A Detailed Global Model of Iodine Plasma for Optimization and Diagnostics of Electric Thrusters

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Abstract: The iodine plasma model developed lately by DEDALOS Ltd. is here extended to characterize electric thrusters of at least 1 kW class and to reproduce theoretically the main spectral lines of the first and of the second iodine spectra. These are necessary for optical emission spectroscopy diagnostics allowing for the device optimization including thrust preview. Diagnostics is based on comparison of the obtained theoretical spectra with experimental ones. Two thruster spectra from the literature have been used to validate the model for absorbed powers up to about 2 kW.

1. Introduction

Global Models (GM) of Iodine plasma have lately acquired a particular interest due to their application in characterization and in optical diagnostics of Electric Thrusters (ET) fed by iodine (see [1] and references therein). Using of iodine as ET propellant was suggested already at the beginning of the century [2]. In the present work we address a Detailed Global Model (DGM) supported by an extended atomic database of iodine species. DGM allows for detailed characterization of ETs when the absorbed power ($P_{ABS}$) is not much higher than 1 kW. Our calculations show that when $P_{ABS}$ reaches this value the presence of twice or higher ionized iodine species becomes particularly important. Presence of such species play a fundamental role in the thruster functioning and is essential for the thrust evaluation. Study of the concomitant first and second order iodine spectra is necessary for Optical Emission Spectroscopy (OES). Increase of the thruster energy class leads to considerable presence of more ionized iodine species, in particular if $P_{ABS}$ per volume is higher. Calculation / acquisition of higher than the second order spectra must be taken into consideration in this case.

The overall iodine fed ETs functioning and the species expected to be encountered in it are here studied on the basis of an Iodine Detailed Global Model (IDGM). This model allows for a realistic evaluation of the presence of iodine species, for an overall description of the ET functioning and for OES diagnostics based on the calculation of detailed theoretical spectra.

In studying the iodine fed ETs, extensive use of Plasma Components Composition (PCC) diagrams and of Functioning Diagrams (FD) is made here, as was also the case in Ref. [1]. However, because higher $P_{ABS}$ values are of interest here, we discuss PCCs belonging to $P_{ABS}$ values going up to 1 kW. Also, we comment a FD for iodine fed ETs for pressures going up to 10 mTorr, reaching higher total ionization percentage $\xi_{TOT}$ values. Iodine propellant being unavailable in situ, it is important to insure its efficient use. In so doing, we also discuss the obtained total ionization during the thruster functioning, on the basis of two FD forms giving the $\xi_{TOT}$ dependence either on the absorbed power or on the pressure, an often used parameter.

Following the review of the main IDGM results addressing plasma compositions and ionization, we compare obtained theoretical spectra with the corresponding experimental ones, which have been presented in Refs. [1] and [3]. These experimental spectra available in the literature had been acquired recently in a gridded and in a Hall type ET correspondingly.

Details of the averaged GM elaboration [4] and of the iodine homonuclear series structure are not described here, as both have been often made available in the literature. Iodine data resources and their evaluation have been discussed elsewhere [1].

After the present introduction, we describe briefly in Section 2 selected iodine data and general characteristics of iodine theoretical spectra. In Section 3 we present modeling results obtained by IDGM, depending on the $P_{ABS}$, the pressure $p$ and the electron temperature $T_e$. Section 4 analyzes the iodine fed ET functioning on the basis of FD diagrams. In Section 5 we compare with OES in mind our iodine theoretical spectra to experimental ones which are provided by Refs. [1] and [3]. Expected thruster characteristics are also addressed in this section. This task involved occasionally
investigation of the theoretical first xenon spectrum. Section 6 contains conclusions of this work and its scheduled continuation.

2. Atomic / Ionic Iodine Structure and the Corresponding First and Second Spectra

It is well known that the Ground Level (GL) structure of neutral iodine contains two cores, while each of its first three ions contains five. In our recent Iodine Global Model (IGM) presentation [1], only description of spectra corresponding to the first cores had been included, contained in three theoretical spectra figures belonging to I I and one belonging to I II. We remind that the iodine cores are identical to those of the rare gases homonuclear sequencies once the charges considered in the latter series are increased by one.

While only lines belonging to the first cores \(^{3}P_2\) of I I and \(^{4}S_{3/2}\) of I II were addressed in the initially provided spectra, we lately evaluated additional data involving the \(^{3}P_0, {^{3}P_1}\) cores in addition to \(^{3}P_2\) one of the I I and the first three cores \(^{4}S_{3/2}, {^{2}D_{3/2}}, {^{2}D_{5/2}}\) of the I II species. These data, which are shortly addressed in the following, are incorporated in our IDGM model. The resulting improved theoretical spectra encompass the quasi-totality of the main lines present in VUV and visible regions experimental spectra of I I, I II. This is illustrated for two experimental cases in Section 5.

2.1. \(^{3}P_{0,1,2}\) Cores of I I Spectrum

These two cores have been added in addition to the \(^{3}P_3\) core to 6s-6p multiplet calculations of the first iodine spectrum. As was the case with [1], only \(^{3}P_0\) core is considered for the visible lines of 6p-6d, 6s-7p multiplets, plus the 6p-7s one generating infrared lines. Besides the transitions inside the \(^{3}P_0\) and \(^{3}P_1\) cores we have also included the more intense intercombination lines between the three cores \(^{3}P_{0,1,2}\), as follows:

- In the 500 nm to 700 nm wavelengths region: three lines between cores \(^{3}P_2\) - \(^{3}P_0\) and eight lines between cores \(^{3}P_2\) - \(^{3}P_1\).
- Eight lines between \(^{3}P_0\) and \(^{3}P_1\) cores, not involving the \(^{3}P_2\) one. From these, four lines lie in the 800 nm to 1000 nm region and four lines lie in the 900 nm to 1200 nm region.

2.2. Resonant Lines of I I Spectrum

In extending the previously considered \(^{3}P_3\) lines number, resonant lines have also been added, corresponding to \(^{3}P_0\) and \(^{3}P_1\) lines of the 5p-6s multiplet of I I. Notice that for 5p-7s and 5p-6d multiplets only \(^{3}P_2\) core transitions are still considered, as was the case with [1].

2.3. \(^{3}D_{3/2,5/2}\) Cores of I II Spectrum

In addition to the existing first \(^{4}S_{3/2}\) core, these two cores have been added to the second iodine theoretical spectrum calculations. The addressed multiplets are 6s-6p and 5d-6p, plus the resonant 5p-6s and 5p-5d ones. The more intense among the intercombination lines from the three cores have also been added. These include:

- Two 6s-6p lines, the 6s(\(^{3}D_3\))-6p(\(^{1}F_3\)) between cores \(^{4}S_{3/2}\) - \(^{4}D_{3/2}\) at 571.21 nm and the 6s(\(^{3}D_2\))-6p(\(^{1}P_1\)) between cores \(^{4}S_{3/2}\) - \(^{4}D_{5/2}\) at 543.95 nm;
- One 5d-6p line, the 5d(\(^{3}D_2\))-6p(\(^{1}D_2\)) between cores \(^{4}S_{3/2}\) - \(^{4}D_{5/2}\) at 349.74 nm;
- Three 5d-6p lines, the 5d(\(^{3}D_1\))-6p(\(^{1}D_2\)) at 498.69 nm, the 5d(\(^{3}D_1\))-6p(\(^{1}F_2\)) at 521.63 nm and the 5d(\(^{3}D_1\))-6p(\(^{1}F_3\)) at 514.97 nm, the three of them between cores \(^{4}S_{3/2}\) - \(^{4}D_{5/2}\).

3. Evaluation of Iodine Plasma Composition Based on the IDGM

In this section we examine the composition of the iodine fed ETs plasma, dependent on the variation of two fundamental parameters, namely \(P_{ABS}\) and \(p\). We first focus on a typical plasma form factor of 5 cm radius and of 13 cm length and discuss the obtained IDGM results. Concomitant \(P_{ABS}\) values addressed for the plasma having this form factor vary from 0.2 kW to 5.0 kW. Such values are often used in typical examples. Together with the succeeding IDGM results pertaining to a smaller form factor plasma of 2 cm radius and of 3 cm length which is also addressed here for a \(P_{ABS}\) value of 16 W, we tackle characterization of two common types of ETs, namely gridded and Hall type. Functioning of the latter will be discussed in Section 4. The cases of micro thrusters and of Helicon type ones, where the plasma volumes could be clearly smaller, refer currently to lower \(P_{ABS}\) values; they will be both addressed elsewhere. Inversely, for higher ET dimensions the addressed \(P_{ABS}\) values have to be increased in a parametric way in view of the chosen feed, in order to keep the ionization percentage sufficiently high. Influence of the of the absorbed power and of pressure depending on the ET functioning are separately addressed in the following.

3.1. Pressure Depending of the Iodine Propulsion Plasma Composition

We describe here ET characterization corresponding to the typical case of 1 kW \(P_{ABS}\), a value clearly higher than the one of 600 W addressed previously in [1]. Such an increase of the \(P_{ABS}\) values allows for a quite improved utilization of the propellant, even in case that the pressure is
e.g. of the order of 10 mTorr, thus allowing for a convenient thrust.

Figure 1, illustrating a typical case of an iodine fed ET plasma constitution, presents a pressure depending PCC for a 20 sccm iodine feed. This typical feed is used throughout in the presented theoretical examples of Sections 3, 4 and 5. The substantial absorbed power of 1 kW creates a plasma composed mainly of I\(^n\) species where n = 0, 1, 2, 3, while the investigated pressure spans a range of 10 mTorr.

The addressed P\(_{\text{ABS}}\) of 1 kW is quite high, resulting to a thorough ionization of the considered plasma of 1 dm\(^3\) volume, as illustrated in Figure 1, where curves showing the total values of neutral and of singly, doubly and trebly ionized iodine species populations entitled I\(GLS\(_{\text{TOT}}\), I\(^+\)GLS\(_{\text{TOT}}\), I\(^{2+}\)GLS\(_{\text{TOT}}\) and I\(^{3+}\)GLS\(_{\text{TOT}}\) bear correspondingly blue, green, red and indigo colors. The total species density n\(_{\text{TOT}}\) and the electron density n\(_{e}\) are shown by continuous and by broken thick black lines correspondingly, bearing empty stars for the former.

In view of the 20 sccm feed pertaining here for a quite high P\(_{\text{ABS}}\) value, the main result observed in Figure 1 is that the total density of the singly ionized species is more than seven times higher than this of the neutral ones for 1 mTorr pressure. However, for 10 mTorr pressure, this factor becomes slightly higher than two. Inversely, although for 1 mTorr pressure the presence of the twice ionized species equals the presence of the singly ionized ones, with the contribution to the total thrust expected from the former being double than the contribution expected from the latter, for 10 mTorr pressure the presence of the twice ionized species becomes orders of magnitude lower than the presence of the singly ionized ones.

For pressure values lower than about 2 mTorr, the values of n\(_{e}\) exceed the n\(_{\text{TOT}}\) ones in view of the sustained ionization in this region. Both densities of the neutral and of the singly ionized species increase with the pressure in absolute values. For I and I\(^+\) this increase reaches about two and one orders of magnitude correspondingly, when the pressure increases from 1 mTorr to 10 mTorr (cf. with figure 7 of [1]). Inversely, as we show previously, presence of twice ionized species diminish very fast when p increases. I\(^{3+}\) species are present in the plasma at the chosen conditions, but they exceed the Figure 1 low limit of density only for pressure values around 1 mTorr. Their presence diminishes when pressure increases, even faster than this of I\(^{2+}\).

In what concerns populations of the excited states, we observe that they are clearly lower than the GL ones. In order to include in Figure 1 at least the more present excited species, their values are shown multiplied by ten. Thus, populations of both neutral iodine excited species and of two singly ionized ones exceed the 10\(^{10}\) cm\(^{-3}\) low limit of Figure 1 and are shown with broken and dot broken curves correspondingly. These curves concern the level 3 of I I and levels 10 and 9 of I II. For the correspondence of the used level numbers with the quantum description of the excited levels see Section 5, where the metastable character of these levels is also discussed.

Complementary information on the ET plasma characteristics is shown in Figure 2, a figure concomitant of Figure 1, addressing more specifically percentages of the main plasma ionized constituents. Their evaluation is a mandatory issue for ET characterization. colors attributed to iodine species in Figure 2 are similar to those used in Figure 1. Total ionization percentage \(\xi_{\text{TOT}} = n_{\text{ION}} / n_{\text{TOT}}\) and electrons percentage \(\xi'_{\text{TOT}} = n_{e} / n_{\text{TOT}}\) are shown by black lines, continuous with full dots and broken with empty dots correspondingly. It is to be noted that the \(\xi_{\text{TOT}}\) parameter used here as a measure of the plasma ionization, addresses only the sum of each ion type numbers, irrespectively of the ionization charges. Then, in calculating the resulting thrust, the number of each ion must be multiplied by the number of the charges that each ion bears, reaching a value equal to \(\xi'_{\text{TOT}} = n_{e} / n_{\text{TOT}}\), due to the quasi-neutrality assumption. Consequently, as shown in Figure 2, \(\xi'_{\text{TOT}}\) exceeds 100 % for low pressures where the ionization is considerable, with sustainable presence of twice ionized iodine species densities. Temperatures of electrons T\(_{e}\) are also indicated in Figure 2 by red
thin curves bearing full squares ■. The is increasing very fast for pressure values around 1 mTorr. Ions and gas temperatures $T_{\text{IONS}}$ and $T_{\text{GAS}}$ correspondingly, have been multiplied by ten in order to be included in Figure 2. They are shown by thin curves with empty diamonds ◊ and triangles △ correspondingly. $T_{\text{IONS}}$ values increase when pressure values are diminishing and for higher pressures approach the $T_{\text{GAS}}$ values, which remain the same for all pressure values.

Figure 2 illustrates the increase of the neutral species presence when the pressure is increasing. Percentage of the singly ionized species is increasing up to pressures of about 2 mTorr, reaching a plateau for higher pressure values. In the high pressure region, presence of all the ionized species with $q > 1$ is low and $I^+$ follows practically the total ionization percentage values.

Interestingly, twice ionized species are the main contributors of positive charges for 1 mTorr, although their number is comparable to this of the singly ionized ones, as it can also be seen in Figure 1. For the same pressure of 1 mTorr, the very scarce trebly ionized species provide about 10% of the present total charge.

It is interesting to compare the PCC shown in Figure 1 with a PCC belonging to a lower form factor of $R = 2.0$ cm and $L = 3.0$ cm. We present such a PCC in Figure 3, obtained for $P_{\text{ABS}} = 16$ W. $Q_{\text{TOT}}$ is also of 20 sccm and the pressure spans the same range with Figure 1. Both form factor and $P_{\text{ABS}}$ pertaining to Figure 3 are lower, with the latter diminishing about twice than the former. As a consequence, the main result observed in Figure 3 is that the total density of the singly ionized species is about four times lower than this of the neutral ones for 1 mTorr pressure. For 10 mTorr pressure, this factor increases to more than an order of magnitude. Presence of twice ionized species is orders of magnitude lower than the presence of the singly ionized ones, being just visible in Figure 3 for pressure values around 1 mTorr. Excited species present in the plasma are very scarce at the conditions of Figure 3, therefore we can show the presence of the two main ones only after multiplication by a factor of ten. They belong to $I^76s\ (3, m)$ neutral species and to $I^+5d\ (10, m)$ singly ionized ones shown in Figures 1 and 3.

### 3.2. Influence of the Absorbed Power on the Plasma Composition

The mandatory role which the absorbed power plays on the plasma equilibrium conditions of ET functioning can be appreciated through Figure 4, a power depending PCC diagram giving the plasma composition for form factor of 5 cm radius and of 13 cm length in case of an indicative pressure of 5 mTorr, with the feed set always at 20 sccm. Colors of Figure 4 are the same with those of Figures 1, 2.

As the pressure must stay constant at 5 mTorr, $n_{\text{TOT}}$ diminishes slowly with absorbed power, divided by about two when $P_{\text{ABS}}$ is increasing 25 times. As was illustrated in Figures 1 and 2, the essential of the plasma ionization for about 5 mTorr pressure is following the form of the singly ionized species curve, therefore $n_e$ and $I_{\text{GLS}_{\text{TOT}}}$ values are about the same. They increase slowly to attend the $n_{\text{TOT}}$ values with increasing $P_{\text{ABS}}$. However, the $I^{5d}_{\text{GLS}_{\text{TOT}}}$ species become more abundant than the neutral ones in the $P_{\text{ABS}} = 5$ kW region. For this reason $I^{5d}_{\text{GLS}_{\text{TOT}}}$ abundance becomes slightly lower than the $n_e$ density. For 5 mTorr, trebly ionized $I^{3+}$ species are so scarce that are not included in Figure 4.

Populations belonging to the various cores of the neutral and ionized species are shown separately by thin curves of various types marked...
by GL1 to GL5. Those belonging to the first core are prevailing for the neutral and the singly ionized species.

A diagram concomitant to Figure 4 PCC, showing additional aspects of the plasma properties under the same conditions prevailing for Figure 4 is given in Figure 5.

This figure is somewhat similar to Figure 2, except that species percentages and \( T_e \) values are given as a function of \( P_{\text{ABS}} \) instead of \( p \). The used symbols are those of Figure 2. It is to be noticed that for \( P_{\text{ABS}} = 500 \) W neutral and singly ionized species have similar values. Doubly ionized species contribute very little to the total plasma ionization, except for about \( P_{\text{ABS}} = 5 \) kW. Trebly ionized species are practically absent, as reported in the discussion of the Figure 4 PCC. \( \xi_{\text{TOT}} \) and \( \xi'_{\text{TOT}} \) percentages are shown by continuous and dashed black curves correspondingly. The latter is expected to exceed 100 % for values of \( P_{\text{ABS}} = 5 \) kW.

4. Functioning of Iodine Fed Thrusters

As was mentioned previously, it is possible to obtain an insight of the iodine fed ETs functioning by using the adequate FD, elaborated here on the basis of the IDGM results. As an example, we address an ET functioning case which is illustrated in Figure 6. This figure shows a FD giving the dependence of pressure on the thruster plasma ionization percentage in case of 20 sccm feed. Form factor chosen for this FD is of 5 cm radius and of 13 cm length. Pressure varies from 1 mTorr to 10 mTorr, with absorbed power values going from 200 W to 5 kW. Under these conditions, the corresponding electron temperatures obtained by IDGM vary from 1.2 eV up to 5 eV. The broken vertical line in Figure 6 indicates results referring to the PCC case shown in Figure 4, incorporated in the FD. Results for \( P_{\text{ABS}} = 600 \) W obtained from IGM and contained in figure 10 of [1] are also incorporated in Figure 6. These are very similar to those obtained by IDGM, because the I\(^+\) species are very scarce for this \( P_{\text{ABS}} \) value. Ionization percentage values for 200 W shown in Figure 6 are practically the same with those contained in figure 10 of [1].

Although IDGM contains one more ionized species and also an increased number of excited states, results remain practically the same with those obtained by IGM for relatively low \( P_{\text{ABS}} \).
However, intensities of the obtained theoretical spectral lines are quite different than those presented in [1], as will be discussed in Section 5. Also, the arrow belonging to 1 kW of absorbed power in the 4 mTorr region which is shown in Figure 6 has a very different direction from this shown in the aforementioned figure 10 of [1]. This means that the ionization gain for lower pressures becomes less important when $P_{\text{ABS}}$ values are sufficiently high for a given feed. Consequently, quite high ionization of the ET plasma can be obtained when sufficient power is available, even for pressures of about 10 mTorr or higher.

We remind that the pressure and absorbed power values shown in Figure 6 correspond to an iodine feed of $Q_{\text{TOT}} = 20$ sccm. For higher feed values, increased densities of ionized species could be obtained only if the available power is increased accordingly. Consequently, increasing of the propellant feed is useless if the necessary absorbed power is not available.

It has to be repeated here that the $\xi_{\text{TOT}}$ percentage values given in the ordinate refer to the number of the ions without taking into account the charge of each of them. The total charges obtained, which lead to the effective thrust, can be better appreciated by using figures concomitant to the PCCs ones, as was the case with Figure 2 shown previously, where the total electron number density $n_e$ was shown together with the percentage of each ion species multiplied by its charge. Moreover, it has to be noted that no ionized species with $q > 3$ are for the moment included in the model. Consequently, even high absorbed power values which lead in principle to increased $T_e$ values, are artificially unable to ionize the $q = 3$ species. This artifact constitutes an inconvenience with increasing $P_{\text{ABS}}$ as the presence of $I^+$ becomes more important. Therefore, we estimate that for the moment the model cannot treat correctly cases referring to $P_{\text{ABS}} > 2$ kW. An extended version of IDGM, including higher ionized species and valid for up to 10 kW, will be soon available and published elsewhere. Towards this aim, an extended study of the iodine homo-nuclear series is under way.

The influence on the ionization percentage of the $P_{\text{ABS}}$ increasing is specifically illustrated in Figure 7, which constitutes a typical power depending FD. Curves of different colors bearing full dots correspond to electron temperatures. Isobaric curves are black and bear full stars.

In view of the model validity observations made in the preceding paragraph, Figure 7 shows $\xi_{\text{TOT}}$ values in logarithmic scale for absorbed powers going only up to 2 kW. This figure belong to a 20 sccm feed and a form factor of $R = 5$ cm radius and of $L = 13$ cm length. In fact Figure 7 is an inverted form of Figure 6 and relates to the ET thrust, a function of the absorbed power in view of various pressure values. Both the isobaric curves giving the plasma pressure values and the electron temperature values given in isothermal form show sustained increase of $\xi_{\text{TOT}}$.

The four isobaric curves for 1.0 mTorr, 2.0 mTorr, 5.0 mTorr and 10.0 mTorr are crossing all of the $T_e$ isothermal curves belonging to 5 eV, 2.5 eV, 1.5 eV and 1.2 eV for $P_{\text{ABS}}$ values around 500 W. When $P_{\text{ABS}}$ is low, especially for the 2.5 eV and somewhat for the 1.5 eV $T_e$ isothermal curves, the 2.0 mTorr and 5.0 mTorr isobaric curves refer to lower $\xi_{\text{TOT}}$ values than those of $T_e$, but for high $P_{\text{ABS}}$ values the situation is inverted. The isobaric curve belonging to 1.0 mTorr is near to the 5 eV isothermal one after $P_{\text{ABS}}$ values of 500 W, while pressure of 10.0 mTorr refers practically to 1.2 eV electron temperature irrespectively to the absorbed power.

Special interest is paid to the plasma total ionization. $n_e$ constitutes a measure of the latter, in view of the plasma quasi-neutrality and the corresponding total ionization charges $\xi_{\text{TOT}}'$ are directly related to the thrust. $\xi_{\text{TOT}}'$ curves are given in Figure 8, in which all parameters remain those of Figure 7. It must be precised that the percentage of $\xi_{\text{TOT}}'$ appearing in the ordinate of Figure 8 is evaluated on the basis of Figure 7 ordinate one, therefore values of more than 100 % appear artificially in the former.
We notice that in Figure 8 both isothermal and isobaric curves are located higher than those obtained in the $\xi_{\text{TOT}}$ case, whenever the absorbed power is sufficient to ionize the iodine species in a level allowing at least for noticeable $I_2^+$ formation. For high pressure values, we observe that even an absorbed power of 2 kW is not sufficient to obtain a profit from the available feed of 20 sccm if the pressure is not lower, say, to 5 mTorr.

5. Obtained Theoretical Spectra and their Comparison with Experiment

As reported previously, inclusion of the detailed atomic properties of the iodine species in the IDGM leads to realistic theoretical spectra which are here meant both for comparison to those coming from the standard iodine I data available by NIST [5] and also for plasma diagnostics in two typical iodine fed ET cases. The latter belong to different ET classes, namely a low power gridded ET and a more powerful Hall type one. For both cases, detailed comparison of theoretical to experimental spectra has been made. Results are available to interested readers on request.

5.1. Overall First Iodine Spectrum

The increased number of multiplets contained in IDGM leads to theoretical models comparing with the standard first and second iodine spectra of [5] in a quite satisfactory manner. As an example we present in Figure 9 a theoretical first iodine spectrum which may be obtained in case of a small form factor of $R = 2.0$ cm and $L = 3.0$ cm, with absorbed power of $16$ W, a pressure of $6$ mTorr, a gas feed of $Q_{\text{TOT}} = 20$ sccm and a gas temperature of $T_{\text{GAS}} = 853$ K. Main pattern of the Figure 9 spectrum is analogous to that obtainable from [5]. However, it has to be noted that the conditions which have been selected for calculations leading to Figure 9 are not obligatory those pertaining to the experimental iodine spectrum contained in [5].

5.2. OES Diagnostics of a Gridded ET

We aim here OES diagnostics of an iodine fed ET which was described in [1]. For the characterization of this device we calculate theoretical spectra pertaining to the same conditions with those of Section 5.1: small form factor of $R = 2.0$ cm and $L = 3.0$ cm, a feed of $Q_{\text{TOT}} = 20$ sccm and gas temperature of $T_{\text{GAS}} = 853$ K. For an absorbed power of $16$ W and a pressure of $6$ mTorr we obtain a first order theoretical iodine spectrum of which the part belonging to the region around 500 nm is shown in Figure 10.
The main $^3P_2$ 6s-7p lines are present in this region. The obtained spectrum is to be compared with the experimental one coming from figure 15 of [1], which has been obtained by Prof. P.J. Klar and his team in the University of Giessen. Because the theoretical spectrum is very similar to the experimental one in the addressed region, we conclude that the experimental conditions are comparable with the ones chosen for the spectral calculations.

5.3. OES Diagnostics of a Hall Type Thruster

We compare here a theoretical spectrum obtained by IDGM in the 450 nm to 700 nm region for a quite higher absorbed power of $P_{\text{abs}} = 200$ W with the experimental one shown in figure 8 of [3]. The latter shows the emission spectrum from a similar power Hall ET plume, with data provided by [6]. In our calculations, form factor is $R = 2.5$ cm and $L = 5.0$ cm, for the same iodine feed of $Q_{\text{TOT}} = 20$ sccm. Our theoretical results for the second order iodine spectrum in the region of 450 nm to 700 nm are shown in Figure 11. They reproduce practically all the experimental lines for the investigated region involving the UV and visible region belonging to wavelengths shorter than 700 nm. This indicates that, as expected, the iodine propellant is almost fully ionized, the I I lines being practically absent. In fact, for a pressure of 1.5 mTorr the pressure depending PCC obtained for this case gives a high ionization percentage with up to 80 % of singly ionized iodine species.

In the higher wavelength region, figure 8 of [3] shows a rich pattern of lines. Ref. [3] identifies these lines as the first order of the Xe spectrum addressed in [6]. This part of the ET spectrum is due to the neutral Xe species formed in the Xe fed low energy hollow cathode which are mixed with the principal part of the plume and not yet ionized / thermalized by higher energy electron collisions. Concomitant theoretical Xe spectra have been obtained previously and discussed in [7-9] and references therein. As an example, we present in Figure 12 such a Xe I spectrum coming from [9] in the 760 nm to 1000 nm region, at about 1 eV $T_e$.

The spectrum of Figure 12 reproduces in a satisfactory way the higher wavelengths part of figure 8 of [3]. Note that no lines of the Xe II spectrum are clearly visible in figure 8 of [3].

6. Conclusions

General modeling considerations of iodine fed ETs have been addressed previously in [1]. These were compared successfully with a RF type ion thruster of low power. Low power RF ion thruster fed by iodine was also the subject of [10], containing a work from BUSEK Co with CubeSat application in mind. In the present work, two distinct cases of iodine propulsion have been
addressed and studied by means of the extended IDGM model. These allow for an insight of ET functioning addressing various basic parameter values. In both cases, comparison of theoretical spectra obtained also by IDGM model with available experimental ones in the frame of OES diagnostics, validated the model which constitutes a powerful tool for ET study.

Moreover, calculated PCC and FD diagrams show schematically constitution of the plasma, $T_e$ and $n_e$ in typical cases. Both are expressed as a function of the plasma pressure and of the absorbed power. $P_{ABS}$ can also be used in FD diagrams, as those previously obtained in case of $O_2 / N_2$ mixture based plasma [4,12] with ABET thrusters in mind. FD diagrams for iodine fed ETs with flow rate values in abscissa and $P_{ABS}$ in ordinate constitute an iso-thrust diagram, similar to this of [13] which refers to $N_2$ feed. Such diagrams obtained by IDGM for ET prototypes will be presented elsewhere.

When absorbed power is lower than 2 kW, it was shown that IDGM constitutes a powerful tool both for modeling and for diagnostics of iodine fed ETs. Modeling adapted to higher power applications as these addressed in [11] necessitates extension of IDGM to include higher ionized iodine species.

7. References


