Global Modeling of CO$_2$ Discharges with Aerospace Applications

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We developed a global model aiming to study discharges in CO$_2$ under various conditions, pertaining to a large spectrum of pressure, absorbed energy, and feeding values. Various physical conditions and form factors have been investigated. The model was applied to a case of radiofrequency discharge and to helicon type devices functioning in low and high feed conditions. In general, main charged species were found to be CO$_2^+$ for sufficiently low pressure cases and O$^-$ for higher pressure ones, followed by CO$_2^+$, CO$^+$, and O$_2^+$ in the latter case. Dominant reaction is dissociation of CO$_2$ resulting into CO production. Electronegativity, important for radiofrequency discharges, increases with pressure, arriving up to 3 for high flow rates for absorbed power of 250 W, and diminishes with increasing absorbed power. Model results pertaining to radiofrequency type plasma discharges are found in satisfactory agreement with those available from an existing experiment. Application to low and high flow rates feedings cases of helicon thruster allowed for evaluation of thruster functioning conditions pertaining to absorbed powers from 50 W to 1.8 kW. The model allows for a detailed evaluation of the CO$_2$ potential to be used as propellant in electric propulsion devices.

1. Introduction

Global Modeling (GM) has been lately extensively used for theoretical study of various types of plasma discharges in view of their applications. Reviews of GM applications including references to older publications can be found elsewhere; see, for example, [1, 2], for an extensive bibliography on the subject. GM allowed for successful investigation of plasmas of various compositions addressing natural conditions and specifically physical conditions and form factors with various applications in mind. In what concerns CO$_2$, to which focuses the present study, its presence in the atmosphere of Earth is of paramount importance for the environment [3], being a main greenhouse gas. Besides, CO$_2$ is a constituent of various atmospheres in the solar system planets and satellites [4–6]. Carbon oxides are also present in the composition of asteroids and comets [7]. Moreover, various laboratory and industrial applications call for the study of CO$_2$ plasmas, such as various types of plasma reactors. In this domain, we compare our theoretical results with experimental ones obtained in a radiofrequency discharge [3] meant to investigate the efficiency of CO$_2$ dissociation in view of reducing the CO$_2$ emissions. We also address here specifically Electric Propulsion (EP) applications using CO$_2$ as propellant, because of its important presence in various space environments. Noteworthy, EP devices dedicated to low Mars orbit satellites propulsion are of paramount importance in this context. Also, as was the case with previous GM studies [2, 8–10] the present GM of CO$_2$ discharges can be used as a basis of atmospheric entrance studies, notably in the case of Mars (typically 95% of CO$_2$ plus N$_2$ and Ar), provided the important hydrodynamic constraints are taken into consideration.

Functioning Diagrams (FD) and the corresponding Plasma Components Composition (PCC) diagrams which are obtained in the present study are important to monitor experimentally EP devices, mainly by optical emission spectroscopy and also theoretically by comparison with corresponding results (electron temperature $T_e$, line intensities) obtained from “zero-dimensional” collisional-radiative models. The latter are also useful for calculating the resonant vacuum ultraviolet (VUV) line intensities and so evaluate the radiative plasma cooling and the erosion of the plasma facing components in thrusters. With increasing absorbed energy and functioning time, erosion evaluation becomes particularly important.

In Section 2 of the present paper, the essentials of a GM are reported summarily, together with the necessary atomic
and molecular parameters, notably those used in the CO₂ case. Atomic and molecular data being of interest to our GM are specifically addressed. Description of the GM elaboration techniques is not reported here, as it is available elsewhere (see e.g., [I, 2, II] and references therein). Also, sensitivity of the used parameters is not specifically investigated, because previous GM studies of various plasmas compositions showed in general a smooth variation [12]. In Section 3, theoretical results obtained from our model and general considerations concerning CO₂ discharges in higher pressures, pertaining to lower electron temperatures (\(T_e\)), are given and commented. They are compared in Section 4 with GM results obtained for plasmas of various compositions including mixtures with Ar and with the aforementioned experimental results for CO₂ from [3]. In Section 5, our GM results pertaining to lower pressures are given. They are of specific interest to EP because ionization is a key parameter for thrust. In general, these sufficiently ionized plasmas are characterized by quite high \(T_e\). These results can be compared with previously obtained ones for EP applications using a common propellant such as Ar but also in case of feeding with N₂O, N₂, and O₂ and with mixtures of the two latter ones, hence with the air in various altitudes. An overview of such results is given in [2]. In Section 5 FDs giving the total ionization percentage \(\xi_{\text{TOT}}\) as a function of pressure \(p\), for various absorbed power \(P_{\text{abs}}\), and \(T_e\), values and occasionally the corresponding PCCs, are presented for each EP case investigated. Concomitant \(T_e\) and \(\xi_{\text{TOT}}\) variations are also discussed in Section 5. Conclusions are given in Section 6.

2. GM Equations and CO₂ Atomic and Molecular Data

In this section, after giving a short description of the GM construction, necessary for the introduction of the basic definitions, we review the CO₂ atomic and molecular data which we had used in our model.

2.1. Summary Model Description. The GM is essentially composed of one power balance equation and of a system of particle balance equations [10]. The power balance equation, giving the power dependence of the electron density, can be written in a condensed form as follows:

\[
P_{\text{abs}} = \sum_X e_{\text{IONIX}} n_X n_e + \sum_X (e_e + \epsilon_i) k_{\text{RW,X}} n_X n_e
\]

(1)

\(X\) represents here each of the main Ground Level (GL) species, with \(k_{\text{IONIX}}\) and \(k_{\text{RW,X}}\), the corresponding ionization rate and the wall recombination rate. The total energy loss \(e_{\text{IONIX}} = e_e + \epsilon_i + e_{\text{C.X}}\) is essentially composed of three terms, \(e_e\) and \(\epsilon_i\) being the mean kinetic energy lost per electron and per ion, respectively, and \(e_{\text{C.X}}\) the energy lost to collisions of electrons with heavy particles \(X\). All \(e_{\text{C.X}}\) have to be calculated for the main considered heavy particles \(X\), namely, CO₂, CO, O, and O₂. Moreover, \(V\) represents the plasma volume and \(n_e\) and \(n_X\) are the densities of electrons and of the species \(X\), respectively, as usually. The area for effective loss \(A_{\text{eff}}\) included in the term \(k_{\text{RW}}\) of (1) is given by \(A_{\text{eff}} = 2\pi(h_t R^2 + h_p RL)\) with \(R\) and \(L\) the radius and length of the plasma and \(h_t\) and \(h_p\) the axial and radial edge to center ratios of positive ion density. These are modified Godyak factors that can be extended to high pressure, as derived in [13] or to electronegative discharges [14]. The plasma sheath depends strongly on the Bohm velocity \(u_B\), which for CO₂ is \(u_{B,\text{CO}_2} = (eT_e/M_{\text{CO}_2})^{1/2}\), where \(e\) is the electron charge and \(M_{\text{CO}_2}\) is the mass of the CO₂ molecule. An example of sheath calculation has been given in [10]. For the plasma reactor case, we use a combined cross section value of 285 Å² for the ion moment transfer corresponding to an ionic sheath composition of 40% CO₂, 40% of CO³, and 20% of O₂.

Each of the particle balance equations is constituted by the sum of all the creation and destruction terms for a given species \(j\) and can be written:

\[
\frac{dn_j}{dt} = \sum R_{\text{Production}}^j - \sum R_{\text{Loss}}^j
\]

(2)

where \(\sum\) denotes the sum of all \(R_{\text{Production}}^j\) and \(R_{\text{Loss}}^j\) terms. For an equation pertaining to \(j\), each term includes production or loss rates involving the species \(j\). Production and loss reaction rates are given by the product of the reactant densities \(n_i\) with the corresponding rate coefficient \(k_j:\)

\[
R_j = k_j \cdot \prod n_i \quad \text{(cm}^{-3} \text{ s}^{-1})
\]

(3)

2.2. Atomic and Molecular Data Description. A list of the considered CO₂ states with their energies is given in Table 1. Inelastic reactions considered in the model are given in Tables 2 to 4 including occasionally references where they have been previously reported. Table 1, containing structure data of CO₂, includes the energies of the excited states, both electronic and vibrational. Excitation of all those states is taken into account by the collisional energy loss term \(e_{\text{C.CO}_2}\). The character of each electronic transition, allowed or forbidden, is indicated following [15]. Energy values were taken from [16, 17] and excitation cross sections used in \(e_{\text{C.CO}_2}\) from [15, 16]. The list of the 20 processes included in the GM, involving the CO₂ and CO species and their ions, is given in Table 2. Note that CO₂ elastic scattering rate is introduced only in the power balance equation under \(e_{\text{C.CO}_2}\), in order to determine the entirety of energy losses, including those coming from various types of GL excitation, dissociation, and ionization. Reaction rates are separately included in the respective particle balance equations and participate in the determination of the populations provided by the set of the statistical equations. Table 3 gives the list of the 20 processes involving oxygen species included in the GM. Processes involving carbon species are contained in Table 4. Table 3 constitutes an extended version of Table 4 appearing in [12]. No source is given for cross sections/rate coefficients for which references are available in [12]. Moreover, reference [17] contains an extended list of related references. It has to be noted that C₂ formation on the wall has been neglected in the present status of the model. Rates for
Table 1: Structure description of the states of CO$_2$ as included in the GM.

<table>
<thead>
<tr>
<th>i</th>
<th>Configuration</th>
<th>Energy (eV)</th>
<th>Type</th>
<th>Excitation energy sources</th>
<th>Excitation cross sections sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$^3X$</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$^3X$ (010)</td>
<td>0.083</td>
<td></td>
<td>[16, 17]</td>
<td>a, b in [16]</td>
</tr>
<tr>
<td>3</td>
<td>$^3X$ (100)</td>
<td>0.172</td>
<td></td>
<td>[16, 17]</td>
<td>b, c in [16]</td>
</tr>
<tr>
<td>4</td>
<td>$^3X$ (001)</td>
<td>0.29</td>
<td></td>
<td>[16, 17]</td>
<td>a, b in [16]</td>
</tr>
<tr>
<td>5</td>
<td>$^3\Sigma_u^+$</td>
<td>8.15</td>
<td>Forbidden</td>
<td>d in [16]</td>
<td>e in [15]</td>
</tr>
<tr>
<td>6</td>
<td>$^3\Pi_g$</td>
<td>8.73</td>
<td>Forbidden</td>
<td>d in [16]</td>
<td>e in [15]</td>
</tr>
<tr>
<td>7</td>
<td>$^3\Delta_u$</td>
<td>8.80</td>
<td>Forbidden</td>
<td>d in [16]</td>
<td>e in [15]</td>
</tr>
<tr>
<td>8</td>
<td>$^3\Pi_g$</td>
<td>8.93</td>
<td>Allowed</td>
<td>d in [16]</td>
<td>e in [15]</td>
</tr>
<tr>
<td>9</td>
<td>$^3\Sigma_u^+$</td>
<td>9.32</td>
<td>Allowed</td>
<td>d in [16]</td>
<td>e in [15]</td>
</tr>
<tr>
<td>10</td>
<td>$^3\Pi_u$</td>
<td>11.00</td>
<td>Allowed</td>
<td>d in [16]</td>
<td>e in [15]</td>
</tr>
<tr>
<td>11</td>
<td>$^3\Pi_u$</td>
<td>11.31</td>
<td>Forbidden</td>
<td>d in [16]</td>
<td>e in [15]</td>
</tr>
<tr>
<td>12</td>
<td>$^1\Pi_u$</td>
<td>11.39</td>
<td>Allowed</td>
<td>d in [16]</td>
<td>e in [15]</td>
</tr>
</tbody>
</table>

a: Nakamura [18]; b: Kitajima et al. [19]; c: Kochem et al. [20]; d: Nakatsuji [21] as reported in [16]; e: extrapolated in the low energy region following the Quasi-Classical approximation.

Table 2: Reactions involving CO$_2$, CO$_3^+$, CO, and CO$^+$ species considered in the CO$_2$/CO plasma kinetics.

<table>
<thead>
<tr>
<th>Number</th>
<th>Process Description</th>
<th>Source for the cross section/rate coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CO$_2$ + e$^-$ → CO$_2$ + 2e$^-$ (I) CO$_2$ ionization</td>
<td>f in [16]</td>
</tr>
<tr>
<td>2</td>
<td>CO$_2$(v = 0) + e$^-$ ↔ CO$_2$(v) + e$^-$ (II) CO$_2$ vib. (de-)excitation</td>
<td>a, c in [16], see Table 1</td>
</tr>
<tr>
<td>3</td>
<td>CO$_2$ + e$^-$ → O$^+$ + CO + 2e$^-$ (IV) CO$_2$ dissociative ionization</td>
<td>f in [16]</td>
</tr>
<tr>
<td>4</td>
<td>CO$_2$ + e$^-$ → CO$^+$ + O + 2e$^-$ (V) CO$_2$ dissociative ionization</td>
<td>f in [16]</td>
</tr>
<tr>
<td>5</td>
<td>CO$_2$ + e$^-$ → CO$^+$ + O$^+$ (IV) CO$_2$ dissociative attachment</td>
<td>h in [16]</td>
</tr>
<tr>
<td>6</td>
<td>CO$_2$ + e$^-$ → CO + O (1D) + e$^-$ (II) CO$_2$ dissociation</td>
<td>g in [16]</td>
</tr>
<tr>
<td>7</td>
<td>CO$_2$ + e$^-$ → CO + O (3P) + e$^-$</td>
<td>CO$_2$ dissociation</td>
</tr>
<tr>
<td>8</td>
<td>CO$_2$ + e$^-$ → CO + O$^+$ (IV) CO$_2$ dissociative attachment</td>
<td>h in [16]</td>
</tr>
<tr>
<td>9</td>
<td>CO$_2$ + e$^-$ → CO$_2$ + O$^+$</td>
<td>CO$_2$ recombination with O$^+$</td>
</tr>
<tr>
<td>10</td>
<td>CO$_2$ + e$^-$ → CO + O$^+$ (V) CO$_2$ dissociative attachment</td>
<td>i in [4]</td>
</tr>
<tr>
<td>11</td>
<td>CO + e$^-$ → CO$^+$ + 2e$^-$ (III) CO$_2$ dissociative ionization</td>
<td>CO$_2$ recombination leading to the O(3P) products.</td>
</tr>
<tr>
<td>12</td>
<td>CO + e$^-$ → C$^+$ + O + 2e$^-$ (IV) CO$_2$ dissociative ionization</td>
<td>[17]</td>
</tr>
<tr>
<td>13</td>
<td>CO + e$^-$ → C + O$^+$ + 2e$^-$ (IV) CO$_2$ dissociative ionization</td>
<td>[17]</td>
</tr>
<tr>
<td>14</td>
<td>CO + e$^-$ → C + O$^+$ + e$^-$ (IV) CO$_2$ dissociative attachment</td>
<td>[17]</td>
</tr>
<tr>
<td>15</td>
<td>CO$_2$ + e$^-$ → C + O (IV) CO$_2$ dissociative attachment</td>
<td>[17]</td>
</tr>
<tr>
<td>16</td>
<td>CO + e$^-$ → C$^+$ + O</td>
<td>CO$_2$ recombination leading to the O(3P) products.</td>
</tr>
<tr>
<td>17</td>
<td>CO$^+$ + O$^-$ → CO + O (IV) CO$_2$ recombination with O$^-$ (IV) CO$_2$ dissociative attachment</td>
<td>Evaluation, present work</td>
</tr>
<tr>
<td>18</td>
<td>CO + O(1D) → CO + O$^+$ (IV) CO$_2$ recombination with O$^-$</td>
<td>Evaluation, present work</td>
</tr>
<tr>
<td>19</td>
<td>CO$_2$ + O(1D) → CO + O$_2$ (IV) CO$_2$ dissociation with O(1D)</td>
<td>j in [23]</td>
</tr>
<tr>
<td>20</td>
<td>CO + O(1D) → CO$_2$ (IV) CO$_2$ formation from O(1D) + CO</td>
<td>Evaluation, present work</td>
</tr>
</tbody>
</table>

f: Lindsay and Mangan [24]; g: LeClair and McConkey [25]; h: Rapp and Briglia [26] as reported in [16]; i: Seiersen et al. [27] as reported in [4]; j: Sedlacek et al. [28] as reported in [23].

(I) Ionization rates from vibrationally excited levels of CO$_2$, based on values for ionization from CO$_2$($v = 0$) multiplied by a factor of 1.5.

(II) Vibrational (de-)excitation for $v = 001, 010$, and 100 values.

(III) Using the rate for CO$_2$ dissociation leading to the O(3P) products.

(IV) The CO$_2$ dissociative attachment rate from vibrationally excited levels is based on values for ionization from CO$_2$($v = 0$) multiplied by a factor of 1.5.

(V) We used rate coefficient reported in [4] divided by a factor of 3.

Reactions listed in Tables 1 to 4 were obtained by integration of cross sections, when the latter are available.

Excitation, dissociation, and ionization rates entering in (1) and (2) have been separately calculated and/or evaluated using our standard computer codes and also available measurements. To obtain the rate coefficients introduced in our GM, the evaluated cross sections have been integrated from threshold up to around 500 eV over a Maxwellian distribution. In doing so, available elastic collision cross sections have been interpolated for higher collision energies. Rate coefficients have been parameterized with algebraic polynomials and are all valid in the range 0.1 to 100 eV, following standard procedures detailed in [29]. Occasionally, these are noted by indexes corresponding to the process...
Table 3: Reactions involving oxygen species considered in the CO₂ plasma kinetics.

<table>
<thead>
<tr>
<th>Number</th>
<th>Process</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>O + e⁻ → O⁺ + 2e⁻</td>
<td>O ionization</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>O⁺ wall → O</td>
<td>O⁺ wall recombination</td>
<td>Formula (4), from [22]</td>
</tr>
<tr>
<td>3</td>
<td>O₂ wall → (1/2) O₂</td>
<td>O₂ wall formation</td>
<td>Formula (5), from [22]</td>
</tr>
<tr>
<td>4</td>
<td>O₂ + e⁻ → O₂⁺ + 2e⁻</td>
<td>O₂ ionization</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>O₂⁺(v = 0) + e⁻ ↔ CO₂(v) + e⁻</td>
<td>O₂⁺ vib. (de-)excitation</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>O₂⁺ wall → O₂</td>
<td>O₂⁺ wall recombination</td>
<td>Formula (4), from [22]</td>
</tr>
<tr>
<td>7</td>
<td>O₂ + e⁻ → O + O</td>
<td>O₂⁻ diss. recombination</td>
<td>[31]</td>
</tr>
<tr>
<td>8</td>
<td>O₂ + e⁻ → 2O(3P) + e⁻</td>
<td>O₂ dissociation</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>O₂ + e⁻ → O(1D) + e⁻</td>
<td>O₂ dissociation</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>O(1D) wall → O(1P)</td>
<td>O(1D) wall deexcitation</td>
<td>Formula (5), from [22]</td>
</tr>
<tr>
<td>11</td>
<td>O(1P) + e⁻ → O(1D) + e⁻</td>
<td>O(1D) excitation/deexc.</td>
<td>Formula (5), from [22]</td>
</tr>
<tr>
<td>12</td>
<td>O(1D) wall → (1/2) O₂</td>
<td>O₂ wall formation</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>O(1D) + e⁻ → O⁺ + 2e⁻</td>
<td>O(1D) ionization</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>O₂ + e⁻ → O⁺ + O + e⁻</td>
<td>O₂ diss. attachment</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>O₂ + e⁻ → O⁺ + O⁺ + e⁺</td>
<td>O₂ dissociative ionization</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>O₂ + e⁻ → O⁺ + O⁺ + 2e⁺</td>
<td>O₂ dissociative ionization</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>O⁺ + O⁻ → 2O</td>
<td>O⁺ recombination with O⁻</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>O₂⁺ + O⁻ → O₂ + O</td>
<td>O₂⁺ recombination with O⁻</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>O + O⁻ → O₂ + e⁻</td>
<td>O⁺ recombination with O</td>
<td>[32]</td>
</tr>
<tr>
<td>20</td>
<td>O₂ + O⁻ + O₂⁺ → O + O₂⁺⁺</td>
<td>O⁺/O₂⁺⁺ charge exchange</td>
<td>[33]</td>
</tr>
</tbody>
</table>

(VI) Vibrational (de-)excitation for v = 1 and v = 2 values.

Table 4: Reactions involving carbon species considered in the CO₂ plasma kinetics.

<table>
<thead>
<tr>
<th>Number</th>
<th>Process</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CO₂ + e⁻ → C⁺ + 2O + 2e⁻</td>
<td>CO₂ diss. ionization</td>
<td>f in [16]</td>
</tr>
<tr>
<td>2</td>
<td>C⁺ wall → C</td>
<td>C⁺ wall recombination</td>
<td>Formula (4), from [22]</td>
</tr>
<tr>
<td>3</td>
<td>C + e⁻ → C⁺ + 2e⁻</td>
<td>C⁺ ionization</td>
<td>[34]</td>
</tr>
<tr>
<td>4</td>
<td>C⁺ + CO → C⁺ + CO⁺</td>
<td>C⁺/CO⁺ charge exchange</td>
<td>Evaluation, present work</td>
</tr>
<tr>
<td>5</td>
<td>C⁺ + O⁻ → C⁺ + O⁺</td>
<td>C⁺/O₂⁺ recombination</td>
<td>Evaluation, present work</td>
</tr>
</tbody>
</table>

f: Lindsay and Mangan [24], as reported in [16].

(IONIZ, RW, ...) or to the state (X, X⁺, ...), as is the case in (I). Collisions involving the wall (wall recombination RW, X⁺ and deexcitation DXW, j) have rates described by the formulas proposed in [22]:

\[ k_{\text{RW},X} = \frac{\nu_{\text{LX+}} A_{\text{eff}}}{V} \left( \text{s}^{-1} \right) \]  \hspace{1cm} (4)

\[ k_{\text{DXW},j} = \left[ \frac{\Lambda^2}{D_j} + \frac{2V(2-\gamma_j)}{A_{\text{eff}}\nu_j} \right]^{-1} \left( \text{s}^{-1} \right) \]  \hspace{1cm} (5)

with \( \Lambda^2 = (\pi/L)^2 + (2.405/R)^2 \) the effective diffusion length and \( D_j \) the neutral diffusion coefficient of excited species \( j \). The latter is given by \( D_j = (k_BT_{\text{GAS}}\lambda_j)/(\nu_j M_j) \), where \( k_B \) represents the Boltzmann constant and \( T_{\text{GAS}} \) is the gas temperature. The mean free path for collisions between two neutral species is \( \lambda_j = 1/\pi \sigma_{j,X} \), where \( \sigma_{j,X} \) is the cross section pertaining to state \( j \) of the one species with the other species \( X \). Moreover, \( \nu_j \) is the neutrals mean velocity \( \nu_j = (8k_BT_{\text{GAS}}/\pi M_j)^{1/2} \) and \( \gamma_j \) is the sticking coefficient for the excited species \( j \) on the wall surface. For CO₂(ν) and for O₂(ν)

we used here \( \gamma = 0.5 \). For O₂ formation on the wall, we also use (5) but conveniently adapted to the considered O species, with sticking parameter value \( \gamma_O = 0.17 \). This value has been previously proposed for stainless steel by [30].

2.3. Energy Losses from Electron Collisions in Low Ionization Cases. Determining the total collisional energy losses per electron-ion pair created is an important part of the development of a GM. It is essential for the power balance equation formulation, relating the electron density \( n_e \) to the input power as a function of the plasma constituents and of their energy losses due to collisions with electrons as a function of \( T_e \). For each atomic or molecular species, energy is mainly lost by elastic scattering (ELAS), ionization (IONIZ), electronic excitation (EXC), vibrational excitation (VIB), and dissociation (DISS) processes, noted by the corresponding indexes as previously. These abbreviations are also used occasionally in the figures.

Whenever the ionization percentage is low (e.g., as in plasma reactors with ionization of about 1% or less), with \( T_e \) not too high, the energy losses due to ions can be neglected.
In this case, evaluation of the collisional energy losses, noted here $\varepsilon_{C,\text{CO}_2}$, is based on the following equation:

$$
\varepsilon_{C,\text{CO}_2} = E_{\text{IONIZ},\text{CO}_2} + E_{\text{ELAS},\text{CO}_2} \frac{k_{\text{ELAS,CO}_2}}{k_{\text{IONIZ},\text{CO}_2}} + \sum_j E_{\text{VIB}\text{CO}_2,j} \frac{k_{\text{VIB,CO}_2,j}}{k_{\text{IONIZ},\text{CO}_2}} + \sum_j E_{\text{EXC,CO}_2,j} \frac{k_{\text{EXC,CO}_2,j}}{k_{\text{IONIZ},\text{CO}_2}} + \sum_k E_{\text{DISS,CO}_2,k} \frac{k_{\text{DISS,CO}_2,k}}{k_{\text{IONIZ},\text{CO}_2}}$

(6)

involving specifically CO$_2$. The $\varepsilon_{C,\text{CO}_2}$ values, which we obtained, and consequently the electron density calculated by the GM are also here very sensitive on the values of the ionization cross sections, hence on the rate coefficients introduced in the collisional energy losses calculation. An equation similar to (6) exists, valid for $\varepsilon_{C,\text{CO}}$ parameter.

In case of plasma reactors functioning in inductively coupled plasma mode, most of the created ions are expected to recombine on the metallic wall and in view of the absorbed power the ionization percentage does not usually exceed 1%. In such conditions, given the also low percentage of the excited states population, the energy is practically lost by electron collisions with neutral ground level particles $e^{-}+\text{CO}_2$, $e^{-}+\text{CO}$, $e^{-}+\text{O}_2$, $e^{-}+\text{O}$ through elastic, ionization, and excitation processes. As populations of carbon species are expected to be quite smaller, losses by ionizing $e^{-}+\text{C}$ collisions have not been taken into account. This is also the case for the ionized species collisions, of which densities are often orders of magnitude smaller.

The main rate coefficients concerning CO$_2$, which we have used in the present GM, are shown in Figure 1 in order to ease the comparison of their relative importance.

The general properties of the electron collisional energy loss parameter are very important in determining where the absorbed energy is spent. Omitting significant components from the set of collisional processes entering in the model pattern may result to a considerable lowering of the corresponding electron collisional energy loss parameter values. In principle, values corresponding to molecules are much higher than those of C, O, and Ar plasmas of low $T_e$ containing less than 1% of atoms, due to the presence of extravalent states.

We evaluated the collisional energy losses of the CO$_2$, CO, O$_2$, and O that are of interest here mostly on the basis of cross sections coming from the literature. Especially for the last two species, see [2] and references therein. References pertaining to CO$_2$ have been given previously. Especially for CO, main references providing cross sections used for evaluation are [35–37] besides [17]. Elastic collision cross sections are very similar in CO$_2$ and CO. The obtained electron collisional energy loss parameters for both of them are given in Figure 2 (black curve for CO$_2$ and red one for CO) in the region of about 1 eV to 100 eV. The values become comparable in the region of about four eV.

3. Theoretical Results Pertaining to Pressure and Power Variations

We present and discuss GM results obtained for CO$_2$ discharges in a large region of pressures, typically from 1 mTorr to 1 Torr. We evaluate the plasma constituents densities, the $T_e$, the remaining CO$_2$ percentage, and the total ionization percentage $\xi_{\text{TOT}}$ for a typical discharge form factor of $L = 30.0$ cm and $R = 8.0$ cm. These dimensions are practically the same as those of the experiment reported in [3]. The model could in principle give valid results even for higher pressures, provided that the number of terms in the power balance equation is extended to encompass more vibrational states of CO$_2$, CO, and O$_2$ molecules and their reactions and that the number of the particle balance equations is increased.
3.1 Discharge Characteristics as a Function of the Pressure for 250 W of Absorbed Power. We assume here a gas temperature $T_{\text{GAS}} = 400$ K. Results pertaining to a lower feeding of 15 sccm are shown in Figures 3 to 5.

Density values for $n_e$ and ionic species are shown in the bottom of Figure 3 multiplied by 100. Those pertaining to values of $p > 40$ mTorr, not shown in order to simplify the figure, are given in Figure 4. The obtained total plasma density and densities of CO$_2$, CO, O$_2$, and O and of their ions are shown for a low feeding of 15 sccm. Results of calculations of the two O atom ground levels (GL), O($^3$P) and O($^1$D), densities are given separately. Also, $v = 0$ indicates population densities of ground vibrational levels and the prefix Tot shows total density values. We see in Figure 3 that CO is slightly more present in the discharge than the total CO$_2$ (Tot CO$_2$) for low pressures. The inverse is true for high pressures, say after 100 mTorr. Densities of the GLs of atomic oxygen are higher than those of O$_2$, for lower pressures, where the latter is more easily dissociated, while for higher pressures O$_2$ density becomes an order of magnitude higher than the O($^3$P) GL one. The O($^1$D) densities, being much smaller than those of O($^3$P), are shown multiplied by 100. The presence of C in the discharge is lower than that of O, down to an order of magnitude for high pressures. High pressure densities of neutral components are varying following approximately a slope of $p/k_B \cdot T_{\text{GAS}}$. The plasma is low ionized, with the ion densities strongly diminishing after 100 mTorr and tending to a slope around $1/n_{\text{TOT}}$, where $n_{\text{TOT}}$ represents the total density including all species.

The low ionized species densities are shown separately in Figure 4 in the 40 mTorr to 600 mTorr pressure region. Densities of positive ions CO$_2^+$, CO$^+$, and O$_2^+$ diminish to a rather similar way with increasing pressure. However, O$^-$ density leading to electronegativity bypasses this of CO$_2^+$ after 200 mTorr. O$^-$ and C$^-$ densities become negligible. Figures 3 and 4 illustrate the continuous diminishing of the electron density $n_e$.

As is shown in Figure 5, when the pressure increases from 1 mTorr to 1 Torr, $T_e$ is falling from about 4.4 eV to about 1.2 eV while the remaining CO$_2$ amount increases slowly, beginning from 28% for low pressures before stabilizing to about 43%. The quotient of the total O atoms to this of C atoms remains evidently equal to 2.
While our results for a 15 sccm feeding indicate a percentage of the remaining CO₂ stabilizing to about 43%, this corresponding to a higher feed of 100 sccm shows the same tendency but leading to a higher percentage, of 73% approximately. Obviously, the absorbed power of 250 W considered in both cases while being able to dissociate more than half of CO₂ for the low feeding is not sufficient to dissociate much more than a quarter of the provided CO₂ when the feeding increases to 100 sccm.

Results pertaining specifically to a higher feeding of 100 sccm are shown in Figures 6 to 8. In Figure 6, similar to Figure 3 but for a high feeding, the total plasma density and densities of CO₂, CO, O₂, and C of their ions together with O²⁻(P) and O²⁺(D) values are also given as a function of the pressure. Density values for nᵣ and ionic species are shown in the bottom of Figure 6 multiplied by 100. Except for CO₂⁺⁺, values for ionic species pertaining to values of $p > 40$ mTorr, not shown in order to simplify the figure, are given in the next Figure 7. We see that here CO is less present than Tot CO₂ in the discharge, followed by O₂. For lower pressures, densities of the atomic oxygen GLs are clearly higher than this of O₂, where the latter is more easily dissociated, while for higher pressures, O₂ density is almost an order of magnitude higher than the atomic oxygen one. Here also, densities of neutrals vary approximately according to a slope of $p/k_B \cdot T_{GAS}$. The plasma is low ionized, with the ion densities diminishing after 100 mTorr following a slope proportional to $1/T_{TOT}$.

As was the case in Figure 4, pertaining to a 15 sccm feeding, we show separately in Figure 7 our ion densities results for high pressures (40 mTorr to 600 mTorr). Variations are analogous to those shown in Figure 4 but with O⁺ being quite more abundant than C⁺, with differences being up to one order of magnitude for low pressures.

We show in Figure 8 that, with increasing pressure, $T_e$ is falling from about 4.2 eV to about 1.3 eV as was the case with 15 sccm feeding, while the remaining CO₂ amount starts from...
61% for 1 mTorr and becomes 73% for 1 Torr, quite different than in the 15 sccm case, shown in Figure 5.

3.2. Influence of the Absorbed Power. It is also interesting to know for a given feeding how the discharge properties vary with $P_{abs}$, when the pressure is kept constant. Typical results obtained for the low feeding of 15 sccm addressed previously are illustrated in Figures 9 to 11 for a pressure of 80 mTorr. Results are calculated for absorbed power values varying from 80 W to 1000 W and are illustrated by small symbols, joined by lines to ease the eye. For the sake of simplicity, only neutral species densities values are shown in Figure 9. Those of ionic species are given separately in Figure 10. Note that no symbols are included to mark the $n_e$ and ionization percentage $\xi_{TOT}$ values in the corresponding curves. Experimental values from [3] illustrated in Figures 9 to 14 by big symbols will be discussed in the next section, where experimental results for various gases pressures and mixtures will be also addressed.

Figure 9 shows a PCC as a function of the absorbed power $P_{abs}$ for a $n_{TOT}$ value of $2 \cdot 10^{15}$ cm$^{-3}$. Main components are total CO$_2$ (Tot CO$_2$) and CO with the latter starting evidently from lower density values than the former but arriving to about double values for 1 kW of absorbed power. O$_2$ densities increase slightly both for Tot O$_2$ and for vibrational state $v = 0$. O(3P) density, an order of magnitude lower than this of Tot CO$_2$, increases with absorbed power and finally exceeds this of Tot O$_2$. O(1 D) density is roughly two orders of magnitude smaller. The C density is one order of magnitude lower that the density of O(3P) for an absorbed power of 80 W, the difference diminishing for high absorbed powers.

Ionized components are separately shown in Figure 10 and have quite low densities. Densities of CO$^+$, O$_2^+$, C$^+$, and O$^+$ components presented in Figure 10 start from low values for 80 W and increase with absorbed power. Inspection of Figure 10 shows that with increasing absorbed power the O$^-$ and CO$^+_2$ densities remain about the same, although slightly diminishing, while CO$^+$ and O$_2^+$ densities increase considerably. Densities of singly ionized positive atomic species (C$^+$, O$_2^+$) start from very low densities for low $P_{abs}$ but increase with $P_{abs}$ considerably, much faster than...
Plain lines: present results
Big symbols: EXPER. Spencer and Gallimore 2011 [3]
- EXPER. remaining CO₂%
- GM remaining CO₂%
- Typical experiment Tₑ
- GM Tₑ
- GM ionization% (x10³)
- GM electronegativity

Figure 11: Remaining CO₂, Tₑ, ξTOT, and α as a function of the absorbed power Pₐbs; EXPER stands for experiment.

the molecular ones (up to two orders of magnitude). For 1 kW, densities of C⁺ and of O⁺ become the same as this of CO₂⁺. As expected, nₑ is increasing with the absorbed power, reaching quite higher values than those which are commonly encountered for Pₐbs < 500 W. Important results concerning the remaining CO₂ percentage in the discharge and the electronegativity (empty stars) are illustrated in Figure II, together with Tₑ values shown by the red line joining squares.

Both remaining CO₂ (full black squares) and electronegativity α (empty stars) are fast diminishing with increasing absorbed power and in rather similar way. In Figure II, calculated Tₑ values noted by red squares are also illustrated. They have rather low values and vary very little. Inversely, the ξTOT values represented by the blue line although increasing with Pₐbs they remain clearly very small; hence, they are shown multiplied by a factor of 10³.

Results obtained for a higher feeding of Q₂CO₂ = 100 sccm and for 280 mTorr pressure are illustrated in Figures 12, 13, and 14 in a similar way with Figures 9, 10, and 11 correspondingly. Typical Q₂CO₂ and p values have been selected in order to ease the comparison with the available experiment of [3].

Comparing the PCCs shown in Figures 9 and 12 we see that CO density never reaches the CO₂ density values illustrated in the second figure. This fact was expected, as the feeding is significantly higher while the absorbed power remains the same. The ionic components shown in Figure 13 present a quite bigger difference between O⁺ and C⁺ densities than this shown in Figure 10 for the same ions, suggesting that for large feedings O atoms are ionized preferably than C ones.

Finally, the remaining CO₂ shown in Figure 14 varies much slower than in the low fed discharge of Figure II, as the absorbed powers are not sufficient to dissociate the CO₂ in case of abundant feeding. Electronegativity α (empty stars) is here much higher than in the case shown in the analogous Figure II and ionization percentage ξTOT (blue line) is an order of magnitude smaller.
In the following we compare experimental results from the Cathode Test Facility at the Plasmodynamics and Electric Propulsion Laboratory (PEPL) of the University of Michigan, III, published in [3], with the corresponding theoretical results of our model. In this experiment, a radiofrequency discharge constituted by a cylinder of length of about 30 cm (approximate value taken from the Figure 1 diagram of [3]) and of radius 7.5 cm ends in a chamber of 244 cm of length and of 61 cm of diameter. It is powered by 1kW radiofrequency double helix antenna supply of 13.56 MHz. Although Cathode Test Facility was mainly fed by CO\textsubscript{2}, additional Ar feeding was also provided, results of which we consider of minor importance for the moment; we address this subject later on. Details on the facility and results on CO\textsubscript{2} dissociation in radiofrequency discharges are given in [3] and references therein. Specifically, experimental results addressed here are taken from Figures 2(a) and 2(b) of [3]. They have been included in Figures 3 to 14 of the previous section, noted by big symbols and by the mentioned "experiment". Full pink stars are used for \(n_\text{TOT}\) and triangles, squares, and inverse triangles are used for CO, Tot CO\textsubscript{2}, and Tot O\textsubscript{2} densities correspondingly.

Figures 3 to 5 and Figures 6 to 8 compare pressure depending results and Figures 9 to 11 and Figures 12 to 14 power depending ones for the previously chosen cases of 15 sccm low feeding and of 100 sccm high feeding correspondingly. A pressure around 80 mTorr has been chosen for the low feeding of 15 sccm case and a higher pressure of around 280 mTorr and more for the high feeding of 100 sccm. Note that typical form factors selected for our calculations which are shown in the figures are very near to those pertaining to the experiment. Double values are occasionally indicated for the experiment, because of small discrepancy in theory-experiment pressures. In any case, the two values indicated for Q\textsubscript{CO\textsubscript{2}} = 15 sccm feeding are always very close. In Figure 3 the total theoretical density \(n_\text{TOT}\) varies with a slope of \(p/k_B T_{\text{GAS}}\). We used our theoretical values of \(n_\text{TOT}\) to obtain approximate absolute values of the densities corresponding to the experiment, as only the values of the exhausting flow rates are provided in [3]. For \(P_{abs} = 250\) W, theoretical total CO\textsubscript{2} (Tot CO\textsubscript{2}) and CO values are in very good agreement with experimental ones, with total O\textsubscript{2} (Tot O\textsubscript{2}) values slightly higher than the experiment. Ion densities, being significantly lower, have not been measured; therefore, no comparison is possible for the theoretical results shown in Figures 4 and 7. The vertical green bar shows typical \(n_e\) values reported in [3] with the green curve giving theoretical \(n_e\) values. These are in agreement in the case of Figures 3 and 4 with the commonly expected values mentioned in [3]. Figure 5 gives theoretical values obtained for the remaining CO\textsubscript{2} percentage which are slightly lower than the experimental ones for a pressure slightly less than 100 mTorr.

Figure 6, which pertains to a feed of Q\textsubscript{CO\textsubscript{2}} = 100 sccm for the same absorbed power of 250 W, shows the experimental \(n_\text{TOT}\) identified to the theoretical one, the latter varying according to the same slope of \(p/k_B T_{\text{GAS}}\) given in the Figure 3 case. Experimental values of Tot CO\textsubscript{2} in pressures about 300 mTorr are in total agreement with the theory, while the latter gives CO and O\textsubscript{2} densities slightly higher than the experiment. Calculated electron densities \(n_e\) are within \(10^{11} - 10^{13}\) cm\textsuperscript{-3}, as expected. The calculated remaining CO\textsubscript{2} percentage in this case is in very good agreement with the experiment, while \(T_e\) values are rather low. It is to be noted that we have made an approximate evaluation of the remaining CO\textsubscript{2} when following the experiment. The experimental values of the remaining CO\textsubscript{2} percentage, appearing in the figures (namely, Figures 5, 8, 11, and 14), have been calculated by us without taking into account the other plasma constituents and notably the atomic oxygen O(\(^3\)P) which, according to our calculations, is present in a considerable amount. Reference of its presence was made in [3]. Hence, the experimental values to be compared with our calculations should be slightly smaller if the O(\(^3\)P) presence was taken into account. For a more accurate calculation of the remaining CO\textsubscript{2} percentage, see Table 5 in the following. Inspection of Figure 8 shows a very good agreement of theory with experiment for the remaining CO\textsubscript{2} percentage for a pressure about 300 mTorr. However, theoretical \(T_e\) values are quite lower (about half) than those expected (red vertical bar) in this pressure region.

Variations of the theoretical plasma component densities of the PCC for 15 sccm shown in Figure 9 compare rather favorably with the experimental data. However, it has to be noted that, although this PCC refers to 80 mTorr pressure,
the compared experimental pressure values are in fact slowly increasing with the absorbed power, going up to 103 mTorr for 1 kW. Also, the calculated electron density is rather higher than the typical one for high $P_{abs}$.

For a low feeding of $Q_{CO_2} = 15$ sccm, Figure 11 shows theoretical values of the remaining CO$_2$ percentage near to the experimental ones, but theoretical $T_e$ values are again about half than those often observed experimentally, which are illustrated by the red vertical bar.

Results of our calculations for a feeding of 100 sccm and a higher pressure of 280 mTorr (with the experimental ones going up to 344 mTorr) are illustrated in Figure 12 for neutral species. Note that no comparison with our theoretical results illustrated in Figure 13 was possible as was also the case with the 15 sccm feeding (Figure 10), experimental ionized species densities being not measured in [3]. Inspection of Figure 12 shows that our theoretical results for neutral species are in satisfactory agreement with the experiment. This is not the case with the remaining CO$_2$ percentage corresponding to high absorbed power values shown in Figure 14, where our calculations show a remaining CO$_2$ percentage as high as 43% for 1 kW absorbed power, while the experimental value is about 31%. Otherwise, the generally small discrepancies observed will be now reconsidered following a detailed evaluation of the influence of the mixing with Ar. In doing so, we elaborated Table 5 illustrating the change of the results in comparison which is due to the Ar presence.

Table 5 shows species percentages calculated from the ratios of exhausting flow rate for the experiment. It provides a first comparison of the results obtained by our model for pure CO$_2$, for pure Ar and for a CO$_2$/Ar mixture of about [CO$_2$]:[Ar] 60:40 corresponding approximately to the experiment (indicated by †). Our theoretical results for the corresponding feedings (column $Q_{TOT}$) are given in four rows (indicated by ††). The last one of the four gives the results obtained by a separate GM, for a mixture of CO$_2$ and Ar. The differences between CO$_2$ plasma results pertaining to 15 sccm and 25 sccm are in general small, except for the $n_+/n_{TOT} - n_{Ar}$ ratio case. For the Ar plasma a previously available GM [10] has been used, giving much higher $n_e$ and $n_+$ values ($n_e$ represents the total density of positive ions), because there is no energy spent in chemistry processes in the Ar case. Then, for the [CO$_2$]:[Ar] mixture calculations only the $n_e$ and $n_+$ densities change considerably, but these have not been measured in any case. For the latter, calculated values are particularly high. Values shown in the last row, adapted to the mixture with Ar, are those to be retained for comparison, instead of those of the first row. This small change leads to more satisfactory values for the theory-experiment comparison.

5. Electric Propulsion Applications of CO$_2$ Discharges Global Modeling

GMs have been lately used to support the EP technology, when Ar [10], N$_2$,O and N$_2$/O$_2$ mixtures [38] are used as propellants. Details are available in [2]. Given the type and the form factor of the thruster and the composition of the propellant, GMs provide important information which can be contained in diagrams as follows.

(i) Functioning diagram (FD) which is composed of iso-$T_e$ and iso-$P_{abs}$ curves defining the ionization percentage of the plasma as a function of the pressure.

(ii) Plasma components composition (PCC) diagram which contains the curves giving the density variation of each component of the plasma, also as a function of the pressure.

FD and PCC diagrams are on the basis of the thruster modeling, also allowing for optimization, monitoring and evaluation of the erosion of the propellant facing surfaces, through nonperturbing optical emission spectroscopy diagnostics [39, 40]. It is evident that optical emission spectroscopy has to be adapted to the type and to the form factor of the device. When the propellant has a varying composition, as is the case with air-breathing technology, FD and PCC diagrams become of paramount importance [41] because changes of the N$_2$/O$_2$ percentage lead to discharges with quite different characteristics. A typical application of our CO$_2$ GM is the technical support for CO$_2$ breathing thrusters, which are expected to be used in low and very low trajectory devices meant to work, for example, in the Martian atmosphere environment, where the atmospheric density is significantly lower than this of the Earth for the same altitude.

In the present work, we address only three typical cases of our CO$_2$ GM application in EP, namely, a low pressure case for a thruster functioning with a low feeding rate (Section 5.1) and with a high feeding one (Section 5.2) and also a case of higher pressure, for a thruster functioning under high feeding (Section 5.3). As was the case with previous calculations aiming at helicon thruster modeling, the Landau damping approximation has been used in the first two cases [10]; this approximation allows for considerable simplification of the calculations. However, in the third case, where the expected $n_e$ is low and the pressure rather high; this approximation is not applicable and was not used.

5.1. Low Pressure, Low Feeding Devices. We consider here a small helicon type thruster of a length of $L = 13$ cm and of core radius $R_c = 0.3$ cm. The CO$_2$ feeding is of 20 sccm and the pressure varies from 3 mTorr to 10 mTorr. Results of the GM for this case are shown in Figure 15, giving the applicable FD when the absorbed power varies from 50 W to 1000 W.

Depending on the pressure, the considered $P_{abs}$ values allow for $T_e$ values from 5 eV up to 60 eV. The thick arrow corresponds to $P_{abs} = 200$ W; its slope indicates how handy is the plasma ionization in this case. The concomitant PCC of Figure 16 shows the corresponding densities of the plasma constituents for $P_{abs} = 200$ W.

Although Figure 16 is somewhat analogous to Figures 3 and 6, because of the high absorbed power in a small volume the ionic species and $n_e$ become here much higher. CO$_2^+$ (black empty triangles) is the most abundant species for low pressures, replaced by O$^+$ (red crosses) for the higher ones. The most abundant neutral species are successively O(3P) (red empty squares) and CO (full blue triangles). As is the
Table 5: Results obtained taking into account the presence of Ar in the discharge. Conditions: $p = 80 \text{ mTorr}$; $P_{abs} = 250 \text{ W}$; $T_{\text{GAS}} = 400 \text{ K}$; approximate form factor $L = 30 \text{ cm}$; $R = 8 \text{ cm}$.

<table>
<thead>
<tr>
<th>Discharge case</th>
<th>$Q_{tot}$ (sccm)</th>
<th>$T_e$ (eV)</th>
<th>$n_e$ (+)</th>
<th>$O^-$ (+)</th>
<th>$n_Ar$</th>
<th>$n_{CO_2}/(n_{TOT} - n_{Ar})$</th>
<th>$n_{CO}/(n_{TOT} - n_{Ar})$</th>
<th>$n_{O}/(n_{TOT} - n_{Ar})$</th>
<th>$n_{C}/(n_{TOT} - n_{Ar})$</th>
<th>$n_{Ar}/n_{TOT}$</th>
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<tr>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>[CO$_2$]:[Ar] 60:40</td>
<td>25 (15 + 10)$^+$</td>
<td>1.537$^+$</td>
<td>4.32$^+$</td>
<td>15.83$^+$</td>
<td>38.8$^+$</td>
<td>37.8$^+$</td>
<td>16.1$^+$</td>
<td>6.8$^+$</td>
<td>0.6$^+$</td>
<td>33.6$^+$</td>
</tr>
<tr>
<td>GM CO$_2$</td>
<td>25$^+$</td>
<td>1.606$^+$</td>
<td>5.21$^+$</td>
<td>10.49$^+$</td>
<td>48.1$^+$</td>
<td>32.7$^+$</td>
<td>14.5$^+$</td>
<td>4.4$^+$</td>
<td>0.3$^+$</td>
<td>100$^+$</td>
</tr>
<tr>
<td>GM CO$_2$</td>
<td>25$^+$</td>
<td>1.568$^+$</td>
<td>5.49$^+$</td>
<td>9.77$^+$</td>
<td>38.1$^+$</td>
<td>38.7$^+$</td>
<td>17.4$^+$</td>
<td>5.1$^+$</td>
<td>0.6$^+$</td>
<td>35.7$^+$</td>
</tr>
<tr>
<td>GM CO$_2$</td>
<td>25$^+$</td>
<td>1.467$^+$</td>
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<td></td>
<td>38.8$^+$</td>
<td>37.8$^+$</td>
<td>16.1$^+$</td>
<td>6.8$^+$</td>
<td>0.6$^+$</td>
<td>34.0$^+$</td>
</tr>
<tr>
<td>GM Ar</td>
<td>25$^+$</td>
<td>1.337$^+$</td>
<td>8.42$^+$</td>
<td>4.41$^+$</td>
<td>41.1$^+$</td>
<td>41.1$^+$</td>
<td>10.3$^+$</td>
<td>6.8$^+$</td>
<td>0.6$^+$</td>
<td>34.0$^+$</td>
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<tr>
<td>Experiment</td>
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<tr>
<td>[CO$_2$]:[Ar] 60:40</td>
<td>25 (15 + 10)$^+$</td>
<td>1.568$^+$</td>
<td>5.49$^+$</td>
<td>9.77$^+$</td>
<td>38.1$^+$</td>
<td>38.7$^+$</td>
<td>17.4$^+$</td>
<td>5.1$^+$</td>
<td>0.6$^+$</td>
<td>35.7$^+$</td>
</tr>
</tbody>
</table>

Experimental density ratios (given in percentage) calculated from the flow of species created in the discharge measured in [3] with help of the present theoretical results. $n_A$ and $n_C$ percentage (indicated by $\Delta$) are evaluated assuming 7.4% of the sum of C + O percentages.

$^+$ densities in $10^{10}$ cm$^{-3}$. 
case for the ions, abundance of Tot CO$_2$ (black squares), although being the most important for low pressures, is exceeded by O($^3$P) and CO abundances for higher ones. The temperature of the gas is taken as $T_{\text{GAS}} = 400$ K. Figure 17 shows in this case the considerably high $T_e$ (red squares) for small pressure values and the total ionization parameter $\xi_{\text{TOT}}$ (blue circles, values to be read at the right side of the figure) which vary from 70% to 50% approximately. The indicated remaining CO$_2$ percentage $\rho$ stays very small, about 10% only.

5.2. Low Pressure, High Feeding Devices. It is evident that whenever we aim to investigate a situation analogous to this reported in Section 5.1 but with a higher CO$_2$ feeding, typically of 80 sccm instead of 20 sccm, the characteristics of the discharge are quite different. Practically, such an increase of the feeding should not be a problem in case of “in situ” availability of the propellant even if the ionization percentage remains low. Figure 18 shows the corresponding FD for the same pressures with those of Figure 15 but for higher feeding. However, higher $P_{\text{abs}}$ lines are added in this case, in order to obtain results in a sufficiently high ionization region. Because of the inclusion of increased $P_{\text{abs}}$ values, the $T_{\text{GAS}}$ has been considered here as varying, according to the formula $T_{\text{GAS}} = 0.17 \times P_{\text{abs}} + 515$ (K) which was conveniently shifted to reach a gas temperature $T_{\text{GAS}} = 600$ K when $P_{\text{abs}} = 500$ W. Comparing the FDs belonging to 20 sccm and to 80 sccm, we see that with increasing feeding the ionization becomes more difficult for the same $P_{\text{abs}}$. This is manifested by the slope of the thick arrow, also present in Figure 18. It illustrates the previously observed fact [2] that optimization of the feeding is an important part of the thruster study.
5.3. High Pressure, High Feeding Devices. Another interesting case is encountered when both the pressure and the feeding are quite high. Such a case could be considered, for example, when the thruster environment is in a quite high pressure and of course when the propellant is abundant. Innovating types of EP could be devised in such cases, possibly using mixtures as propellants in order to increase the ionization and hence the thrust. Figure 19 shows a FD corresponding to such a case.

Although the length $L = 13$ cm was kept the same, we address here a larger device, with $R_C = 0.8$ cm. Because of the large feeding rate selected ($Q_{CO_2} = 200$ sccm), we are interested in higher pressure values and we seek higher $P_{abs}$ values, going up to 1800 W for a pressure of about 10 mTorr in order to approach 60% of ionization. Figure 20 shows a PCC diagram concomitant to the FD of Figure 19 in case of 1400 W of $P_{abs}$. For a pressure doubling to go from 10 mTorr to 20 mTorr, the total density $n_{TOT}$ is also about doubling and the $n_i$ increases rather slower from $4.5 \times 10^{13}$ to $7 \times 10^{13}$ cm$^{-3}$. Densities of O$^3$P, CO, and CO$_2$ are similar and slightly exceeded by the most abundant ion O$^+$. O$_2$ and O$^-$ densities are much smaller than those of O$^3$P, CO and CO$_2$ and O$_2^-$ almost absent.

Figure 21 shows concomitant variations of $T_e$, of ionization and of remaining CO$_2$ percentage for the conditions corresponding in the previous Figure 20. The latter never exceeds 20%, even for a high pressure of 20 mTorr. The total ionization percentage diminishes roughly from 50% to 30% with increasing pressure, which indicates that an abundant in situ source of CO$_2$ has to be available in order to consider CO$_2$ as EP propellant under such conditions. The electron temperature falls for increasing pressures, in a similar way in this case to the ionization percentage.

6. Conclusions

A systematic exploitation of our GM devoted to CO$_2$ discharges allowed for description of the latter in various typical conditions. Applications of interest to radiofrequency type plasma reactors and CO$_2$ atmospheres and to EP technology have been separately addressed according to their specificity. For the first applications, available experimental data [3] allowed for theory-experiment comparison, with satisfactory results leading to a first validation of our model. For the second type of applications, FD and PCC analysis allowed for developing a basis for study, optimization, and diagnostics of plasma thrusters when they are fed with CO$_2$. Because of lack of dedicated experimental devices, no validation has been possible for the moment concerning plasma thruster devices.
We are looking forward to finding experimental facilities which will help us to do so. In all, the present model was able to provide satisfactory characterization of various cases of CO₂ plasmas.

For low ionized plasmas, the interrelation of dimensions, feeding, absorbed power, pressure, ionization percentage, electron density, and temperature has been investigated. In case of plasmas exhibiting higher ionization degree, pertaining to lower pressure and considerable absorbed power values, characteristics concerning electric plasma thrusters have been systematically studied and summarized using standard FD and PCC diagrams. These are presented for selected plasma conditions. Low and high pressure conditions have been addressed separately and the need for higher absorbed power in the second case in order to reach satisfactory ionization levels has been again illustrated. It is evident that adequate experimental facilities are needed to obtain a better insight on CO₂ plasmas of interest to electric propulsion, a development to which our CO₂ model is meant to contribute substantially.

The presented diagrams can be used for modeling of discharges in CO₂ atmospheres, including mixtures with other gases, reacting or inert, present in aerospace environments. These have a significant potential for industrial applications, for example, to reduce unwanted CO₂ abundance [3] and extract usable oxygen. They are also meant for use in EP when CO₂ is used as propellant in various propulsion devices, also in case of feeding by gas mixtures. In fact, as was shown throughout the elaboration of Table 5, the present model can be extended in order to obtain modeling of gas mixtures, whenever the corresponding GMs are already available. This allows for straightforward study of CO₂, N₂, and O₂ mixtures discharges of current interest to industrial applications [5, 42].

**Nomenclature**

\[ D_j: \quad \text{Neutral diffusion coefficient, } D_j = \left( k_B T_{\text{GAS}} \Lambda \right) / \left( v_j M_{\text{CO}_2} \right) \]

DISS: Dissociation

\[ DXW, j: \quad \text{Deexcitation on the wall for a species } j \]

\[ E_{\text{IONIZ}}: \quad \text{Ionization energy} \]

ELAS: Elastic

EP: Electric Propulsion

EXC: Excitation

FD: Functioning Diagram

GL: Ground Level

GM: Global Model

\[ h_t: \quad \text{Axial edge to center ratio of positive ion density} \]

\[ h_r: \quad \text{Radial edge to center ratio of positive ion density} \]

HeIT: Helicon thruster

IONIZ: Ionization

ICP: Inductively Coupled Plasma

\[ j: \quad \text{Species state(s)} \]

\[ k_B: \quad \text{Boltzmann constant, } k_B = 1.3807 \times 10^{-23} \text{ J} \cdot \text{K}^{-1} \]

\[ k_j: \quad \text{Processes rate coefficient involving state } j \]

L: Plasma length

\[ M_{\text{CO}_2}: \quad \text{CO}_2 \text{ mass} \]

\[ n_e: \quad \text{Electron density} \]

\[ n_i: \quad \text{Total density of positive ions} \]

\[ n_{\text{TOT}}: \quad \text{Total plasma species density} \]

\[ p: \quad \text{Pressure} \]

\[ P_{\text{abs}}: \quad \text{Absorbed power} \]

PCC: Plasma Components Composition

\[ R: \quad \text{Plasma radius} \]

\[ R_c: \quad \text{Radius of the plasma core} \]

\[ RW, X^+: \quad \text{Recombination on the wall for } X^+ \text{ species} \]

\[ T_e: \quad \text{Electron temperature} \]

\[ T_{\text{GAS}}: \quad \text{Gas temperature} \]

\[ u_B: \quad \text{Bohm velocity, } u_B = \left( eT_e / M_1 \right)^{1/2} \]

\[ V: \quad \text{Discharge volume} \]

\[ \epsilon, \epsilon_{C,X}: \quad \text{Collisional energy loss of the electrons, colliding with species } X \]

\[ v_j: \quad \text{Neutral mean velocity, } v_j = \left( 8k_B T_{\text{GAS}} / \pi M_1 \right)^{1/2} \]

\[ \gamma_j: \quad \text{Sticking coefficient for the neutral species } j \text{ on the wall surface} \]

\[ \xi_{\text{TOT}}: \quad \text{Total ionization percentage} \]

\[ \rho: \quad \text{Remaining } \text{CO}_2 \text{ percentage} \]

\[ \sigma_{j,X}: \quad \text{Cross section pertaining to state } j \text{ with species } X. \]

**Conflict of Interests**

The authors declare that there is no conflict of interests regarding the publication of this paper.

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