Study of a Hall effect thruster working with ambient atmospheric gas as propellant for low earth orbit missions

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We present calculation results of Hall effect thruster performance with a two-dimensional hybrid model when ambient atmospheric gas (composed of essentially atomic oxygen and nitrogen molecules at an altitude of 250 km) is used as propellant. Simple analytical laws are also used to analyze the effect of propellant mass on thruster performance. In comparisons with conventional xenon propellant, the ionization layer (layer where the gas is ionized) is largely increased due to less favorable ionization cross sections of the atmospheric gases. The consequence is that the channel geometry and magnetic field strength adopted for xenon are no longer suitable for low mass propellants. Analytical works and calculations show that a reduced magnetic field and a longer channel length lead to a benefit in the ionization of atmospheric gases. Calculations also show that a propellant mass flow of 3 mg.s^{-1} of atomic oxygen (or nitrogen molecules) is necessary to counteract the drag force of 20 mN at an altitude of 250 km.

Nomenclature

roman characters

B	=	magnetic field strength (T)
b_c	=	channel width (m)
B_{max}	=	maximum of magnetic field strength (T)
B_0	=	maximum of magnetic field strength for nominal conditions
d	=	channel mean diameter (m)
e	=	electron charge constant (1.6×10^{-19} C)
E	=	electric field (Vm^{-1})
$I_{\dot{m}}$	=	neutral equivalent (A)
I_d, I_i, I_e	=	discharge, ion and electron current (A)
$I_{i,j}$	=	ion current of the *j*th species (A)
I_{sp}	=	specific impulse (s)
J_e	=	electron current density (A.m^{-2})
J_H	=	heating of the electrons by the electric field (A.V.m^{-3})
K, K_{in}, K_{out}	=	parameters for anomalous transport
k_B	=	Boltzmann constant (1.38×10^{-23} JK^{-1})

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k_i , k_l, k_{diss} = ionization, inelastic, dissociation rate coefficient (m^3s^{-1})
L = channel length (m)
L_B = magnetic layer thickness (m)
$\dot{m}$ = xenon anode mass flow rate (mgs^{-1})
m_a, m_e = atom, electron mass (kg)
m_{Xe} = xenon atom mass (2.1887×10^{-25} kg)
n, n_a, n_e, n_i = plasma, neutral, electron and ion number density (m^{-3})
n_0 = reference plasma number density (m^{-3})
P = electric power (W)
r = radial direction
S_c = channel cross section area (m^2)
T = thrust (N)
T_e = electron temperature (eV)
U_d = discharge voltage (V)
V = electric potential (V)
V^* = electric potential along the magnetic field lines (V)
v_a, v_i = neutral, ion velocity (ms^{-1})
x = axial direction

greek characters

α = propellant utilization efficiency
β = energy accommodation coefficient
δ = discharge voltage loss coefficient
ΔU = potential drop in the ionization layer (V)
ε = electron mean energy (eV)
Γ_a, Γ_e = neutral, electron flux ($m^{-2}s^{-1}$)
γ_{rec} = recombination coefficient
η = thruster efficiency
κ = inelastic power losses (eVm^3s^{-1})
λ_i = ionization length (m)
μ = cross magnetic field electron mobility ($m^2V^{-1}s^{-1}$)
μ_c, μ_{ano} = collisional, anomalous cross magnetic field electron mobility ($m^2V^{-1}s^{-1}$)
Π = effective energy loss coefficient for electron-wall collisions (eVm^3s^{-1})
χ_j = neutral fraction of the *j*th species
ζ_j = ratio between the *j*th species and molecule masses

I. Introduction

The interest of Hall effect thrusters (HETs) for Low Earth Orbit (LEO) missions is actually limited because a large amount of xenon must be stored to compensate continuously the ambient air drag force that acts on the spacecraft. The storage of the total amount of propellant necessary to cover the total time duration of the mission leads to a large weight penalty. The constraints and changes in term of mission requirements (higher thrust, lower payload charge, etc.) for small mass satellites result to an impossible use for such engines. The situation can be different if the constituents of the atmosphere (O_2 and N_2 molecules and N and O atoms) that produce the drag force could be considered as propellant gas. In the context of propulsion, others gases than xenon in the noble list with lower cost such as krypton, argon or neon have been tested in vacuum chamber experiments. A gain in exhaust velocity is achievable because of their low masses (see e.g. [1]). As far as we know, HETs have not been extensively studied with oxygen and nitrogen propellants. The goal of this study is to examine the possibility to use ambient air molecules/atoms to propel a spacecraft with HETs for low earth orbit missions.

The drag force that acts on a satellite in a LEO depends of the altitude through the local air density. Based on data on air density provided by the atmospheric model of the Earth [2], D. Di Cara and co-workers have studied a scenario where an electric thruster (HET or gridded ion engine) is used on a spacecraft for Earth Observation at an altitude of 250 km [3]. In the case of a mission at a constant altitude (circular orbit) the thruster must compensate a drag force that varies between 2 and 20 mN (as a function of the solar activity). In the worst case, the thruster must reach 20 mN. At an altitude of 250 km, the atmosphere is mainly constituted by the atomic oxygen (due to oxygen molecules dissociation) and nitrogen molecules [2]. The densities of atomic oxygen and nitrogen molecules at this altitude for mean solar activities are 2×10^{15} m^{-3} and 10^{15} m^{-3} respectively. The pressure is on the order of 10^{-6}-10^{-7} Torr. In this paper, we are interested in the ionization and acceleration of a given flow of nitrogen and oxygen at the channel entrance without considering others technical challenges (e.g. the oxidation of the LaB6 cathode in an oxygen atmosphere, storage of the propellant to increase the density at the channel entrance as proposed by D. Di Cara and co-workers [3], etc.).

The rest of the report is organized as the following. We start from the simple thrust equation to examine the consequence of the use of low mass propellants (section II). The consequence on the ionization of the propellant in the channel of HETs for low mass gases is examined in section III. The model is briefly presented in section IV. The section V is dedicated to numerical results. Finally, the main conclusions are summarized in section VI.

II. Thrust equation

The thrust is the reaction force that counteracts the acceleration of the ions, it can be written as [4] as :

$$T = \alpha\dot{m}\sqrt{U_d(1-\delta)2e/m_a} \quad (1).$$

In eq. (1), e is the elementary charge, m_a is the atomic mass, $\dot{m}$ is the mass flow of the working gas, and U_d is the discharge voltage, α is the propellant efficiency, and δ is the discharge voltage loss coefficient. In the equation above, two parameters $\dot{m}$ and U_d depend on the working conditions, while α and δ are related to the discharge efficiency (see below). Let us now examine separately the terms before and under the square root of Eq. (1).

The propellant efficiency can be defined as the ratio between the ion current I_i and the equivalent current of the propellant mass flow injected - $I_{\dot{m}} = e\dot{m}/m_a$:

$$\alpha = \frac{I_i}{I_{\dot{m}}} \quad (2).$$

Notice that Eq. (2) is strictly valid for singly charged ions that we consider in this study. For a given mass flow rate, the propellant efficiency reaches a plateau for a discharge voltage threshold. This corresponds to a high enough electron energy to efficiently ionize the propellant gas. The experimental work reported by Kim [5] gives a threshold of 200 V for a xenon mass flow of 3 mg.s^{-1}. Lazurenko *et al.* propose a criteria indicating that the minimum mass flow rate capable to offer a high propellant efficiency is reduced for large discharge voltage [6]. The thrust is directly proportional to $\alpha\dot{m}$ (see Eq. (1)]. The capability of using atmosphere gases as propellants will depend on the large propellant efficiency for low mass propellants to avoid a storage that induces large penalties.

The applied loss voltage coefficient δ involving in Eq. (2) accounts for different losses (ionization, spread of the distribution, etc.) due to the overlap between the ionization and acceleration regions that has been observed in HETs both experimentally [7] and with models [8]. The term $U_d(1-\delta)$ under the square root in Eq. (2) can be seen as a kind of effective acceleration potential that really accelerates the ions. In HETs, δ has been estimated from ion distribution measurements in the HET plume. Results show that δ remains always low ($\delta \leq 0.1$) for xenon [7], and for krypton [9], for 1kW-HET. For a micro-HET of 10-50 W, $\delta \sim 0.3$ [10]. We will assume that δ can be also low for low mass propellant. In other words, the square root term in Eq. (2) seems not to be a large constrain even at low mass flow rate.

From this simple analysis, we remark that the key issue for using HETs on board satellites positioned in LEO orbit is to find favourable conditions to maintain a high level of ionization in order that the thruster can work for reduced propellant mass flow. Indeed, most of the discharge current is carried by the ions and is consequently proportional to the mass flow injected. This condition is also important to operate at a reduced electric power W (W

$= I_d U_d$ - where I_d is the discharge current, sum of the ion I_i and electron I_e currents) and to avoid propellant storage on board LEO satellites.

III. Ionization length for low mass propellant gases

The ionization length λ_i is given by the following relation [5] :

$$\lambda_i = \frac{\mathrm{v}_a}{n_e k_i} \quad (3),$$

where n_e is the electron density and v_a is the neutral atom velocity. The ionization length is proportional to the atom velocity, which determines the time passed by the atoms in the ionization length. The ionization length is inversely proportional to the ionization rate that characterizes the ionization probability and to the plasma density ; a large number of electrons increases the probability that one of them make a collision with one neutral.

We can characterize the propellant efficiency α by calculating the difference between the neutral flux at the end of the channel length L and at the entrance (normalized by the neutral flux at the entrance)

$$\alpha = 1 - \exp\left[- L/\lambda_i\right] \quad (4).$$

A propellant efficiency above 0.8 requires a minimum channel length L of two times the ionization length λ_i. In the literature, the criteria discussed above is referred to the Melikov-Morozov criteria [11].

We must here add an important remark. A direct comparisons between λ_i with L as we propose is somewhere ambiguous for two reasons : 1) scaling laws are most of the time zero dimensional, space gradient are neglected. The magnetic layer is consequently merged with the channel length. All the quantities calculated with scaling laws (electric field, plasma density, etc.) are constant along the channel length. In real devices, the situation is different, the magnetic field magnitude is peaked at the channel exit and decreases to low magnitude values in the anode plane, in order to concentrate the region of high plasma density and accelerating electric field near the channel exhaust [5]. Numbers of studies have demonstrated the significant role of the thickness of the magnetic layer L_B on the thruster efficiency (see e.g. [12], [13]) for a same channel length, consequently λ_i has also to be a fraction of L_B. 2) in the one-dimensional approach proposed here, we neglect the recombination of ions on walls and the re-emission of neutral atoms. As a consequence, the length of the ionization region must be increased to give an opportunity of neutrals coming from the ion recombinations on walls to be re-ionized. In the rest of the section, to conserve $\alpha = 0.8$, we fix L to 5 times λ_i (see further calculations)

Let us now express the electron density n_e in Eq. (3) as a function of the mass flow injected (considering a high propellant efficiency). If we assume that the plasma is quasineutral, the electron density n_e is equal to the ion density n_i, the plasma density n can be written as a function of the propellant mass flow, the atom mass, the ion velocity v_i and the channel cross section area S_c (= $\pi d b_c$ – d and b_c are the mean diameter and width of the channel) :

$$n = \frac{\dot{m}}{\mathrm{v}_i S_c m_a} \quad (5).$$

Finally, if we combine Eqs. (4) and (5), we can write an equation where the ionization length λ_i depends on discharge voltage, propellant characteristic (atomic mass, mass flow, and ionization rate) and thruster geometry through the channel cross section area :

$$\lambda_i = \frac{\mathrm{v}_a \mathrm{v}_i m_a}{\dot{m} k_i} S_c \quad (6).$$

Because the ion and atom velocities are both inversely proportional to $\sqrt{m_a}$, the ionization length λ_i is independent from the propellant mass. The propellant efficiency given by Eq. (4) is also independent from the propellant mass for a same channel length. We have plotted in Fig. 1a the ionization rate as a function of the electron mean energy assuming a Maxwellian distribution function for the electrons. All the data plotted in Fig. 1a can be found in [14].

We have calculated the channel length L as a function of mass flow and ionization rate, considering a propellant efficiency of 0.8 and, $L = 5\lambda_i$. The conditions are the following : the temperature of injection of the neutrals is 800 K, the average voltage drop that accelerates ions in the ionization layer ΔU = 50 V [12], and the channel cross section area is 40 cm^2 (typical of the PPS®1350 engine). Figure 1b presents the profile of L for a mass flow of propellant that varies between 0.5 and 5.5 mg.s^{-1} and a ionization rate between 10^{-14} and 2×10^{-13} m^{3}s^{-1} (corresponding to typical mean electron energy encountered in HETs - between 20 and 60 eV).

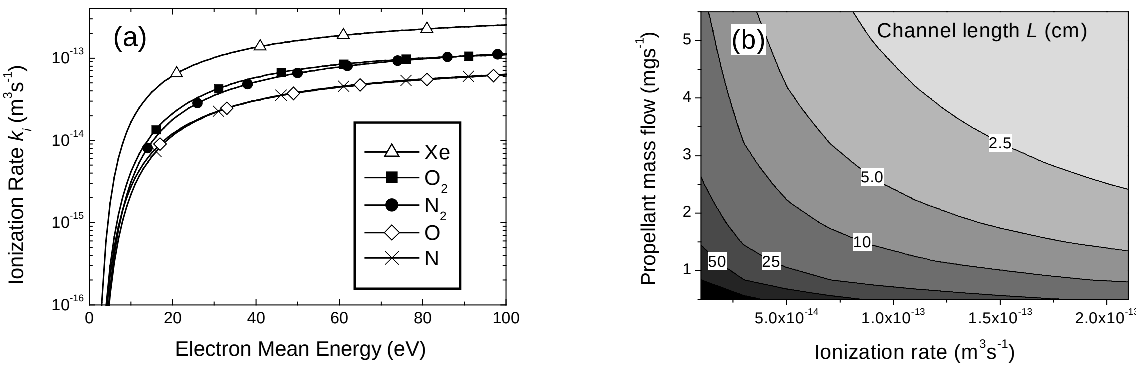

Figure 1 : (a) Ionization rates as a function of the electron mean energy for gas and molecules of the Earth atmosphere, plus xenon, (b) Channel length L as a function of the ionization rate k_i and propellant mass flow $\dot{m}$.

For typical conditions for a thruster operating with xenon, the electron energy is on the order of 30 eV, the ionization rate is 10^{-13} m^{3}s^{-1} (see Fig. 1a). If we keep constant the discharge voltage and make the hypothesis that the electron energy is on the same order for oxygen and nitrogen molecules/atoms, the ionization rate is around 5×10^{-14} m^{3}s^{-1} (Fig. 1a). For a mass flow of 5 mg.s^{-1}, the optimised channel is 2.5 cm in the case of xenon and near 10 cm for ambient air propellants. We clearly conclude from this simple analytical study is that the optimisation of the channel length for xenon is no longer pertinent for low mass propellant. One can argue that the ionization length can be reduced by reducing the cross section area S_c involving in Eq. (6). If we change the ratio surface over volume, more ions can reach the ceramic walls. The consequence can be also an excessive heating and a damage of the wall surfaces.

The situation is more complex in reality ; as an example the molecules can be dissociated before being ionised. We have completed the analytical approach with a numerical model that is describes in next section.

IV. Overview of the two-dimensional hybrid model

The basis of the model has been previously described in [15], [16]. The model assumes a cylindrical symmetry. The model takes into account the whole channel and the near outside region where the cathode is localized. The model is hybrid, i.e. electrons are treated as a fluid, and ions and neutrals as particles. The ions and neutrals are collisionless while the electrons undergo many collisions due to the magnetic confinement. We come back to the kinetic description of the heavy species transport and the fluid approach for electrons in sub-sections A and B, respectively.

A. Kinetic description of heavy species transport

We manage the number of particles in the system using the efficient macro-particle technique. Each macro-particle represents a large number of ions and neutrals. The total number of macro-particles used in the calculations can reach 400 000. In the rest of the study, we use the terminology ions and neutrals for ion macro-particles and neutral macro-particles, respectively, for simplicity. The equations of motion of ions (only singly charged) and neutral atoms and molecules are solved until the heavy species leave the computational domain or neutral particles being ionised or dissociated for molecules. In this study, we neglect the influence of the magnetic field on the low mass ion motions. Ions are created inside the volume according to the ionisation source term. Ions impacting on walls are recombined and news atom or molecules are formed (see below). The neutrals are injected in the simulation domain through the anode plane, we neglect the backpressure (the density of neutrals at an altitude of 250 km is some orders of magnitude below the density inside the thruster channel). The flux is released uniformly into the annular channel isotropically. The initial velocity distribution is a Maxwellian with a temperature of 800 K. N and O atoms can be formed after dissociation of N_2 and O_2 molecules. The energy of dissociation of molecules is on the order of 10 eV. After dissociation, two atoms are formed, most of the time one excited state atom and other one at ground state [17], [18]. The kinetic energy carried by the two atoms considered at ground state is fix to 1 eV.

The question of neutral-wall interactions in the context of ambient air components must be assessed because atomic oxygen/nitrogen can be recombined to form O_2/N_2 molecules. The recombination coefficient γ_{rec} of atomic oxygen/nitrogen (defined as the number of atoms that forms molecules after a collision with a wall) is still an open question in plasma discharge. It depends on the pressure, temperature, surface state, and even on the chemical composition of the surface. The recombination coefficient of oxygen on silica materials that constitutes the wall materials of HETs has been measured in the context of the re-entry of space vehicle in the Earth atmosphere at high temperature. For low pressure and temperature, works of Greaves and Linnett [19] report a γ_{rec} on the order of 7×10^{-4}. The number of times that an atom collides with the channel walls before being ionized or before leaving the channel is less than 100. The probability for a neutral atoms to form molecules is very low. The same argumentation for nitrogen on boron nitride leads us to consider that the recombination is negligible in the conditions of these study. The question of the energy of the reflected atoms/molecules after colliding with the ceramic walls and/or the energy of atoms/molecules that are reemitted after the neutralization of ions that hit the walls must also be examined. The β coefficient is defined as the energy accommodation coefficient. When β = 0, the energy of the neutral particle is equal to the incident particle energy, at the opposite, when β = 1 most of the energy of the incident particle is transferred to the walls, and the neutral particle is thermalized (we consider a wall temperature at 800 K [20]). We have fix the β coefficient to β = 0.9, based on work reported in Ref. [Maz21].

B. Fluid approach of the electron transport

A particle description of the electrons would be much more time consuming and not adapted to a parametric study of the device. We therefore prefer a fluid approach to calculate electron properties. The model assumes a quasineutral plasma, the plasma density n being obtained from the ion transport. The electric potential V is calculated from a current conservation equation with a given potential drop between anode and cathode and assuming that the electrons follow a Boltzmann law along the B field lines [1] :

$$V = V^* + \frac{k_B T_e}{e}\ln\left(\frac{n}{n_0}\right) \quad (7).$$

In Eq. (7), V^* is constant potential along the B field lines, k_B is Boltzmann constant, n_0 is a reference plasma density, and T_e is the electron temperature (constant along the magnetic field lines).

The electron energy defined as $\varepsilon = 3/2\ k_B\ T_e$ involving in the calculation of the electric potential though the Eq. (7) and electron-atom collision rates is calculated from the following equation :

$$\frac{\partial(n\varepsilon)}{\partial t} + \frac{5}{3}\nabla.(n\mu\varepsilon) - \frac{10}{9}\nabla.(n\mu\varepsilon\nabla\varepsilon) = -e\Gamma_e E - n_a n\kappa - n\Pi \quad (8),$$

where μ is the electron mobility perpendicular to the magnetic field, E is the electric field, and κ is an effective energy loss coefficient for collisions with neutral gas particles that includes ionization and excitation processes, and Π is a effective energy loss coefficient when electrons collide with walls. We use the same formulation of Π as in Ref. [16]. The inelastic lost power κ detailed in Ref. [22].

The difficulty concerns the description of the electron transport perpendicular to the B field lines. Electrons drift from the cathode to the anode, in the direction perpendicular to the B field by collisions. Taking into account only the "classical' electron-atom collisions is far from being sufficient to reproduce measured discharge currents. Our model has to assume that others "anomalous" phenomena play a role inside and outside the channel, increasing the mobility of the electrons in the direction perpendicular to the magnetic field lines. The electron mobility perpendicular to the magnetic field μ is then expressed as the sum of two terms μ_c and μ_{ano} the first one corresponds to electron-atom collision and the second one to the anomalous transport :

$$\mu = \mu_c + \mu_{ano} = \frac{m_e}{e}\frac{\nu_m}{B^2} + \mu_{ano} \qquad (9),$$

where m_e is the electron mass, ν_m is the electron-atom elastic frequency that is proportional to the elastic rate k_m. We have calculated the elastic rate assuming a Maxwellian distribution function. The electron-atom elastic cross sections are given in [14]. We use a very simple approach to account for the electron anomalous transport assuming that it varies as $1/B$. The anomalous electron mobility is written as :

$$\mu_{ano} = \frac{K}{16B} \qquad (10),$$

where K is a parameter. Anomalous transport is applied inside and outside the thruster channel with two different coefficients K_{in} and K_{out} with $K_{\text{in}} < K_{\text{out}}$. Reasonably coefficients to match experimental observations are $K_{\text{in}} = 0.1$ and $K_{\text{out}} = 0.2$ [23] for a channel length of 2.5 cm. We do not intend here to make a detailed study on the influence of the anomalous transport on plasma properties, mainly because we do not have measurements of plasma properties for others gases than xenon.

V. Calculations of thruster performance for low mass propellants

In all this study, we fix the discharge voltage U_d = 300 V. We show averaged in time results. We have performed calculations for low mass propellants for different situations. In sub-section A, we show the limiting effect of an increase of the channel length on magnetic layer thickness. In sub-sections B and C, we calculate the thruster efficiencies for atmospheric gases for a channel length of 2.5 cm and 5 cm, respectively. In sub-section D, we calculate the thruster performance considering a scenario where the satellite is positioned at an altitude of 250 km.

A. Magnetic field profiles for longer channel

The analytical formulation of an optimized thruster for low mass propellants is closely linked to an increase of the magnetic layer thickness L_B to maintain a high ionization efficiency, as we have already mentioned. We have performed magnetic calculations with the FEMM code [24] for varying channel length L to examine the possibility that L_B increases when L increases. We show in Fig. 2 the magnetic field strength along the channel centerline for a channel length varying from 2.5 to 10 cm. When the channel length varies, the magnetic field gradient as the magnetic field line curvatures do not change in the region outside the channel. For a given channel length, L_B is larger when the magnetic screens are removed (see Fig. 2, L = 2.5 cm). The influence of the channel length on L_B is very limited. As we see in Fig. 2, we can only gain a factor of 2 when L increases. Another way to enlarge the magnetic layer thickness is to permit that more magnetic flux enters in the channel. In practice, that can be achieved by increasing the distance between the inner and outer magnetic poles, and the consequence is a larger channel width b_c. This situation can be adopted for larger electric power HETs, but is no longer suitable for missions we are interested in this study. The main result of this very simple magnetic study is that the design for a HET working efficiently in xenon is no longer able to permit a large increase of the magnetic layer thickness. The calculations we have done for low mass propellants have consequently been limited for longer channel.

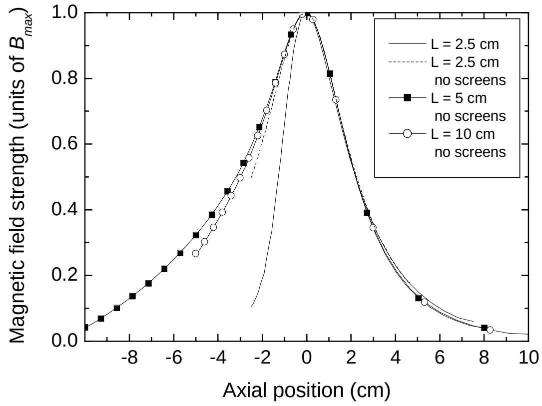

Figure 2 : Axial profile of the magnetic field strength along the channel centerline for varying channel length (the exhaust plane is at x = 0).

B. Calculations of the HET efficiency for ambient air propellants for *L* = 2.5 cm

We have calculated the thruster performance for various propellants, propellant mass flows, and magnetic field strengths, for L = 2.5 cm. We have to modify the definition of the ionization efficiency when atoms can be formed after dissociation of molecules. The propellant efficiency α is easily generalized for molecules :

$$\alpha = \frac{m_a}{e\dot{m}} \sum_{j=1}^{2} \frac{I_{i,j}}{\zeta_j} \qquad (11),$$

where $I_{i,j}$ is the ion current of the jth species, and ζ_j is ratio between the jth species and the initial molecule masses (ζ_j = 1 for molecules and ζ_j = 2 for atoms).

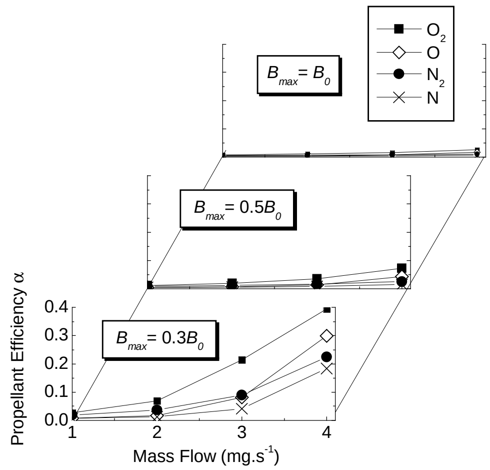

Figure 3 : Propellant efficiency α as a function of propellant mass flow and magnetic field strength for different ambient propellant gases and for L = 2.5 cm. Same scale is used.

We have plotted in Fig. 3 the propellant efficiency α for different mass flows and magnetic field strengths. We observe that the magnetic field strength used for to obtain a high ionization efficiency for xenon ($B_{max} = B_0$) is not adapted to efficiently ionize ambient air propellant gases. One way to increase the ionization efficiency is to reduce the magnetic field strength. The electron flux is controlled by anomalous diffusion in the acceleration region, because the electron mobility is inversely proportional to the magnetic field strength [see Eq. (10)] and hence a reduced magnetic field leads to a higher electron current flowing in the discharge channel. A reduction of the magnetic field strength leads also to an increase of the electron energy. Let us detail the heating of the electrons by the electric field. The first term of the right-hand side of energy equation can be expressed as (neglecting diffusion in the acceleration region) :

$$J_H = -e\Gamma_e E = en\mu_{ano} E^2 \propto n\frac{K}{B}E^2 \quad (12).$$

If we write that the discharge voltage is concentrated in the magnetic field layer, Eq. (12) writes :

$$J_H \propto n\frac{K}{B}\left[\frac{U_d}{L_B}\right]^2 \quad (13).$$

For constant L_B and U_d, we see that a decrease of B results in an increase of the electron energy through the heating of the electrons by the electric field. The higher the energy, the lower the cost to create an electron-ion pair and higher is the propellant efficiency. For same mass flows, we observe some noticeable differences between gases. As an example, for a propellant mass flow of 4 mg.s^{-1} and for a maximum magnetic field strength of $0.3\times B_0$, α reaches 0.4 for O_2 and remains below 0.2 for N.

For $B_{max} = 0.3\times B_0$, the discharge current and thruster efficiency are visible in Fig. 4 for the gases considered in this study. As we have already mentioned, a reduction of the magnetic field strength leads to an increase of the electron current and hence a large discharge current (~ 12 A for O) as we see at $\dot{m}$ = 4 mg.s^{-1} in Fig. 4a. Another difficulty for a HET working with ambient air gases is related to the cathode working. Indeed, as we see, the cathode has to deliver a larger current than in the xenon case. The consequence of such high electric power is a reduced thruster efficiency η (defined as the electric power converted in thrust), as shown in Fig. 4b. For $\dot{m}$ = 4 mg.s^{-1}, the thruster efficiency η varies between 0.06 for N to 0.12 for O_2.

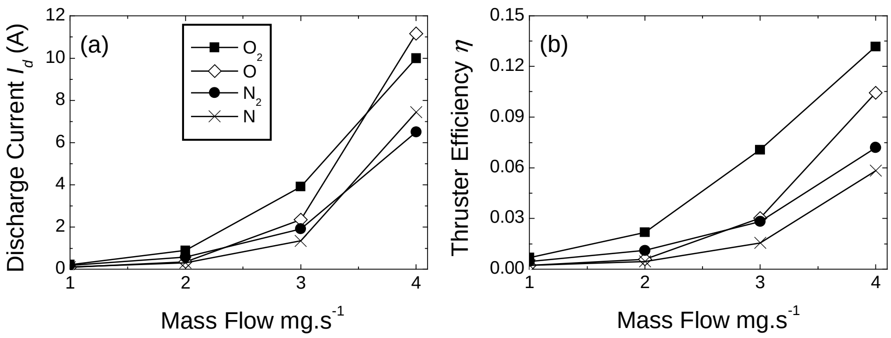

Figure 4 : Discharge current I_d and thruster efficiency η as a function of propellant mass flow for different ambient propellant gases for $B_{max} = 0.3\times B_0$ and for L = 2.5 cm.

C. Calculations of the HET efficiency for ambient air propellants for *L* = 5 cm

Scaling laws have demonstrate the interest of an increase of the channel length in order to increase the propellant efficiency. We fix $B_{max} = 0.3\times B_0$ and we show in Fig. 5 the propellant and thruster efficiencies for L = 5 cm together with same calculations for L = 2.5 cm already reported in Figs. 3 and 4. As expected, we obtain an increase of the propellant efficiency and hence of the thruster efficiency but not as large as we can think regarding scaling laws. An increase of the channel length leads to an increase of the magnetic layer thickness L_B, that contributes positively to the propellant efficiency. Nevertheless, if we come back to Eq. (13), we see that an increase of L_B for same U_d, leads to a diminution of the electric field in the acceleration region. As a conclusion, the gain of propellant efficiency results from a balance between the increase of the ionization layer thickness and a decrease of the electron heating.

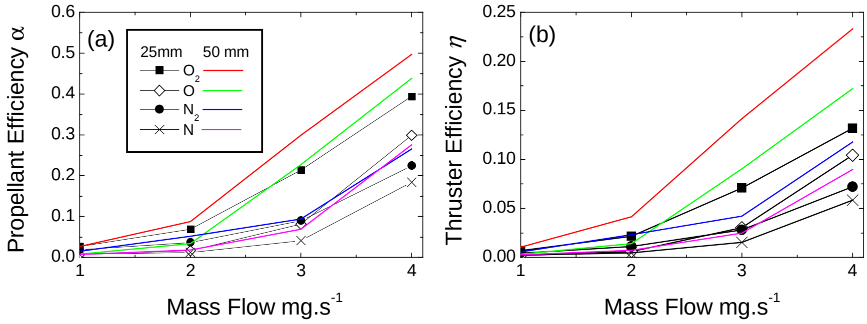

Figure 5 : Calculations of the propellant efficiency α and thruster efficiency η as a function of propellant mass flow for two different channel lengths and different ambient propellant gases for B_{max} = 0.3×B_0.

D. Calculations of the HET performance at an altitude of 250 km

We have finally considered the case of the a satellite at an altitude of 250 km. A thrust in the range of 20 mN to maintain the satellite on a LEO is required. At this altitude the atmosphere is mainly constituted with O and N_2. We show in Fig. 6 the thrust T for varying mass flow rates for these two gases. The thrust is calculated as the force opposite to the acceleration of ions (including the force due to ion impingement on walls and neglecting the force exerted by the neutrals).

A magnetic field below $B_{max} = 0.3\times B_0$ does not permit to achieve the level of thrust necessary except of very large propellant mass flows, which is totally impracticable for such kind of missions. We compare two channel length cases, L = 2.5 cm and L = 5 cm. We can define a minimum mass flow that can be used for the required mission. For L = 2.5 cm, for oxygen atoms and nitrogen molecules, the minimum mass flow is 3.2 and 3.5 mg.s^{-1}, respectively. A benefit of increasing the channel length exists, especially for O, the minimum mass flow is reduced to 2.6 mg.s^{-1} for L = 5 cm (see Fig. 6).

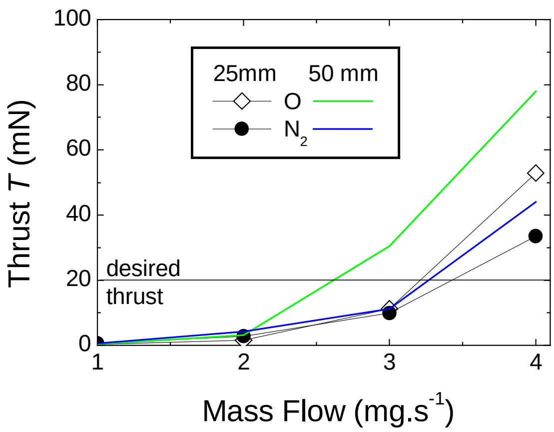

Figure 6 : Calculations of the thrust T for N_2 and O as a function of propellant mass flow for two different channel lengths and for B_{max} = 0.3×B_0.

VI. Conclusions

We have studied the working of a HET in the context of LEO applications to compensate drag force when the ambient air atoms and molecules are used as propellants. We are mainly interested in thruster performance study, disregarding problems related to cathode and storage necessity, that already been addressed in the literature. A study of mission requirements has point out the importance of a thruster working at low mass flow rates to reduce as much as possible the storage of propellant and the electric power that will be a limiting factor for the missions considered. We have combined analysis with simple analytical scaling laws and hybrid model results to determine conditions where ambient air can be used as propellants. In comparisons with actually used gas such as xenon, results show that low mass propellants such as air atoms/molecules offer the disadvantage of a larger ionization layer. We have demonstrated that, for same mass flows, the origin of a larger ionization layer is not due to a larger velocity of atoms for low mass propellants but from the difficulty to ionize such atoms/molecules. Nitrogen atoms and molecules also offer an other disadvantage related to a higher electron energy cost necessary to create an electron-ion pair. Indeed, for a same channel length, the propellant efficiency and hence the thrust is reduced for low mass propellants that constitute the atmosphere. The conditions established for the xenon gas (geometry, magnetic field) are no longer suitable for ambient air propellants for LEO orbit.

For a fixed discharge voltage, we have examined favorable conditions where the propellant efficiency can be increased. This is on a first importance if the HET has to work at relatively low mass flow rates. A first idea leads us to decrease the magnetic field strength in order to increase both electron current and electron heating. An increase of propellant efficiency has been noticed, together with a low thruster efficiency. A second idea is to increase the channel length or more precisely the magnetic field layer thickness. We have seen that for the HET actual magnetic field configuration, an increase of channel length does not always induce an increase of the magnetic field layer thickness. The benefit effect of an increase of channel length is consequently limited, as observed. Some works have to be done to propose a magnetic circuit able to axially scale the magnetic field profile [25].

We finally have determined mass flow rate conditions considering a scenario where a satellite is positioned at an altitude of 250 km. The main components of the atmosphere are O and N_2 and the desired thrust is in the range of 20 mN. Calculations show that a mass flow on the order of 3 $mg.s^{-1}$ fulfills the required mission. The electric power is around 1 kW and the thruster efficiency is 0.1. Fur such level of mass flow, the question of the necessity to store mass propellants is enforced.

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