Analysis of Airbreathing Hall-Effect Thrusters

Leonid Pekker*
ERC Inc., Edwards Air Force Base, California 93524
and
Michael Keidar†
George Washington University, Washington, DC 20052

DOI: 10.2514/1.B34441

The principle idea of using airbreathing electrical propulsion for a vehicle flying at orbital speed on the edge of Earth’s atmosphere is examined. In this paper, a simple model of a Hall-effect thruster in which the propellant is an ambient air is presented. A new mode of the airbreathing thruster operation is presented in which incoming air is fully ionized without preliminary compression. The required lengths of the thruster chamber, the magnetic fields, the thrust, and other parameters of an ideal airbreathing Hall-effect thruster are calculated as a function of the flying altitude of the vehicle. For instance, in the case of the 95-km orbit, the lengths of thruster chamber of 47.8 cm, the Hall thruster gap of 2.3 cm, and the applied voltage of 3 kV, the model gives the thrust of about 9.1 N and the power range of about 700–800 kW depending on the strength of a magnetic field. The thruster might be powered using electromagnetic beams generated at ground power stations or crafts flying at higher orbital altitudes where the drag force is negligible. The estimates presented show that the beam receiver size will not exceed the size of the vehicle and should not generate a drag force larger than the calculated thrust.

Nomenclature

\[ \begin{align*}
A & \quad \text{mass of a heavy particle, au} \\
B & \quad \text{strength of the magnetic field} \\
D_{\text{diff}} & \quad \text{ambient gas diffusion coefficient} \\
E & \quad \text{strength of the electric field} \\
E_{\text{jet}} & \quad \text{energy flow leaving the Hall thruster with the plasma jet} \\
E_{\text{loss}} & \quad \text{heat losses at the anode} \\
E_{\text{gas}} & \quad \text{energy losses at the wall} \\
E_{\text{ion}} & \quad \text{ionization cost} \\
F & \quad \text{electron charge} \\
F_{\text{drag}} & \quad \text{drag force} \\
F_{\text{drag}} & \quad \text{drag factor} \\
J & \quad \text{electron current density} \\
J_{\text{e}} & \quad \text{ion current density} \\
H & \quad \text{altitude of satellite orbit} \\
L & \quad \text{length of the Hall-thruster chamber} \\
L_{\text{dis-rec}} & \quad \text{length of dissociative recombination} \\
\ln \Lambda & \quad \text{Coulomb logarithm} \\
M & \quad \text{mass of a heavy particle} \\
M_{\text{e}} & \quad \text{mass of an electron} \\
m_{\text{e}} & \quad \text{electron number density} \\
n_{\text{gas}} & \quad \text{number density of ambient gas} \\
n_{\text{i}} & \quad \text{ion number density} \\
n_{\text{pl}} & \quad \text{number density of plasma} \\
P & \quad \text{electric power put into the discharge} \\
r_{\text{o}} & \quad \text{inner radius of the opening of the airbreathing Hall thruster} \\
r_{\text{b}} & \quad \text{outer radius of the opening of the airbreathing Hall thruster} \\
r_{\text{D}} & \quad \text{debye radius} \\
r_{\text{L}} & \quad \text{electron cyclotron radius} \\
S & \quad \text{effective cross section of the satellite due to drag force} \\
T_{\text{e}} & \quad \text{electron temperature} \\
T_{\text{e,jet}} & \quad \text{electron temperature in the plasma jet} \\
T_{\text{gas}} & \quad \text{ambient gas temperature} \\
T_{\text{i,jet}} & \quad \text{ion temperature in the plasma jet} \\
\text{Thrust} & \quad \text{thrust} \\
V_{\text{b}} & \quad \text{Bohm velocity} \\
V_{\text{e,drift}} & \quad \text{electron drift velocity} \\
V_{\text{r}} & \quad \text{electron thermal velocity} \\
V_{\text{gas}} & \quad \text{thermal velocity of ambient gas} \\
V_{0} & \quad \text{orbital velocity, 7.8 km/s} \\
\gamma & \quad \text{coefficient of secondary electron emission} \\
\Delta V & \quad \text{change in the velocity} \\
\lambda_{\text{gas}} & \quad \text{ambient gas mean free path} \\
\mu_{\text{r}} & \quad \text{electron mobility} \\
\sigma_{\text{gas}} & \quad \text{collision cross section of ambient gas molecules} \\
\sigma_{\text{ion}} & \quad \text{ionization cross section} \\
\tau_{\text{dis-rec}} & \quad \text{characteristic dissociative recombination time} \\
\tau_{\text{e-life}} & \quad \text{electron lifetime in Hall thruster} \\
\tau_{\text{ion}} & \quad \text{ionization time} \\
\tau_{\text{c}} & \quad \text{characteristic time of convective removal of molecular nitrogen ions from the plasma chamber} \\
\tau_{\text{wall}} & \quad \text{characteristic collision time for gas molecule with wall} \\
\tau_{0} & \quad \text{time that a gas molecule is flying through the thruster chamber} \\
V_{\text{ei}} & \quad \text{electron–ion collision frequency} \\
\phi_{0} & \quad \text{the Bohm sheath potential} \\
\phi & \quad \text{applied voltage} \\
\omega_{\text{He}} & \quad \text{electron cyclotron frequency}
\end{align*} \]

Presented at the 42nd Plasma Dynamics and Laser Conference, Honolulu, Hawaii, June 27–30, 2011; received 31 August 2011; revision received 4 May 2012; accepted for publication 11 May 2012. Copyright © 2012 by the American Institute of Aeronautics and Astronautics, Inc. The U.S. Government has a royalty-free license to exercise all rights under the copyright claimed herein for Governmental purposes. All other rights are reserved by the copyright owner. Copies of this paper may be made for personal or internal use, on condition that the copier pay the $10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923; include the code 0022-4865/12 and $10.00 in correspondence with the CCC.

*Senior Research Staff Engineer; leonid.pekker.erc@edwards.af.mil.
†Associate Professor; keidar@gwu.edu. Associate Fellow AIAA.

I. Introduction

This work is motivated by increasing interest in military and civil spacecraft flying at the altitudes of 70–120 km. Because the drag at such altitudes is still significant, the thrusters of such a satellite should work continuously to maintain the orbit altitude. This demands that a significant amount of propellant be stored on-board satellites that use ordinary thrusters for propulsion. However, using
airbreathing thrusters, in which the propellant is ambient air, looks very attractive for such spacecraft, particularly for long-duration missions; airbreathing thrusters allow significantly increased payload-to-weight ratio for such satellites. Using airbreathing thrusters in Mars and other planets’ atmospheres becomes even more attractive because of multiyear satellite missions and the high cost of payloads.

In a recent paper [1], Diamant has proposed a two-stage cylindrical Hall-effect thruster for airbreathing electric propulsion, in which the first stage is an electron cyclotron resonance ionization stage and the second stage is a cylindrical Hall thruster. Diamant built such a thruster and demonstrated its operation on xenon gas. As follows from his assumptions, his two-stage cylindrical Hall thruster is able to work at a 220 km orbit with ambient air passively compressed by a factor of 500 [1]. However, achieving such a large passive gas compression seems to be difficult and will be associated with substantial drag. In the Busek conception of an airbreathing Hall thruster [2], the compression of air is achieved by a diffuser. It is not clear what compression ratio of the ambient air can be achieved by using such a diffuser at orbits of about 100 km, where the gas mean free paths are tens of centimeters and comparable with the dimensions of the thruster. Furthermore, the use of a diffuser can significantly increase the drag because gas is reflected diffusely in space [3].

In the present work, we propose a simple configuration for an airbreathing Hall-effect thruster (shown in Fig. 1; the struts holding the center piece are not shown), in which the incoming airflow is ionized and accelerated directly in the Hall thruster chamber without preliminary compression as in [1,2]. Such a design leads to a decrease of the possible drag, however, its feasibility warrants careful consideration, which is the subject of this paper. The description of the model and numerical results are provided in Secs. II and III, respectively, and the conclusions are given in Sec. IV.

II. Description of the Model

The following assumptions are made in the model: 1) no drag due to ambient gas passing through the Hall thruster chamber, illustrated in Fig. 1, corresponding to a condition in which the ambient gas freely flows through the thruster chamber without a significant interaction with the wall; 2) the gas jet leaving the thruster chamber is fully ionized providing the maximum thrust; 3) the plasma in the Hall thruster is quasi-neutral, \( n_i = n_e = \rho_{pl} \), corresponding to a condition in which \( r_D \) is smaller than the characteristic dimensions of the thruster, in our case, Fig. 1, \( r_D \) must be smaller than \( r_D = r_D \); 4) the electron cyclotron radius is much smaller than the Hall thruster gap, \( r_D < r_D - r_D \), as is required for confinement of electrons in the Hall thruster.

The first assumption is well satisfied when the characteristic time required for a gas molecule to reach the wall and transfer its momentum, \( t_{wall} \), is larger than the time required for the molecule to freely fly through the thruster chamber, \( t_0 = L/V_0 \), i.e.

\[
\frac{t_{wall} \cdot V_0}{L} > 1
\]  

In the case of free molecular flow considered in this paper, when the gas mean free path is larger than \( r_D - r_D \), Fig. 1, \( t_{wall} \) can be estimated as

\[
t_{wall} = \frac{r_D - r_D}{V_{gas}}
\]  

It is worth noting that here we did not take into account the drag created by struts holding the center piece of the thruster because this is not critical for our simple model.

The second assumption is fulfilled when the ionization time of a gas molecule

\[
t_{ioniz} = \frac{1}{V_T \cdot n_e \cdot \rho_{ioniz}}
\]  

is much smaller than \( t_0 \). Let us estimate \( t_{ioniz} \). The equation describing the mass conservation law for the heavy particles can be written as

\[
V_0 \cdot n_{gas} = n_{pl} \cdot V_0^2 + 2 \cdot e \cdot \varphi
\]  

where the left-hand side in Eq. (4) is the flux of incoming gas and the right-hand side is the ion flux leaving the chamber. In Eq. (4) we have assumed that the downstream plasma in the thruster chamber is quasi-neutral and fully ionized. In Eq. (4) we have neglected the influence of the gas cloud created by the reflection of the ambient gas from the front side of the thruster (see Fig. 1) on the gas flow incoming into the thruster chamber. In the case of free molecular flow, where the ambient gas mean free path is larger than the characteristic radius of the thruster \( r_D \), the reflected ambient gas molecules travel far from the vicinity of the thruster opening before colliding with the ambient gas flow, and therefore, cannot change the gas flow into the plasma chamber significantly. For that reason, our assumption that the gas flow into the plasma chamber is \( V_0 \cdot n_{gas} \cdot \pi \cdot (r_D - r_D) \) seems to be quite reasonable for our simple model.

It should be stressed that in the model we assume the ambient gas is pure molecular nitrogen. This is a reasonable assumption because the air contains 78% nitrogen and 21% oxygen and their electron impact ionization cross sections are similar [4]. In the model, we neglect the dissociation of molecular nitrogen assuming that \( M = M_0 \). Because for electron energies between 20 and 80 eV the ionization and dissociation cross sections of molecular nitrogen are close and the ionization cross section of molecular nitrogen is much larger than the ionization cross section of atomic nitrogen [5], neglecting the dissociation of nitrogen should not lead to a significant error and is reasonable for our simple model. As will be shown in Sec. III, the dissociative recombination of molecular nitrogen does not play a critical role either: the rate of convective removal of \( N_2^+ \) from the plasma chamber is about the same or faster than the dissociative recombination of \( N_2^+ \).

Because \( e \cdot \varphi \) is usually much larger than the kinetic energy of an ambient gas molecule at the entrance plane of the Hall thruster (for nitrogen molecules it is about 8.75 eV), the \( n_{pl} \) can be written as

\[
n_{pl} = n_e = \frac{V_0 \cdot n_{gas}}{\sqrt{\frac{2 \cdot e \cdot \varphi}{M_0}}}
\]  

Substituting Eq. (5) and \( V_0 = 9.8 \text{ km/s} \) into Eq. (3), we obtain that condition \( t_0 \gg t_{ioniz} \) is fulfilled when

\[
47.6 \cdot L \cdot n_{gas} \cdot \rho_{ioniz} (T_e) \cdot \left( \frac{\varphi}{A \cdot T_e} \right)^{1/2} > 1
\]  

where \( T_e \) in Eq. (6) is measured in eV.

On the other hand, the electron lifetime in the Hall thruster \( t_{ioniz} \) must be larger than the ionization time for an electron (\( V_T \cdot n_{gas} \cdot \rho_{ioniz} \)) 1; otherwise, the electron will leave the thruster chamber before producing any ionization events; \( t_{ioniz} \) can be estimated as
airbreathing thrusters, in which the propellant is ambient air, looks very attractive for such spacecraft, particularly for long-duration missions; airbreathing thrusters allow significantly increased payload-to-weight ratio for such satellites. Using airbreathing thrusters in Mars and other planets' atmospheres becomes even more attractive because of multyear satellite missions and the high cost of payloads.

In a recent paper [1], Diamant has proposed a two-stage cylindrical Hall-effect thruster for airbreathing electric propulsion, in which the first stage is an electron cyclotron resonance ionization stage and the second stage is a cylindrical Hall thruster. Diamant built such a thruster and demonstrated its operation on xenon gas. As follows from his assumptions, his two-stage cylindrical Hall thruster is able to work at a 220 km orbit with ambient air passively compressed by a factor of 500 [1]. However, achieving such a large passive gas compression seems to be difficult and will be associated with substantial drag. In the Busek conception of an airbreathing Hall thruster [2], the compression of air is achieved by a diffuser. It is not clear what compression ratio of the ambient air can be achieved by using such a diffuser at orbits of about 100 km, where the gas mean free path is tens of centimeters and comparable with the dimensions of the thruster. Furthermore, the use of a diffuser can significantly increase the drag because gas is reflected diffusely in space [3].

In the present work we propose a simple configuration for an airbreathing Hall-effect thruster (shown in Fig. 1; the struts holding the center piece are not shown), in which the incoming airflow is ionized and accelerated directly in the Hall thruster chamber without preliminary compression as in [1, 2]. Such a design leads to a decrease of the possible drag, however, its feasibility warrants careful consideration, which is the subject of this paper. The description of the model and numerical results are provided in Secs. II and III, respectively, and the conclusions are given in Sec. IV.

II. Description of the Model

The following assumptions are made in the model: 1) no drag due to ambient gas passing through the Hall thruster chamber, illustrated in Fig. 1, corresponding to a condition in which the ambient gas freely flows through the thruster chamber without a significant interaction with the wall; 2) the jet leaving the thruster chamber is fully ionized providing the maximum thrust; 3) the plasma in the Hall thruster is quasi-neutral, \( n_i = n_e = n_{pl} \), corresponding to a condition in which \( r_{pl} < r_{c} \), smaller than the characteristic dimensions of the thruster; in our case, Fig. 1, \( r_{pl} \) must be smaller than \( r_{c} - r_{a} \); 4) the electron cyclotron radius is much smaller than the Hall thruster gap, \( r_{c} < r_{c} - r_{a} \), as is required for confinement of electrons in the Hall thruster.

The first assumption is well satisfied when the characteristic time required for a gas molecule to reach the wall and transfer its momentum, \( \tau_{wall} \), is larger than the time required for the molecule to freely fly through the thruster chamber, \( \tau_{o} = L/V_{o} \), i.e.

\[
 f_{drag} = \frac{\tau_{wall}}{L} \geq 1 
\]

In the case of free molecular flow considered in this paper, when the gas mean free path is larger than \( r_{c} - r_{a} \), Fig. 1, \( \tau_{wall} \) can be estimated as

\[
 \tau_{wall} = \frac{r_{c} - r_{a}}{V_{T_{e}}} 
\]

It is worth noting that here we did not take into account the drag created by struts holding the centerpiece of the thruster because this is not critical for our simple model.

The second assumption is fulfilled when the ionization time of a gas molecule

\[
 \tau_{ion} = \frac{1}{V_{T_{e}} \cdot n_{e} \cdot \sigma_{ion}}
\]

is much smaller than \( \tau_{o} \). Let us estimate \( \tau_{ion} \). The equation describing the mass conservation law for the heavy particles can be written as

\[
 V_{0} \cdot n_{gas} = n_{pl} \sqrt{\frac{2 \cdot e \cdot \varphi}{M_i}}
\]

where the left-hand side in Eq. (4) is the flux of incoming gas and the right-hand side is the ion flux leaving the chamber. In Eq. (4) we have assumed that the downstream plasma in the thruster chamber is quasi-neutral and fully ionized. In Eq. (4) we have neglected the influence of the gas cloud created by the reflection of the ambient gas from the front side of the thruster (see Fig. 1) on the gas flow into the thruster chamber. In the case of free molecular flow, where the ambient gas mean free path is larger than the characteristic radius of the thruster, \( n_{gas} \sim r_{c} \), the reflected ambient gas molecules travel far from the vicinity of the thruster opening before colliding with the ambient gas flow and, therefore, cannot change the gas flow into the plasma chamber significantly. For that reason, we assume that the gas flow into the plasma chamber is \( V_{0} \cdot n_{gas} \cdot n_{i} \cdot (r_{o}^{2} - r_{a}^{2}) \) seems to be quite reasonable for our simple model.

It should be stressed that in the model we assume the ambient gas is pure molecular nitrogen. This is a reasonable assumption because the air contains 78% nitrogen and 21% oxygen and their electron impact ionization cross sections are similar [4]. In our model, we neglect the dissociation of molecular nitrogen assuming that \( M = M_{i} \). Because for electron energies between 20 and 80 eV the ionization and dissociation cross sections of molecular nitrogen are close and the ionization cross section of molecular nitrogen is much larger than the ionization cross section of atomic nitrogen [5], neglecting the dissociation of nitrogen should not lead to a significant error and is reasonable for our simple model. As will be shown in Sec. III, the dissociative recombination of molecular nitrogen does not play a critical role either; the rate of convective removal of \( N_{2}^{+} \) from the plasma chamber is about the same or faster than the dissociative recombination of \( N_{2} \).

Because \( e \cdot \varphi \) is usually much larger than the kinetic energy of an ambient gas molecule at the entrance plane of the Hall thruster (for nitrogen molecules it is about 8.75 eV), the \( n_{pl} \) can be written as

\[
 n_{pl} = n_{e} = \sqrt{\frac{2 \cdot e \cdot \varphi}{M_i}}
\]

Substituting Eq. (5) and \( V_{0} \) as 7.8 km/s into Eq. (3), we obtain that condition \( \tau_{o} \gg \tau_{ion} \) is fulfilled when

\[
 47.6 \cdot L \cdot n_{gas} \cdot \sigma_{ion}(T_{e}) \cdot \left( \frac{\varphi}{A \cdot T_{e}} \right)^{-1/2} > 1
\]

where \( T_{e} \) in Eq. (6) is measured in eV.

On the other hand, the electron lifetime in the Hall thruster \( \tau_{e,life} \) must be larger than the ionization time for an electron \( (V_{T_{e}} \cdot n_{gas} \cdot \sigma_{ion})^{-1} \); otherwise, the electron will leave the thruster chamber before producing any ionization events; \( \tau_{e,life} \) can be estimated as

\[
 \tau_{e,life} = \frac{r_{c} - r_{a}}{V_{T_{e}}} 
\]

Fig. 1 Schematic of airbreathing Hall thruster (not to scale).
and finally calculate the thrust [Eq. (15)], the power [Eq. (16)], the ion and electron currents [Eqs. (17) and (18)], and other parameters of the airbreathing Hall-effect thruster at a given satellite orbit.

### III. Numerical Results

In the numerical results presented in this section the collision cross section for molecular nitrogen gas $\sigma_{\text{gas}}$ was taken as $4.4 \times 10^{-19}$ m$^2$ [10]; this corresponds to

$$\lambda_{\text{gas}} = \frac{1.63 \times 10^{-5} \cdot 7[K]}{P[Pa]}$$

The ionization cross section of molecular nitrogen as a function of electron temperature, Fig. 2, was calculated using data [5], and $f_n \Lambda$ was taken as 13.5; the inner and outer radii of the Hall thruster chamber were chosen as 0.03 and 0.053 m, respectively. The calculations have been performed for two Hall thruster lengths, 0.478 and 0.239 m, the applied voltage of 3 kV, $E_{\text{ion}} = 40$ eV, and for satellite orbits of 90 and 95 km.

For $H = 90$ km (where the ambient gas pressure is 1.38 mTorr) and $L = 0.478$ m the Paschen breakdown threshold voltage in air is about 3.5–4 kV [11]. Thus, the Paschen breakdown threshold voltages corresponded to the chosen in the model altitude of satellite orbits and the lengths of the Hall-thruster chambers, are larger than the applied voltage of 3 KV chosen in the model. However, taking into account that the magnetic field in the thruster chamber, Fig. 1, works as an electrical insulator and Paschen breakdown threshold curves correspond to the two infinite parallel electrodes, while the thruster chamber is an "open" channel, Fig. 1, the breakdown voltage in the thruster, Fig. 1, is expected to be significantly larger than the applied voltage.

Because ambient mean free paths at the 90 and 95 km altitudes are 0.023 and 0.057 m, respectively, and are therefore on the order of $r_s$, the model assumption of free molecular flow is reasonable for these altitudes, see Sec. II. The drag factors [Eq. (1)] calculated with $T_{\text{gas}} = 185$ K corresponded to these altitudes are 1 and 0.5 for $L = 0.478$ and 0.239, respectively. Thus, the first assumption of the model is reasonable too. We would like to note that because the thrust of Hall thrusters [Eq. (15)] is generally much larger than the maximal drag $\pi \cdot (r_z^2 - r_0^2) \cdot M \cdot n_{\text{gas}} \cdot V_e^2$ that might be produced by the air flowing through the Hall chamber, this assumption is not critical for the airbreathing Hall thruster concept.

Figures 3 and 4 show the ratios of $r_0 / T_{\text{ionis}}$, thick solid lines, $r_0 / T_{\text{life}}$, $V_T$, $n_{\text{gas}}$, $\sigma_{\text{ionis}}$, thick broken lines, and $(r_0 - r_s) / r_s$ thick dot lines [Eqs. (6), (10), (11), and (14)] calculated for the satellite orbits of 90 and 95 km, respectively; they correspond to the second and forth assumptions of the model; the thin solid lines in Figs. 3 and 4 correspond to unity. As one can see for the satellite orbit of 90 km, these assumptions are satisfied for magnetic fields in the ranges of 10–40 and 10–50 G correspondingly for $L = 0.478$ and 0.239 m; and for the orbit of 95 km in the ranges of 6–16 and 8–18 G correspondingly for $L = 0.478$ and 0.239 m. The third assumption of the model [Eq. (13)] and $\omega / \omega_{\text{ce}} \gg 1$ condition are very well satisfied in all ranges of magnetic fields, lengths of Hall thruster chamber, and orbits considered in the paper: the minimal value of

![Graph](image-url)
Airbreathing Hall-effect thruster, $H = 95$ km, $\phi = 3$ kV, $r_i = 0.053$ m, and $r_e = 0.03$ m

$r_e - r_i / r_D$ was 647 at $H = 95$ km, $B = 16$ G and $L = 0.478$ m; and the minimal value of $\omega_{He} / \nu_0$ was 407 at $H = 90$ km, $H = 33$ G, and $L = 0.478$ m.

Because the airbreathing Hall thruster plasma in our model is assumed to be fully ionized, the thrust [Eq. (15)] is determined only by the ambient gas number density and the applied voltage, and the ion current [Eq. (18)] is determined by the ambient gas number density only. The model gives $j_i = 8.9 \cdot 10^4$ and $3.65 \cdot 10^4$ A/m$^2$ for $H = 90$ and 95 km, respectively; and Thrust = 2.23, and 9.12 N correspondingly for $H = 90$ and 95 km, and $\phi = 3$ kV. The obtained results are very understandable: with a decrease in the satellite orbit, the ambient gas density increases, leading to an increase in the ion current and the thrust; an increase in the applied voltage leads to smaller $\Delta V$ and, therefore, larger thrust. Of course, a higher orbit will lead to a smaller drag force that the thrust will need to compensate for. The drag will depend on the satellite geometry; this paper considers the generic satellite, thus, specific drag estimations go beyond the scope of this paper.

Figures 5 and 6 show the electron temperature, power, and $j_i / j_e$ vs magnetic field for $H =$ 90 and 95 km, respectively. In these figures we have selected magnetic fields for which the model assumptions are satisfied. As was expected with a decrease in the Hall chamber length, the electron temperature increases, and with an increase in the magnetic field it decreases, as shown in Figs. 5a, 5b, 6a, and 6b. Because the ion current in the model is independent of the magnetic field (ions are not magnetized), the electrical power decreases and the ratio of $j_i$ to $j_e$ increases with an increase in the magnetic field (they are magnetized), as illustrated in Figs. 5c–5f and 6c–6f. Because the electron component of the total current sharply decreases with magnetic field, as shown in Figs. 5e, 5f, 6e, and 6f, $P$ flattens for large magnetic fields, Figs. 5c, 5d, 6c, and 6d.

Airbreathing Hall-effect thruster, $H = 90$ km, $\phi = 3$ kV, $r_i = 0.053$ m, and $r_e = 0.03$ m

Fig. 5 Plots a), c), and e) corresponds to $L = 0.478$ m and plots b), d), and f) to $L = 0.239$ m.
Airbreathing Hall-effect thruster, $H = 95$ km, $\phi = 3$ kV, $r_\text{f} = 0.053$ m, and $r_\text{g} = 0.03$ m

![Graphs a), b), c), d), e), and f)](image)

Fig. 6 Plots a), c), and e) corresponds to $L = 0.478$ m and plots b), d), and f) to $L = 0.239$ m.

Now, let us estimate the characteristic dissociative recombination time for molecular nitrogen ion and compare it with the characteristic time of convective removal of $N_2^+$ from the plasma chamber. $\tau_{\text{dis-rec}}$ and $\tau_{\text{rec-n}}$ can be estimated as

$$
\frac{1}{\tau_{\text{dis-rec}}} = \alpha(T_e) \cdot n_e = 5.844 \cdot 10^{-14} \frac{n_e}{T_e^{3/2}} \quad (28)
$$

$$
\tau_{\text{rec-n}} = L \cdot \sqrt[3]{\frac{M_i}{2 \cdot e \cdot \phi}} \quad (29)
$$

where $\alpha$ is the dissociative recombination rate coefficient [12] and temperature is measured in electron volts. Combining Eqs. (28) and (29) and substituting $n_e$ from Eq. (5) we obtain that if

$$
L_{\text{dis-rec}} = 1.49 \cdot \frac{T_e^{3/2}}{n_e} \quad (30)
$$

where $L_{\text{dis-rec}}$ is calculated as $\tau_{\text{rec-n}} \cdot (2 \cdot e \cdot \phi/M_i)$, the dissociative ionization of molecular nitrogen ions is small and can be neglected.

As can be seen from Eq. (30), with an increase in $n_e$, and an increase in $\phi$, the $L_{\text{dis-rec}}$ decreases as expected. Substituting in Eq. (30) $n_e = 7.12 \cdot 10^{19}$ m$^{-3}$ and $2.95 \cdot 10^{19}$ m$^{-3}$ that correspond to $H = 90$ and 95 km, respectively, $\phi = 3$ kV and $T_e = 20$ eV (Figs. 5a, 5b, 6a, and 6b), we obtain that $L_{\text{dis-rec}} = 154$ and 372 m for $H = 90$ and 95 km, respectively. This shows that neglecting the dissociation of molecular nitrogen in the model is a reasonable assumption.

We have also examined the airbreathing Hall thruster with the selected $L$, $r_\text{f}$, and $r_\text{g}$, and $\phi$ for the 100 km satellite orbit, but could not find a value of $B$ to satisfy the model assumptions at this altitude.

The reason it is difficult to increase the orbital altitude is that with a decrease in $n_e$, the magnetic field must be decreased to increase the electron temperature and consequently the ionization rate to maintain the ionization length smaller than $L$. However, such an increase in the electron temperature leads to a significant increase in the electron gyro radius, which becomes larger than the Hall thruster channel gap $r_\text{f} - r_\text{g}$. One can argue that increase of the applied voltage can help to keep the ionization length smaller than $L$ and a simultaneous increase of the Hall channel gap can satisfy the model conditions, but that would increase the power level above a reasonable level (<3–5 MW). A decrease in $H$ down to 80 km leads to a decrease in the $\lambda_{\text{gas}}$ to such a degree that the gas flow becomes strongly collisional, $\lambda_{\text{gas}} \approx 4.3 \text{ mm} \ll r_\text{f} - r_\text{g}$. This indicates that a niche for the presented airbreathing Hall-effect thruster mode (i.e., almost full ionization without compression) is at orbital altitudes of approximately around 90–95 km.

IV. Conclusions

The idea of using airbreathing electrical propulsion for a vehicle flying at orbital speed on the edge of Earth’s atmosphere has been examined for a thruster based on the Hall effect. We have shown that, conceptually, such a thruster can indeed work effectively at the orbits of about 90–95 km, producing significant thrust in the range of 9.1–22 N for considered conditions. It was found that with an increase in the altitude the power level to operate the thruster in this mode increases. On the other hand, at lower orbits the gas flow becomes collisional. Thus, it can be concluded that 90–95 km orbit range is optimal for the airbreathing Hall thruster operating in the full ionization mode without compression.
It should be pointed out that the power required maintaining such a high level of thrust is in the order of 1.6–2 MW for \( H = 90 \text{ km} \) and 700-800 kW for \( H = 95 \text{ km} \) with thrust-to-power ratio of 13 mN/kW, which is comparable with a typical high-efficient electric propulsion device. It should be noted that this power level is just less than an order of magnitude higher than the present-day new Hall thrusters under development [13]. Also, it should be stressed that for high-power thrusters, the energy efficiency can reach 80% and higher [13]. If one also uses recuperation of the heat back into electrical power, the energy efficiency of the thruster can be even higher. Therefore, assume that one must radiate 200 kW with a radiator surface temperature of 1200 K. Assuming that the radiator surface emissivity is one, it is found that the area of the radiator is approximately 1.7 m². Because the body of the craft can function as a radiator, a small, thin radiator wing should only add a minimum drag penalty. A detailed thermal management calculation of the thruster was out of the scope of the present work.

It should be stressed that in the model it has been assumed that the plume is fully ionized corresponding to the maximum possible thrust and power. However, if this condition is softened, assuming that the plume can be only partially ionized, the parameters of the thruster become less "extreme" and may lead to use of the thruster at higher orbital altitude. Recall that while the airbreathing concept seems to be reasonably achieved in terms of thrust production, it can be realized with high power available only. Thus, analysis of available power generation and power transmission is warranted as part of the overall airbreathing thruster and satellite analysis. As an example a beamed power transmission has been considered for this application. It is shown that for the considered beamed power level, the beam receiver on the spacecraft is not expected to generate drag force larger than the thrust.

Note that this paper has considered a highly simplified model of the plasma-wall interaction inside the thruster chamber. In particular, zero secondary electron emission (SEE) scenario was invoked to describe the sheath formation. Such treatment is limited to the wall materials with a low SEE [14]. Further analysis of the airbreathing concept should involve broader conditions for the SEE, thus extending operational parameters of this device.

In the future there are plans to use a direct simulation Monte Carlo method or other numerical approach to investigate the performance of the suggested airbreathing Hall-effect thruster.

References


J. Blandino
Associate Editor