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RESEARCH PAPER

Transport Parameters and Dielectric Strength of Electrical Discharges in an Arc Discharges in Carbon Dioxide Gas

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ABSTRACT

The two-term approximation solution of Boltzmann equation analysis has been used to calculate the electron energy distribution function (EEDF), dielectric strength and the electron swarm parameters in carbon dioxide. The electron swarm parameters have been calculated over the wide range of reduced density electric field strength E/N varying from 0.1 to 1000 Td (1Td= 10^{-17} V.cm^{2}). These parameters, namely electron drift velocity, mean electron energy, electron temperature, characteristic energy, transverse diffusion coefficient, electron mobility, reduced ionization and attachment Townsend coefficients have been compared with the available previous theoretical and experimental results. The values of the critical reduced electric field strength $(E/N)_{cr}$ from the curves of reduced effective ionization coefficient (α-η)/N are calculated. In addition, excitation rate and fractional power transfer to elastic and inelastic collisions are explained.

KEY WORDS: CO2 electric discharge, EEDF, dielectric strength, swarm parameters, electron temperature, reduced electric field strength (E/N)cr.
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1. INTRODUCTION

Carbon dioxide gas play an important role in technological application, atmospheric physics, pulsed-power switching, particle detector, low temperature plasma , CO_2 gas laser (Koushki, Zand, Haghighi, & Neshati, 2015; Uchii et al., 2007) . In high voltage technology carbon dioxide used as admixture for circuit breakers and in health care used as additive to oxygen for medical use as a respiration simulant.

The CO_2 is a man-made and long-lived greenhouse gas with a global warming potential similar to that of CF_3I (GWP~1) and 23,900 times smaller than that of Sulfur hexafluoride SF_6 (Christophorou, Olthoff, & Van Brunt, 1997). Carbon dioxide at room temperature (300 K) is a colorless, nontoxic, totally non-flammable gas, at low concentrations is odorless, at high concentration has acidic odor, it has a low critical temperature (304.1 K) and high critical pressure (7.3773 MPa), that not deplete the ozone layer. The density of CO_2 is 1.67 times greater than that of dry air (Pierantozzi, 2000).

Several studies have found that Carbon dioxide (CO_2) is a selected gas for replacing SF_6 in high-voltage switchgear for the transmission and distribution of electricity (Seeger, Avaheden, Pancheshnyi, & Votteler, 2016) at room temperature in the pressure range 0.05-0.5 MPa.

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However the dielectric strength of SF_6 (8.9 KV/mm) is greater than that of CO_2 (1.93 KV/mm). When a small amount of oxygen (O_2) with high dielectric strength add to CO_2 can effectively ameliorate the value of critical reduced electric field strength $(E/N)_{cr}$ (Hu Zhao, Deng, & Lin, 2017).

The electron kinetics, the electron energy distribution function (EEDF), rate coefficient, the effect of vibrational excitation and power transfer were studied by (Ogloblina, Tejero-del-Caz, Guerra, & Alves, 2020).

The electron motion at low pressure with mean electron energies in the range of 0.5-3.0 eV are called cold plasma, electron distribution function have non-maxwellian shape due to electron molecule collision processes. The electron swarm parameters, the electron energy distribution function and the percentage of energy loss during the different collision processes may be calculated from a set of collisional cross- sections of CO_2 by using the Monte Carlo Simulation method or the Boltzmann equation. The electron energy distribution function (EEDF) is normalized by $f(\varepsilon).\varepsilon^{1/2}d\varepsilon$ (Nighan, 1970), it is difficult to measure experimentally .

The electron transport parameters in CO_2 have been investigated by (Hake Jr & Phelps, 1967) by using Boltzmann equation over the range of E/N varying from 0.02 to 100 Td, and by Monte Carlo simulation methods (Kucukarpaci & Lucas, 1979) within the range $10<E/N\leq3000$ Td, (where E is the electric field and N gas density, $1Td=10^{-17}$ Vcm^2 , 1 V/cm.Torr=3.0341Td at 293 K). The electron swarm parameters of CO_2 for low $E/N\leq30$ Td were measured by (Elford, 1966; Pack, Voshall, & Phelps, 1962). Moreover, the electron drift velocity and characteristic energy for pure N_2 and CO_2 over the range $10\leq E/N\leq700$ Td have been studied by (Roznerski & Leja, 1984; Saelee, Lucas, & Limbeek, 1977). The electron drift velocity and longitudinal diffusion coefficient of both pure N_2 and CO_2 at room temperature have been measured experimentally in the range $20\leq E/N\leq 1000$ Td using double-shutter drift tube technique by (Hasegawa, Date, Shimozuma, Yoshida, & Tagashira, 1996), ionization and attachment coefficient in CO_2 obtained for $60\leq E/N\leq152$ Td by (Alger & Rees, 1976). The electron transport parameters in pure CO_2 and CO_2-SF_6 mixtures were measured over the range $100\leq E/N\leq700$ Td by (Hernández-Ávila, Basurto, & De Urquijo, 2002) using the pulsed Townsend technique.

(Li, Guo, Zhao, Jia, & Murphy, 2015) calculated the critical reduced electric filed strength $(E/N)_{cr}$ for CO_2 and CO_2- Cu mixtures using Boltzmann equation at different temperature and pressure 0.4 MPa. Sun et al., 2015 investigated dielectric breakdown of CO_2 at different temperature and pressure using two-term solution of Boltzmann equation. (Grofulović, Alves, & Guerra, 2016) studied the electron swarm motion of CO_2. (Pietanza, Colonna, D'Ammando, Laricchiuta, & Capitelli, 2016) investigated the role of Superelastic vibration collision on electron energy distribution function (EEDF) and percentage power transfer in cold CO_2 discharge. (Wang & Bogaerts, 2016) studied the effect of inelastic collision on the electron energy distribution function , reduced effective ionization coefficient, critical reduced electric field strength and ion kinetics of CO_2 in the range of temperature varying from 300 K to 5000 K by using Boltzmann equation. (H Zhao, Gu, & Li, 2017) studied the reduced ionization coefficient and critical reduced electric field strength at room temperature of pure CO_2 gas and its mixtures with 10 different gases.

Recently (Jawad & Jassim, 2019), calculated the electron swarm parameters of CO_2, Xe-CO_2 and Kr-CO_2 mixtures at room temperature over the range of E/P varying from 35 to 350 V/cmTorr. (Grofulovic, 2019) investigated electron swarm parameters of pure CO_2 and rotational Raman in pulsed CO_2-O_2 and CO_2-N_2 discharge under non-equilibrium condition.

The electron transport parameters are also calculated in binary gas mixtures, Ar-CO_2 (Yoshiharu Nakamura, 1995), SF_6-CO_2 (Xiao, Li, & Xu, 2001), CO_2-Air (De Urquijo et al., 2009), CO_2-N_2 and CO_2-O_2 (Yousfi, de Urquijo, Juarez, Basurto, & Hernandez-Avila, 2009), c-C_4F_8-CO_2 (Deng, Lu, & Xiao, 2012), CF_3I-N_2 and CF_3I-CO_2 (Yun-Kun & Deng-Ming, 2013), CF_3I-CO_2 (Xiaoling, Juntao, & Dengming, 2016), Fluoronitriles-CO_2 (Nechmi, Beroual, Girodet, & Vinson, 2017),), C_4F_7N-CO_2 (Long et al., 2019; Zheng et al., 2019) and CO_2-CO mixtures (Ogloblina et al., 2019). Furthermore, (Davies, 1978) measured the ionization and attachment coefficients in pure CO_2 and ternary CO_2-N_2-He gas mixtures over the range 76.3 $Td\leq E/N\leq98.9$ Td, and (Egüz, Chachereau, Hösl, & Franck, 2019) experimentally measured the electron swarm parameters in ternary C_4F_7N-O_2-CO_2, $C_5F_{10}O$-O_2-CO_2 and $C_5F_{10}O$-O_2-N_2 mixtures over a wide range of E/N. (Wedding, 1985) investigated the electron drift velocity, Townsend ionization coefficient and diffusion coefficients both D_L and D_T in CO_2-N_2-He-CO gas mixtures of the ratio 6:34:54:6 by using time-of-flight (TOF) method, over the range of E/N varying from 100 to 500 Td.

The dielectric breakdown voltage and density reduced critical electric field strength $(E/N)_{cr.}$of carbon dioxide and its mixtures was calculated at which the balancing electron generation and electron loss are in equilibrium derived from Boltzmann transport equation, this method was used by (Brand & Kopainsky, 1979; Itoh, Shimozuma, & Tagashira, 1980; Laska, Mašek, Krasa, & Peřina, 1984; Hu Zhao et al., 2017). The critical reduced electric field strength $(E/N)_{cr}$ and breakdown voltage for pure CO_2 and mixtures were analyzed theoretically and experimentally by several authors. (Yousfi et al., 2009) investigated electron drift velocity (v_d), longitudinal diffusion coefficient (D_L) and effective ionization coefficient ($(\alpha-\eta)/N$) of CO_2, N_2, O_2 and their mixtures CO_2-N_2 and CO_2-O_2 experimentally (time-resolved pulsed Townsend technique) and theoretically (multi-term Boltzmann equation method), covering the range 0.01Td $\leq$E/N$\leq$1000 Td. (Sun et al., 2015) calculated reduced ionization coefficient (α/N), reduced attachment coefficient (η/N) and the dielectric properties of hot CO_2 at different temperature and pressure by solving Boltzmann equation. (Vass, Korolov, Loffhagen, Pinhao, & Donkó, 2017) were investigated electron swarm parameters and the effective ionization coefficient $(\alpha-\eta)/N$ in CO_2 gas experimentally under time-of-flight conditions using scanning drift tube over the range 15 Td$\leq$E/N$\leq$2660 Td, as well as theoretically by solving Boltzmann transport equation and Monte Carlo simulation method. The electron mobility, longitudinal diffusion coefficient and effective ionization rate coefficient of CO_2, N_2 and Ar were measured by (Haefliger & Franck, 2018) using pulsed Townsend experiments.

(Beaty, Dutton, & Pitchford, 1980; Dutton, 1975) published a large data on the electron transport parameters in number gases over a wide range of E/N. We previously reported a detailed explanation to calculate electron swarm parameters by solving two-term solution of the Boltzmann equation (Othman, Taha, & Sailh, 2019; Othman, Taha, & Salih, 2019).

The object of the present article is to calculate the electron swarm parameters, namely (drift velocity, mean electron energy, diffusion coefficient, characteristic energy, electron mobility, ionization and attachment coefficient), reduced effective ionization coefficient, reduced critical electric field strength and mechanisms for fraction power transfer due to collision processes for pure CO_2 over a wide range of reduced electric field strength E/N varying from 0.1 to 1000 Td by solving two-term solution of Boltzmann equation at temperature 300 K and pressure 1 atm..

2. Theory

2.1. The Boltzmann Equation

The basic of homogeneous electron Boltzmann transport equation yielding to calculate the electron energy distribution function takes the form (Frost & Phelps, 1962; Holstein, 1946).

$$\frac{E^2}{3}\frac{d}{d\varepsilon}\left(\frac{\varepsilon}{NQ_m^T(\varepsilon)}\frac{df_0(\varepsilon)}{d\varepsilon}\right)+\frac{2m}{M}\frac{d}{d\varepsilon}\left(\varepsilon^2 NQ_m^T(\varepsilon)f_0(\varepsilon)\right)+\frac{2mK_BT_g}{Me}\left(\varepsilon^2 NQ_m^T(\varepsilon)\frac{df_0(\varepsilon)}{d\varepsilon}\right)+$$
$$\sum_J(\varepsilon+\varepsilon_J)f_0(\varepsilon+\varepsilon_J)NQ_J(\varepsilon+\varepsilon_J)-\varepsilon f_0(\varepsilon)N_J\sum_J Q_J(\varepsilon)=0 \qquad 1$$

Here, K_B is the Boltzmann constant, T_g is the gas temperature, m/M is the ratio of electronic to atomic mass, $Q_J(\varepsilon)$ is the cross sections for various excited states, ε_J is the threshold energy of the Jth excited state, and $Q_m^T(\varepsilon)$ is the total effective momentum transfer cross sections defined as follows,

$$Q_m^T(\varepsilon) = Q_m(\varepsilon) + \sum_j Q_e(\varepsilon) + Q_i(\varepsilon) + Q_a(\varepsilon) \qquad 2$$

Where $Q_m(\varepsilon)$ is momentum transfer cross-section, $Q_e(\varepsilon)$ is excitation cross-sections (vibration and electronic), $Q_i(\varepsilon)$ is ionization cross-sections and $Q_a(\varepsilon)$ is attachment cross-sections. The last term express gain of energy by electrons due to second kind (superelastic) collision. The equation (1) applies to swarm of electron drifting through an gas and mixtures under influence of a uniform dc electric field (E).

2.2. Transport parameters

The electron transport coefficient in given gases under the influence of dc applied electric field, calculated by using a two-term solution of the Boltzmann equation, the resulting solution gives the electron energy distribution function which depend on the reduced electric field strength E/N, the gas temperature and electron collision cross- sections, and play important parameters for calculation of the electron swarm parameters.

The electron energy distribution function can be normalized by (Morgan & Penetrante, 1990),

$$\int_0^\infty f_o(\varepsilon)\sqrt{\varepsilon}\,d\varepsilon = 1 \qquad 3$$

the electron energy distribution function was chosen as Maxwellian function at temperature T_g with mean electron energy $\langle\varepsilon\rangle = \frac{3}{2}K_B T_g = \frac{3}{2}T_e$ (T_e is electron temperature in eV) is given by (Jiang & Economou, 1993),

$$f(\varepsilon) = \frac{2}{\sqrt{\pi}}\left(K_B T_g\right)^{-3/2}\exp\left(-\frac{\varepsilon}{K_B T_g}\right) \qquad 4$$

the mean electron energy in term of EEDF is expressed as,

$$\langle\varepsilon\rangle = \int_0^\infty \varepsilon^{3/2} f_o(\varepsilon)\,d\varepsilon \qquad 5$$

while the reduced electron mobility is given by,

$$\mu_e N = -\frac{1}{3}\sqrt{\frac{2e}{m}}\int_0^\infty \frac{\varepsilon}{Q_m^T(\varepsilon)}\frac{\partial f_o(\varepsilon)}{\partial\varepsilon}\,d\varepsilon \qquad 6$$

The drift velocity v_d, the density transverse diffusion coefficient $D_T N$ and characteristic energy ε_k are given by (Smith & Thomson, 1978),

$$v_d = -\frac{\overline{E}}{3}\sqrt{\frac{2e}{m}}\int_0^\infty \frac{\varepsilon}{NQ_m^T(\varepsilon)}\frac{\partial f_o(\varepsilon)}{\partial \varepsilon}d\varepsilon \qquad 7$$

$$D_T N = \frac{1}{3}\sqrt{\frac{2e}{m}}\int_0^\infty \frac{\varepsilon}{Q_m^T(\varepsilon)} f_o(\varepsilon) d\varepsilon \qquad 8$$

$$\varepsilon_k = \frac{eD_T}{\mu_e} \qquad 9$$

From the computed drift velocity v_d the reduced ionization and attachment coefficients are obtained as (Tuan, 2014, 2016),

$$\frac{\alpha}{N} = \frac{1}{v_d}\sqrt{\frac{2e}{m}}\int_i^\infty Q_i(\varepsilon) f_o(\varepsilon)\varepsilon d\varepsilon \qquad 11$$

$$\frac{\eta}{N} = \frac{1}{v_d}\sqrt{\frac{2e}{m}}\int_a^\infty Q_a(\varepsilon) f_o(\varepsilon)\varepsilon d\varepsilon$$

12Where, $Q_i(\varepsilon)$, $Q_a(\varepsilon)$ are ionization and attachm

The reduced effective ionization is given by (Hu Zhao, Li, Jia, & Murphy, 2013).

$$\overline{\alpha} = \frac{\alpha}{N} - \frac{\eta}{N} = \frac{\alpha - \eta}{N} = 0 \qquad 13$$

The rate constant for the jth excitation is obtained by the following formula (Y Nakamura & Lucas, 1978),

$$R_{sj} = \left(\frac{2e}{m}\right)^{1/2}\int_0^\infty NQ_{sj}(\varepsilon) f_o(\varepsilon)\varepsilon d\varepsilon \qquad 14$$

where Q_{sj} is electron cross-sections of excitation of level (j) in species (s).

The electron energy loss (P_j) is,

$$P_j = \frac{\varepsilon_j R_{sj}}{e\overline{E}v_d} \qquad 16$$

Where ε_j is the threshold energy for the excitation.

3. Collision Cross Section

The electron swarm parameters and EEDF in Carbon dioxide (CO_2) gas calculated from the sets cross- sections (elastic and inelastic) reported by (Kieffer). This sets includes 14 collisional processes: one effective momentum-transfer cross section (Q_m), eight vibration excitation (Q_{v1}- Q_{v8}) with threshold energy 0.083, 0167, 0.252, 0.291, 0.339, 0.422, 0.505 and 2.5 eV respectively and two electronic excitation (Q_{ex}) cross-sections with threshold energy of 7.0 and 10.5 eV, one attachment (Q_a) and ionization cross-sections with threshold energy 3.85 eV and 13.3 eV respectively and one superelastic de-excitation.

4. Results and discussion

The electron cross-sections were explained in section (3) have been used in present calculation to obtain electron swarm parameters and comparison with the previous theoretical and experimental values. The energy range for the CO_2 cross-sections has been taken from 0.001 eV to 500 eV, which is typical of the dielectric properties and breakdown voltage at room temperature. The necessary condition for the two-term solution to be valid, that the momentum transfer cross-sections is larger than the inelastic cross-sections (Smith & Thomson, 1978; Tanaka, 2004). In the case of CO_2 molecules the elastic cross-section are large.

Normalized electron energy distribution function (EEDF) in pure CO_2 for different values of E/N at temperature 300 K and pressure 1 atm is shown in figure 1. For electron energies $\leq$ 2.5 eV, the maximum value of EEDF decreases as E/N values increases. However, for electron energies greater than 2.5 eV, the shape of EEDF reversed, the tail of the distribution function is shifted towards high energy which indicates that at high E/N values the electrons accelerated and increase their kinetic energies and there are only little thermal electrons that have energies greater than the ionization potential. At low electron energies the shape of the EEDF depend on the momentum transfer cross-sections, at high energies the distribution function influenced by the collision frequency for inelastic collisions, for this condition the EEDF play the important parameters to calculate the swarm parameters.

Figure 2 shows the effect of temperatures on the normalized electron energy distribution function at fixed value of E/N=60 Td and a pressure of 1 atm. For the energy range $\leq$3.5 eV, the maximum value of the electron energy distribution function decreases with increasing temperature. However, for temperature above 300 K the shape of EEDF reversed when the energy of electron greater than 3.5 eV. At high temperature CO_2 molecule begins to dissociate and the kinetic energies of electrons increases with temperature, this is the reason the tail of EEDF shifted toward the right.

Figure 3 shows the effect of pressure on the electron energy distribution function (EEDF) at fixed value of E/N= 60 Td and a temperature of 300 K. For the range of electron energy less than 2 eV the EEDF decreases with increasing pressure, for energies greater than 2 eV, leads to a higher maximum value, this behavior is opposite to that found in Sulfur hexafluoride SF_6 (Wang, Murphy, Rong, Looe, & Spencer, 2013; Wang, Tu, Mei, & Rong, 2013; Hu Zhao et al., 2013).

Figure 4a and 4b are shown the influence of superelastic collisions on EEDF at reduced electric field strength 1 Td and 70 Td with and without second kind (superelastic) collision respectively. For both cases the effect of superelastic can be seen that superelastic collisions are affect the EEDF at low reduced electric field strength E/N, but are not important at high E/N values. At high values of E/N the electrons gain their energies from the applied d.c electric field. The study of the effect of second kind (superelastic) collisions in Carbone dioxide was explained in literatures of (Pietanza, Colonna, D'Ammando, et al., 2016; Pietanza, Colonna, D’Ammando, Laricchiuta, & Capitelli, 2016).

Figure 5 shows the mean electron energy varying from (0.025 eV to 14.85 eV) for different values of E/N (0.1 Td to 1000 Td), at high E/N the mean electron energy sensitive to inelastic collisions. The change of mean electron energy is progressive exponentially, the electron gain all energies from the applied electric field. Comparison has been made with the theoretical results of (Kucukarpaci & Lucas, 1979) and (Jawad, 2015) a good agreement has been observed.

Figure 6 shows calculated electron temperature as a function of E/N from the relation $\langle \varepsilon \rangle = (3/2)T_e$, where $\langle \varepsilon \rangle$ is mean electron energy and T_e is electron temperature in unit eV. At E/N≥ 4 Td the variation of electron temperature is more nonlinear this due to large vibrational cross-sections CO_2 in the energy ranges (3 eV to 5 eV). The theoretical values of (Hu Zhao et al., 2017) are in good agreement compared with the present calculation.

The results of electron drift velocity as a function of E/N is shown in figure 7
which increases with increasing E/N values, the results are compare with the theoretical values of (Grofulovic, 2019; Raju, 2018) and experimental values of (Elford & Haddad, 1980; Yoshiharu Nakamura, 1995; Vass et al., 2017). A good agreement has been shown over the entire range of E/N. The characteristic energy is shown in figure 8 and the agreement is good over the entire range of E/N when compared with previous values, i.e. it agrees well with the experimental values of (Lakshminarasimha & Lucas, 1977; Rees, 1964) and theoretical values of (Jawad, 2015). In fact, as reported by (Kucukarpaci & Lucas, 1979) the values should be about 10% lower than the present values.

The reduced transverse diffusion coefficient D_TN for pure CO_2 is shown in figure 9, together with theoretical and experimental values for comparison. The present calculation were found in good agreement with theoretical values of (Deng et al., 2012; Grofulovic, 2019) and experimental values of (Hernández-Ávila et al., 2002; Yoshiharu Nakamura, 1995; Vass et al., 2017; Wagner, Davis, & Hurst, 1967). At high E/N>30Td the values of (Grofulovic, 2019) lower than the calculated values. In fact, experimental data of (Wagner et al., 1967) and (Yoshiharu Nakamura, 1995) should be higher than the present results. The normalized reduced electron mobility μ_eN is shown in figure 10, the calculated values are agree with theoretical values of (Grofulovic, 2019; Raju, 2018) and experimental values of (Elford & Haddad, 1980; Haefliger & Franck, 2018; Yousfi et al., 2009). For low value of E/N the data of (Yousfi et al., 2009) slightly higher than present calculation. In the case of CO_2, when reduced electric field strength (E/N) is around (25-30) Td, a maximum values in the reduced electron mobility can be observed, then electron mobility decreases with increasing E/N, because during the range E/N≥30 Td, the attachment coefficient decrease the number of electrons.

Figure 11, shows the reduced ionization coefficient α/N in comparison with the experimental data of (Conti & Williams, 1975; Hernández-Ávila et al., 2002; Yoshiharu Nakamura, 1995; Townsend, 1902) as well as the theoretical results of (Grofulovic, 2019; Sun et al., 2015; Hu Zhao et al., 2017). Throughout the range of 60 Td≤E/N≤1000 Td good agreements has been observed. For E/N<140 Td, the theoretical values of (Grofulovic, 2019) slightly lower about 8% compare with the present results. In addition, figure 12 shows the comparison of the calculated reduced attachment coefficient η/N in carbon dioxide with the previous literatures. A deviation between the calculated and experimental data of (Alger & Rees, 1976) can be observed due to the cross-sections for the three body attachment, However, the calculated values show in good agreement with theoretical results of (Sun et al., 2015; Hu Zhao et al., 2017) at room temperature.

Figure 13 compares the calculated values of the reduced effective ionization coefficient (α-η)/N with experimental values measured at room temperature by (Alger & Rees, 1976; Dahl, Teich, & Franck, 2012; Haefliger & Franck, 2018) and theoretical values calculated by (Sun et al., 2015; Yousfi et al., 2009; Hu Zhao et al., 2017). The present values are in good agreement with previous data. The two-term approximation solution of Boltzmann equation used to calculate the reduced critical electric field strength $(E/N)_{cr.}$, which is important coefficient for the purpose of identification the insulation performance of gases. From the point of intersection between the density reduced effective ionization coefficient (α-η)/N and the zero line E/N, the reduced critical electric field strength $(E/N)_{cr}$ in pure Carbone dioxide molecule were calculated equal to 84 Td. In comparison the dielectric strength of CO_2 in agreement with the results of (Alger & Rees, 1976) 93 Td, (Dahl et al., 2013) 81 Td, (Sun et al., 2015) 86 Td, and (Haefliger & Franck, 2018) 86 Td, but slightly greater than the results of (Yousfi et al., 2009), 84 Td and (Hu Zhao et al., 2017) 77.3 Td. At low E/N≤85 Td, the reduced attachment coefficient dominates and negative values for the effective ionization are observed.

Excitation rates for the vibrational levels 010, 020, 030+110, 001, 200 and 300, with threshold energy of 0.083, 0.0167, 0252, 0.291, 0.339 and 0.505 eV respectively and electronic excitation of two levels with threshold energy 7 eV and 10.5 eV are calculated according to equation 15, which is shown in figure 14. The excitation rates increases with increasing E/N up to about 100 Td, where it reach the maximum value then start to decreases monotonically with increasing E/N, except the electronic level with threshold energy 10.5 eV where it reaches a constant value at high E/N. In fact, during the inelastic collision processes most of the electron energy will transfer to the electronic levels and ionization.

The mechanism of fraction power transfer to elastic and inelastic processes over the entire E/N varying from 0.1 Td to 1000 Td is summarized in figure 15. For low range 0.1≤E/N≤6 Td the loss is only by elastic and vibrational collision, for the range 6≤E/N≤40 Td about 98% energy transfers to only vibrational collision. For intermediate E/N values the vibrational and electronic excitation are the main of energy loss. For high reduced electric field strength E/N the energy loss are sensitive to the electronic levels having threshold energies of 3.1 eV and 10.5 eV and the ionization processes are the main of energy loss. As shown in figure the energy loss by attachment process is very small.

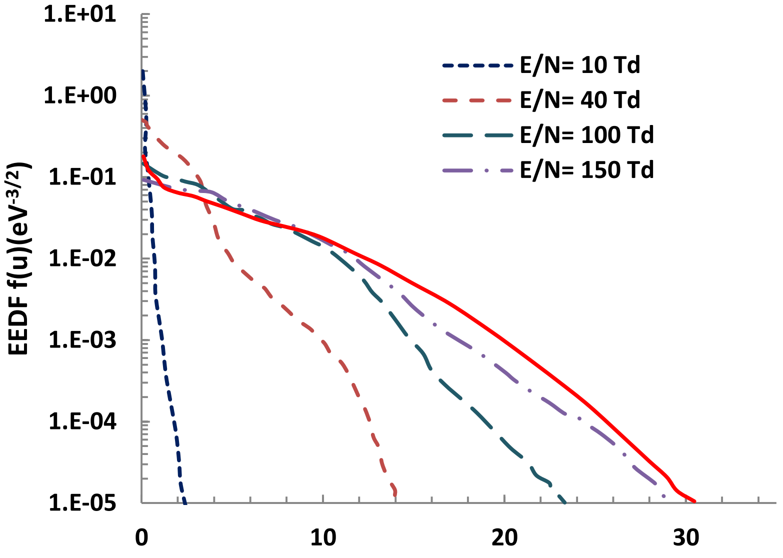

Figure 1. Electron energy distribution function in CO_2 for different reduced electric fields E/N at a temperature of 300 K and pressure of 1 atm.

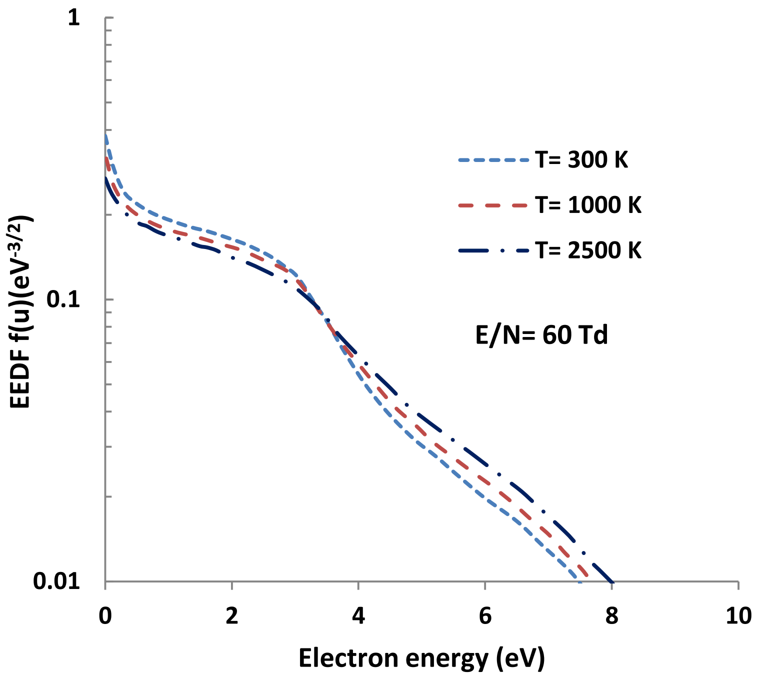

Figure 2. Electron energy distribution function in CO_2 for various temperatures at reduced electric field E/N =60 Td and pressure of 1 atm.

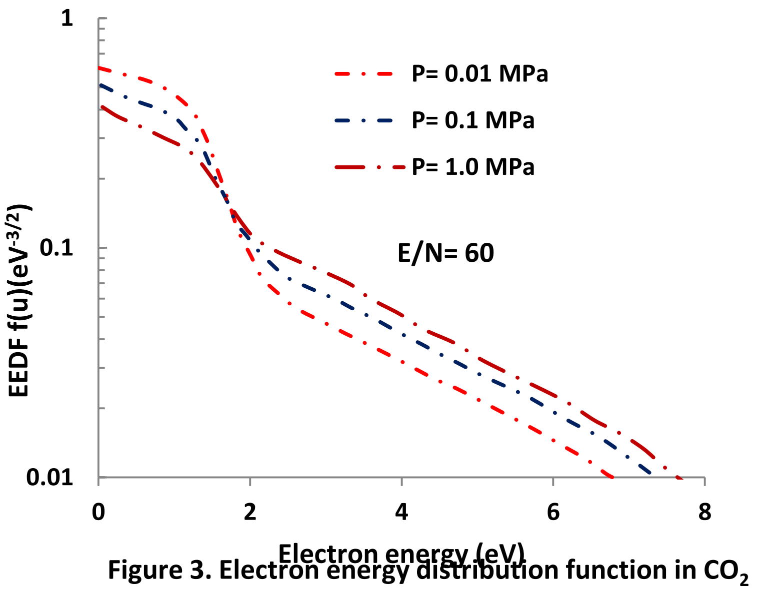

Figure 3. Electron energy distribution function in CO_2 for various pressure at reduced electric field E/N =60 Td and temperature of 300 K.

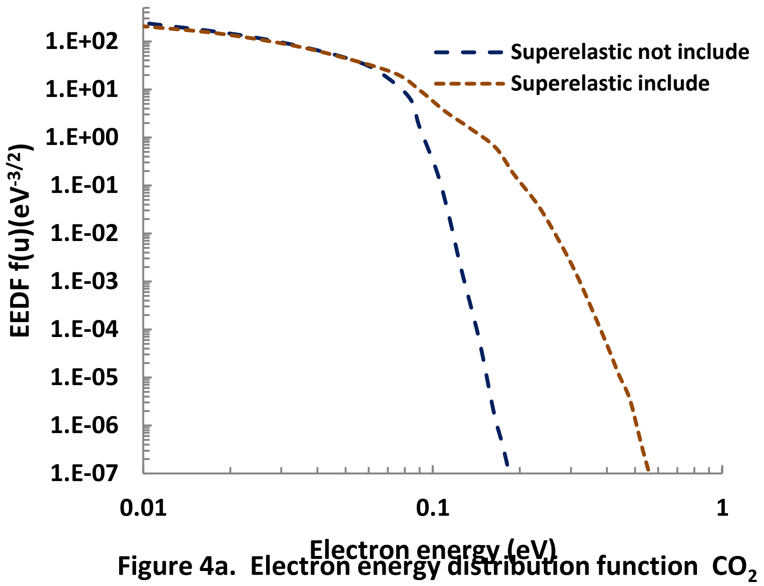

Figure 4a. **Electron energy distribution function CO_2 for E/N= 1 Td, with and without the superelastic process.**

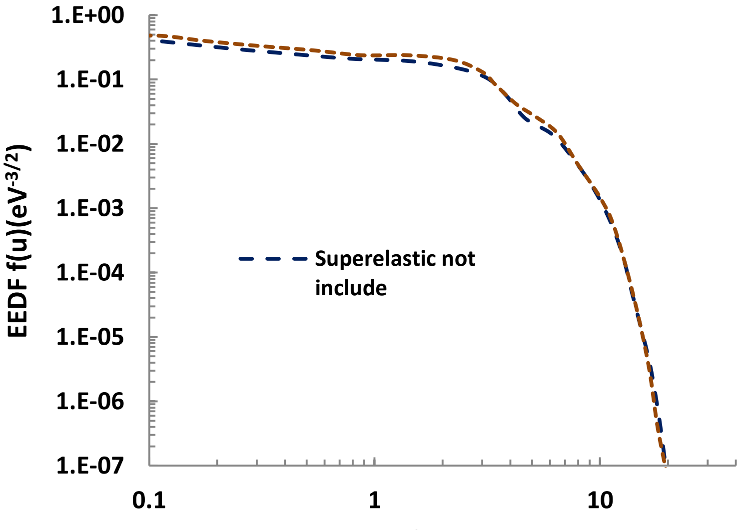

Figure 4b. Electron energy distribution function in CO_2 for E/N= 70 Td, with and without the super-elastic process.

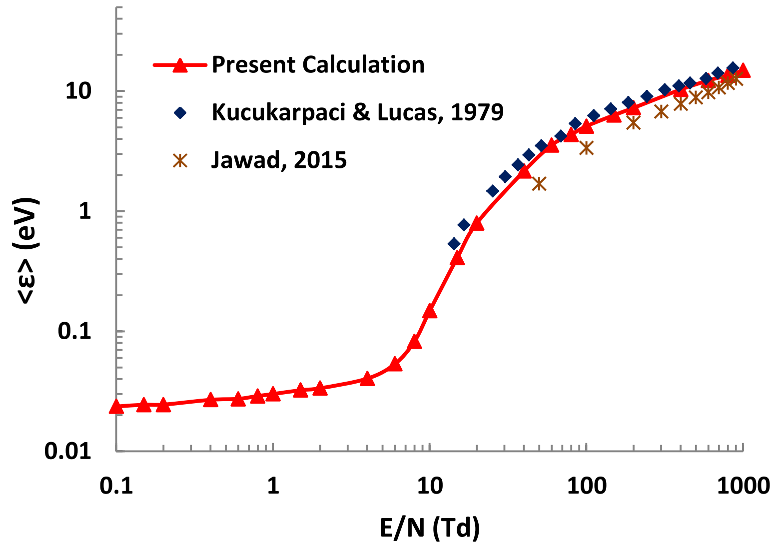

Figure 5. Mean electron energy in CO_2 as a function of reduced electric field strength E/N.

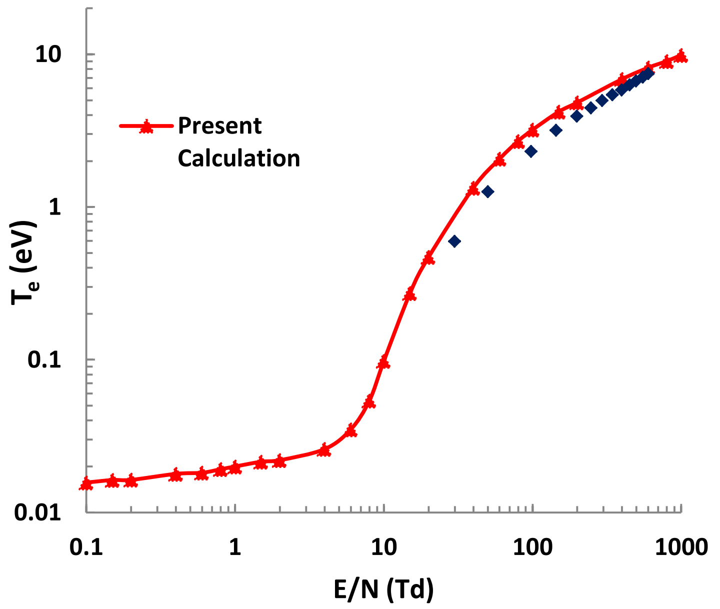

Figure 6. Electron temperature in CO_2 as a function of reduced electric field strength E/N.

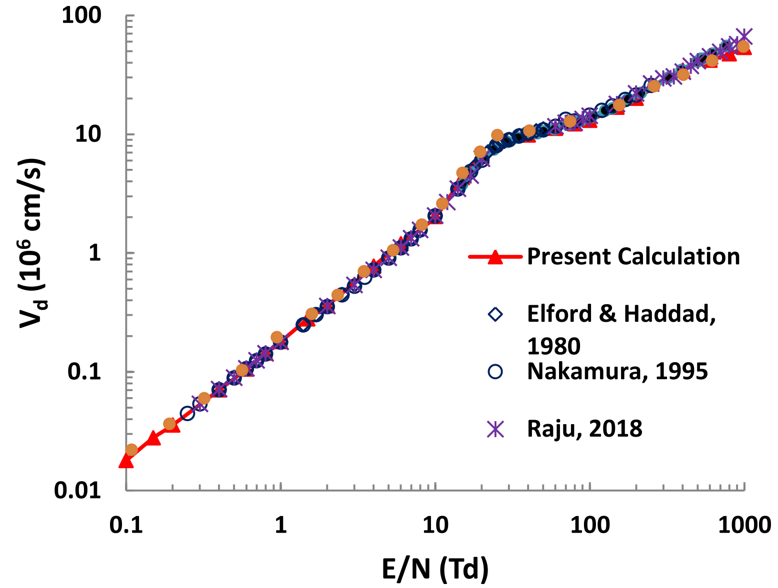

Figure 7. Electron drift velocity in CO_2 as a function of reduced electric field strength E/N.

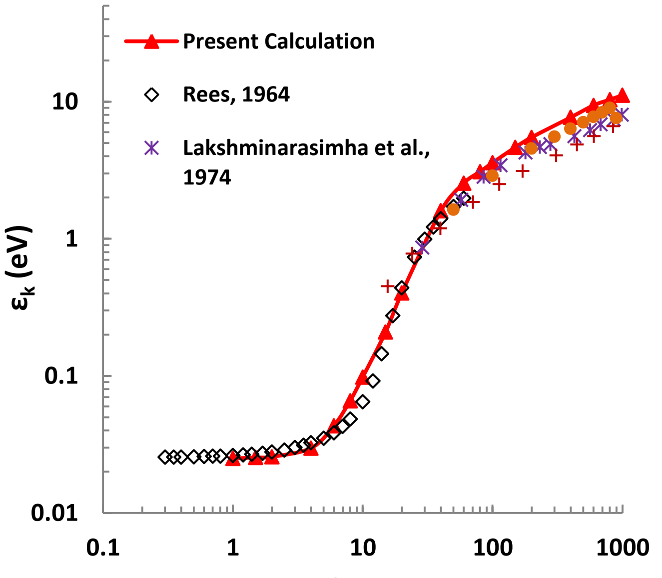

Figure 8. Charactristic energy in CO_2 as a function of reduced electric field strength E/N.

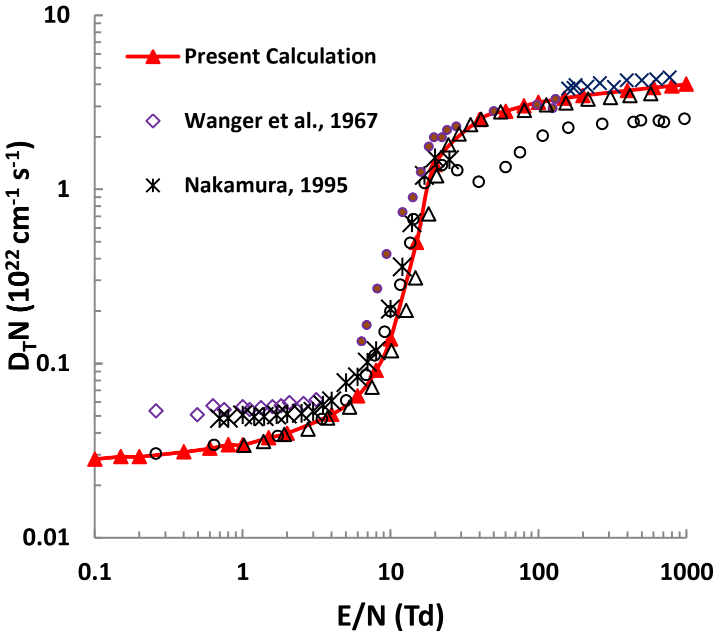

Figure 9. Reduced diffusion coefficient in CO_2 as a function of reduced electric field strength E/N.

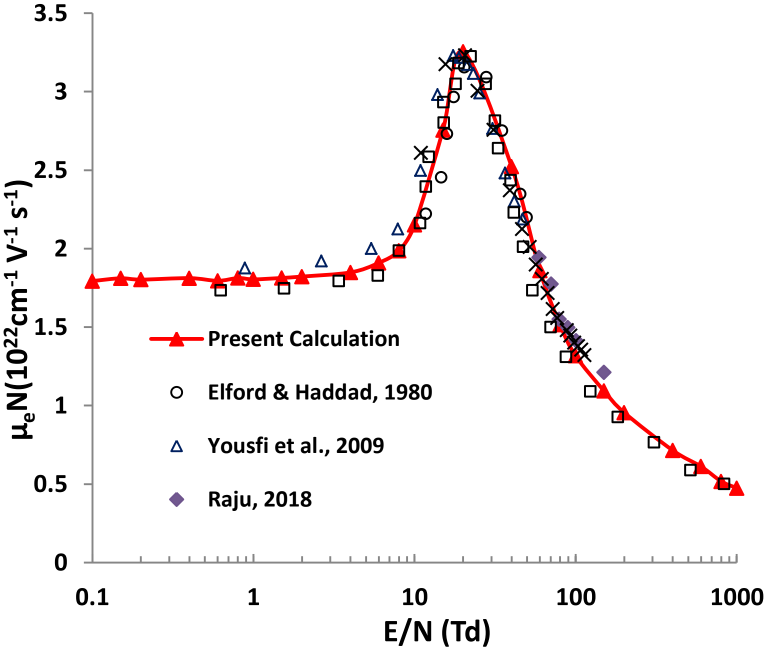

Figure 10. Reduced electron mobility in CO_2 as a function of reduced electric field strength E/N

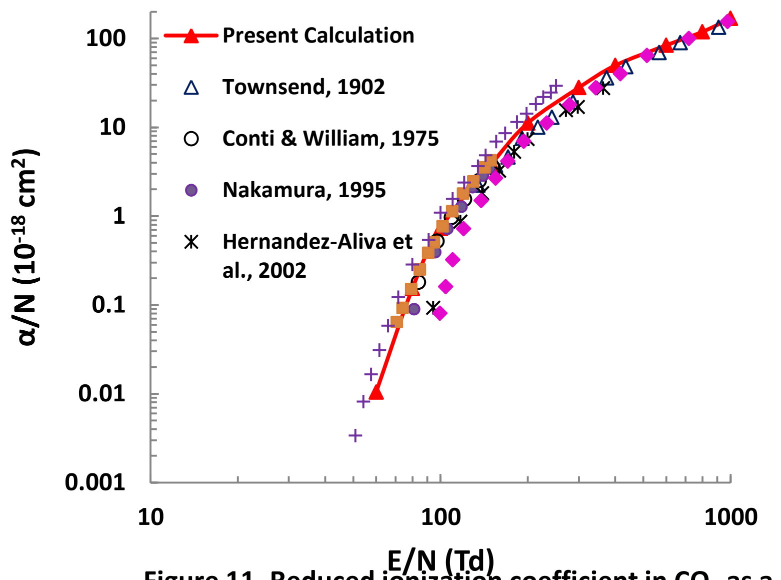

Figure 11. Reduced ionization coefficient in CO_2 as a function of reduced electric field strength E/N.

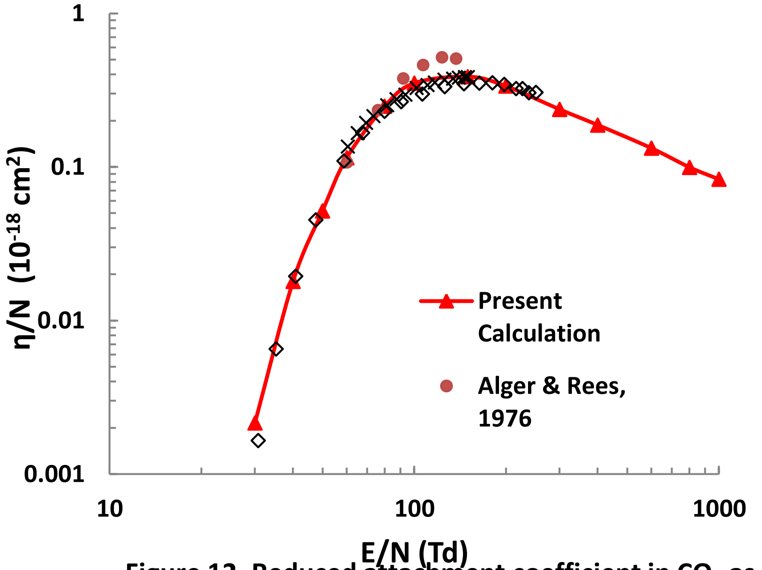

Figure 12. Reduced attachment coefficient in CO_2 as a function of reduced electric field strength E/N.

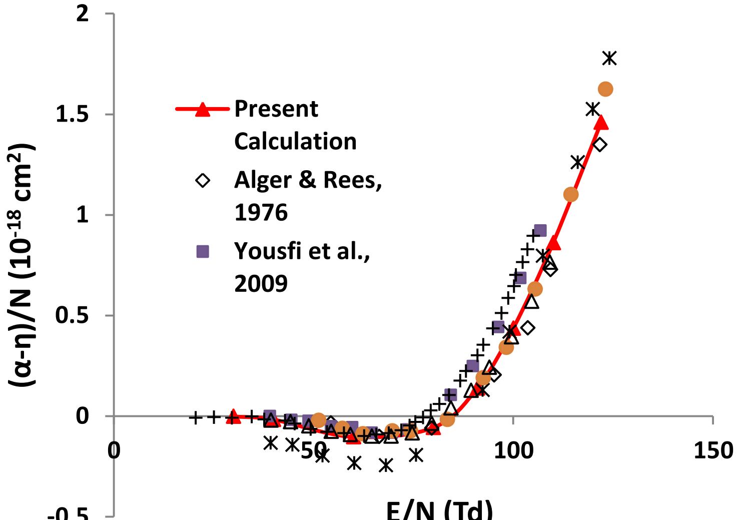

Figure 13. Effective reduced ionization coefficient in CO_2 as a function of reduced electric field strength E/N.

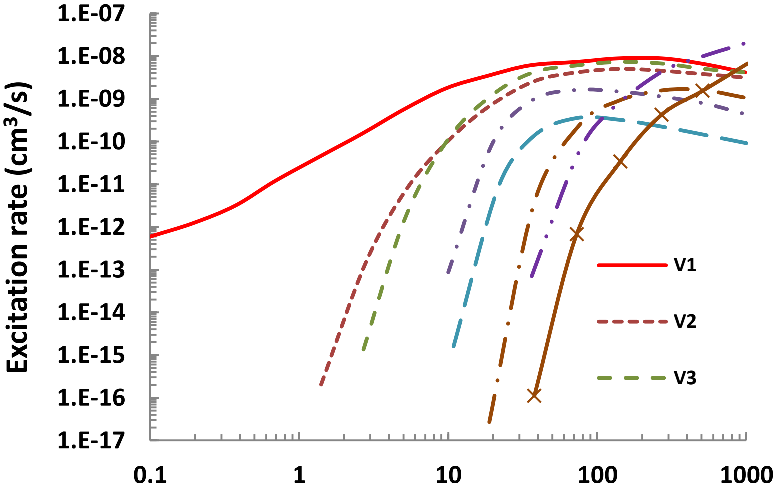

Figure 14. Electron impact excitation rates for the 010(0.083 eV), 020(0.167 eV), 030+110(0.252 eV), 001(0.291 eV), 200(0.339 eV), 300(0.505 eV) vibrational levels, electronic excitation rates E1(7.0 eV), E2(10.5 eV) and ionization (13.3 eV) as a functio

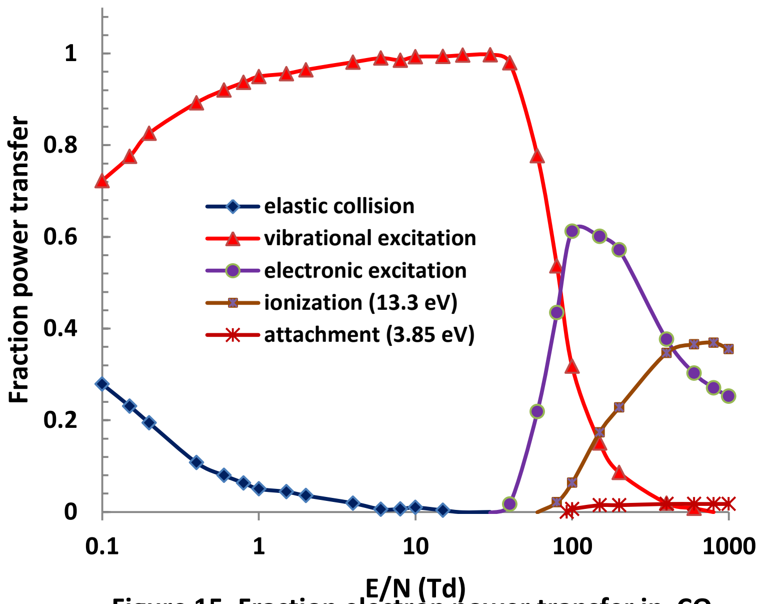

Figure 15. Fraction electron power transfer in CO_2 as a function of reduced electric field strength E/N.

5. Conclusion

The electron swarm parameters in Carbon dioxide (CO_2) have been calculated for an E/N range from 0.1 to 1000 Td using two term-solution of Boltzmann equation method , in which the influence of ionization and attachment coefficient taken into account. These parameters, namely (electron drift velocity, mean electron energy, electron temperature, characteristic energy, electron mobility and transverse diffusion coefficient) have been compared with the previous theoretical and experimental values. Also the effect of E/N, temperature and pressure on EEDF was studied. Moreover, the reduced ionization coefficient (α/N), reduced attachment coefficient (η/N) and reduced effective ionization coefficient (α-η)/N were derived from EEDF. Then the reuced critical electric field strength $(E/N)_{cr}$ are obtained from the effective ionization curve. In addition, the excitation rate and the fraction power transfer to different types of elastic and inelastic collision has been explained.

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