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Iodine as a propellant for gridded electric space propulsion systems

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Abstract: A global model of gridded electric thrusters has been developed using iodine as the input propellant. Results are compared with those obtained using xenon under the same operating conditions, and similar performances are found. In parallel, a new experiment has been constructed to test iodine in the PEGASES plasma thruster, and to benchmark the model.

Keywords: iodine, electric gridded thruster, PEGASES, global model

1. Introduction

Most state-of-the-art electric propulsion systems such as gridded thrusters and Hall effect thrusters, make use of xenon as a propellant gas. However, xenon is very rare, is expensive to produce, and is used in a number of other competing industrial applications (such as lighting). Alternatives to xenon are currently being investigated, and iodine has emerged as a potential candidate because of its lower cost, larger availability, its solid state at ambient temperatures and pressures (thus removing the need for high pressure propellant tanks), its low vapour pressure, and its low ionization potential. Recently Busek has experimentally demonstrated the advantages of iodine with a full working gridded thruster [1].

In order to compare performances of an Iodine plasma with those of a xenon plasma [2] under the same conditions in an electric gridded thruster, a global model has been developed. The plasma parameters as densities and temperature were calculated to finally quantify the thruster properties (efficiencies, specific impulse...). Model results will be compared with experimental results obtained with a dedicated experimental set-up using iodine as propellant fin the PEGASES thruster (an electric gridded thruster accelerating both positive and negative ions extracted from an ion-ion plasma obtain inside the ionization chamber).

2. Geometry and assumptions of the model

An illustration of the system to be modelled is shown in Fig. 1. The thruster is a cylindrical chamber with an inner radius R and a length L. It is powered by a radio frequency inductive coil with a radius R_c. The volume of the plasma and the total inside area can be calculate as $V = \pi R^2 L$ and $A = 2\pi R^2 + 2\pi RL$. The neutral gas is injected at a fixed rate Q_0. Grid transparency for neutrals is fixed at 0.3, and 0.7 for positive ions. We assume that the ion transparency is independent of the nature of ions.

Positive ions are accelerated across the two grids system with a voltage difference V_{grid}. The velocity they reach is

$$v_{beam} = (2eV_{grid}/M)^{1/2}$$

with M the mass of the ion we consider and e the elementary charge.

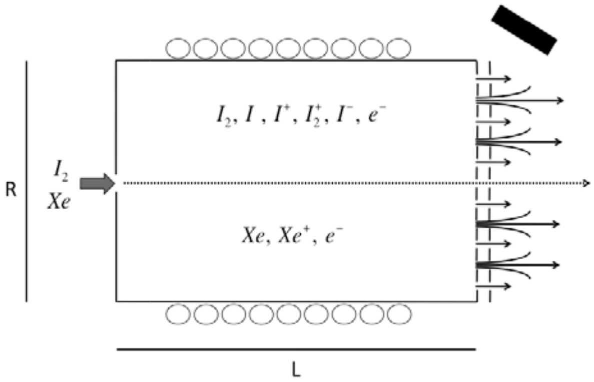

Fig. 1. Schematic of the electric gridded thruster model: the chamber is surrounded by a coil powered at 13.56 MHz, the neutral gas (Xe or I_2) is injected on the left and positive ions are accelerated by biased grids on the right.

Gas heating is included in this model, but we consider that the ion temperature is different from the gas temperature, and we assume that the ion temperature is the same for all ion species.

Considering that the electronegativity, defined by negative ion density over electron density, is lower than 1, the plasma is treated as electropositive in this model.

3. Iodine chemistry in the model

Though iodine is a corrosive gas and chemically active with certain metals as titanium, copper or silver, we do not consider chemistry on surfaces in this model. The set of reactions used is listed in Table 1. Some species and reactions are not taken in count in the model, such as direct electron attachment to I_2 and I:

- $e^- + I_2 \rightarrow I_2^-$
- $e^- + I \rightarrow I^-$

The attachment to I_2 molecule leads to the formation of I_2^- ions in a very instable state [3]: the electron is lost very quickly after by auto-detachment. The same process occurs for I^- ions.

Table 1. Chemistry of the model.

Excitation of I_2	$e^- + I_2 \rightarrow e^- + I_2^*$
Excitation of I	$e^- + I \rightarrow e^- + I^*$
Elastic collision of I_2	$e^- + I_2 \rightarrow e^- + I_2$
Elastic collision of I	$e^- + I \rightarrow e^- + I$
Dissociative Attachment	$e^- + I_2 \rightarrow I^- + I$
Dissociative Ionization	$e^- + I_2 \rightarrow I^+ + I + 2\,e^-$
Ionization of I_2	$e^- + I_2 \rightarrow I_2^+ + 2\,e^-$
Ionization of I	$e^- + I \rightarrow I^+ + 2\,e^-$
Charge exchange	$I^- + I_2^+ \rightarrow I_2 + I$
Ion recombination	$I^- + I^+ \rightarrow 2I$
Wall recombination	$I \rightarrow 1/2\ I_2$
Dissociation	$e^- + I_2 \rightarrow 2I + e^-$

4. Global model

Three types of equations are used in this model: particle balance equations, a gas heating equation and an electron power balance equation.

We wrote a particle balance equation for each species of the plasma (I_2, I, I_2^+, I^+, I^- and electrons). In this type of equation time variations of densities are described as the result of production and destruction of the considered species, produced or lost by chemical reactions described in Table 1.

Gas temperature is calculated by considering all the mechanisms responsible for power losses or energy gains of neutral gas [4]. These mechanisms are transcribed and included in the gas heating equation, where gas temperature variations are the result of the balance between cooling and heating terms.

Finally, to assess absorbed or lost power by electrons in the plasma, it is necessary to establish an electron power balance equation: electron temperature variations are here the effect of the balance between the absorbed power term and the lost power terms, i.e., terms describing all the chemical reactions with an electron involved.

5. Results and comparison with xenon

Fig. 2. shows the specific impulse and thruster efficiency obtained for an iodine plasma and a xenon plasma under the same conditions, conditions described in Table 2.

Table 2. Thruster parameters.

Dimensions	Injection and grids		Coil properties
R = 6 cm	$M_I = 127$	$M_{Xe} = 131$	N = 5
L = 10 cm	$Q_{mg} = 0.9$ mg/s		$L_{coil} = 4.84$
$R_c = 7$ cm	$V_{grid} = 1000$ V		$R_{coil} = 2\ \Omega$

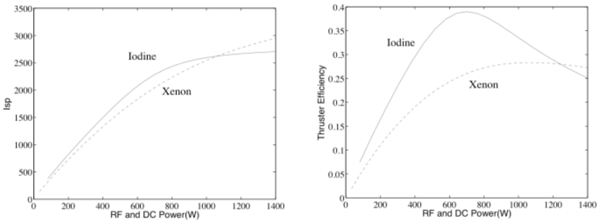

Fig. 2. Specific impulse and thruster efficiency for iodine plasma and xenon plasma.

The specific impulse is the ratio of the total thrust on the quantity of propellant used to obtain this thrust. Around 800 W of power used, which is the average power used for this kind of thruster, we can observe that iodine has a higher specific impulse than xenon, which means that less propellant is necessary to iodine to produce the same thrust.

Thruster efficiency is the mass efficiency multiply by the electric efficiency. As for specific impulse, around 800 W of power used, thruster efficiency for iodine is more important than for xenon.

According to the model, iodine as propellant for an electric gridded thruster shows comparable, and even better results than Xenon under the same conditions.

6. Experimental Set-up

The experimental set-up is shown in Fig. 3. Solid iodine (under crystal form) is heated to sublimate, then injected inside PEGASES where the neutral gas is heated and ionized. A mass flow controller allows a fine control on the iodine mass flow. The whole injection system needs to be heated to avoid deposition of iodine on surfaces. Pressure is measured with three gauges and vacuum is obtained with a turbo-molecular pump and a primary dry pump. A 3D translation stage inside the vacuum chamber allows volumetric plasma studies using electrostatic probes. This dedicated test bench is under construction and preliminary results will come soon.

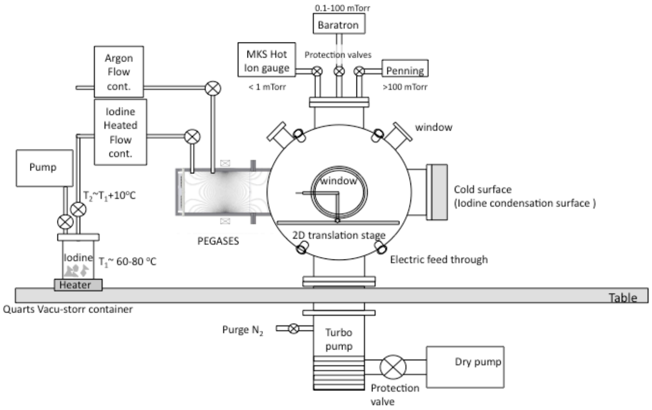

Fig. 3. Schematic of the experimental set up with iodine as propellant for the PEGASES thruster.

7. Acknowledgment

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