electron transport and the plasma parameters of the CO$_2$ gas mixture

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Abstract. Electron Swarm Parameters in plasma gas mixtures of CO$_2$ have been calculated. Studies focused on four gas mixtures with CO$_2$, He, and N$_2$ in the ratio 5%: 55%: 40%, 2.5%: 45%: 52.5%, 10%: 50%: 40% and 40%: 40%: 20% respectively. Calculations of the electron energy distribution function $f$ ($e$), drift velocity $V_d$, mobility $\mu$, electron diffusion $D$, $D/\mu$, electron average energy $<e>$ and electric field $E$ in the range of electric field to gas number density ratio $E/N$ from $1\times10^{-15}$ to $5\times10^{-15}$ at 300 K were reported in this work. The theoretical calculations shown helium has a good effect on the electrons transition parameters of CO$_2$ laser. Furthermore, at low energy, the total collision rate is increasing slowly for higher electron energy.

1. Introduction

Recently carbon dioxide and nitrogen mixture with a various concentration of helium are representing the new trend in high power CO$_2$ lasers. The helium is working as a catalyst to increase the mean energy of the applied electric field to the rate of gas number density ($E/N$) without further losses [1-3]. To understand the basic collisions processes is necessary to predict of the electrical excitation efficiency of different gas mixture. So the physics of swarms is provided the full picture and it is provide a fundamental of non-equilibrium plasma modelling. [4]. Among all the particles, the electrons represent the effective objects in the energy transition due to their ability to carry energy, and the transport coefficients are representing the fundamental interest. However, it is very complex to evaluate that transition by experimental setups so that we are using modelling methods to quantify the electric, chemical, and hydrodynamic characterizations of discharges gases and electrons at atmospheric pressure[5, 6].

Deductions have been performed of predicting the fractional energy transfer from an electron to the vibration level $00^1$ returns to the ground state through the levels of $10^0$, $20^0$ and $01^1$ and laser radiation is emitted. The accurate values of the electron swarm parameters in gas mixtures with different concentrations ratios of CO$_2$, N$_2$ and He for wide range of the applied electric field to gas number density ratio ($E/N$) were necessary and calculated by using Boltzmann equation[4, 5]. The present work is aim to calculate the electron swarm parameters for the mixture CO$_2$–N$_2$–He mixture which is involved in the composition of CO$_2$ laser. The calculation was analyzed by using two term approximation of the Boltzmann equation.
2. Methodology

The time dependent form of the first-order integral-differential equation for a mixture of gases subject to excitation field can be solved numerically using the relevant cross section data to obtain the electron energy distribution function[7, 8]. The Boltzmann equations allow us to calculate the different parameters of electron swarms that measured in variety of drift tube experiments.

\[
\begin{align*}
\left(\frac{mu}{2e}\right)^{1/2} \frac{\partial f_o}{\partial t} &= \frac{E^2}{3} \frac{\partial}{\partial u} \left( \sum_k N_k Q^k_m \right)^{-1} \left( 1 + \frac{m\omega}{2e(\sum_k N_k Q^k_m(u))^2} \right)^{-1} \frac{\partial f_o}{\partial u} \\
+ &2m \frac{\partial}{\partial u} \left[ u^2 \left( \sum_k N_k Q^k_m \right) f_o \right] + \frac{2mkT}{e} \frac{\partial}{\partial u} \left[ u^2 \left( \sum_k N_k Q^k_m \right) f_o \right] + \\
+ & \sum_j \sum_k \left[ (u + u_{jk}) f_o(u + u_{jk}) N_k Q^k_j (u + u_{jk}) - [u f_o(u) N_k Q^k_j (u)] \right] + \sum_j \sum_k \left[ (u - u_{jk}) f_o(u - u_{jk}) N_k Q^k_j (u - u_{jk}) - [u f_o(u) N_k Q^k_j (u)] \right]
\end{align*}
\]

Since

\[
\begin{align*}
E^2 &= \frac{E_0^2}{2} \\
\omega &= 2\pi f \\
\bar{E} &= E_0 \cos(\omega t)
\end{align*}
\]

Where \( f, E, N, N_k, M_k, Q^k_j (u), k \) are the excitation frequency, the applied electric field in unit of (V cm\(^{-1}\)), the total gas number density (cm\(^{-3}\)), the total gas number density of molecules of species \( K \) (cm\(^{-3}\)), the mass in grams of a molecules of species \( K \), the momentum transfer cross section (cm\(^2\)) for elastic collisions of electrons of energy \( u \) (eV), with molecular species \( K \), the constant of Boltzmann and the temperature of the molecular gas respectively. The sum \( j \) over all inelastic electron-molecule processes and the sum \( K \) is over the molecular species which were by (vibrational excitation, electronic excitation, ionization etc), \( u_{jk} \) is the energy loss in unit of electron volts (eV) for the \( j \)th inelastic process in species \( K \) and \( Q^k_j \) refers to the inelastic cross section for this process (sm\(^2\)). The quantity \( Q^k_j \) is the cross sections for super elastic collisions and related to the \( Q_0 \).

There are several ways to calculate the swarm parameters, but all of them based on the solving of the Boltzmann equation. The numerical calculation using the computer simulation method mention elsewhere [4] to obtain the distribution function \( F(u) \), it can be calculate the transport and phenomena of parameters like drift velocity \( V_d \), mobility \( \mu \), diffusion coefficient \( D \), \( D/\mu \) and electron average energy \(< \varepsilon >\) are given by[7, 9].

\[
\begin{align*}
V_d &= \mu E \\
\mu &= \frac{1}{3} \left( \frac{2e}{m} \right)^{1/2} \int_0^\infty \frac{u}{\sum_k N_k Q^k_m(u)} \frac{df_o}{du} du \\
D &= \frac{1}{3} \left( \frac{2e}{m} \right)^{1/2} \int_0^\infty \frac{u f_o(u)}{\sum_k N_k Q^k_m(u)} \\
< \varepsilon > &= \sum_k \varepsilon_k n_k \Delta \varepsilon / n_o
\end{align*}
\]
where

$$
\varepsilon_k = \frac{D}{\mu} = \frac{D}{\sum n_k} \\
n_o = \sum n_k
$$

Where $n_o$ and $\Delta \varepsilon$ are the total gas number density and the energy zoning (energy width) respectively. The framework approximation of the weakly ionized gas collision is using to solve that problem. In this approximation, the predominant interaction is that of electrons colliding with the molecules in their ground state, whereas the interactions between electrons and excited molecules are also considered as super elastic collisions or stepwise ionization.

3. Results and Discussion

The swarm parameters accuracy that measured in present work are 2%-4% for the electron drift velocity, 6%-10% for the diffusion coefficient and 4%-6% for the average energy of electrons. Table (1) present the four mixtures of gases with various concentrations over the range $1 \times 10^{-19}$ to $5 \times 10^{-15}$ V cm$^2$ that using in this work. The data like vibration, ionization and momentum transfer are loaded to computer program[9]. The equation (2) has been solved numerically for different CO$_2$: He: N$_2$ mixtures concentration over a range of E/N values at temperature 300°K.

Figure 1 shows the electron energy distribution function is suitable for pumping carbon dioxide lasers. Furthermore, this function is strongly affected by changing either of E/N or the gas concentration. Our results are have good matching with theoretical calculations and experimental data mention elsewhere [10]. There are found helium has a good effect on the electrons transition parameters of CO$_2$ laser [11].

![Figure 1. Electron energy distribution function, $f(\varepsilon)$ for different CO$_2$:He:N$_2$ concentration.](image)

| Table 1. Composition of laser gas mixtures. |
|-------------------------------------------|
| Mixture | CO$_2$ | He | N$_2$ |
|---------|-------|----|------|
| 1       | 5     | 55 | 40   |
| 2       | 2.5   | 45 | 52.5 |
| 3       | 10    | 50 | 40   |
| 4       | 40    | 40 | 20   |

Figure 2 shows the electron drift velocities $V_d$ for the gases mixture as a function of the E/N. At the low E/N the drift velocity $V_d$ values is $3 \times 10^3$, $4 \times 10^3$, $1 \times 10^4$, and $2 \times 10^4$ cm for the 1, 2, 3 and 4 mixture. It can be clearly observed the increasing $V_d$ of that mixtures with increasing E/N, but at for high values it decreases. It is interesting to note that the drift velocity depends on the CO$_2$ concentration. However the N$_2$ or He effects is very complex to explain because the lack information about the total collision crosses section. But we can say the proportion of CO$_2$ increases in the mixture, the drift velocity increases over the intermediate E/N values and then decreases at higher E/N values due to the very particular changes in the elastic momentum collision cross sections.
The figures (3,4,5,6 and 7) present the mobility $\mu$, diffusion coefficient $D$, characteristic energy $D/\mu$, electron average energy $<E>$ and electric field $E$ respectively increased with applied electric field to the total gas number density ratio and the percentage of the helium in the $\text{CO}_2$ : $\text{He}$ : $\text{N}_2$ mixture. For more accurate diffusion coefficients use very low pressures with reducing the applied electric field. At low $E/N$ the distribution of electron is “quasi-Maxwellian”. It is only over this region that the mean electron energy is equal to the thermal energy of the neutral gas constituents. Furthermore, for a Maxwellian distribution at low $E/N$, electron diffusion is entirely isotropic, and hence, the classical Einstein relation applies. As $E/N$ increases from thermal values, the electron distribution becomes non-Maxwellian, and diffusion ceases to be isotropic. There is no more details analyse in the literatures to explain the behaviour of $D$. Generally, the variations of the characteristic energies are very representative the relative important between the actions of the electric field due to collisions.
When the field effects predominate, there is a rapid increase in \( D \), which leading to a certain cases in the energy distribution. Obviously, this behaviour of energies interaction depends on the variation of the total collision cross section with the energy of electrons. However, at low energy, the total collision rate is increasing slowly for higher electron energy. So, the mean energy variation is mainly affected by the inelastic processes, which determine the values of \( D \). The electric filed present a linear behaviour with the E/N that give the good approve to normal energy distribution after collision.

4. Conclusions

The electron swarm parameters of CO\(_2\) laser with gas mixtures (He and N\(_2\)) have been analyzed for an E/N range between \( 1 \times 10^{-19} \) to \( 5 \times 10^{-15} \) V cm\(^2\) using a Boltzmann transport equation. We have present important swarm parameters, such as drift velocity, mobility, characteristic energy, electron average energy, and Diffusion coefficients. The set collection of the cross sections for both carbon dioxide and nitrogen which, when used with the numerical solution of the Boltzmann equation technique with accurately predict the magnitude of the electron swarm parameters, mean energies over a wide range of E/N between \( 1 \times 10^{-19} \) to \( 5 \times 10^{-15} \) V cm\(^2\). Our data hopeful useful for the modelling and understanding of atmospheric pressure nonthermal gases discharges used in many plasma and laser devices and applications.

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