

Article

Rarefied Intake Flow in an Atmospheric-Breathing VLEO Hall Thruster

Miah Md Ashraful Alam ^{1,*}, Md. Mamun ², Takayuki Kuri ², Md. Kawsarul Islam ³ and Md. Mesbah Uddin Saadi ³ 

¹ Department of Systems Engineering, Osaka Sangyo University, Osaka 574-8530, Japan

² Graduate School of Engineering, Osaka Sangyo University, Osaka 574-8530, Japan; mamun193016@gmail.com (M.M.); s24mf12@ge.osaka-sandai.ac.jp (T.K.)

³ Department of Mechanical Engineering, Dhaka University of Engineering & Technology, Gazipur 1707, Bangladesh; ahmedkawsarul2000@gmail.com (M.K.I.); mdmesbahuddinsaadi@gmail.com (M.M.U.S.)

* Correspondence: alam@tm.osaka-sandai.ac.jp

Abstract

Atmosphere-breathing Hall thrusters (ABHTs) have emerged as a promising propulsion technology for very low Earth orbit (VLEO) satellites because they can utilize residual atmospheric particles as propellant, reducing the need for onboard propellant storage. In this paper, the feasibility of an ABHT system was investigated through a combined experimental and numerical approach. Experimental tests using the THT-VI Hall thruster demonstrated stable operation with air propellant and achieved specific impulses up to 2847 s under high-voltage conditions, indicating the potential for atmospheric drag compensation. To evaluate the intake performance, Direct Simulation Monte Carlo (DSMC) simulations were conducted at an altitude of 180 km to examine the effects of intake geometry, including the duct aspect ratio and intake-to-thruster area ratio. The results showed that the intake system can generate discharge chamber pressures of approximately 10^{-3} – 10^{-1} Pa, which is sufficient for Hall thruster operation, but the maximum collected mass flow rate (0.298 mg/s) remained below the required 1.5 mg/s. Several modified intake configurations improved particle transport and reduced aerodynamic drag with the best design increasing mass flow rate by approximately 7.5 times compared with the baseline configuration. These findings indicate that the primary limitation of ABHT systems is the intake mass transport capability rather than the thruster performance itself. A further optimization of intake geometry and spacecraft integration is required to enable sustained VLEO operation.

Keywords: air-breathing Hall thruster; very low Earth orbit (VLEO); electric propulsion; numerical simulation; air-intake section



Academic Editor: Martin Tajmar

Received: 19 May 2026

Revised: 22 June 2026

Accepted: 29 June 2026

Published: 30 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Very low Earth orbit (VLEO) satellites have become a primary focus of modern space missions, including Earth observation and telecommunications [1,2]. Working in low-altitude environments (e.g., below 450 km) offers many advantages, including lower communication latency, higher remote sensing resolution, and satellite re-entry with lower energy consumption [3,4]. But this low altitude also comes with a substantial drawback for missions: very high aerodynamic drag. As the spacecraft crosses Earth's upper atmosphere, it encounters residual atmospheric particles that slow it down. This drag results in a persistent depletion of energy and orbital velocity, culminating in a slow decline in the

satellite's altitude above Earth. A consequence of the lack of an active drag compensation method is rapid orbital decay, ultimately restricting the satellite's operational lifetime and leading to uncontrolled re-entry. The occasional need to counter this drag has driven research into new propulsion methods that can provide continuous thrust to recover orbital height and extend mission duration [2].

Figure 1 illustrates the concept of atmosphere-breathing electric propulsion (ABEP) systems, which have been proposed as a promising solution. Rather than carrying copious amounts of propellant onboard like traditional propulsion methods, ABEP systems represent a radical new approach. Instead, they directly gather atmospheric particles from the surrounding environment and utilize these as a propellant for an electric thruster [5]. This drag-compensation process is the key advantage of ABEP technology, enabling long operational durations in VLEO without frequent refueling [5–7].

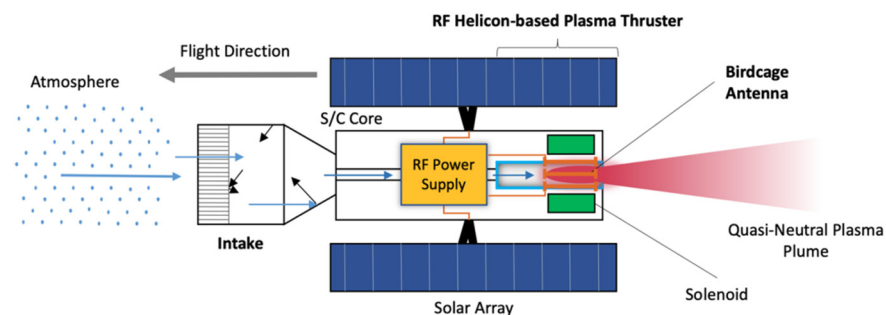


Figure 1. ABEP concept using an radio frequency (RF) helicon plasma thruster [8].

The intake is one of the most complex and innovative parts of an ABEP, including methods for capturing atmospheric particles and funneling them into the thruster. When the proposed concept expands from micro payload applications to a VLEO smallest system, the intake will need to be designed for optimized operation at orbital velocities (~ 7.8 km/s) for VLEO satellites [9,10]. The performance and efficiency of the ABEP system largely depend on its intake design. Moreover, this intake must be incorporated into the overall spacecraft design so that it does not create excessive drag; a large or inefficient intake could worsen the atmospheric drag problem [11–13], thereby defeating the purpose of the ABEP system in the first place. In a low-density regime, the gas flow generally exhibits free-molecular behavior in which particle motion is regulated by interactions with solid surfaces rather than by collisions with neighboring particles. This rarefied flow regime, characterized by a high Knudsen number ($Kn > 10$), poses challenges for intake design [9,14–17]. The intake has to collect those sparse particles efficiently and funnel them into the thruster, where they will be ionized and accelerated. At the outer limits of these abilities lies this rarefied flow regime, where the efficiency with which particles are collected and compressed is a key consideration in providing sufficient propellant mass to the thruster.

Gas–surface interactions (GSIs) resulting from collisions between atmospheric species and the intake surface significantly affect the performance of intake systems. The nature of reflection (specular: perfectly elastic, diffuse: inelastic) determines the proportion of kinetic energy retained by a particle after collision and the efficiency at which a particle can be trapped [18,19]. One important parameter in modeling these interactions is the accommodation coefficient, which measures how much energy is exchanged between the particle and the wall. Various gas–surface interaction models can be used to simulate particle behavior at the intake walls, such as the Maxwell and Cercignani–Lampis–Lord (CLL) models, depending on the relevant gas species and the intake material properties. Such models help clarify the required features of an intake system that collects particles in a drag-efficient manner [10,11,20]. In the VLEO region between 150 km and 250 km, the

composition is dominated by nitrogen (N_2) and atomic oxygen. The intake system must be designed to operate effectively in this atmospheric environment, whose flow properties are influenced by solar activity, orbital parameters, and seasonal segmentation. The ability to function effectively in these highly variable environments is a primary challenge in the design of ABEP systems for VLEO missions [21,22].

This paper investigates the feasibility of atmospheric-intake Hall thrusters for VLEO applications through a combined experimental and DSMC-based numerical approach. Hall thrusters were selected because they offer higher thrust density and greater tolerance to mixed atmospheric species than gridded ion engines, making them suitable for atmosphere-breathing electric propulsion in VLEO. Unlike ion thrusters, which require highly controlled propellant flows to ensure stable ion extraction and minimize grid erosion, Hall thrusters can operate under less stringent intake conditions. First, Hall thruster experiments were conducted to determine the propellant supply requirements and propulsion performance under air operation. Subsequently, DSMC simulations were performed to evaluate whether a rarefied atmospheric intake can provide the pressure and mass flow rates required for sustained thruster operation. A parametric analysis of intake geometry was conducted to assess its impact on compression, mass flow rate, and aerodynamic drag. The results indicate that for atmospheric-intake Hall thrusters, achieving the required mass flow rate is a more critical challenge than attaining the necessary discharge chamber pressure. Intake geometries that enhance particle capture and promote smooth flow transitions improve the mass flow rate while limiting aerodynamic drag.

2. Methodologies

2.1. Experimental Setup

This paper utilized two types of Hall thrusters, THT-III and THT-VI, as shown in Figure 2. The THT-III is a compact unit that measures 42 mm on the inside and 70 mm on the outside. The THT-VI is a medium-sized unit with a channel having an inner diameter of 56 mm and an outer diameter of 100 mm.

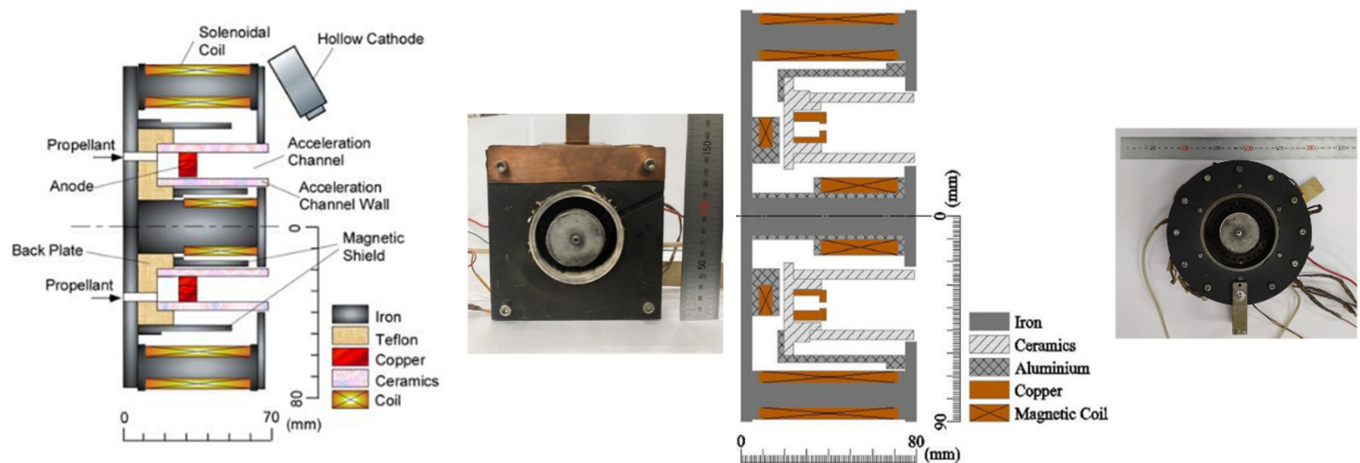


Figure 2. Configuration of the Hall thrusters: THT-III (left) and THT-VI (right).

A schematic of the experimental apparatus is shown in Figure 3. The Hall thrusters were mounted on rigid pendulums inside vacuum chambers with diameters of 1.2 m and 2.25 m. A high-vacuum environment was created using a rotary pump and a turbomolecular pump to operate the Hall thrusters. Thrust was estimated from pendulum displacement using a laser displacement sensor.

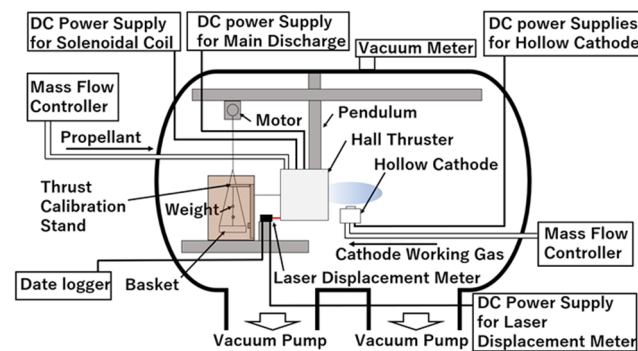


Figure 3. Arrangement of experimental equipment.

This paper compares the operating characteristics of THT-III and THT-VI during nitrogen operation. Additionally, air operation was performed using THT-VI. The experiments were conducted in ground-based vacuum facilities to evaluate the intrinsic performance and propellant requirements of the Hall thrusters under air operation rather than to reproduce the complete VLEO environment. The effects of rarefied atmospheric intake conditions and orbital flow characteristics were subsequently evaluated through DSMC simulations.

The Hall thruster experiments were conducted to establish the operational requirements of the propulsion system and to provide reference performance parameters for the intake analysis. In an atmosphere-breathing Hall thruster (ABHT), the intake and thruster cannot be evaluated independently because the intake must supply a sufficient mass flow rate and pressure to sustain thruster operation. Therefore, the experimentally obtained thrust, specific impulse, exhaust velocity, and propellant mass flow rate were used as benchmarks to assess whether the rarefied atmospheric intake could provide adequate propellant under VLEO conditions. The numerical intake simulations presented in the subsequent sections were performed based on these experimentally determined operating requirements.

The geometrical specifications and experimentally measured performance of the THT-VI Hall thruster are summarized in Table 1. In particular, the experimentally determined operating mass flow rate of 1.5 mg/s was used as the reference requirement for the DSMC intake analysis to evaluate whether the atmospheric intake could provide sufficient propellant for sustained Hall thruster operation under representative VLEO conditions.

Table 1. Geometrical specifications and experimental performance of THT-VI Hall thruster.

Parameter	Value
Thruster Type	Hall Thruster (THT-VI)
Inner Channel Diameter	56 mm
Outer Channel Diameter	100 mm
Propellant	Air (80% N ₂ , 20% O ₂)
Operating Mass Flow Rate	1.5 mg/s
Discharge Voltage Range	150–350 V
Thrust at 250 V	20.79 mN
Maximum Thrust	41.89 mN
Specific Impulse at 250 V	1413 s
Maximum Specific Impulse	2847 s
Exhaust Velocity at 250 V	13.86 km/s
Maximum Exhaust Velocity	27.93 km/s
Operating Objective	Atmospheric drag compensation in VLEO

2.2. Numerical Analysis

In previous research on atmospheric-intake Hall thrusters, air was assumed to be drawn into the satellite's air intake and compressed, and then nitrogen or air was used to evaluate the thruster performance. Building on this function, this paper simulates the air intake section to investigate whether the Hall thruster under consideration can achieve atmospheric compensation. For the analysis, OpenFOAM v2312 distribution [23], was used. OpenFOAM is developed and distributed by OpenCFD Ltd. (Berkshire, UK), a subsidiary of ESI Group. In addition, SALOME [24] developed by CEA (Paris, France) and EDF (Paris, France), and Para View [25] developed by Kitware Inc. (Clifton Park, NY, USA), are employed to support the simulation workflow. The procedure involves modeling and meshing the satellite geometry and air intake section in SALOME, conducting fluid dynamics in OpenFOAM, and performing visualization and quantitative data analysis in Para View.

2.2.1. Knudsen Number and Classification of Flow

The Knudsen number (Kn) is a dimensionless parameter used to assess flow rarefaction and is defined as [26]

$$Kn = \frac{\lambda}{L} \quad (1)$$

Here, L denotes the characteristics length (e.g., tube diameter or spacecraft dimension), and λ represents the mean free path. If the module diameter is d , then

$$\lambda = \frac{1}{\sqrt{2}\pi d^2 n} \quad (2)$$

Here, n denotes the number density, representing the number of molecules per unit volume. Let p represent the pressure, k the Boltzmann constant (1.380649×10^{-23} J/K), and T the absolute temperature. Moreover, if ρ represents the mass density and R the specific gas constant (287 J kg $^{-1}$ K $^{-1}$ for air), which is related to the Boltzmann constant through $R = k_B N_A / M$, then the equation of state can be expressed as

$$p = nkT = \rho RT \quad (3)$$

$$\lambda = \frac{kT}{\sqrt{2}\pi d^2 p} \quad (4)$$

$$Kn = \frac{kT}{\sqrt{2}\pi d^2 p L} \quad (5)$$

As the pressure decreases and the molecular number density n becomes smaller, the mean free path λ increases. As it becomes longer than the representative length L , intermolecular collisions are rare, and molecules predominantly interact with the confining walls. In this regime, where $\lambda \gg L$, the flow is governed solely by the exchange of momentum and energy between individual gas molecules and the wall, rather than by collisions between gas molecules, which is a condition referred to as free molecular flow [26]. Conversely, when $\lambda \ll L$, the flow behavior is determined by the cumulative effect of numerous intermolecular collisions, allowing the fluid to be treated macroscopically as a continuous medium. This description is known as the continuous flow approximation. On the basis of the Knudsen number, Hard Sphere (H.S.) Tsien and Guthrie et al. have classified the flow regions of dilute gases as summarized in Tables 2 and 3 [27–29]. Since analytical solutions for such dilute flows are generally intractable, numerical methods, most notably the Direct Simulation Monte Carlo (DSMC) technique, are commonly employed to investigate their behavior.

Table 2. Classification of flow based on H.S. Tsien.

$\text{Kn} < 0.01$	$0.01 < \text{Kn} < 0.1$	$0.1 < \text{Kn} < 10$	$\text{Kn} > 10$
Continuous Flow	Slip Flow	Transition Flow	Free Molecular Flow

Table 3. Classification of flow based on Guthrie.

$\text{Kn} < 0.01$	$0.01 < \text{Kn} < 0.1$	$10 < \text{Kn}$
Continuous Flow	Intermediate Flow	Molecular Flow

2.2.2. The Boltzmann Equation

The Boltzmann equation governs the behavior of dilute gases and forms the basis of rarefied gas dynamics [30,31].

$$\frac{\partial}{\partial t}(nf) + c \cdot \frac{\partial}{\partial r}(nf) + F \cdot \frac{\partial}{\partial c}(nf) = \int_{-\infty}^{\infty} \int_0^{4\pi} n^2 (f^* f_1^* - f f_1) c_r \sigma d\Omega dc_1 \quad (6)$$

Here, f is the molecular velocity distribution function, n is the number density, c is the molecular velocity, r is the spatial coordinate, and F represents external forces. The term c_r denotes the relative velocity between colliding molecules, σ is the differential collision cross-section, and $d\Omega$ represents an element of solid angle. The right-hand side represents the collision integral accounting for intermolecular interactions.

Due to the complexity of the collision term, analytical solutions of the Boltzmann equation are generally intractable. Therefore, numerical approaches, such as the DSMC method, are widely employed for the analysis of rarefied gas flows [32–34].

2.2.3. Numerical Methods

But for a large value of the Knudsen number, it should be treated as a free molecular flow instead of a continuous fluid. To model this scenario, a kinetic approach based on the Boltzmann equation is required. Hence, the flow in this scenario can be considered free-molecular. In this paper, numerical analysis is performed using the DSMC method where each simulation particle represents multiple real molecules.

$$f(c) = \frac{1}{(2\pi RT_0)} \exp\left(-\frac{|c|^2}{2RT_0}\right) \quad (7)$$

where $f(c)$ denotes the molecular velocity distribution function, c is the molecular velocity vector, R is the specific gas constant, and T_0 represents the freestream temperature. Molecular inflow, motion, and collisions are calculated at each time step. DSMCFoam solver in OpenFOAM is used for the simulations. The HS, VHS (Variable Hard Sphere), and VSS (Variable Soft Sphere) models are used to describe molecular collisions [35].

2.2.4. Computer Specifications

Table 4 shows the specifications of the computer used for the DSMC simulations in this paper. To reduce the computational cost of the DSMC simulations, each reference particle represented 1.0×10^7 real particles, and the mesh resolution was optimized using a maximum cell size of 0.002 mm, a minimum cell size of 0.0015 mm, and a wall-adjacent cell size of 0.0005 mm [36–38].

Table 4. Specifications of the computer used.

CPU	Intel® Core™ i7-14700KF
Memory	64 GB
HDD	SEAGATE ST1000VN0008 (10 TB)

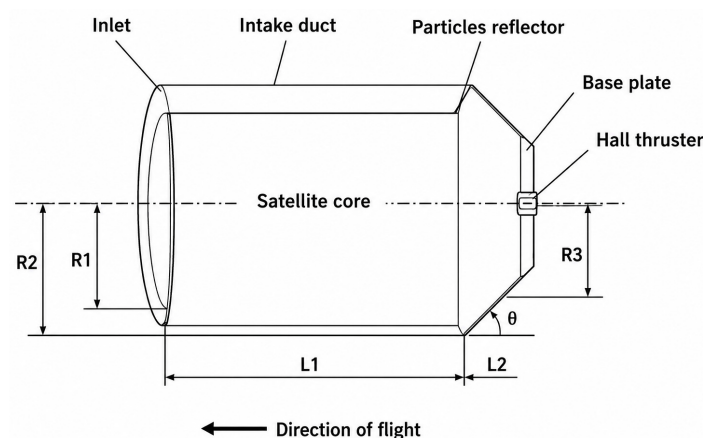
2.3. Geometric Model

Figure 4 illustrates the geometric model of the atmospheric-intake Hall thruster employed in this simulation. The model is adopted from a previously reported atmospheric-intake ion engine configuration [39]. Although the original configuration was developed for an atmospheric-intake ion engine, it was adopted in this paper because the intake compression process in VLEO is primarily governed by rarefied gas dynamics and intake geometry rather than by the specific type of electric thruster. Both ion and Hall thrusters require the intake system to maximize pressure recovery and mass flow rate while minimizing aerodynamic drag. Therefore, the intake aspect ratio (χ), compression ratio (G), and the ratio of the thruster cross-sectional area to intake area (η) were selected as the key parameters for evaluating the intake performance. The geometry is determined by six parameters: the satellite core radius R_1 ; the satellite outer radius R_2 , which denotes the outer radius of the satellite and was varied as 1.1 m, 1.2 m, and 1.4 m, corresponding to intake aspect ratios (χ) of 20, 10, and 5, respectively; the satellite back panel radius R_3 , the air intake duct length L_1 , the distance L_2 between the satellite core and the satellite back panel, and the reflector half-angle θ . For this paper, the selected values are $R_1 = 1$ m, $L_1 = 2$ m, $L_2 = 0.2$ m, $R_3 = 0.8$ m, and $\theta = 45^\circ$. The Hall thruster is mounted on the satellite's rear panel. The following equations represent the key geometric and performance parameters used to evaluate the proposed intake system:

$$\chi = \frac{L_1}{R_2 - R_1} \quad (8)$$

$$\eta = \frac{\frac{\pi}{4}(D_0^2 - D_i^2)}{\pi(R_2^2 - R_1^2)} \quad (9)$$

$$G = \frac{P_c}{P_0} \quad (10)$$

**Figure 4.** Geometric model of an atmospheric intake Hall thruster.

Here, D_0 and D_i are the outer and inner diameters of the Hall thruster, respectively; P_c is the pressure in the discharge chamber, χ is the geometric ratio representing intake

duct slenderness, η is the ratio of thruster cross-sectional area to intake area, S is the scaling factor used for geometric reduction, and P_0 is atmospheric pressure. Therefore, the ratio of the Hall thruster cross-sectional area to the intake area is varied in the simulations. Due to computational limitations, the baseline simulations were conducted using a 1/20-scale model. Geometric scaling reduces the characteristic length of the intake and consequently increases the Knudsen number under identical atmospheric conditions. However, because this paper focuses on the relative effects of intake geometry on pressure recovery, mass flow rate, and aerodynamic drag in the rarefied flow regime, the key performance trends are preserved. A 1/100-scale model was additionally analyzed to assess the sensitivity of the simulation results to geometric scaling and to support extrapolation to the full-scale configuration. In addition, a 1/100-scale model was analyzed to investigate the influence of geometric scaling on the simulation results. In the numerical analysis, the pressure P_c [Pa], compression ratio G , the mass flow rate J [mg/s], and the atmospheric drag D [mN] of the satellite within the Hall thruster discharge chamber are output to evaluate the performance of the air intake section [11,40].

2.4. Simulation Conditions

Previous studies have shown that atmospheric-intake electric propulsion systems are most effective at orbital altitudes of 150–200 km [41]. Solar activity affects atmospheric density at a given altitude. Therefore, an orbital altitude of 180 km is assumed with atmospheric conditions corresponding to average solar activity ($F_{10.7} = 329$) based on the MSISE-90 model [42]. In the DSMC simulation, each sample particle represents 10^7 real particles with the VHS model assigned as the default for molecular collision detection in the DSMCfoam solver. The flow velocity was set to 7.8×10^3 m/s, which is the same as the orbital speed of a satellite.

The atmospheric composition was assumed to consist of N_2 , O, and O_2 , which together account for approximately 99.4% of the atmosphere at the considered altitude. Chemical reactions were neglected. For gas–surface interactions, the Specular Reflection model was employed, whereby particles reflect specularly from the wall surface. The environmental conditions at an altitude of 180 km for this paper are given in Table 5, and the DSMC simulation conditions used in this paper are shown in Table 6. The atmospheric pressure at 180 km is approximately 1.80×10^{-4} Pa, requiring significant compression for thruster operation [43–45].

Table 5. Environmental conditions at an altitude of 180 km.

Chemical Species	N_2	O_2	O
Volume Fraction (%)	51.4	45.9	2.7
Density [kg/m^3]	5.51×10^{-1}	1.8×10^{-4}	-
Pressure [Pa]	-	-	-
Flow Speed [m/s]	7.8×10^{-3}	-	-
Temperature [K]	877.67	-	-

The boundary conditions used in the DSMC simulation are presented in Figure 5. The inlet is defined as a free-stream condition, the outlet is set as the outflow boundary, and the solid surfaces are treated as wall boundaries.

To minimize boundary effects, the computational domain was extended axially by 100 mm in both the upstream and downstream directions, while the radial extent was set to 200 mm in diameter [46,47].

Table 6. Computational conditions.

Description	Value
Number of real particles represented per reference particle	1.0×10^7 particles
Model when particles collide with the wall	Specular Reflection
Time step	1.0×10^{-9} s
Cell shape	Quadratic
Maximum mesh size	0.002 mm
Minimum mesh size	0.0015 mm
Mesh size around the wall	0.0005 mm
Mesh size around the Hall-Slats	0.25 mm

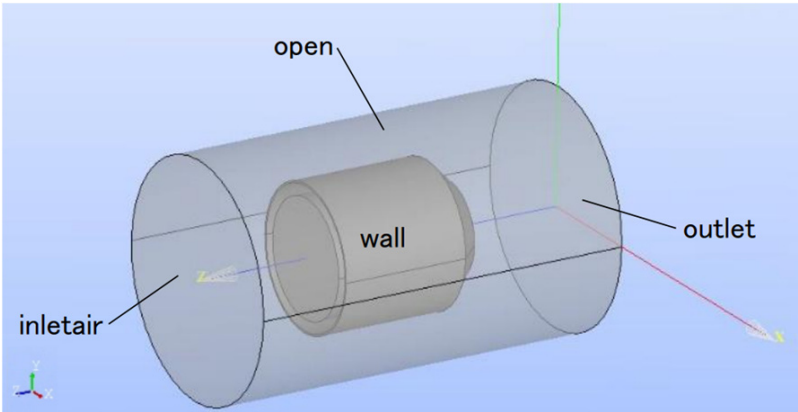


Figure 5. Boundary conditions for DSMC simulation.

3. Results

3.1. Experimental Results

Using THT-VI, operational tests were conducted with the propellant changed to air. The air used had a molar ratio of 80% nitrogen and 20% oxygen. The air operation results confirmed stable operation similar to that observed during nitrogen operation. Compared to nitrogen operation, higher propulsion performance was achieved during air operation. At a mass flow rate of 1.5 mg/s and a discharge voltage of 250 V, a thrust of 20.79 mN, a maximum specific impulse of 1413 s, and a maximum jet velocity of 13.86 km/s were achieved. This improvement is attributed to the lower ionization energy and higher atomic mass of oxygen.

Furthermore, additional experiments were conducted, including a high-voltage range of 150–350 V to enhance propulsion performance. As a result, we recorded a thrust of 41.89 mN, a maximum specific impulse of 2847 s, and a maximum jet velocity of 27.93 km/s. The results for THT-VI operation in air are shown in Figure 6, and those for operation including the high-voltage range are shown in Figure 7.

The experiments were conducted to establish the operating requirements of the Hall thruster under air propellant conditions rather than to reproduce the VLEO environment. The experimentally determined mass flow rate of 1.5 mg/s and the corresponding propulsion performance metrics were used as reference values for the DSMC intake simulations to assess whether the proposed intake system could sustain Hall thruster operation in VLEO.

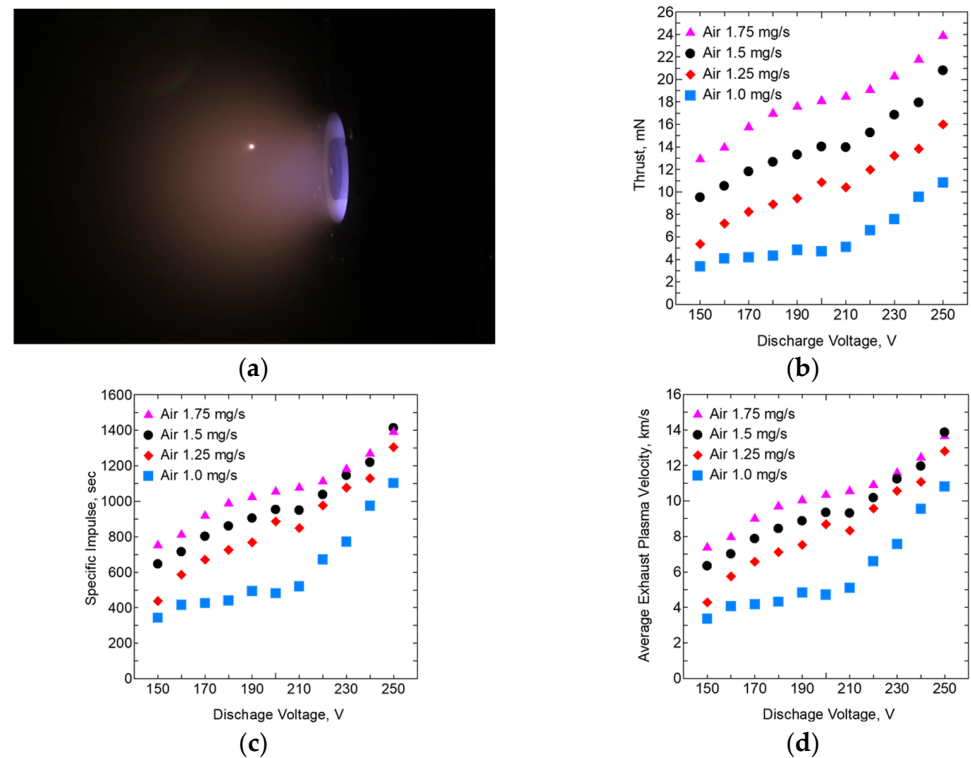


Figure 6. Operational results of THT-VI operating with air propellant: (a) photograph at 200 V, (b) thrust versus discharge voltage, (c) specific impulse versus discharge voltage, and (d) exhaust plasma velocity versus discharge voltage.

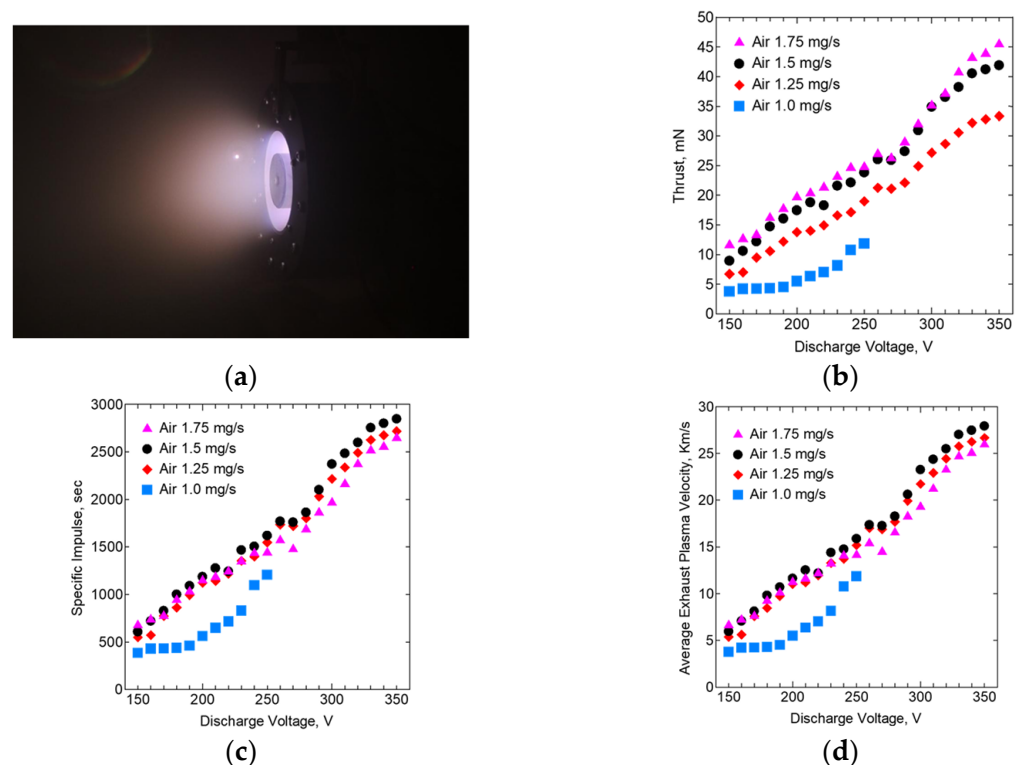


Figure 7. Operational results of THT-VI with air propellant including the high-voltage operating range: (a) photograph at 300 V, (b) thrust versus discharge voltage, (c) specific impulse versus discharge voltage, and (d) exhaust plasma velocity versus discharge voltage.

3.2. Computational Results

3.2.1. Verification of Simulation

To verify the DSMC implementation, the present simulations were compared with the atmospheric-intake model reported in ref. [39], which employed the RARAC-3D code. Although a different DSMC solver (DSMCFoam) was used in this paper, the same intake geometry, operating conditions, and performance metrics were adopted to enable a direct comparison. Agreement in the predicted discharge chamber pressure and compression ratio demonstrates the reliability of the present numerical approach.

Figure 8 shows the results of pressure P_c and the resulting compression ratio G when the aspect ratio χ of the air intake duct is varied, as obtained from simulations using the RARAC-3D code in the prior study [39] and the DSMCFoam code in this paper. R_2 is set to 1.1 m, 1.2 m, and 1.4 m to vary the aspect ratio of the air intake duct. In this case, χ becomes 20, 10, and 5, respectively. The condition $\eta = 0$ is used for consistency. The pressure at the center of the satellite's rear panel is output as the discharge chamber pressure. The results demonstrate strong quantitative agreement between the two simulations, confirming the reliability of the present DSMC implementation.

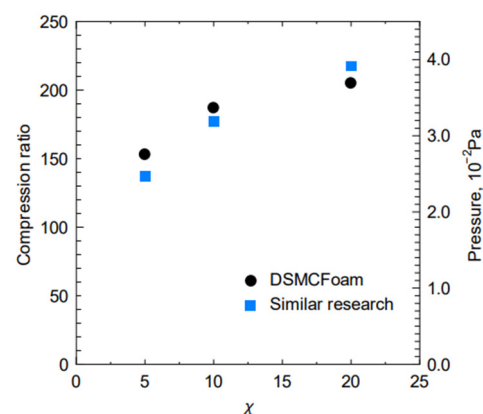


Figure 8. Discharge chamber pressure (right axis) and compression ratio (left axis) versus intake aspect ratio at 180 km altitude for a null cross-sectional ratio ($\eta = 0$).

3.2.2. Effect of Air Intake Duct Aspect Ratio

The reference condition is defined as $\eta = 0.05$ at $\chi = 10$ as the reference condition while keeping the Hall thruster scale fixed and varying the aspect ratio χ to 5 and 20. The pressure distribution for each aspect ratio is shown in Figure 9, and the velocity distribution is shown in Figure 10. Additionally, Figure 11 shows the pressure and mass flow rate in the discharge chamber as the air intake duct aspect ratio χ is varied, and Figure 12 shows the atmospheric drag on the satellite.

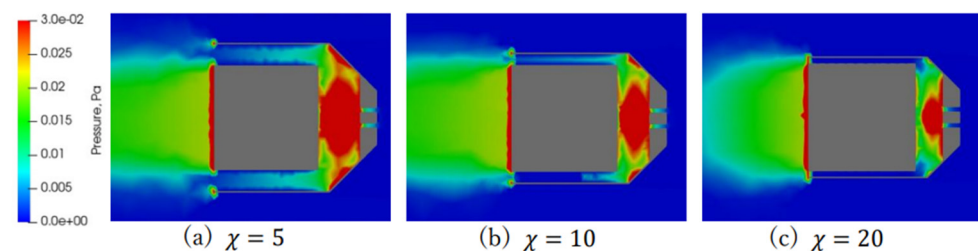


Figure 9. Pressure distribution for various air intake duct aspect ratios.

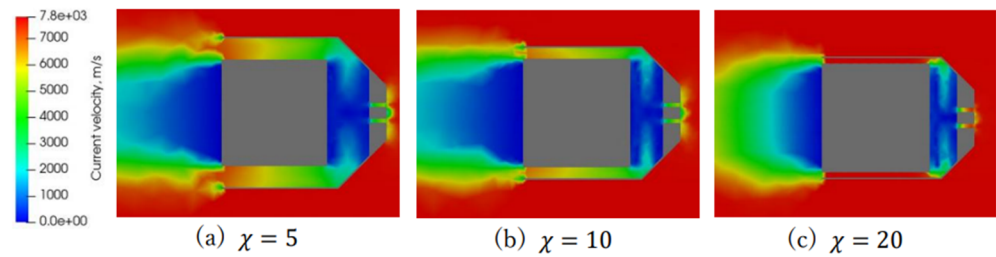


Figure 10. Velocity distribution for various air intake duct aspect ratios.

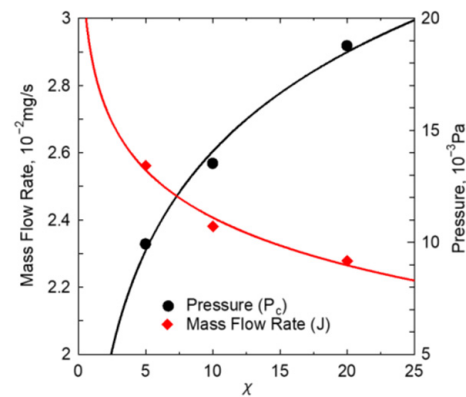


Figure 11. Pressure versus mass flow rate for various air intake duct aspect ratios.

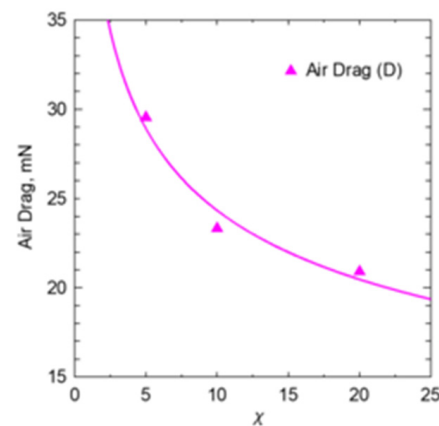


Figure 12. Air resistance versus air intake duct aspect ratio.

Increasing χ narrows the intake duct, reducing particle backflow and increasing the pressure near the Hall thruster inlet, as shown in Figure 9. However, the reduced intake area decreases the captured mass flow rate and lowers atmospheric drag. The corresponding quantitative variations in discharge chamber pressure, mass flow rate, and drag are presented in Figures 11 and 12.

3.2.3. Effect of Area Ratio on Air Intake Performance

To investigate the effect of the ratio of the Hall thruster's cross-sectional area to the air intake area on performance, simulations were performed for $\eta = 0.02, 0.05$, and 0.1 at $\chi = 10$. The pressure distribution for each Hall thruster cross-sectional area ratio relative to the air intake area is shown in Figure 13, and the velocity distribution is shown in Figure 14. Figure 15 shows the discharge chamber pressure and mass flow rate, and Figure 16 shows the atmospheric drag.

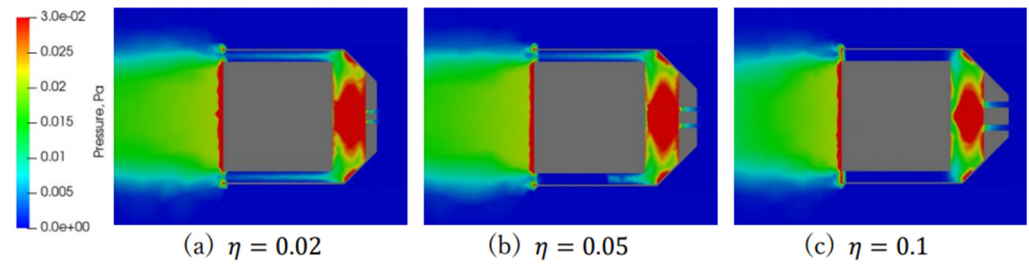


Figure 13. Pressure distribution for varying cross-sectional area ratio.

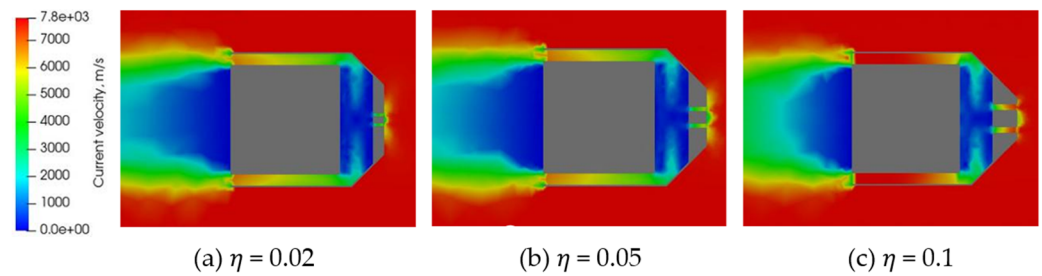


Figure 14. Velocity distribution for varying cross-sectional area ratio.

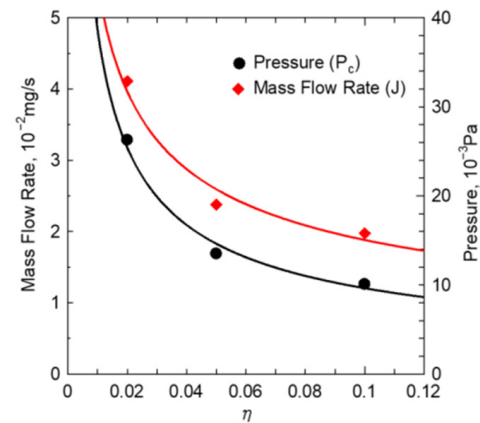


Figure 15. Discharge chamber pressure and mass flow rate vs. cross-sectional area ratio.

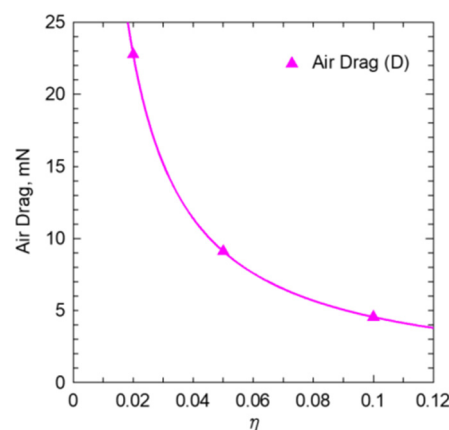


Figure 16. Atmospheric drag variation with cross-sectional area ratio.

As η decreases, the intake area relative to the Hall thruster cross-sectional area increases, resulting in higher pressure and mass flow rate near the Hall thruster inlet, as shown in Figure 13. However, the larger intake area also increases atmospheric drag. The quantitative relationships between η and the resulting pressure, mass flow rate, and drag are summarized in Figures 15 and 16.

3.2.4. Effect of Geometric Scaling on Air Intake Performance

The model dimensions for analysis were reduced to 1/20. To evaluate the influence of geometric scaling on the simulation results, an additional 1/100-scale model was also considered. A reference model consisting of a satellite rear panel $\chi = 10$ and $\eta = 0$ without a Hall thruster was considered. Figure 17 shows the pressure distributions for the 1/20- and 1/100-scale models. The velocity distributions are displayed in Figure 18.

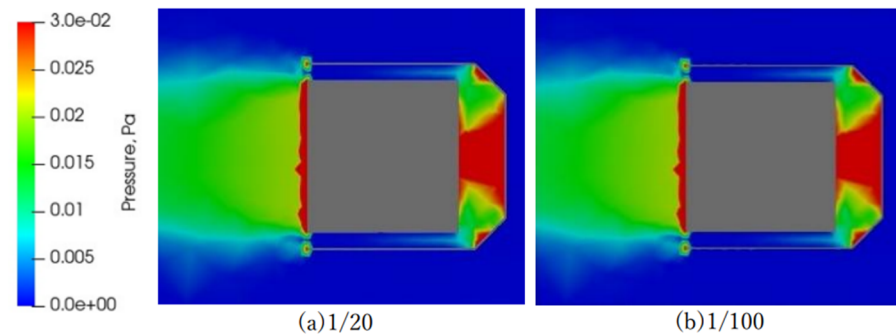


Figure 17. Pressure distribution at an altitude of 180 km for $\eta = 0$ and $\chi = 10$: (a) 1/20-scale model and (b) 1/100-scale model.

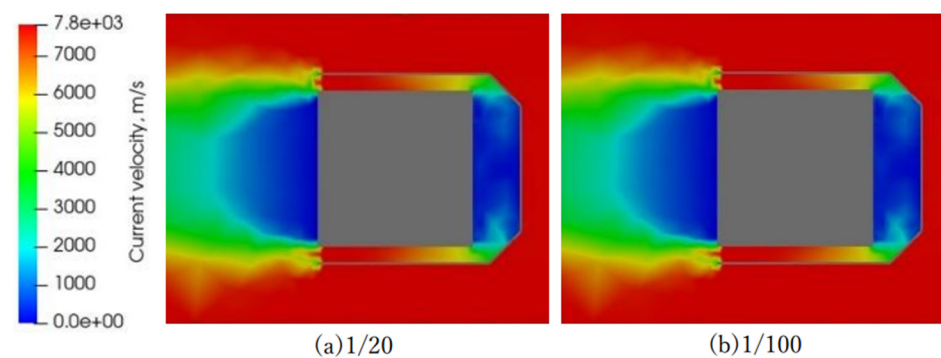


Figure 18. Velocity distribution at an altitude of 180 km for $\eta = 0$ and $\chi = 10$: (a) 1/20-scale model and (b) 1/100-scale model.

The atmospheric drag on the satellite is described by the following equation, where ρ is the density of the atmosphere, v is the velocity of the satellite relative to that of the atmospheric surrounding it, and C_D is a drag coefficient specific to that body:

$$D = \frac{1}{2} \rho v^2 C_D \pi R_2^2 \quad (11)$$

From Equation (11), the atmospheric drag D of a satellite is proportional to the square of the satellite's outer radius R_2 , provided the satellite shape remains the same, which is consistent with the results of this simulation. The two scales' pressure and velocity distributions do not significantly differ from one another. It was concluded that the impact of a change in model dimensions on the simulation results is small. And the atmospheric drag D is 1.03 mN for the 1/20 scale and 4.12×10^{-2} mN for the 1/100 scale.

3.3. Simulation Using the Optimized Model

The effects of intake aspect ratio and cross-sectional area ratio on atmospheric drag, mass flow rate, and discharge chamber pressure were verified based on prior simulations.

The intake achieved pressures in the range of 10^{-3} Pa to 10^{-1} Pa, which was consistent with Hall thruster operation. The required mass flow rate of 1.5 mg/s was not achieved. This restriction is explained by the intake shape used in ion thruster designs [39]. Therefore,

improved intake geometries were investigated. A list of the improved model shapes is shown in Figure 19. The modified geometries were selected to investigate design strategies for improving intake performance while maintaining low atmospheric drag. Specifically, the proposed modifications target enhanced pressure recovery, reduced particle backflow, lower flow losses, and improved particle transmission toward the Hall thruster inlet. Models A–F represent systematic variations in the shock cone configuration, duct length, downstream volume, and outer wall geometry to evaluate the influence of these parameters on the mass flow rate, discharge chamber pressure, and atmospheric drag.

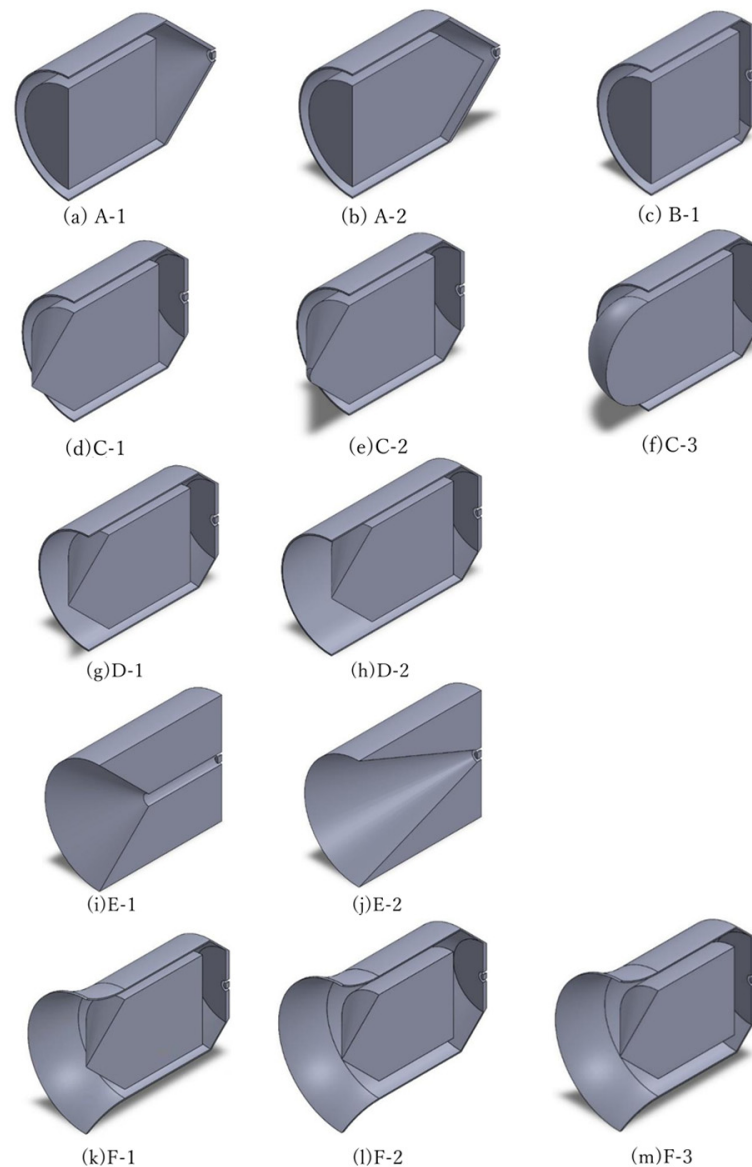


Figure 19. Schematic illustrations of the improved intake geometries (Models A–F) used for performance evaluation.

Different intake alterations, such as changes in base geometry, shock cone design, duct length, and outer wall expansion, are shown by models A–F (Figure 19). The models are mainly based on $\chi = 10$, while some situations are extended to $\chi = 5$. Pressure and velocity distributions are shown in Figures 20 and 21, while discharge chamber properties and atmospheric drag are presented in Figures 22 and 23.

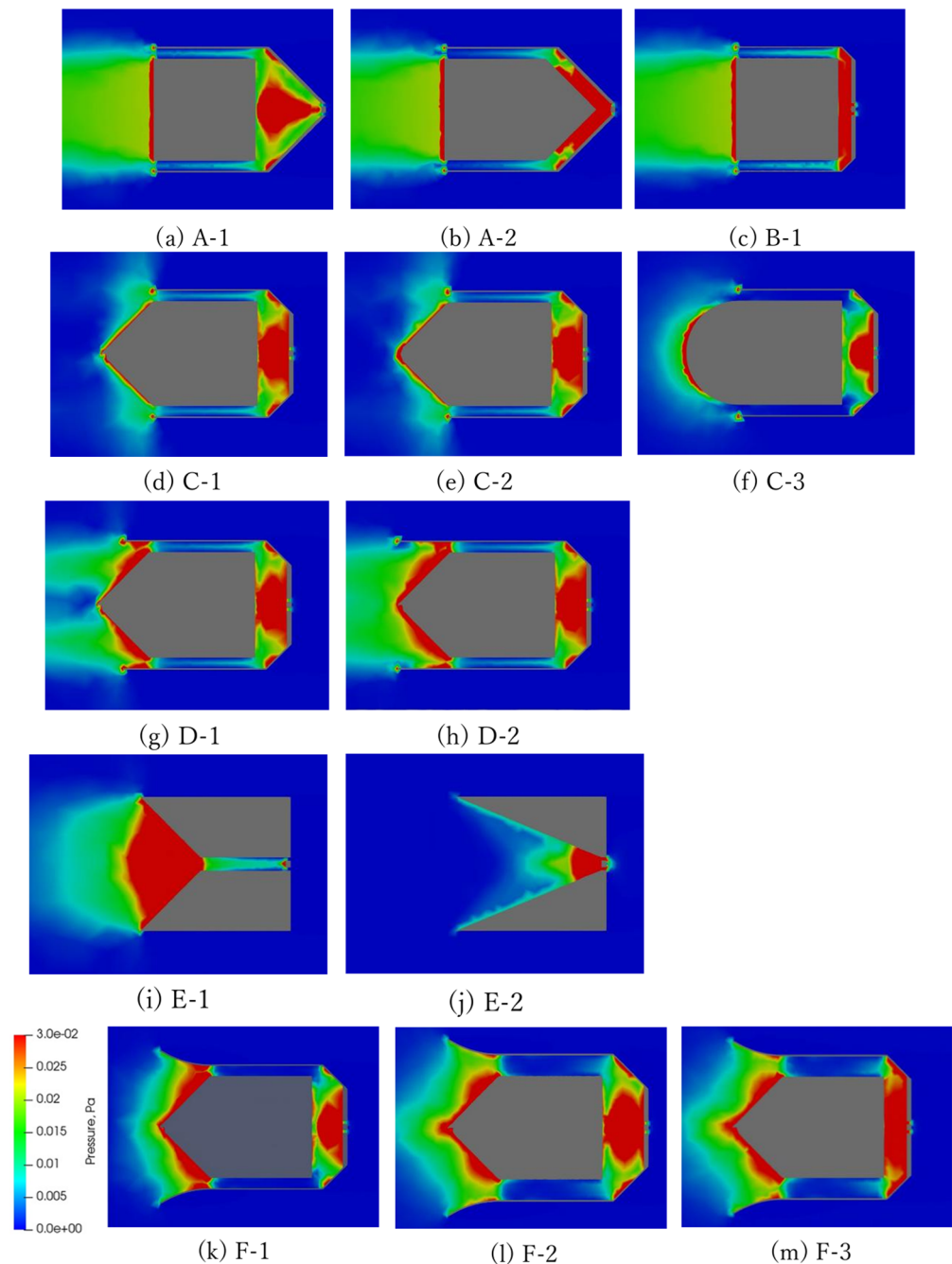


Figure 20. Pressure distributions for each modified model geometry.

While certain designs also decreased air drag, several modified models outperformed the baseline configuration in terms of mass flow rates. The discharge chamber pressure and mass flow rate rose as the downstream volume was reduced. While Model F demonstrated little improvement and increased drag, Model C's shock cone modification reduced drag by about 10%. The mass flow rate rose as χ was reduced, but drag also increased.

Overall, Model E-2 exhibited the best performance. The differences among Models A–F are mainly governed by particle transmission efficiency and pressure recovery within the intake duct. Geometries with reduced downstream volume and smoother area transitions improved particle confinement, resulting in a higher discharge chamber pressure and mass flow rate, whereas abrupt geometric changes increased the particle backflow and flow losses. Compared with atmospheric-intake ion engines [39], Hall thrusters require a significantly higher propellant mass flow rate (1.5 mg/s), making particle capture and

transmission the primary design considerations. Owing to its progressive area transition, Model E-2 reduced drag to 20.04 mN (~13% reduction) and increased the mass flow rate to 0.298 mg/s (~7.5 times higher than the baseline). Nevertheless, the required operating mass flow rate of 1.5 mg/s was not achieved. Since the atmospheric drag remains lower than the experimentally measured thrust, further increasing the intake area based on the E-2 geometry may provide additional improvements in mass flow rate.

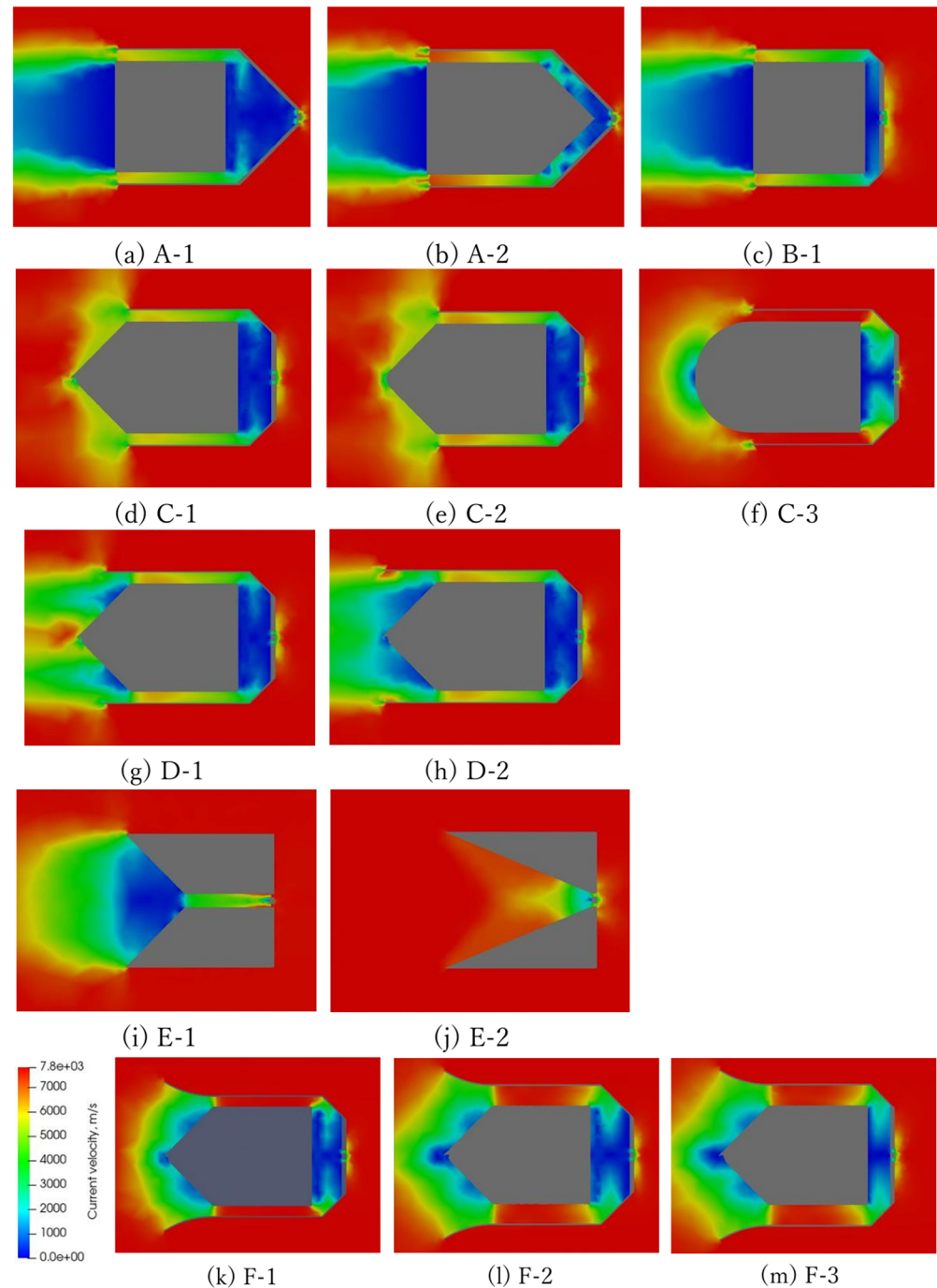


Figure 21. Velocity distributions for each modified model geometry.

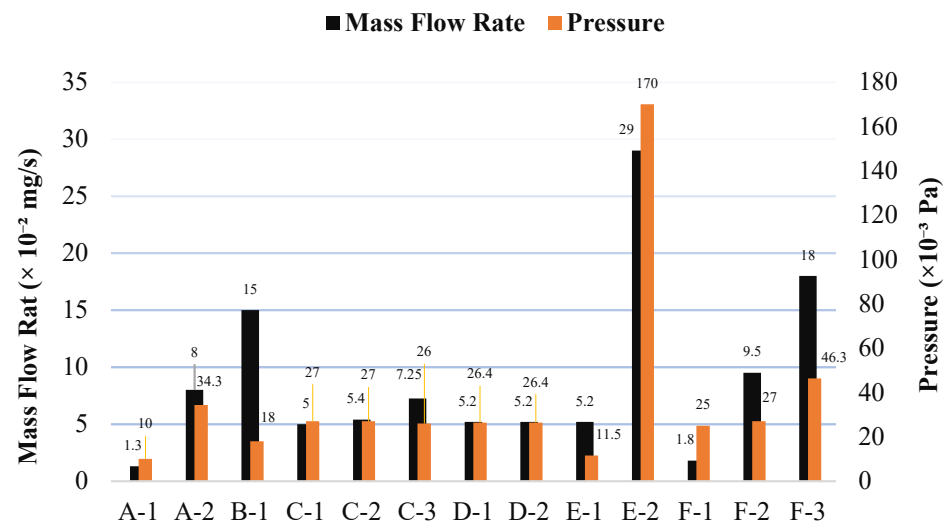


Figure 22. Pressure and mass flow rate of the improved model.

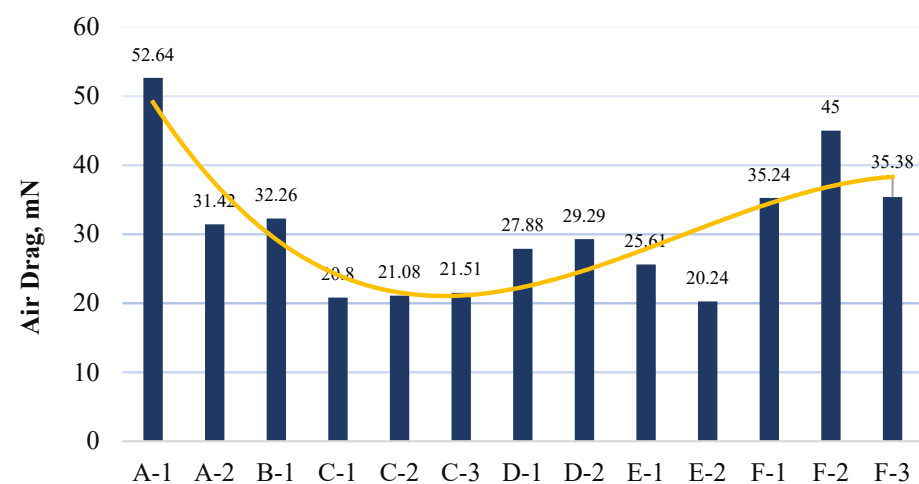


Figure 23. Atmospheric resistance of the improved model.

4. Challenges and Limitations

4.1. Summary of Simulation Results

The impact of the intake aspect ratio and cross-sectional area ratio on the discharge chamber pressure, mass flow rate, and atmospheric drag was verified by numerical analysis. Compression in the 10^{-3} Pa to 10^{-1} Pa range was made possible by the intake. Nevertheless, the necessary propellant mass flow rate of 1.5 mg/s was not attained even with the upgraded model.

Based on the simulation results, a moderate intake aspect ratio and a larger intake area are recommended to improve particle capture and pressure recovery. In addition, intake geometries with smooth flow transitions, such as the E-2 configuration, can significantly enhance the mass flow rate while reducing aerodynamic drag. These findings provide useful design guidelines for future atmosphere-breathing Hall thruster systems operating in VLEO. Although the required operating mass flow rate of 1.5 mg/s was not achieved, the optimized E-2 geometry increased the mass flow rate by approximately 7.5 times compared with the baseline configuration. Further optimization through larger intake areas and full-scale simulations was not investigated in this paper because of the substantial computational cost associated with high-fidelity DSMC simulations.

4.2. Challenges and Future Improvement Strategies

Due to computational limitations, the mesh resolution and number of sample particles were restricted, which may affect the quantitative accuracy of the simulation results, particularly in predicting detailed particle interactions and local flow behavior within the intake. Increasing the mesh density and particle count in future studies would improve numerical accuracy, although this would require significantly greater computational resources.

In addition to improving numerical resolution, structural modifications to the intake geometry may further enhance performance. One promising approach is to incorporate a lattice structure in the intake section [11]. Such a structure can suppress particle backflow while preserving the effective intake area, thereby improving the compression efficiency and increasing the mass flow rate without significantly increasing aerodynamic drag. Figure 24 illustrates the conceptual configuration of a lattice structure inside the air intake. Although this concept was not directly simulated in this paper, it represents a potential direction for future intake design optimization.

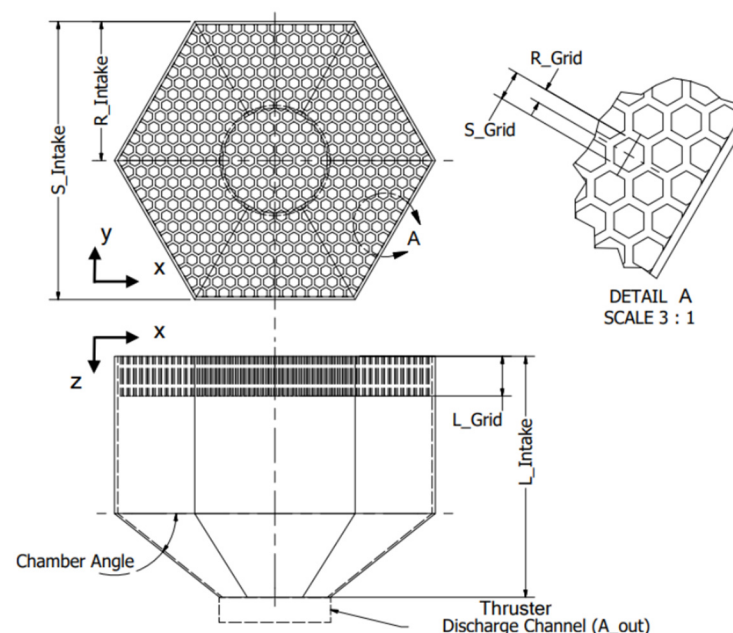


Figure 24. Concept of the lattice structure installed in the air intake section [11].

5. Conclusions

With a focus on Hall thrusters as atmospheric compensation devices, this paper examined the feasibility of atmospheric-intake electric propulsion for long-term orbit maintenance in VLEO. Experimental tests demonstrated stable Hall thruster operation with nitrogen and air propellants, while DSMC simulations were used to evaluate the capability of the atmospheric intake system to supply the required propellant under VLEO conditions. The measured exhaust velocities exceeded the orbital velocity in all tested operating conditions. The ability to meet drag compensation requirements was partially demonstrated by achieving specific impulses exceeding 2500 s under high-voltage operating conditions. Numerical simulations revealed the influence of intake geometry on pressure recovery, mass flow rate, and aerodynamic drag. Although the intake achieved discharge chamber pressures within the required range of 10^{-3} – 10^{-1} Pa, the required intake mass flow rate of 1.5 mg/s was not achieved even with the optimized geometry. A comparison between the experimentally measured thrust and the simulated aerodynamic drag indicates that the available propulsion performance is sufficient to overcome the predicted drag under certain operating conditions. Specifically, the maximum measured thrust of 41.89 mN exceeded

the minimum simulated drag of 20.04 mN obtained for the optimized E-2 intake geometry. These results indicate that intake performance, rather than thruster capability, remains the primary limitation for sustained VLEO operation. Further studies should therefore focus on optimizing intake and spacecraft design to increase propellant capture efficiency.

Author Contributions: M.M.A.A.: Conceptualization; Supervision; Writing—review and editing. M.M.: Data curation; Investigation; Writing—original draft. T.K.: Methodology; Software; Visualization. M.K.I.: Investigation; Resources; Validation. M.M.U.S.: Investigation; Data curation; Validation. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data that support the findings of this paper are available from the corresponding author upon reasonable request.

Acknowledgments: The authors gratefully acknowledge the continuous support and excellent research environment provided by the Aerospace Fluid Dynamics Laboratory, Graduate School of Engineering, Osaka Sangyo University, Japan. The laboratory's advanced computational facilities and academic guidance played a vital role in the successful completion of this research.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ABEP	Atmosphere-Breathing Electric Propulsion
ABHT	Atmosphere-Breathing Hall Thruster
CFD	Computational Fluid Dynamics
CLL	Cercignani–Lampis–Lord
CPU	Central Processing Unit
DSMC	Direct Simulation Monte Carlo
GSI	Gas–Surface Interaction
HDD	Hard Disk Drive
HS	Hard Sphere
Kn	Knudsen Number
MSISE	Mass Spectrometer and Incoherent Scatter Extended Model
RF	Radio Frequency
VHS	Variable Hard Sphere
VLEO	Very Low Earth Orbit
VSS	Variable Soft Sphere

References

1. Crisp, N.H.; Roberts, P.; Livadiotti, S.; Oiko, V.; Edmondson, S.; Haigh, S.; Huyton, C.; Sinpetru, L.; Smith, K.; Worrall, S.; et al. The benefits of very low earth orbit for earth observation missions. *Prog. Aerosp. Sci.* **2020**, *117*, 100619. [\[CrossRef\]](#)
2. Andreussi, T.; Ferrato, E.; Paissoni, C.A.; Kitaeva, A.; Giannetti, V.; Piragino, A.; Schäff, S.; Katsonis, K.; Berenguer, C.; Kovacova, Z.; et al. The AETHER project: Development of air-breathing electric propulsion for VLEO missions. *CEAS Space J.* **2022**, *14*, 717–740. [\[CrossRef\]](#)
3. Livadiotti, S.; Crisp, N.H.; Roberts, P.C.; Worrall, S.D.; Oiko, V.T.; Edmondson, S.; Haigh, S.J.; Huyton, C.; Smith, K.L.; Sinpetru, L.A.; et al. A review of gas-surface interaction models for orbital aerodynamics applications. *Prog. Aerosp. Sci.* **2020**, *119*, 100675. [\[CrossRef\]](#)
4. Roberts, P.C.E.; Crisp, N.H.; Romano, F.; Herdrich, G.H.; Oiko, V.T.; Edmondson, S.; Haigh, S.J.; Huyton, C.; Livadiotti, S.; Lyons, R.E.; et al. Discoverer: Making commercial satellite operations in very low Earth orbit a reality. In *Proceedings of the International Astronautical Congress (IAC)*; IAF: Washington, DC, USA, 2019.
5. Romano, F.; Massuti-Ballester, B.; Binder, T.; Herdrich, G.; Fasoulas, S.; Schönherr, T. System analysis and test-bed for an atmosphere-breathing electric propulsion system using an inductive plasma thruster. *Acta Astronaut.* **2018**, *147*, 114–126. [\[CrossRef\]](#)

6. Leomanni, M.; Garulli, A.; Giannitrapani, A.; Scortecchi, F. Propulsion options for very low Earth orbit microsatellites. *Acta Astronaut.* **2017**, *133*, 444–454. [CrossRef]
7. Schonherr, T.; Komurasaki, K.; Romano, F.; Massuti-Ballester, B.; Herdrich, G. Analysis of Atmosphere-Breathing Electric Propulsion. *IEEE Trans. Plasma Sci.* **2015**, *43*, 287–294. [CrossRef]
8. Romano, F.; Chan, Y.-A.; Herdrich, G.; Traub, C.; Fasoulas, S.; Roberts, P.; Smith, K.; Edmondson, S.; Haigh, S.; Crisp, N.; et al. RF Helicon-based Inductive Plasma Thruster (IPT) Design for an Atmosphere-Breathing Electric Propulsion system (ABEP). *Acta Astronaut.* **2020**, *176*, 476–483. [CrossRef]
9. Wu, J.; Zheng, P.; Zhang, Y.; Tang, H. Recent development of intake devices for atmosphere-breathing electric propulsion system. *Prog. Aerosp. Sci.* **2022**, *133*, 100848. [CrossRef]
10. Brabants, C. Development of a Methodology for VLEO Intake Performance Testing in a Low-Density Facility. June 2021. Available online: <https://matheo.uliege.be/handle/2268.2/11557> (accessed on 24 March 2026).
11. Romano, F.; Espinosa-Orozco, J.; Pfeiffer, M.; Herdrich, G.; Crisp, N.; Roberts, P.; Holmes, B.; Edmondson, S.; Haigh, S.; Livadiotti, S.; et al. Intake design for an Atmosphere-Breathing Electric Propulsion System (ABEP). *Acta Astronaut.* **2021**, *187*, 225–235. [CrossRef]
12. Rapisarda, C.; Roberts, P.C.; Smith, K.L. Design and optimisation of a passive Atmosphere-Breathing Electric Propulsion (ABEP) intake. *Acta Astronaut.* **2023**, *202*, 77–93. [CrossRef]
13. Raisanen, A.; Faust, A.; Taylor, J.; Higginson, J.; Zuber, M.E. Intake Design for Air-Breathing Electric Propulsion: A Framework. In *Proceedings of the AIAA SCITECH 2025 Forum*; American Institute of Aeronautics and Astronautics: Orlando, FL, USA, 2025. [CrossRef]
14. Zheng, P.; Wu, J.; Zhang, Y.; Wu, B. A Comprehensive Review of Atmosphere-Breathing Electric Propulsion Systems. *Int. J. Aerosp. Eng.* **2020**, *2020*, 8811847. [CrossRef]
15. Andreussi, T.; Ferrato, E.; Giannetti, V. A review of air-breathing electric propulsion: From mission studies to technology verification. *J. Electr. Propuls.* **2022**, *1*, 31. [CrossRef]
16. Vaidya, S.; Traub, C.; Romano, F.; Herdrich, G.H.; Chan, Y.-A.; Fasoulas, S.; Roberts, P.C.E.; Crisp, N.H.; Edmondson, S.; Haigh, S.J.; et al. Development and analysis of novel mission scenarios based on Atmosphere-Breathing Electric Propulsion (ABEP). *CEAS Space J.* **2022**, *14*, 689–706. [CrossRef]
17. Filatyev, A.S.; Golikov, A.; Erofeev, A.; Khartov, S.; Lovtsov, A.; Padalitsa, D.; Skvortsov, V.; Yanova, O. Research and development of aerospace vehicles with air breathing electric propulsion: Yesterday, today, and tomorrow. *Prog. Aerosp. Sci.* **2023**, *136*, 100877. [CrossRef]
18. Cushen, A.T.; Oiko, V.T.; Smith, K.L.; Crisp, N.H.; Roberts, P.C.; Romano, F.; Papavramidis, K.; Herdrich, G. Performance Test Methodology for Atmosphere-Breathing Electric Propulsion Intakes in an Atomic Oxygen Facility. *arXiv* **2024**, arXiv:2406.06299. [CrossRef]
19. Johnson, K.N.; Li, Y.; Ezell, M.J.; Lakey, P.S.J.; Shiraiwa, M.; Finlayson-Pitts, B.J. Elucidating gas–surface interactions relevant to atmospheric particle growth using combined temperature programmed desorption and temperature-dependent uptake. *Phys. Chem. Chem. Phys.* **2024**, *26*, 23264–23276. [CrossRef] [PubMed]
20. Hedahl, M.O.; Wilmoth, R.G. *Comparisons of the Maxwell and CLL Gas/Surface Interaction Models Using DSMC*; NASA Technical Memorandum 110205; National Aeronautics and Space Administration (NASA): Washington, DC, USA, 1995.
21. Sannino, A.; Pessina, V.; Savino, R.; Schein, J. Design and performances of intake for atmosphere-breathing electric propulsion systems with the direct simulation Monte Carlo method. *Phys. Fluids* **2025**, *37*, 027189. [CrossRef]
22. Herdrich, G.; Maier, P.; Rojas, E.G.; Papavramidis, K.; Skalden, J. Advancements of a VLEO satellite system study utilizing an RF Helicon-based Plasma Thruster. In *Proceedings of the Aerospace Europe Conference 2023–10th EUCASS–9th CEAS*, Lausanne, Switzerland, 10–13 July 2023. [CrossRef]
23. Böckler, H.-B.; de Huu, M.; Maury, R.; Schmelter, S.; Schakel, M.D.; Büker, O. Metrology infrastructure for high-pressure gas and liquified hydrogen flows. In *Proceedings of the 19th International Flow Measurement Conference 2022 on Flow Measurement—FLOMEKO 2022*; IMEKO: Chongqing, China, 2023; pp. 1–6. [CrossRef]
24. Yonover, J.M.; Gjesdal, K. *Spinoza in Germany: Political and Religious Thought Across the Long Nineteenth Century*; Oxford University Press: Oxford, UK, 2024.
25. Joseph, N.S.; Selvam, R.P.; Hanley, A.S. Visualization Using Open-Source Software ParaView for Finite Element Class and Research. In *Proceedings of the 2025 ASEE Midwest Section Conference Proceedings*, Fayetteville, AR, USA, 14–16 September 2025; ASEE Conferences. p. 57824. [CrossRef]
26. Knudsen Number—An Overview | ScienceDirect Topics. Available online: <https://www.sciencedirect.com/topics/engineering/knudsen-number> (accessed on 25 March 2026).
27. Scribd. Knudsen Number Effects on Micro-Channel Flow | PDF | Fluid Mechanics | Fluid Dynamics. Available online: <https://www.scribd.com/document/85832266/A-Fm-2002> (accessed on 25 March 2026).

28. Liu, C.; Zhou, G.; Shyy, W.; Xu, K. Limitation principle for computational fluid dynamics. *Shock Waves* **2019**, *29*, 1083–1102. [CrossRef]
29. Islam, A.; Patzek, T. Slip in natural gas flow through nanoporous shale reservoirs. *J. Unconv. Oil Gas Resour.* **2014**, *7*, 49–54. [CrossRef]
30. Soto, R. The Boltzmann equation for dilute gases. In *Kinetic Theory and Transport Phenomena*, 1st ed.; Oxford University Press: Oxford, UK, 2016; pp. 63–94. [CrossRef]
31. Yuan, Y.; Rahman, S. Extended application of lattice Boltzmann method to rarefied gas flow in micro-channels. *Phys. A Stat. Mech. Appl.* **2016**, *463*, 25–36. [CrossRef]
32. Liu, S.; Ding, N.; Fang, M.; Jin, H.; Zhang, R.; Zhuo, C.; Zhong, C. The near-continuum mechanism for extended Boltzmann theory: The non-equilibrium relaxation. *arXiv* **2026**, arXiv:2602.05775v1.
33. Burt, J.; Deschenes, T.; Boyd, I.; Josyula, E. Evaluation of a Hybrid Boltzmann-Continuum Method for High Speed Nonequilibrium Flows. In *Proceedings of the 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*; American Institute of Aeronautics and Astronautics: Orlando, FL, USA, 2010. [CrossRef]
34. Zhang, Y.; Qin, R.; Emerson, D.R. Lattice Boltzmann simulation of rarefied gas flows in microchannels. *Phys. Rev. E* **2005**, *71*, 047702. [CrossRef] [PubMed]
35. Kara, V.; Yakhot, V.; Ekinci, K.L. Generalized Knudsen Number for Unsteady Fluid Flow. *arXiv* **2017**, arXiv:1702.0778. [CrossRef]
36. Wu, J.-S.; Lian, Y.-Y. Parallel three-dimensional direct simulation Monte Carlo method and its applications. *Comput. Fluids* **2003**, *32*, 1133–1160. [CrossRef]
37. Sabouri, M.; Zakeri, R.; Ebrahimi, A. Improving Computational Efficiency in DSMC Simulations of Vacuum Gas Dynamics with a Fixed Number of Particles per Cell. *arXiv* **2024**, arXiv:2407.01589. [CrossRef]
38. Gosma, M.; Gopalan, K.S.; Subramaniam, S.; Stephani, K. Recommended direct simulation Monte Carlo collision model parameters for planetary entry and related applications. *Phys. Fluids* **2025**, *37*, 036156. [CrossRef]
39. Fujita, K. Air Intake Performance of Air Breathing Ion Engines. *J. Jpn. Soc. Aeronaut. Space Sci.* **2004**, *52*, 514–521. [CrossRef]
40. Zheng, P.; Wu, J.; Wu, B.; Zhang, Y. Design and numerical investigation on the intake of atmosphere-breathing electric propulsion. *Acta Astronaut.* **2021**, *188*, 215–228. [CrossRef]
41. Nishiyama, K. A Study of Air Breathing Ion Engine. *SPACE Technol. J. Jpn. Soc. Aeronaut. SPACE Sci.* **2005**, *4*, 21–27. [CrossRef]
42. Ito, K.; Sano, R.; Yano, H.; Arai, K. Numerical Analysis of Meteoroid Impact on Multilayer Insulation for Micro-Spacecraft. *Bull. Res. Cent. Comput. Multimed. Stud. Hosei Univ.* **2024**, *39*, 40–49. (In Japanese) [CrossRef] [PubMed]
43. Zhang, H.; Shan, F.; Fang, H.; Zhang, X.; Zhang, J.; Sun, J. An accurate moving wall boundary algorithm for direct simulation of Monte Carlo in unsteady rarefied flow. *Phys. Fluids* **2021**, *33*, 097105. [CrossRef]
44. Shariati, V.; Ahmadian, M.H.; Roohi, E. Direct Simulation Monte Carlo investigation of fluid characteristics and gas transport in porous microchannels. *Sci. Rep.* **2019**, *9*, 17183. [CrossRef] [PubMed]
45. Composition of the Atmosphere. Available online: <https://peshkin.mech.northwestern.edu/scifair/Atmosphere.html> (accessed on 25 March 2026).
46. Wang, M.; Li, Z. Simulations for gas flows in microgeometries using the direct simulation Monte Carlo method. *Int. J. Heat Fluid Flow* **2004**, *25*, 975–985. [CrossRef]
47. Gallis, M.; Torczynski, J.; Rader, D.; Bird, G. Accuracy and Convergence of a New DSMC Algorithm. In *Proceedings of the 40th Thermophysics Conference*; American Institute of Aeronautics and Astronautics: Seattle, WA, USA, 2008. [CrossRef]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.