Modeling and Optical Diagnostics of Air-breathing Thrusters of 1 kW Class in Very Low Earth Orbit Missions

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ISRU technology propellants as the Earth atmospheric remnants at about 200 km altitudes [1], atmospheric CO_2 of Mars and Venus [2,3] and H2 / He mixtures encountered in Icy Planets [4], are nowadays systematically investigated [5,6]. The present poster focuses to modeling and to the concomitant optical diagnostics of very low Earth orbits air-breathing thrusters. Similar technology has been developed by DEDALOS, addressing planets as Neptune [4] and various bodies of the Solar system. Results illustrated here concern the 1 kW class, an absorbed power being sufficient to dissociate and to ionize atmospheric ISRU propellants from the Solar system in percentages allowing considerable thrust.

Detailed Global Model

The well known 4CDGM model [7] is used for both modeling and diagnostics of air-breathing thrusters. In this model the four main initial components N, N_2, O, O_2 encountered in various percentages according to the traveling altitude are taken into account. A thruster Plasma Components Composition (PCC) diagram with its conjugate and a Functioning Diagram (FD) are used to illustrate part of the obtained results.

Fig. 1 shows a PCC diagram containing the main constituents of a R = 2 cm and L = 18 cm thruster plasma fueled by 40 sccm Earth atmosphere remnants at 180 km of altitude. Absorbed power is P_{abs} = 1 kW and the pressure varies from 1 mTorr to 10 mTorr. The total density is shown by a magenta double dotted line, while the nitrogen species are in blue and the oxygen ones in red. The excited atomic oxygen O level is in orange. Electron density n_e is shown in green.

Fig. 2 shows a diagram concomitant to the PCC of Fig. 1, containing the variations of n_e, of the electron temperature T_e and of the total ionization percentage ξ_{TOT} at conditions similar to those of Fig. 1. We observe in this figure that T_e (green curve with squares ■, values to be read at the left side of the figure) has a value of around 30 eV for a pressure of 1 mTorr. T_e after a plateau, diminishes when pressure increases, going down to slightly less than 5 eV at 10 mTorr.

Values of ξ_{TOT} (green curve with full circles ●, values to be read at the right side of the figure) pass from a plateau when pressure increase, going finally down to about 15 % for 10 mTorr. Because the nitrogen molecules are quite dissociated in view of the absorbed power of 1 kW, overall presence of nitrogen species is higher than the oxygen ones in the bulk of the addressed pressure values, except near 1 mTorr where the low density hampers the N_2 dissociation. The creation of both O^+ and N^+ ions keeps increasing with pressure going from about 2 mTorr to about 3 mTorr, but diminishes afterwards because of the increased total pressure. It can also be seen in Fig. 2 that the percentages of electrons are not far away from the sum of the ionization percentages, the latter being calculated following the total ions number, without distinction of each species charges. This indicates that the presence of doubly ionized species is relatively low near 1 mTorr and practically negligible after 5 mTorr. Therefore, doubly ionized species are not shown in Fig. 2. The formed $N2^+$ and the remaining N2 percentages have low values as in [8], with the latter persisting better for higher pressures.

Functioning Diagram

PCCs like this shown in Fig. 1 belonging to different absorbed powers have been elaborated on the basis of 4CDGM calculations. Such PCCs, allow for evaluation of the thruster functioning in various regimes. They are collectively used to obtain the FD dedicated to 40 sccm atmospheric remnants feed shown in Fig. 3. For the addressed pressure values, the ionized species attend an ionization percentage sufficient to obtain a considerable thrust, especially around 2 -3 mTorr pressure. Detailed description of the obtained PCC, FD and concomitant diagrams are discussed elsewhere.

Non-intrusive Optical Emission Spectroscopy (OES) diagnostics

4CDGM modeling results also to the evaluation of the theoretical spectral lines of the obtained components. For the more significant among them, O, O^+, N and N^+ in agreement with Fig. 1 the spectral lines are presented in Figs. 4 and 5 for the neutral and ionized oxygen case. Such values allow for OES diagnostics [9], provided the corresponding experimental ones are acquired. Thus electron density and temperature of the plasma can be obtained. The plasma temperature and electron density can in principle be diagnosed using any one of the four significant components. For valid model results and sufficiently accurate optical measurements, all of them lead to the same electron density and temperature results. Comparison of the latter constitutes an evaluation of the whole modeling and diagnostics process.

In the presented example of the Fig. 4, the theoretical O I plasma spectrum obtained by 4CDGM in case of a pressure of 3 mTorr is given. Concomitant OES diagnostics should focus to the $3s$ – $3p$ multiplet lines, which lie mostly around 600 nm to 900 nm. Fig. 5 shows the theoretical O II plasma spectrum obtained by 4CDGM for the same pressure of 3 mTorr. Concomitant OES diagnostics should focus to the $3s$ – $3p$ multiplet lines, which lie mostly around 350 nm to 500 nm. As it can be seen in Figs. 4 and 5, the corresponding multiplet lines of the O I spectrum fall in general in a quite higher wavelength region than in the O II case. This is a general feature well known in the plasma spectroscopy.

Comparison of the O I and O II spectra leads directly to the plasma ionization percentage. Theoretical intensities belonging to the nitrogen N I and N II plasma components have been also discussed elsewhere, see e.g. [10].

4CDGM modeling and the related diagnostics for 1 kW class thrusters fueled by the atmospheric remnants expected to be encountered in very low orbits around the Earth constitute a powerful tool for the air-breathing technology support.

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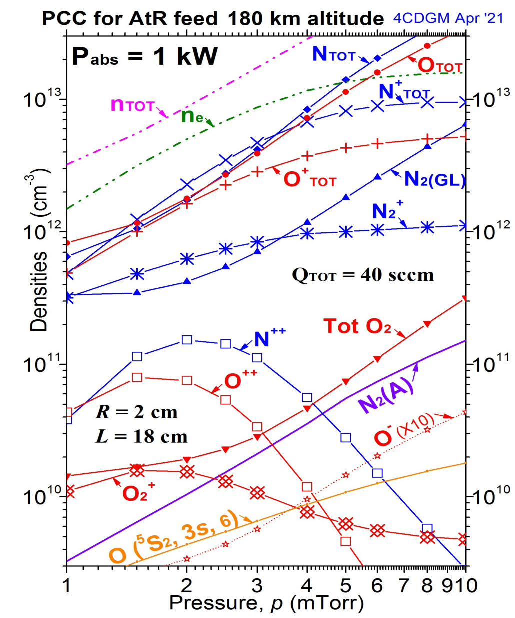

Fig. 1. *PCC for 1 kW absorbed power, 180 km altitude*

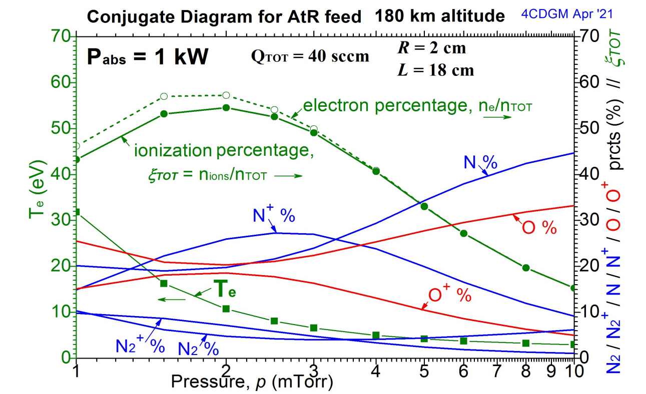

Fig. 2. T_e , ξ_{TOT} *and electron percentage for conditions similar to Fig. 1*

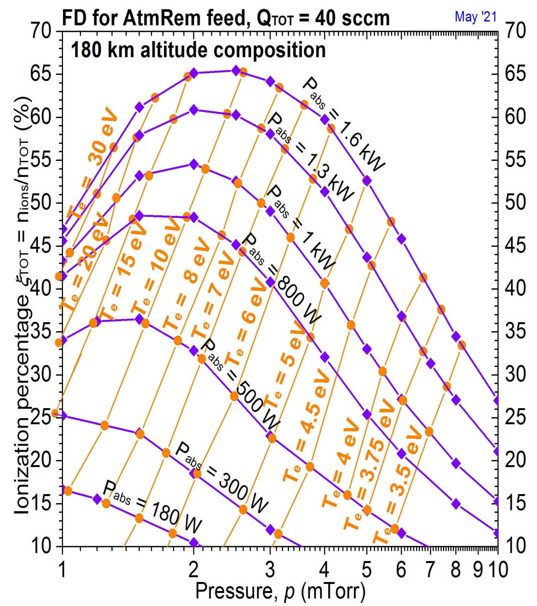

Fig. 3. *FD showing the ionization percentage* ξ_{TOT}

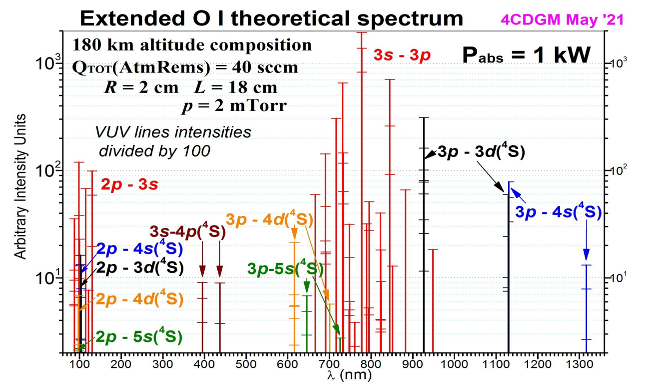

Fig. 4. *O I spectrum. Conditions of Fig. 1 for 2 mTorr pressure*

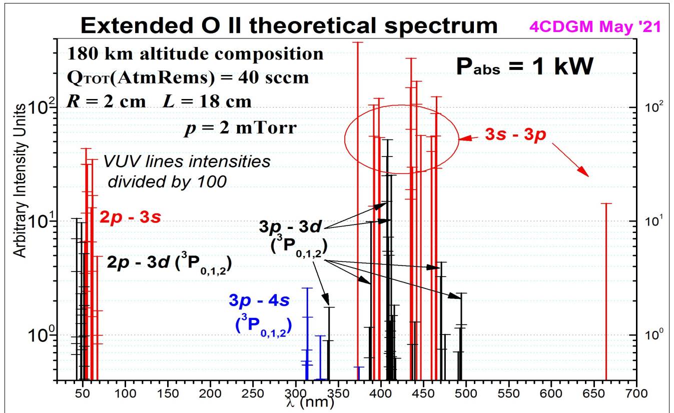

Fig. 5. *O II spectrum. Conditions of Fig. 1 for 2 mTorr pressure*