Research Article

Global Modeling of N_2O Discharges: Helicon Plasma Thruster Application

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A global (volume averaged) model pertaining to N_2O discharges is used to design and to study electric propulsion applications, especially helicon plasma thrusters fed with pure N_2O and also with N_2/O_2 mixtures including air. Results obtained for N_2O feeding are discussed and compared to those pertaining to an air-like N_2/O_2 mixture feeding. An interesting similarity is observed. Comparison of the N_2O model results versus those of Ar shows lower ionization percentage with higher electron temperature for N_2O propellant.

1. Introduction

A global (volume averaged) model (GM) conceived for modeling of discharges fed by N_2O and by N_2/O_2 mixtures including 4 : 1 $[N_2] : [O_2]$ air-like ones [1] is applied to electric propulsion devices in case of pure N_2O and of N_2/O_2 feeding. The main results obtained by this model allowing to characterize the central “core” region part of helicon plasma thrusters (HPT) are presented and discussed. The selected dimensions are the same with those of a previous work addressing an Ar fed HPT [2], namely a cylinder of length $L = 13$ cm and radius $R_T = 1$ cm with plasma “core” radius R_C about 0.3 cm. Functioning is restricted in a rather low pressure region, of 3 mTorr up to 30 mTorr, and the absorbed power varies from 25 W up to 1000 W. Note that both pressure and power ranges have been here enlarged in comparison with the values used in [2] treating an Ar fed HPT which spanned only a 2 mTorr to 10 mTorr region for the pressure and 25 W to 150 W for the absorbed power.

The type of modeling applied here is quite analogous to the one we used recently to design and characterize the Argon fed HPT of [2] but takes into consideration detailed atomic and molecular structure and collision data concerning N_2O and its products. Although the present paper is oriented towards a rather hot thruster plasma region, modeling of the plasma contained in the “mantle” external part of the thruster

and/or of other low temperature plasma applications, quite similar to the one applied in the Plasma Reactor (PR) case of [2] can be obtained in a straightforward manner.

Besides evaluation of T_e and of species densities present in the “core” region in case of N_2O feeding, our GM is further applied to model an air-like mixture fed HPT thruster. This allows for an adequate design and study of air fed HPT thrusters, giving the T_e and the densities of the species in various conditions. Comparison of N_2O fed HPT properties to those of air fed ones and also to those fed by Ar has been made possible by using the present model and the one described in [2]. Results for feeding of HPT by various mixtures can be in principle calculated on the basis of each constituent percentage. However, attention has to be paid whenever the plasma constituents interact among them. In such cases, because of the reactions between the constituents and of the significant energy transfer among them, the percentage calculations are no more acceptable. Such a notable case is encountered, for example, in Ne/Ar mixtures as was described in [3].

General description and characteristics of the used GM for N_2O and for N_2/O_2 mixtures feedings follow those of [1] and are not repeated here. However, we note that the simplification of the collisional energy loss for species X, $\varepsilon_{C,X} = 2E_I^X$ pertaining to the collisionless Landau damping mechanism in relatively low pressure plasmas heated by

helicon waves which is proposed in [4] was used for the energy losses in the “core” region of the HPT. Modification of the ambipolar diffusion coefficient D_a due to the presence of the quite consistent magnetic field in the HPT may be considered, by using equations like those provided in Chapter 5 of [4]. Such a modification was not applied. Instead, a simple factor in the plasma-wall reaction rates, taking into account both the ionic and the neutral species losses from the “core” to the “mantle” region (typically 5% for the ions and 30% for the neutrals), has been used, as was the case in [2]. Note that we use here a slightly modified form of power balance equation, including the ionization terms instead of the recombination ones, which is more adapted to highly ionized plasmas containing molecules. The neutral gas temperature is assumed to be 400 K, but an increase of the gas temperature with the absorbed power could also be considered. Also, energy losses from the singly ionized ions and from the two times ionized ions collisions are neglected, but the ion temperature is also taken into consideration by an additional term for the ion pressure. The ion temperature is here the same for all the types of ions, and it is varying as a function of the pressure.

Helicon sources have been often used for generating ions for space propulsion. Reference [5], containing an overview of their functioning and recent applications, includes an extended bibliography on the subject. Characterization and diagnostics of low power and small form factor HPT were recently presented for Argon feeding [6] and previously for an Ar, N_2 , and air fed minihelicon plasma thruster [7]. High power electric propulsion (EP) is addressed using big form factor HPT; see, for example, [8] for an Ar fed large diameter high density helicon plasma device. Moreover, N_2O and N_2 presence in conventional Hall Effect Thrusters (HET) previously exposed to the atmosphere are expected as an impurity [9].

Use of atmospheric propellants is also under study for other than HPT thrusters [10], as innovative solution for long life (no propellant limited) Low Earth Orbit (LEO) and very LEO missions [11]. An interesting study on air composition in various altitudes is included in [11], showing a very important N_2/O_2 percentage variation. “Air-like” composition often used in the present paper concerns only the sea level air composition, but our model is easily applicable to other mixtures. Results of a recently obtained study of N_2/O_2 RAM EP for LEO operation, based on the present GM, will be published elsewhere. Further validation for both HPT and HET type thrusters global modeling based on comparison with scheduled experiments is under consideration.

In the present paper, after this introduction, we describe in Section 2 results of our N_2O GM for the “core” region of an HPT as a function of the pressure for typical cases of absorbed power. These are compared to analogous results obtained for Ar feeding by using the GM described in [2]. N_2O feeding results are illustrated in Section 3 as a function of the absorbed power. Section 3 contains also a comparison between N_2O and Ar power depending results. In Section 4, we present our results pertaining to ionization percentage, giving “Functioning Diagrams” (FD) for N_2O feeding, which encompass both pressure and power variations on the same

figure. Similar diagrams for Ar feeding are also given and compared. In Section 5, results for an air-like N_2/O_2 mixture feeding are presented and compared to those obtained for N_2O feeding. In so doing, we present a partial FD for 5 sccm feeding by an air-like ($4:1 [N_2]:[O_2]$) N_2/O_2 mixture to be compared with results corresponding to N_2O feeding. Finally, we give the conclusions and perspectives of this work in Section 6.

2. Pressure Dependence of the N_2O Fed HPT Functioning and Comparison with Ar Feeding Results

Results obtained by the GM for N_2O feeding of HPTs depend on various parameters which essentially consist of

- (i) form factor, defined by the cylinder radius R and length L ;
- (ii) gas temperature T_{GAS} ;
- (iii) total pressure p ;
- (iv) absorbed power P_{abs} ;
- (v) flow rate Q .

In this section, we present results obtained in case of N_2O feeding for various pressure values and we compare them to the corresponding results for Ar feeding, while results obtained for various absorbed power values are addressed in Section 3. Pressure dependence of the plasma T_e , of the species densities and of the ionization percentage are discussed separately for low, intermediate and high power values applications. Two values of the last parameter, the flow rate, are considered, namely 5 sccm and 20 sccm.

The simplification introduced in [2] for the Ar case, separating the thruster plasma in “core” and “mantle” regions, is also used here. Figure 1 shows schematically a simple diagram for this “ansatz,” which is described in detail in [2].

The typical thruster radius R_T shown in scale in Figure 1 is also here $R_T = 1$ cm, leading to a core radius $R_C = 0.316$ cm as the area of the “core” cross section is chosen to be 10% of the total one, corresponding to about 30% of the total radius.

2.1. Low Power Applications. Let us consider the “mantle” region of a relatively low absorbed power HPT, say, of 100 W or less. The corresponding flow rate is about 12 sccm, and the pressure is of a few mTorr. The low power HPT physical conditions prevailing in this case are similar to those of a PR partially due to the small radius of the former, around 1 cm, leading to a reduced total volume of plasma. We estimate that the low power absorption in the “mantle” region of an HPT corresponds to a situation where a PR plasma absorbs an intermediate amount of power (150–500 W) in a big volume. The expected electron temperature T_e and the ionization and dissociation percentages of the main constituents as well become then comparable.

Plasmas described previously are in a quite analogous situation with the one of a low power/high pressure ICP “microthruster” of the type proposed lately by Charles and

FIGURE 1: Cross section of the HPT thruster cylinder.

Boswell [12]. In a prototype device, probe measurements were made, indicating a T_e of 3 eV for Ar, which is quite lower than expected, in view of the prevailing low power/high pressure. In the ICP thruster of [12], the power was typically of 20 W, and the pressure was of 1.5 Torr. These values are much lower and higher, respectively, than those used typically for HPT thrusters. Also, in [12], the gas temperature T_{GAS} was considered to be about 300 K, whereas we use a T_{GAS} value of 400 K, as was also the case in our previous Ar work described in [2]. Moreover, flow rate for [12] was of 100 sccm, which constitutes a rather high value for a small thruster, restricting to an ionization percentage of less than 1% for the measured T_e of 3 eV. These values are close to those that we calculated in [2] for the “mantle” region of a low pressure (around 10 mTorr) Ar fed HPT thruster. It should also be noted that, in [12], a global model development to characterize the ICP thruster was mentioned. On the base of our GM, feeding of such a “micro-thruster” with N_2O resulted in n_e , T_e , and species densities analogous to those described in Section 5 of [2] for the case of Ar. Using our GM we obtained in a straightforward manner the corresponding FD leading to low ionization percentages.

2.2. Pressure Depending Description of Intermediate Power Variation Results. For an absorbed power of 50 W, being a typical example of low power HPT thruster, Figure 2 shows our density results for the main species of the “core” as a function of the pressure which varies from 3 mTorr to 10 mTorr. The symbols, the type of lines, and the colors used for the densities of the species are triangles for N_2 , inverted triangles for O_2 , squares for N_2O , full circles for NO, hollow circles for $\text{O}(^3\text{P})$, hollow squares for $\text{O}(^1\text{D})$, and diamonds for N. Points resulting from our calculations are joined by lines only to ease the eye. Plain curves not associated with symbols represent our density results for ions (N_2^+ , N^+ , O_2^+ , O^+ , and O^-), except the N_2O^+ density which is represented by hollow triangles. Moreover, we used a dotted line for the O^- density and a dashed one for the $\text{O}(^1\text{D})$ one. Our n_e results are

FIGURE 2: “Core” region densities of species of a N_2O fed HPT of 50 W absorbed power. Pressure varies from 3 mTorr to 10 mTorr.

plotted with a thick pink dash-dotted line, whereas our total gas density results are represented with a magenta dash-dot-dot line. Also, the first N_2 vibrational level is represented in by a thin blue dashed line. In general, nitrogen densities are plotted in blue, whereas oxygen densities are in red, and the N_2O , N_2O^+ , and NO values are in black. The total gas density, n_{TOT} , increases continuously with the pressure, as well as the electron density. Results obtained for the T_e , the ionization percentage of the N_2O products, and the remaining N_2O percentage, corresponding to the same discharge conditions with those of Figure 2, are shown in Figure 3. Density increase corresponds to an ionization percentage decrease from about 60% for 3 mTorr to 30% for 10 mTorr, as shown in this figure.

The most abundant species appearing in Figure 2 are N and O atoms for neutrals and the N^+ and O^+ for ions, except for low pressures, where N_2O and the N_2O^+ species are important. The N, O, N^+ , and O^+ densities increase smoothly with pressure, while the N_2O density remains constant. Consequently, density of the remaining N_2O diminishes from about 16% for 2 mTorr to 2% for 10 mTorr, as illustrated in Figure 3. N_2 becomes the most important molecular species from 6 mTorr to 10 mTorr, increasing slowly with pressure as illustrated in Figure 2. Notably, the O_2 density is much lower than the N_2 one, due to its low dissociation threshold. N_2 and O_2 dissociation percentages of about 80% and 99%, respectively, are observed. Small part of the neutral atoms (here about 30%) leaves the “core” region for the “mantle” one, to form possibly molecules by influence of the thruster wall. High values of n_e and T_e contribute to the observed important dissociation. As a direct result of the small amounts of N_2O and O_2 species, the O^- density remains at very low values, with an electronegativity of less than 0.1% for 10 mTorr. This is the opposite of what happens in the cold external “mantle” region, where O^- plays an important role. The observed high dissociation percentage of molecular species leads to a “core” plasma of the HPT predominantly composed of atomic N and O species, together with their N^+ and O^+ ions. However,

FIGURE 3: As in Figure 2 but for T_e , ionization percentage (ξ), and remaining N_2O percentage.

appearance of the intense N_2 bands remains important in the spectrum.

We observe a continuous decrease of the T_e with the pressure, passing from more than 13 eV to less than 4 eV, as illustrated in Figure 3 (red line with squares). The ionization percentage (ξ , black circled line) is decreasing from about 61% to 27%. Note that, in the following, ξ stands for the total ionization percentage of the plasma (also sometimes written ξ_{TOT}). It is defined as the sum of the ions densities over the total density of species. The T_e and ξ variations shown in Figure 3 are somewhat analogous with those observed for both the N_2O and the Ar PR cases (see [1, 2]), even if variations are more intense for the thruster and encompass a wider range of values.

Results obtained by our GM for N_2O discharges are compared in Figure 4 to those previously obtained for Ar. In this Figure 4, our T_e and ξ values shown in Figure 3 for N_2O (thick lines) are repeated together with our Ar results (thin lines). For the Ar case, we give separately the percentage of simply ionized ($\xi_{Ar II}$, short dotted line) and doubly ionized ($\xi_{Ar III}$, short dashed line) species. The total Ar ionization percentage ($\xi_{TOT, Ar}$), which is the sum of the two percentages, is also given. This addition leads directly to the percentage of remaining neutrals which are still present in the plasma. Attention has to be made when calculating the thrust that here we added the number of ionized species, without considering the effect of double ionization which may become important. Electron density for N_2O and Ar cases is also plotted (green lines).

2.3. Pressure Depending High Power Results. It is important to know how the pressure modifies the properties of the N_2O discharge when the absorbed power is clearly higher. Therefore, we applied our model also for a fixed absorbed power of 200 W instead of the previous 50 W for the same as previous feeding of 5 sccm. Results obtained are illustrated in Figures 5 and 6 with the same symbols used in Figures 2 and 3. Because the absorbed power is higher, we present results pertaining to an extended pressure variation from 5 mTorr to

FIGURE 4: Comparison of T_e , n_e , and ionized species percentage for N_2O and Ar in the “core” region of a HPT of 50 W absorbed power. Pressure varies from 3 mTorr to 10 mTorr.

FIGURE 5: “Core” region densities of species of a 5 sccm N_2O fed HPT of 200 W absorbed power. Pressure varies from 5 mTorr to 20 mTorr.

20 mTorr instead of the 3 mTorr to 10 mTorr variation shown in Figures 2 and 3. In general, species densities in Figure 5 show a smooth variation in comparison to those of Figure 2 pertaining to 50 W absorbed power. As expected, in the higher power case, molecular species are more dissociated, and more ions are present. Consequently, we observe in Figure 6 that the total ionization percentage ξ_{TOT} (black line joining circles) is higher for 200 W absorbed power than for 50 W. This is also the case for T_e . When more power is available to ionize a bigger percentage of the gas, the ionization percentage increases faster, so, for example, for 10 mTorr ξ becomes typically double than this corresponding to 50 W case, while the electron temperature increases about 20%. Note that here the flow rate value was fixed at 5 sccm. Variation of the flow rate in conjunction with the absorbed power may change radically the character of the discharge.

It is evident that for higher feeding values, results may be quite different. Remaining N_2O percentage is quite higher, and ionization percentage is clearly lower for 20 sccm feeding.

FIGURE 6: As in Figure 5 but for T_e , n_e , ionization percentage (ξ), and remaining N_2O percentage.

FIGURE 7: Comparison of T_e , n_e , and ionized species percentage for N_2O and for Ar in the “core” region of a HPT of 200 W absorbed power and 20 sccm flow rate. Pressure varies from 5 mTorr to 30 mTorr.

This is illustrated in Figure 7 valid for an absorbed power of 200 W and for a feeding of 20 sccm, where a comparison of results obtained for the N_2O , and the Ar cases is given. Note that pressure varies from 5 mTorr up to 30 mTorr. Results are to be compared with those of Figure 4, pertaining to 50 W and 5 sccm. Here, ξ_{TOT,N_2O} and $\xi_{TOT,Ar}$ are quite different to those of Figure 4 (about double for a pressure of 10 mTorr), and the T_e of N_2O is changing in a significant way for the lower pressures (from 5 mTorr up to 10 mTorr). Influence of the flow rate can further be evaluated by comparison between the FDs shown in Figures 13 and 14 and between those of Figures 15 and 16, illustrating pressure variation results for a couple of feedings (5 sccm and 20 sccm) pertaining to N_2O and Ar correspondingly.

3. Dependence on the Absorbed Power

We have seen that the absorbed power constitutes an essential parameter for the HPT functioning. Adequate absorption of

FIGURE 8: Variation of the densities of species in the “core” region of a N_2O fed HPT as a function of absorbed power for 10 mTorr.

the available power by the plasma is also a primary concern in HPT studies. Therefore, after the description of results from pressure variations, we consider now variations of the discharge characteristics as a function of the absorbed power. In Figures 8–12, species densities, T_e and ξ values, are shown also for higher absorbed powers, going from the typical low value of 50 W up to 750 W. Variations of the species densities as a function of the absorbed power, for a typical fixed pressure of 10 mTorr, are illustrated in Figure 8. Most of the ion densities increase with the power, while densities of neutrals decrease, as expected in view of the concomitant n_e increase (dash-dotted pink line). For the 50 W power, the atomic N and O species are preponderant, with their ions already present in an important amount. When power increases from 200 W and up, the N^+ and O^+ become the predominant species, with N and O being the most important neutrals. Molecular ions are also present, especially N_2^+ and N_2O^+ , but their densities are much lower than those of the atomic ions. Variations with the power of the basic parameters T_e , ionization percentage, and N_2O percentage for the same fixed pressure of 10 mTorr are shown in Figure 9. We observe in Figure 9 that T_e and ionization percentage ξ of the N_2O products increase continuously, when the power passes from 50 W to 750 W.

Variations similar to those presented in Figures 8 and 9 were obtained for various fixed pressures. We illustrate in Figures 10 and 11 such variations for a fixed pressure of 7 mTorr. In Figure 10, we see that the densities of species vary rather similarly to those of Figure 8. The total density, however, is here lower in view of the lower pressure of 7 mTorr. In fact, a small pressure decrease from 10 mTorr to 7 mTorr leads to a total density decrease of a factor about two, illustrating an ion pressure of significant importance for lower pressures. As a consequence, the plasma is easier heated and ionized, as is illustrated by the higher T_e and ξ values shown in Figure 11. Comparison of results for the two selected pressures (10 mTorr and 7 mTorr) shows the importance of the pressure parameter in determining the plasma ionization and temperature. Inversely, when plasma

FIGURE 9: As in Figure 8 but for T_e , ionization percentage, and N_2O remaining percentage.

FIGURE 11: As in Figure 10 but for T_e , ionization percentage, and N_2O remaining percentage.

FIGURE 10: Variation of the densities of species for 7 mTorr in the "core" region of a N_2O fed HPT as a function of absorbed power.

parameters including thruster dimensions, flow rate, and absorbed power are determined, it is possible to have an estimation of the pressure based on the relation between the GM results and measurement obtained by optical plasma diagnostics methods (probes, OES).

In order to appreciate the expected differences between N_2O fed HPT and Ar fed HPT which we obtained previously [2], we show in Figure 12 the T_e and the partial and total ionization percentages as a function of the absorbed power, for both feeding cases. Pressure is fixed at 7 mTorr as previously described. Results are plotted with plain lines for N_2O and with dashed lines for Ar. We observe in Figure 12 that the calculated ionization percentages are slightly higher for Ar feeding than for the N_2O one. On the opposite, considerable differences are observed between T_e obtained for the two feedings. Incidentally, this feature may change, for instance, for a Xe fed HPT, where the first ionization threshold of Xe (12.13 eV) is lower than this of N (14.5 eV) and this of O (13.6 eV), while this of Ar (15.76 eV) is higher. Note that, for

FIGURE 12: Comparison of the variations of the T_e , partial and total ionization percentage for the "core" region of a N_2O fed, and of an Ar fed HPT, as a function of absorbed power for 7 mTorr.

molecules, N_2 ionization energy (15.58 eV) is much higher than those of N_2O (12.89) and O_2 (12.1 eV). Percentages of N^+ (ξ_{NII}), O^+ (ξ_{OII}), Ar^+ (ξ_{ArII}), and Ar^{++} (ξ_{ArIII}) are also represented in Figure 12. In view of the continuous variation of Ar^{++} (Ar III spectrum) with power, Ar III becomes clearly visible in the optical emission spectra of the thruster plasma. Comparison of Ar III to Ar II line intensities allows then for a trustful characterization of the HPT plasma, based on OES spectroscopy.

4. Functioning Diagrams for N_2O Fed HPT Giving Ionization Percentage and Comparison with Ar Fueling

Based on the entirety of our results for N_2O fed HPT, we constituted a (T_e versus P_{abs}) diagram, giving the ionization percentages $\xi = n_{ions}/n_{TOT}$ (%) as a function of pressure.

FIGURE 13: “Functioning Diagram” (FD) for the feeding of 5 sccm, for the “core” region of the N_2O fed HPT.

FIGURE 14: As in Figure 13 but for 20 sccm flow rate.

Figure 13 shows such a HPT “Functioning Diagram” (FD) for the feeding of 5 sccm, illustrating ionization percentages variation as a function of pressure, for a set of absorbed power and T_e values. Absorbed power spans a range of 25 W to 1000 W, and T_e spans a range of 3 eV to 30 eV, while variation of pressure is from 3 mTorr up to 30 mTorr. Accordingly, this FD for HPT encompasses a very wide range of plasma parameters. It has to be kept in mind that the present FD is dedicated specifically to a flow rate of 5 sccm. In the diagram of Figure 13, the horizontal broken line shows a 5% limit of ion losses to the “mantle.” The two vertical ones correspond to the pressures selected in the cases of Figures 8 and 9 (10 mTorr) and Figures 10 and 11 (7 mTorr) for a N_2O feeding. Once again, we observe here the big difference of the results when passing from 10 mTorr to 7 mTorr. On each diagram, a thick black arrow shows in bulk variation of the results for 100 W. Orientation of the arrow, namely, the angle formed by the arrow with the horizontal axis, indicates specifically how easy is to increase the ionization percentages for 100 W absorbed power.

FIGURE 15: “Functioning Diagram” (FD) for the feeding of 5 sccm and for the “core” region of the Ar fed HPT.

FIGURE 16: As in Figure 15 but for 20 sccm flow rate.

In order to get a clear picture of the influence of the important feeding parameter, we present in Figure 14 the corresponding FD belonging to a higher N_2O feeding of 20 sccm. Although the main trends remain similar to those illustrated in Figure 13 obtained for 5 sccm feeding, a lowering of the ionization percentage is observed for the 20 sccm case. Such a feature was already observed for an Ar fed thruster [2]. Comparison of Figures 13 and 14 demonstrates the very important feature of sufficiently low flow rate obligation if we want to maintain a high ionization percentage in the thruster. It is possible to use a higher feeding, for example, of 20 sccm instead of the 5 sccm one, only when we dispose of a sufficiently high absorbed power, allowing for a high enough ionization percentage leading to a satisfactory thrust. Consequently, an optimization of the feeding can be made on the basis of the allocated absorbed power.

Analogous diagrams for the Ar case for feedings of 5 sccm and of 20 sccm, based on an Ar GM developed previously [2], are presented in Figures 15 and 16 for comparison. Results vary in a similar way for all the parameters range for the

Ar case as for the N_2O one. Comparison of N_2O and Ar results illustrated in Figures 13 to 16 shows higher ionization percentages for the Ar plasma with lower T_e , in comparison with the N_2O case. This tendency, already observed in Figures 4 and 12, is now generalized to wider plasma domains. The presented FDs start from an ionization of 30% and up, because lower ionization percentages are not of interest for HPT. A general observation based on these diagrams is that varying of the flow rates leads to smooth variations of the results, at least in the range of flow rates and parameters presented here. Also, it is important to observe that in the low pressure region, a small change in pressure can lead to a considerable change of the results.

In comparing N_2O and Ar results for HPT, we observe features analogous with those pertaining to the ICP PRs already presented for Ar feeding in [2]. Indeed, when more and more gas is introduced in the device, it becomes more difficult to maintain a high ionization (and dissociation if any) percentage.

5. Comparison of HPT Functioning When Fed by N_2O and by Air

In order to obtain a larger view of the HPT functioning, we also examined results of feeding with an air-like N_2/O_2 mixture, in comparison with the N_2O feeding results illustrated previously. Similarities observed between N_2O feeding and N_2/O_2 4:1 $[N_2]:[O_2]$ “air-like” mixture one, allow for characterization of an air fed thruster. In Figure 17, T_e and ionization percentages obtained for the two feedings are compared. Absorbed power increases from 50 W to 750 W, as was the case for Figures 11 and 12, while the pressure is also fixed to 7 mTorr. Results obtained for N_2O are represented by plain lines, whereas the air-like ones are plotted with dashed lines. Inspection of Figure 17 shows that the obtained T_e is slightly higher for the air-like mixture than for the N_2O . We also observe that the ξ_{TOT} values corresponding to both feedings are very similar.

It is also interesting to investigate how the ionization percentage varies as a function of the pressure for various T_e and absorbed powers when the HPT is fed with a 4:1 $[N_2]:[O_2]$ N_2/O_2 mixture mimicking the air composition. Such a variation is illustrated in Figure 18, presenting a partial FD for a 5 sccm feeding by an air-like 4:1 $[N_2]:[O_2]$ mixture. We see that when pressure exceeds 10 mTorr, ionization percentage is clearly higher for feeding by N_2/O_2 air-like mixture than by N_2O . On the opposite, when pressure is lower than 7 mTorr, ionization percentage is lower for the mixture than for N_2O .

6. Conclusions and Perspectives

Aiming mainly to HPT applications, the possibility of using N_2O and air for space propulsion was illustrated. However, although the present results concern specifically a form factor typical for HPT devices, and also the Landau damping “ansatz” has been used, the model could easily be modified to apply in other thruster types, notably HET. A calculation of

FIGURE 17: Comparison of the variations of T_e , ionization percentage for the “core” region of a N_2O fed, and of an air fed HPT, as a function of absorbed power for 7 mTorr.

FIGURE 18: “Functioning Diagram” (FD) for the feeding of 5 sccm for the “core” region of an air-like fed HPT.

the main plasma parameters expected in the “core” of N_2O , air, and Ar fed plasma thrusters was presented, and results have been compared. In doing so, the possibility of using air for propulsion was addressed, and the main parameters of the air plasmas (n_e , T_e) are being shown to approach those of the N_2O in most of the considered conditions. Still, for propulsion applications, more work remains to be done in evaluating atomic and molecular data of the ions. The latter are expected to be present in an important amount as was illustrated in Sections 2 to 5, an important fact for propulsion applications. Detailed evaluation of ion energy losses and of their kinetics may improve characterization of both N_2O fed and air fed plasma thrusters. However, the provided FD are expected to be of notable help for various applications. Indeed, besides HPT, the provided FDs are of interest to discharge studies and other industrial plasma applications containing mainly N_2O and/or N_2/O_2 mixtures.

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