

| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |              |                                   |                               | Form Approved<br>OMB No. 0704-0188                                        |                                              |
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| 1. REPORT DATE (DD-MM-YYYY)<br>04-08-2011                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |              | 2. REPORT TYPE<br>Journal Article |                               | 3. DATES COVERED (From - To)                                              |                                              |
| 4. TITLE AND SUBTITLE<br><br>Analysis of Air Breathing Hall-Effect Thruster (Preprint)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |              |                                   |                               | 5a. CONTRACT NUMBER                                                       |                                              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |              |                                   |                               | 5b. GRANT NUMBER                                                          |                                              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |              |                                   |                               | 5c. PROGRAM ELEMENT NUMBER                                                |                                              |
| 6. AUTHOR(S)<br>Leonid Pekker and Michael Keidar                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |              |                                   |                               | 5d. PROJECT NUMBER                                                        |                                              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |              |                                   |                               |                                                                           |                                              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |              |                                   |                               | 5f. WORK UNIT NUMBER<br>50260542                                          |                                              |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br><br>ERC, Inc.<br>Air Force Research Laboratory (AFMC)<br>AFRL/RZSA<br>10 E. Saturn Blvd.<br>Edwards AFB CA 93524-7680                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |              |                                   |                               | 8. PERFORMING ORGANIZATION<br>REPORT NUMBER<br><br>AFRL-RZ-ED-JA-2011-335 |                                              |
| 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br><br>Air Force Research Laboratory (AFMC)<br>AFRL/RZS<br>5 Pollux Drive<br>Edwards AFB CA 93524-7048                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |              |                                   |                               | 10. SPONSOR/MONITOR'S<br>ACRONYM(S)                                       |                                              |
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| 12. DISTRIBUTION / AVAILABILITY STATEMENT<br><br>Approved for public release; distribution unlimited (PA #11615).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |              |                                   |                               |                                                                           |                                              |
| 13. SUPPLEMENTARY NOTES<br>For Publication in the Journal of Propulsion and Power                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |              |                                   |                               |                                                                           |                                              |
| 14. ABSTRACT<br>The principle idea of using air breathing electrical propulsion for a vehicle flying at orbital speed on the edge of Earth's atmosphere is examined. In this paper, we present a simple model of a Hall Effect thruster in which the propellant is an ambient air. The required lengths of the thruster chamber, the magnetic fields, the thrust, and other parameters of an ideal air breathing Hall Effect thruster are calculated as a function of the flying altitude of the vehicle. We demonstrated that an air breathing Hall thruster is indeed capable of providing the needed thrust for near space satellites in the case of the altitudes of about 80-90 km.                                                                                                                                                                                                                                                           |              |                                   |                               |                                                                           |                                              |
| 15. SUBJECT TERMS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |              |                                   |                               |                                                                           |                                              |
| 16. SECURITY CLASSIFICATION OF:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |              |                                   | 17. LIMITATION<br>OF ABSTRACT | 18. NUMBER<br>OF PAGES                                                    | 19a. NAME OF RESPONSIBLE<br>PERSON           |
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**Leonid Pekker (AFRL/ERC) and Michael Keidar (The George Washington University), "Analysis of Air Breathing Hall-Effect Thruster"**

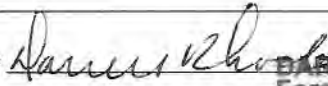
For publication in the *Journal of Propulsion and Power*  
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(Statement A)

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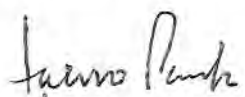
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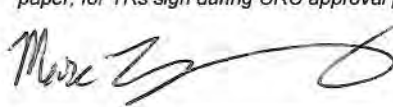
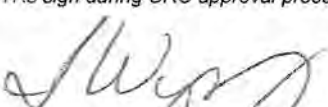
8 Aug 2011

LaDONNA J. DAVIS, Lt Col, USAF  
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 Space and Missile Propulsion Division

Date

# TECHNICAL EDITING AND PUBLISHING REQUEST

(See Page 3 for Instructions)

|                                                                                                                                                                                                                                                                                                 |                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                               |                                                                                                                                                                                                                                                                                                      |                                     |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------|
| <b>TRACKING NO:</b><br>AFRL-RZ-ED-JA-2011-335                                                                                                                                                                                                                                                   |                                     | <b>DATE SENT TO DTIC:</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                                                                                               | <b>PUBLICATION NO:</b>                                                                                                                                                                                                                                                                               |                                     |
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| <b>2a. CONTRACT NUMBER OR IN-HOUSE</b><br>In-house                                                                                                                                                                                                                                              |                                     | <b>2b. PROGRAM ELEMENT NO.</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                                                               | <b>2c. PROJECT NO.</b>                                                                                                                                                                                                                                                                               |                                     |
| <b>2d. TASK NO.</b>                                                                                                                                                                                                                                                                             |                                     | <b>2e. WORK UNIT (JON)</b><br>Required 50260542                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                               |                                                                                                                                                                                                                                                                                                      |                                     |
| <b>3. WORK UNIT MANAGER</b><br>Marcus Young                                                                                                                                                                                                                                                     |                                     | <b>4. OFFICE SYMBOL</b><br>RZSA                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                               | <b>5. PHONE NO.</b><br>5-5624                                                                                                                                                                                                                                                                        |                                     |
| <b>7. CONTRACTOR/CONTRIBUTOR</b> (if delivery order, list both prime and sub)<br>Leonid Pekker                                                                                                                                                                                                  |                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                               | <b>6a. REPORT DATE (MM/YY)</b><br>08/11                                                                                                                                                                                                                                                              |                                     |
| <b>8. AUTHOR(S)</b> (continue on next page, Block 22 (Remarks) if necessary)<br>Leonid Pekker and Michael Keidar                                                                                                                                                                                |                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                               | <b>6b. PERIOD COVERED (MM/DD/YY)</b> (for Tech Reports Only)<br><br>FROM:<br><br>TO:                                                                                                                                                                                                                 |                                     |
| <b>9. TITLE</b> (include volume no., if applicable)<br>Analysis of Air Breathing Hall Effect Thrusters                                                                                                                                                                                          |                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                               | <b>11. PAGE COUNT</b><br>(for Tech Reports only)                                                                                                                                                                                                                                                     |                                     |
| <b>10. SUBTITLE</b>                                                                                                                                                                                                                                                                             |                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                               |                                                                                                                                                                                                                                                                                                      |                                     |
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**22. REMARKS** (Provide any additional information)

This material/paper has been presented at 42nd AIAA Plasmadynamics and Laser Conference, Sheraton Waikiki Conference Center, Honolulu, Hawaii, June 27-30, 2011 and cleared for public release: clearance number is 11218 and STINFO tracking number is AFRL-RZ-ED-VG-2011-244 (viewgraphs) and clearance number is 11127 and STINFO tracking number is AFRL-RZ-ED-TP-2011-189 (conference paper).

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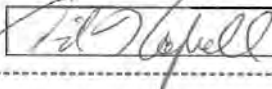
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# Analysis of Air Breathing Hall-Effect Thruster

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The principle idea of using air breathing electrical propulsion for a vehicle flying at orbital speed on the edge of Earth's atmosphere is examined. In this paper, we present a simple model of a Hall Effect thruster in which the propellant is an ambient air. The required lengths of the thruster chamber, the magnetic fields, the thrust, and other parameters of an ideal air breathing Hall Effect thruster are calculated as a function of the flying altitude of the vehicle. We demonstrated that an air breathing Hall thruster is indeed capable of providing the needed thrust for near space satellites in the case of the altitudes of about 80 – 90 km.

## Nomenclature

|                    |                                                             |
|--------------------|-------------------------------------------------------------|
| $A$                | = mass of a heavy particle, in au                           |
| $B$                | = strength of the magnetic field                            |
| $D_{diff}$         | = ambient gas diffusion coefficient                         |
| $E$                | = strength of the electric field                            |
| $E_{jet}$          | = energy flow leaving the Hall thruster with the plasma jet |
| $E_{anode}^{loss}$ | = heat losses at the anode                                  |
| $E_{wall}^{loss}$  | = energy losses at the wall                                 |
| $E_{ioniz}^{cost}$ | = ionization cost                                           |
| $e$                | = electron charge                                           |
| $F_{drag}$         | = drag force                                                |
| $f_{drag}$         | = drag factor                                               |
| $j_e$              | = electron current density                                  |
| $j_i$              | = ion current density                                       |
| $H$                | = altitude of satellite orbit                               |
| $L$                | = length of the Hall thruster chamber                       |
| $\ln \Lambda$      | = Coulomb logarithm                                         |
| $M$                | = mass of a heavy particle                                  |
| $M_i$              | = ion mass                                                  |
| $m_e$              | = mass of an electron                                       |
| $n_e$              | = electron number density                                   |
| $n_{gas}$          | = number density of ambient gas                             |

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|                  |                                                                   |
|------------------|-------------------------------------------------------------------|
| $n_i$            | = ion number density                                              |
| $n_{pl}$         | = number density of plasma                                        |
| $P$              | = electric power put into the discharge                           |
| $r_a$            | = inner radius of the opening of the air breathing Hall thruster  |
| $r_b$            | = outer radius of the opening of the air breathing Hall thruster  |
| $r_D$            | = Debye radius                                                    |
| $r_L$            | = electron cyclotron radius                                       |
| $S$              | = effective cross-section of the satellite due to drag force      |
| $T_e$            | = electron temperature                                            |
| $T_{e,jet}$      | = electron temperature in the plasma jet                          |
| $T_{gas}$        | = ambient gas temperature                                         |
| $T_{i,jet}$      | = ion temperature in the plasma jet                               |
| $Thrust$         | = thrust                                                          |
| $V_B$            | = Bohm velocity                                                   |
| $V_{e,drift}$    | = electron drift velocity                                         |
| $V_{Te}$         | = electron thermal velocity                                       |
| $V_{Tgas}$       | = thermal velocity of ambient gas                                 |
| $V_0$            | = the first cosmic velocity, 7.8 km/s                             |
| $\gamma$         | = coefficient of secondary electron emission                      |
| $\Delta V$       | = delta-V (change in the velocity)                                |
| $\lambda_{gas}$  | = ambient gas mean free path                                      |
| $\mu_e$          | = electron mobility                                               |
| $\sigma_{gas}$   | = collision cross-section of ambient gas molecules                |
| $\sigma_{ioniz}$ | = ionization cross-section                                        |
| $\tau_{e-life}$  | = electron lifetime in Hall thruster                              |
| $\tau_{ioniz}$   | = ionization time                                                 |
| $\tau_{wall}$    | = characteristic time for gas molecule collisions with wall       |
| $\tau_0 = L/V_0$ | = time that a gas molecule is flying through the thruster chamber |
| $\nu_{ei}$       | = electron-ion collision frequency                                |
| $\phi_0$         | = the Bohm sheath potential                                       |
| $\varphi$        | = applied voltage                                                 |
| $\omega_{He}$    | = electron cyclotron frequency                                    |

## I. Introduction

This work is motivated by increasing interest in military and civil spacecrafts flying at the altitudes of 70 - 120 km. Since the drag at such altitudes is still significant, the thrusters of such a satellite should work continuously in order 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, for such spacecrafts, using air breathing thrusters, in which the propellant is ambient air, looks very attractive, particularly for long-duration missions; air breathing thrusters allow significantly increased payload-to-weight ratio for such satellites. Using air breathing thrusters in Mars and other planets atmosphere becomes even more attractive because of multi-years satellite missions and high cost of payloads.

In a recent paper [1], Diamant has proposed a two-stage cylindrical Hall-Effect thruster for air breathing electric propulsion, in which the first stage is an electron cyclotron resonance ionization stage and the second stage is a cylindrical Hall thruster. The author built such a thruster and demonstrated its operation in 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 BUSEC conception of an air breathing 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].

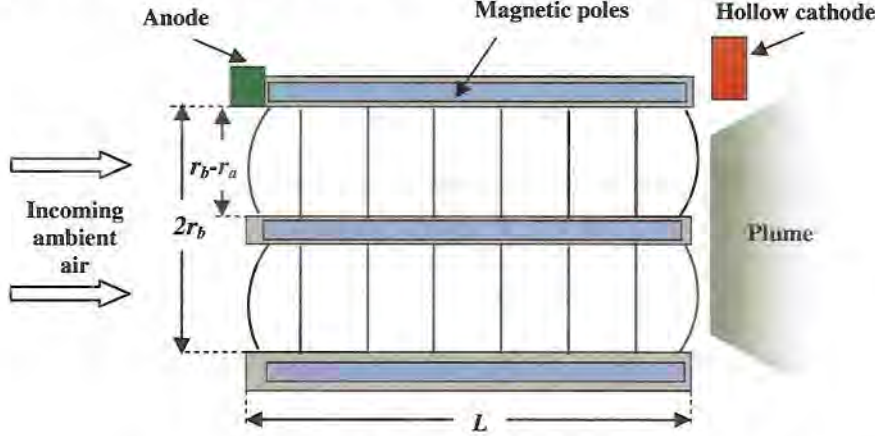


Figure 1. Schematic of air breathing Hall thruster (not to scale).

In the present work we propose a simple configuration of an air breathing Hall-Effect thruster, (shown in Figure 1), in which the incoming air flow 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 Sections II and III, respectively, and the conclusions are given in Section 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 Figure 1, corresponding to a condition in which the ambient gas freely flows through the thruster chamber without a significant interactions 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 quasineutral,  $n_i = n_e = n_{pl}$ , corresponding to a condition in which  $r_D$  is smaller than the characteristic dimensions of the thruster; in our case, Figure 1,  $r_D$  must be smaller than  $r_b - r_a$ ; (4) the electron cyclotron radius is much smaller than the Hall thruster gap,  $r_L < r_b - r_a$ , 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,  $\tau_0 = L/V_0$ , i.e.

$$\frac{\tau_{wall} \cdot V_0}{L} > 1, \quad (1)$$

In the case of free molecular flow, when the gas mean free path is larger than  $r_b - r_a$ , Figure 1,  $\tau_{wall}$  can be estimated as

$$\tau_{wall} = \frac{r_b - r_a}{V_{Tgas}}, \quad (2)$$

and in the case of collisional molecular flow,  $r_b - r_a < \lambda_{gas}$ , as

$$\tau_{wall} = \frac{(r_b - r_a)^2}{D_{diff}} = \frac{(r_b - r_a)^2}{\lambda_{gas} \cdot V_{Tgas}} = \frac{n_{gas} \cdot \sigma_{gas} \cdot (r_b - r_a)^2}{V_{Tgas}}. \quad (3)$$

Here, we have substituted  $(n_{gas} \cdot \sigma_{gas})^{-1}$  for  $\lambda_{gas}$ . Combining Eqs. (2) and (3) we obtain

$$\tau_{wall} = \text{Max} \left[ \frac{r_b - r_a}{V_{Tgas}}, \frac{n_{gas} \cdot \sigma_{gas} \cdot (r_b - r_a)^2}{V_{Tgas}} \right]. \quad (4)$$

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

$$\tau_{ioniz} = \frac{1}{V_{Te} \cdot n_e \cdot \sigma_{ioniz}}, \quad (5)$$

is much smaller than  $\tau_0$ . Let us estimate  $\tau_{ioniz}$ . The equation describing the mass conservation law for the heavy particles can be written as

$$V_0 \cdot n_{gas} = n_{pl} \cdot \sqrt{V_0^2 + \frac{2 \cdot e \cdot \varphi}{M_i}}, \quad (6)$$

where the left-hand side in Eq. (6) is the flux of incoming gas and the right-hand side is the ion flux leaving the chamber. In Eq. (6) we have assumed that the downstream plasma in the thruster chamber is quasineutral and fully ionized.

It should be stressed that in the model we assume the ambient gas is pure molecular nitrogen. This is a reasonable assumption since the air contains 78 percent of nitrogen and 21 percent of oxygen and their electron impact ionization cross sections are similar [4]. In the model, we neglect the dissociation of molecular nitrogen assuming that  $M = M_i$ . Since for electron energies between 20 – 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 of the dissociation of nitrogen should not lead to a significant error and is reasonable for our simple model.

Since  $e \cdot \varphi$  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

$$n_{pl} = n_e = \frac{V_0 \cdot n_{gas}}{\sqrt{\frac{2 \cdot e \cdot \varphi}{M}}}. \quad (7)$$

Substituting Eq. (7) and  $V_0$  as 7.8 km/s into an Eq. (5), we obtain that condition  $\tau_0 \gg \tau_{ioniz}$  is fulfilled when

$$47.6 \cdot L \cdot n_{gas} \cdot \sigma_{ioniz}(T_e) \cdot \left( \frac{\varphi}{A \cdot T_e} \right)^{1/2} > 1, \quad (8)$$

where  $T_e$  in Eq. (8) 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,  $(V_{Te} \cdot n_{gas} \cdot \sigma_{ioniz})^{-1}$ ; otherwise, the electron will leave the thruster chamber before producing any ionization events;  $\tau_{e-life}$  can be estimated as

$$\tau_{e-life} = \frac{L}{V_{e,drift}} = \frac{L}{\mu_e \cdot E} \cdot \left( 1 + \frac{\omega_{He}^2}{v_{ei}^2} \right), \quad (9)$$

It worth noting that in Eq. (9) we have assumed the classical electron transport across the magnetic field, and neglected the collisions of electrons with neutral particles (since a fully ionized plasma is assumed); recall that in the case of a high magnetic field, electron transport in Hall thrusters can approach the classical limit [6]. Substituting in Eq. (9)

$$\mu_e = \frac{e}{m_e \cdot v_{ei}}, \quad v_{ei} = 2.1 \cdot 10^{-12} \cdot \ln \Lambda \cdot n_{pl} \cdot T_e^{-3/2}, \quad \omega_{He} = 1.76 \cdot 10^7 \cdot B, \quad E = \varphi / L, \quad (10)$$

and taking into account that  $\omega_{He} / v_{ei}$  in Hall thrusters is much larger than one, we obtain

$$\tau_{e-life} = 1.5 \cdot 10^{15} \cdot \frac{L^2 \cdot B^2}{\sqrt{\varphi \cdot A} \cdot \ln \Lambda \cdot n_{gas} \cdot T_e^{-3/2}}, \quad (11)$$

where  $B$  is measured in Gauss, and  $T_e$  in eV. Now, taking into account that  $\tau_{e-life}$ , Eq. (11), must be larger than  $(V_{Te} \cdot n_{gas} \cdot \sigma_{ioniz})^{-1}$  we obtain that the following condition on  $L$  must also be satisfied to fulfill assumption 2:

$$4 \cdot 10^{10} \cdot L \cdot B \cdot T_e \cdot \left( \frac{\sqrt{\varphi \cdot A} \cdot \ln \Lambda}{\sigma_{ioniz}(T_e)} \right)^{-1/2} > 1. \quad (12)$$

Thus, we have shown that if the conditions given by Eqs. (8) and (12) are well satisfied, then the gas in the air breathing Hall thruster is well ionized.

Now let us examine the third assumption of the model: that the plasma is quasineutral. Substituting  $n_{pl}$  from Eq. (7) into an equation for the Debye radius [7],

$$r_D = 7.43 \cdot 10^3 \cdot \left( \frac{T_e}{n_{pl}} \right)^{1/2}, \quad (13)$$

and assuming that the gas is fully ionized, we obtain the following equation for the Debye radius:

$$r_D = 10^4 \cdot \left( \frac{T_e \cdot \sqrt{\varphi}}{n_{gas} \cdot \sqrt{A}} \right)^{1/2}. \quad (14)$$

Thus, if the Debye radius, Eq. (14), is much smaller than the characteristic dimension of the thruster,

$$r_b - r_a > 10^4 \cdot \left( \frac{T_e \cdot \sqrt{\varphi}}{n_{gas} \cdot \sqrt{A}} \right)^{1/2}, \quad (15)$$

the plasma in the Hall thruster can be considered quasineutral;  $T_e$  in Eqs. (13) – (15) is measured in electron volts.

Assumption 4 of the model requires that the characteristic electron cyclotron radius be much smaller than the thruster gap. Substituting in an expression for electron cyclotron radius  $V_{Te}$  for electron transfer velocity, we obtain

$$\frac{r_b - r_a}{r_L} = 42 \cdot \frac{(r_b - r_a) \cdot B}{T_e^{1/2}} > 1, \quad (16)$$

where the electron temperature is in electron volts and the magnetic field is in Gauss.

Assuming that all assumptions of the model are fulfilled, the thrust of an air breathing Hall thruster can be estimated as

$$Thrust = \pi \cdot (r_b^2 - r_a^2) \cdot M \cdot V_0 \cdot n_{gas} \cdot \sqrt{\frac{2 \cdot e \cdot \varphi}{M}} \quad (17)$$

and the electric power supplied to the discharge as

$$P = \pi \cdot (r_b^2 - r_a^2) \cdot (j_e + j_i) \cdot \varphi = \pi \cdot (r_b^2 - r_a^2) \cdot (e \cdot n_{pl} \cdot V_{e,drift} + e \cdot n_{gas} \cdot V_0) \cdot \varphi, \quad (18)$$

where  $\pi \cdot (r_b^2 - r_a^2)$  is the opening area of the thruster, and  $M \cdot V_0 \cdot n_{gas}$  and  $\Delta V = \sqrt{2 \cdot e \cdot \varphi / M}$  in Eq. (17) are correspondingly the mass flux entering the thruster and the increase in the velocity of heavy particles due to their acceleration in the Hall thruster chamber. Since the third assumption of the model is that the plasma is quasineutral, in Eq. (18) in the expression for  $j_e$  we have used  $n_{pl}$  instead of  $n_e$ . Substituting in Eq. (17)

$V_{e,drift} = \mu_e \cdot E \cdot V_{et}^2 / \omega_{He}^2$ ,  $n_{pl}$  from Eq. (7), and  $V_0 = 7.8$  km/s and using Eqs. (10), we obtain that

$$j_e = 6.01 \cdot 10^{-35} \cdot \frac{\ln \Lambda \cdot T_e^{-3/2} \cdot A \cdot n_{gas}^2}{B^2 \cdot L}, \quad (19)$$

$$j_i = 1.25 \cdot 10^{-15} \cdot n_{gas}, \quad (20)$$

where  $T_e$  is in eV,  $B$  in Gauss.

Assuming diffuse reflection of gas molecules from the satellite walls [3], the drag force can be estimated as,

$$F_{drag} = M \cdot V_0^2 \cdot n_{gas} \cdot S. \quad (21)$$

It should be stressed that since the gas entering the thruster does not produce drag, the first assumption of the model, the opening area of the thruster,  $\pi \cdot (r_b^2 - r_a^2)$ , is not included in  $S$ .

One of the important parameters governing the discharge in a Hall thruster is the electron temperature. Now let us obtain an equation for electron temperature for an air breathing Hall thruster. An energy conservation equation in the Hall thruster chamber can be written as

$$\pi \cdot (r_b^2 - r_a^2) \cdot (e \cdot n_{pl} \cdot V_{e,drift} + e \cdot n_{gas} \cdot V_0) \cdot \varphi = E_{wall}^{loss} + E_{jet} + E_{anode}^{loss}, \quad (22)$$

where the left-hand side of Eq. (22) is the electric power supplied to the discharge, Eq. (18), while the right-hand of this equation describes the heat losses at the Hall thruster walls and at the anode, and the energy flow leaving the Hall thruster with the plasma jet. Assuming no secondary electron emission from the wall,  $\gamma = 0$ , this corresponds to the case of minimal heat loss to the wall; equations for  $E_{wall}^{loss}$ ,  $E_{jet}$ , and  $E_{anode}^{loss}$  can be written as

$$E_{wall}^{loss} = 2 \cdot \pi \cdot (r_a + r_b) \cdot L \cdot \left[ n_{pl} \cdot V_B \cdot e \cdot (\phi_0 + E_{ion}^{cost}) + 2 \cdot T_e \cdot n_{pl} \cdot \exp\left(-\frac{e \cdot \phi_0}{T_e}\right) \cdot \sqrt{\frac{T_e}{2 \cdot \pi \cdot m_e}} \right], \quad (23)$$

$$E_{jet} = \pi \cdot (r_b^2 - r_a^2) \cdot V_0 \cdot n_{gas} \cdot e \cdot (\phi + T_{i,jet} + T_{e,jet} + E_{ioniz}^{cost}), \quad (24)$$

$$E_{anode}^{loss} = \pi \cdot (r_b^2 - r_a^2) \cdot n_{pl} \cdot V_{e,drift} \cdot \frac{3}{2} \cdot e \cdot T_e. \quad (25)$$

In Eq. (23) we have used the Bohm plasma sheath theory [8] and in Eq. (25) have taken into account the heat flux that the electrons bring to the anode, and neglected the (typically small) ion flux to the anode. The first term in the square brackets on the right-hand side of Eq. (23) describes the heat flux to the wall due to the recombination process plus the kinetic energy flux that ions bring to the wall, and the second term describes the heat flux that electrons bring to the wall. The plasma sheath potential drop,  $\phi_0$ , and the Bohm velocity,  $V_B$ <sup>8</sup>, are

$$\phi_0 = \frac{1}{2} \cdot T_e \cdot \ln\left(\frac{2 \cdot \pi \cdot m_e}{M}\right), \quad (26)$$

$$V_B = \sqrt{\frac{T_e}{M}}. \quad (27)$$

It should be stressed that in our model we have actually divided ions into two parts: the fast ions in the core of the thruster chamber (these ions are accelerated by applied electric field and do not reach the wall) and the slow ions at the vicinity of the wall which reach the wall. The ions created at the wall are accelerated by the sheath potential and reach the wall, where they recombine with electrons and then move back into the chamber as neutrals, and then, they are again ionized in the vicinity of the wall and move back to the wall. Since in our model the neutral particle ionization length is assumed to be much smaller than  $L$ , these newborn ions do not gain much energy from the applied electrical field in this cycle. Therefore, we have neglected the kinetic energy of these ions at the sheath edge as it has been assumed in [8].

Since the ion and electron temperatures in the plasma jet (in the plume, Figure 1) are typically a few electron volts and much smaller than the ionization cost, which is 20 – 40 eV, we will further neglect  $T_{i,jet}$  and  $T_{e,jet}$  in Eq. (24). Substituting the reduced equations for  $E_{wall}^{loss}$ ,  $E_{jet}$ ,  $E_{anode}^{loss}$  into Eq. (22), after some algebra we obtain a final equation for the electron temperature:

$$\begin{aligned} 4.9 \cdot 10^{-20} \cdot \frac{A \cdot n_{gas} \cdot \ln \Lambda}{L^2 \cdot B^2} \cdot \left(\frac{\varphi}{T_e}\right)^{3/2} \cdot \left(1 - \frac{3 \cdot T_e}{2 \cdot \varphi}\right) = \\ = \frac{E_{ioniz}^{cost}}{L} \cdot \sqrt{\varphi} + \frac{1}{(r_b - r_a)} \cdot 1.5 \cdot T_e^{1/2} \cdot \left(E_{ioniz}^{cost} + [2 + \ln(17 \cdot A^{1/2})] \cdot T_e\right) \end{aligned} \quad (28)$$

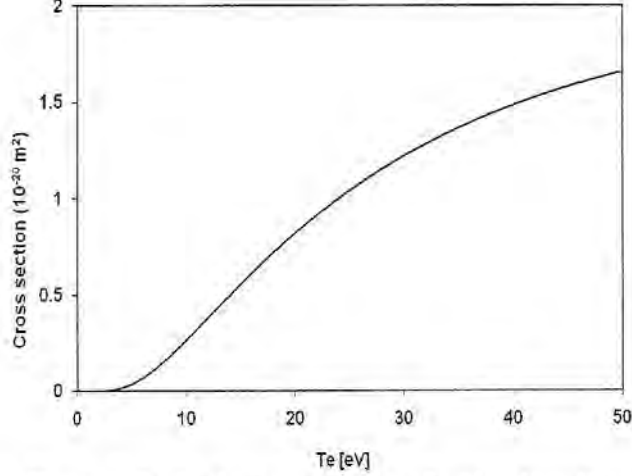
Thus, knowing the parameters of the air breathing Hall thruster ( $L$ ,  $r_a$ ,  $r_b$ ,  $B$ ,  $\varphi$ ) and parameters of the ambient air ( $A$ ,  $\sigma_{ioniz}(T_e)$ ,  $\sigma_{gas}$ ,  $n_{gas}$ ,  $T_{gas}$ ,  $E_{ioniz}^{cost}$ ) using Eq. (28) we can calculate  $T_e$ , then check the assumptions made in the model, Eqs. (1), (8), (12), (15) and (16), and finally calculate the thrust, Eq. (17), the power, Eq. (18), the ion and electron currents, Eqs. (19) and (20), and other parameters of the air breathing 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,  $\sigma_{gas}$ , was taken as  $4.4 \cdot 10^{-19} \text{ m}^2$  [9]; this corresponds to

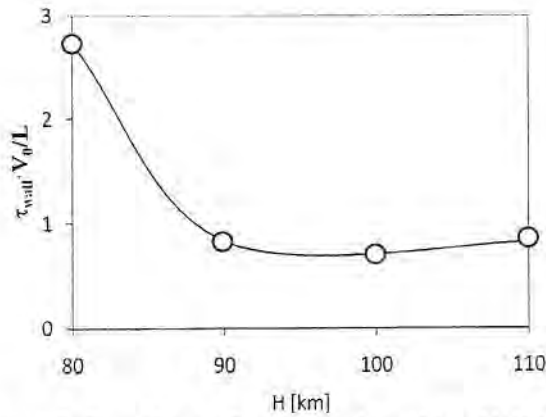
$$\lambda_{gas} = \frac{1.63 \cdot 10^{-5} \cdot T[K]}{P[Pa]} \quad (29)$$

The ionization cross section of molecular nitrogen as a function of electron temperature, Figure 2, was calculated using data [5], and  $\ln \Lambda$  was taken as 13.5; the length and the inner and outer radii of the Hall thruster chamber were chosen as 0.5, 0.03, and 0.05 m respectively. The calculations have been performed for two applied voltages, 3 and 30 kV, and for satellite orbits of 80 and 90 km.



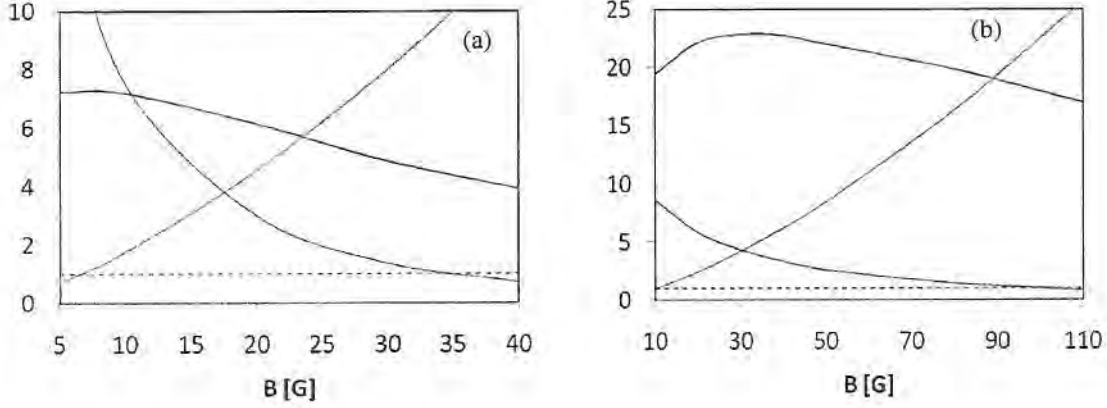
**Figure 2. Ionization cross section of molecular nitrogen**

Figure 3 shows the drag factor  $f_{drag} = \tau_{wall} \cdot V_0 / L$  calculated for 80, 90, 100, and 110 km satellite orbits. As one can see, the first assumption of the model is well fulfilled only for the 80 km satellite orbit. However, since the thrust of air breathing Hall thrusters, Eq. (17), is generally larger than the maximal drag  $\pi \cdot (r_b^2 - r_a^2) \cdot M \cdot n_{gas} \cdot V_0^2$  that might be produced by the air flowing through the Hall chamber, this assumption is not critical for the air breathing Hall thruster concept. It is worth noting that the gas flow through the thruster is free-molecular, Eq. (2), for  $H = 90$  km and larger, and is collisional, Eq. (3), for  $H = 80$  km and smaller. Obviously, for different thruster chamber length and width the transition between the free molecular and the collisional flows can take place at different orbits.

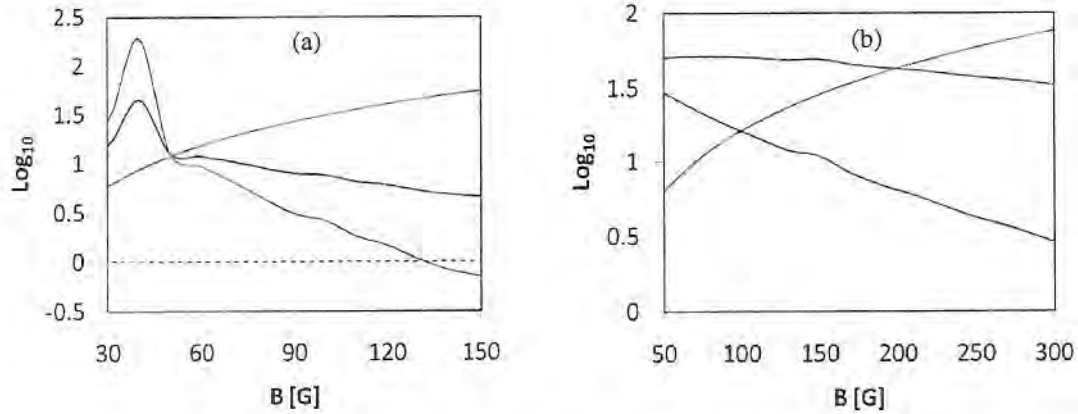


**Figure 3. Drag factor for the air breathing Hall thruster:**  
 $L = 0.5$  m,  $r_b = 0.05$  m, and  $r_a = 0.03$  m

Figures 4 and 5 show the ratios of  $\tau_0 / \tau_{ioniz}$ ,  $\tau_{e-life} \cdot V_{Te} \cdot n_{gas} \cdot \sigma_{ioniz}$ , and  $(r_b - r_a) / r_L$ , Eqs. (8), (12), and (16), calculated for the satellite orbits of 90 and 80 km respectively, the ionization cost of 40 eV, and the applied voltages of 3 kV and 30 kV; they correspond to the second and forth assumptions of the model. As one can see for the satellite orbit of 90 km these assumptions are satisfied for magnetic fields in the ranges of 10 – 30 and 20 – 70 Gauss correspondingly for  $\varphi = 3$  kV and 30 kV; and for the orbit of 80 km in the ranges of 30 – 120 G for  $\varphi = 3$  kV and for  $\varphi = 30$  kV in all region of magnetic fields, 50 – 300 G. The third assumption of the model, Eq. (15), and  $\omega_{He} / \nu_{ei} \gg 1$  condition are very well satisfied in all ranges of magnetic field, potential, and orbit considered in the paper.



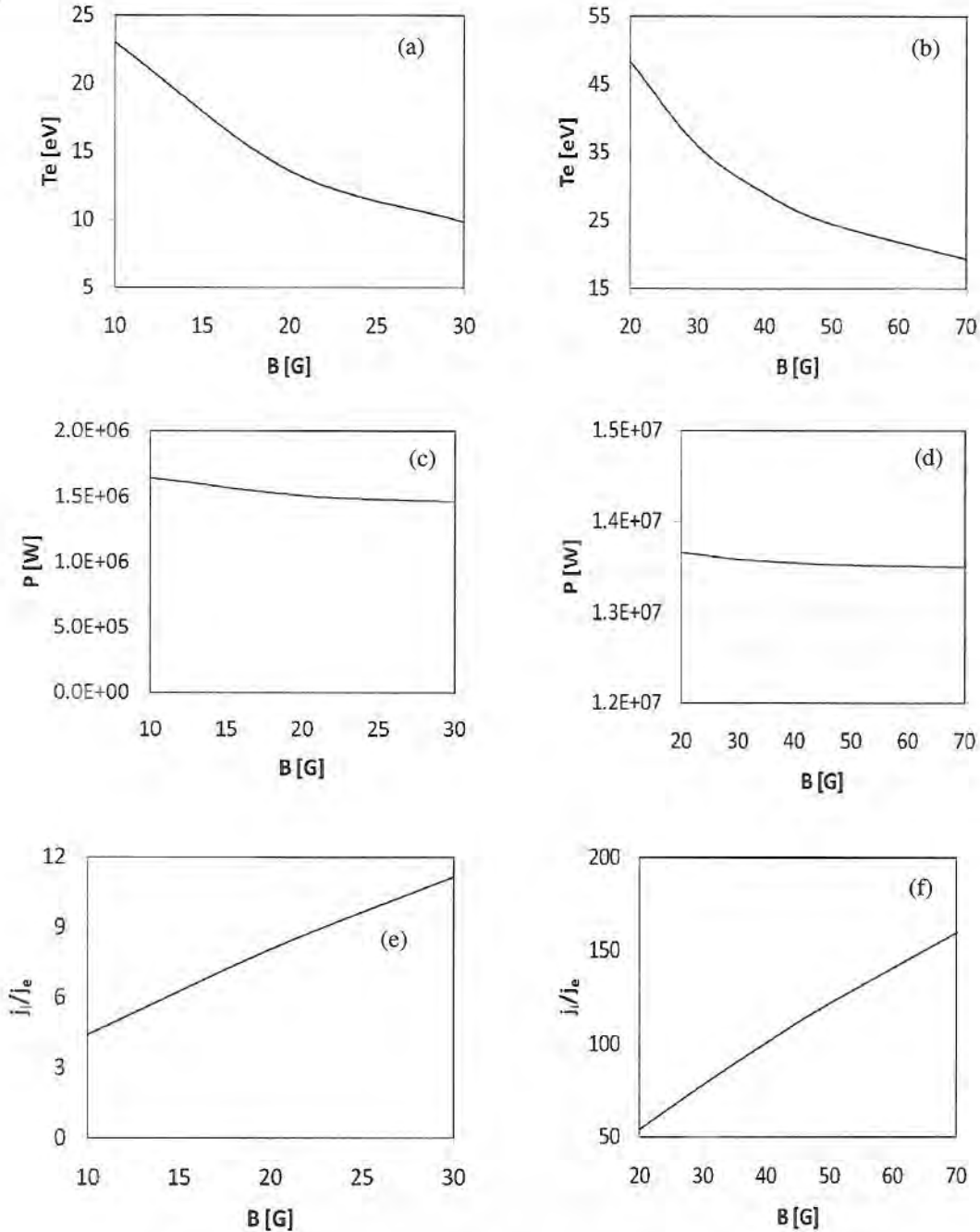
**Figure 4.** The  $\tau_0 / \tau_{ioniz}$  - blue line,  $\tau_{e-life} \cdot V_{Te} \cdot n_{gas} \cdot \sigma_{ioniz}$  - green line,  $(r_b - r_a) / r_L$  - red line calculated for  $H = 90$  km and  $\varphi = 3$  kV - (a) and  $\varphi = 30$  kV - (b); the broken line correspond to unity.



**Figure 5.** The  $\tau_0 / \tau_{ioniz}$  - blue line,  $\tau_{e-life} \cdot V_{Te} \cdot n_{gas} \cdot \sigma_{ioniz}$  - green line,  $(r_b - r_a) / r_L$  - red line calculated for  $H = 80$  km and  $\varphi = 3$  kV - (a) and  $\varphi = 30$  kV - (b).

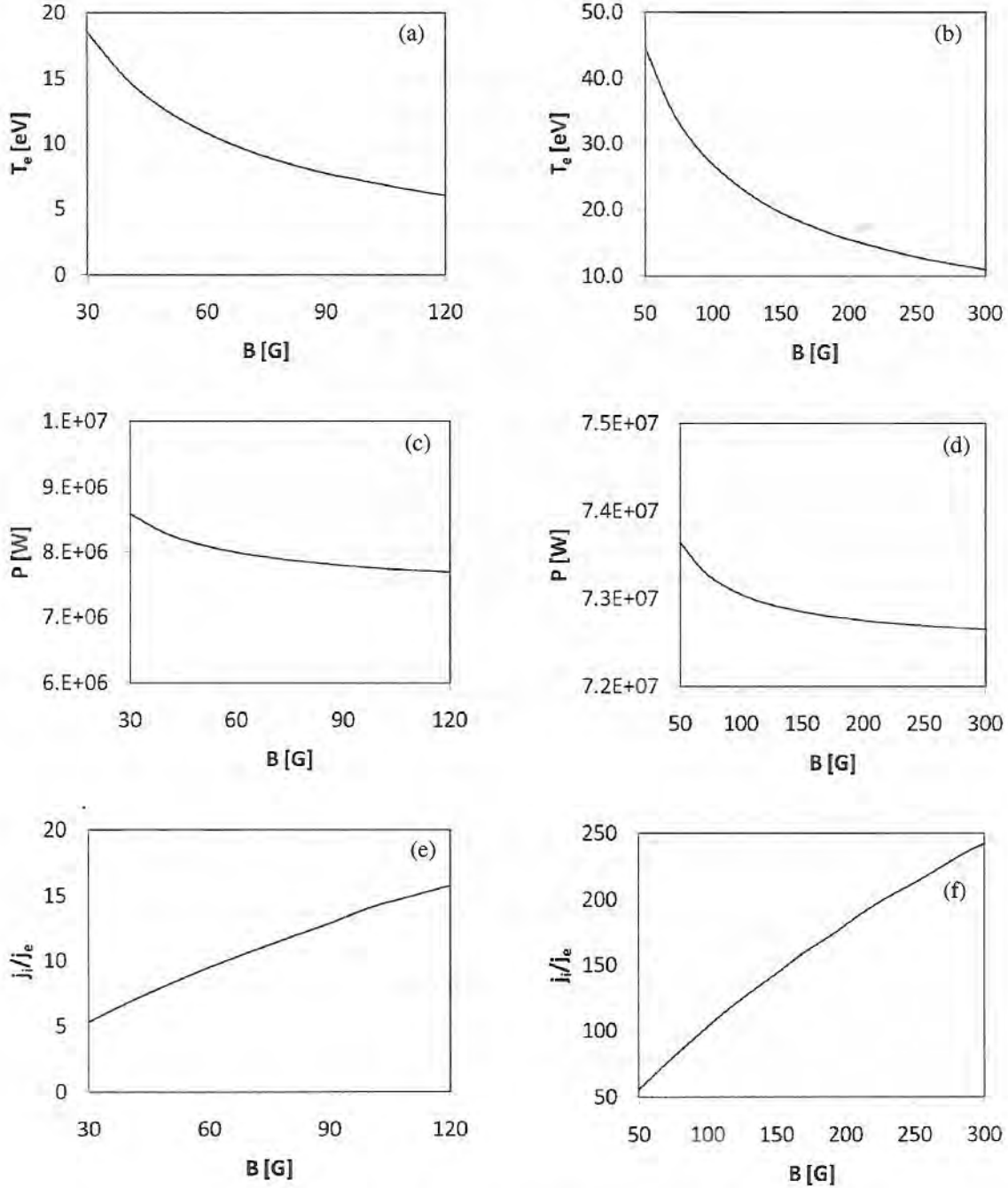
Since the air breathing Hall thruster plasma in our model is assumed to be fully ionized, the thrust, Eq. (20), is determined only by the ambient gas number density and the applied voltage, and the ion current, Eq. (17), is determined by the ambient gas number density only. The model gives  $j_i = 8.9 \cdot 10^4$  and  $4.8 \cdot 10^5$  A/m<sup>2</sup> for  $H = 90$  and 80 km respectively; and  $Thrust = 18.63, 58.94, 100.5$ , and  $317.9$  N correspondingly for  $H = 90$  km,  $\varphi = 3$  and

30 kV and  $H = 80$  km,  $\varphi = 3$  and 30 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; and an increase in the applied voltage leads to larger  $\Delta V$  and, therefore, larger thrust. Of course, a lower orbit will lead to a larger 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.



**Figure 6. Parameters of the air breathing thruster for  $H = 90$  km: plots (a), (c) and (e) correspond to  $\varphi = 3$  kV and plots (b), (d) and (f) to  $\varphi = 30$  kV .**

Figures 6 and 7 show the electron temperature, power, and  $j_i/j_e$  vs. magnetic field for  $H = 90$  and  $80$  km respectively. In these figures we have selected magnetic fields for which the model assumptions are satisfied. As was expected with an increase in the applied voltage, the electron temperature increases, and with an increase in the magnetic field it decreases, as shown in Figures 6a, 6b and 7a and 7b. Since the ion current in the model is independent of the magnetic field (ions are not magnetized), while the electron current decreases with an increase in



**Figure 7. Parameters of the air breathing thruster for  $H = 80$  km: plots (a), (c) and (e) correspond to  $\phi = 3$  kV and plots (b), (d) and (f) to  $\phi = 30$  kV .**

the magnetic field (they are magnetized), the electrical power decreases and the ratio of  $j_i$  to  $j_e$  increases with an increase in  $B$ , as illustrated in Figures 6c - 6f and 7c - 7f. Since the electron component of the total current sharply decreases with magnetic field, as shown in Figures 6e, 6f, 7c, 7f,  $P$  flattens for large magnetic fields, Figures 6c, 6d, 7c, 7d.

We have also examined the air breathing Hall thruster with the selected  $L$ ,  $r_a$ , and  $r_b$  for the satellite orbits of 100 and 110 km. Although we could not select  $B$  and  $\phi$  to satisfy the model assumptions at such high altitude, we believe that changing the geometry of the thruster, for example increasing the length of the thruster, see Eqs. (8) and (12), may allow this.

#### IV. Concluding Remarks

The idea of using air breathing 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 80 – 90 km, producing significant thrust in the range of 20 to 320 N for considered conditions.

It should be pointed out that the power required maintaining such high level of thrust is in the order of MW with thrust-to-power ratio of  $4.37 - 13 \mu\text{N/kW}$  which is comparable with a typical high-efficient electric propulsion device. Recall that while air-breathing 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, power transmission is warranted as a part of the overall air-breathing thruster and satellite analysis.

Note, that this paper has considered relatively 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 [10]. Further analysis of the air-breathing concept should involve broader conditions for the SEE thus extending operational parameters of this device.

We believe that by changing the thruster geometry, we could find reasonable conditions allowing increasing the flying orbit of an air breathing satellite up to 100 – 110 km. It should be stressed that in the model we have assumed that the plume is fully ionized corresponding to the maximum possible thrust and power. However, if we soften this condition, 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.

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