PICLas-based Intake Simulation Activities for the development of an ABEP Specular Intake

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Abstract. Space missions in very low Earth orbit (VLEO) offer advanced capabilities for Earth observation, telecommunications, and security but are challenged by continuous orbit decay. Atmosphere-Breathing Electric Propulsion (ABEP), which uses atmospheric particles as propellant, provides a potential solution. Within the H2020 DISCOVERER, ESA ram-CLEP and ATLAS projects, IRS is developing a specular intake and helicon plasma thruster to advance ABEP systems.
This study uses Direct Simulation Monte Carlo (DSMC) simulations to evaluate specular intake geometries, analyzing particle flux, pressure, mass flow rate, and collection efficiency. The results indicate that reducing the focal length of the parabolic intake significantly improves efficiency and mass flow rate, while increasing the discharge channel diameter proves more effective for achieving these high values as well. As pressure follows an opposing trend to efficiency, and reaching the ignition pressure is crucial, the optimal configuration among the investigated for balancing efficiency and pressure is a discharge channel diameter of 25 mm with a focal length of 3 mm.

Keywords: ABEP, Intake, DSMC, Very low Earth orbit

1 Introduction

Very Low Earth Orbit (VLEO) missions face significant atmospheric drag, necessitating efficient propulsion systems to maintain orbit and extend mission duration. Atmosphere-Breathing Electric Propulsion (ABEP) addresses this challenge by using residual atmospheric particles as propellant for an electric thruster.

The ABEP system, includes an intake that collects atmospheric particles and directs them into the discharge channel, where they are accelerated to generate thrust. This study focuses on the design and simulation of the ABEP intake system to optimize key parameters such as collection efficiency, pressure, and mass flow rate, ensuring effective thruster operation while minimizing the intake's size and volume. Additional insights into ABEP and its platform design are available in Herdrich et al. [1, 2]. Related research on VLEO satellite operations is supported by the DFG-funded CRC 1667 ATLAS at the University of Stuttgart.

2 Related Work

In VLEO, the free molecular flow regime is dominated by infrequent collisions, making particle-wall interactions critical for intake design. These interactions, including absorption, scattering, and chemical reactions, are challenging to model due to limited data on surface properties such as finish, cleanliness, and adsorbed gas layers. This is particularly relevant in VLEO, where interactions with gases like atomic oxygen are significant. The Maxwell model, a simplified approach, distinguishes between specular and diffuse reflections [3], forming the basis for intake design classifications.

Romano [4] demonstrated through simulations that specular intake designs outperform diffuse ones, leading to further studies by Romano, Kun, and Herdrich [5, 6, 2]. The specular design uses the optical principles of a parabolic mirror, directing particles to the focal point of the paraboloid. Particles retain their tangential velocity while their normal velocity is reversed, assuming hyperthermal flow, which is less applicable in VLEO [7] but still provides a better performance than diffuse designs.

Fig. 1 illustrates the functional principle of a parabolic intake based on specular reflection. This study evaluates three geometric modifications:

1. Intake Length (l_{In}): The intake length is varied between 500 mm, 1000 mm and 1500 mm.
2. DC diameter (d_{DC}): The diameter of the DC is scaled to 15 mm, 25 mm and 37 mm.
3. Focal length f: Focal lengths of 3.0 mm, 3.75 mm, and 5.5 mm are evaluated.

These variations influence intake diameter, intake area, and vertex-to-focal point distance $s_{F,\mathrm{IPT}}$.

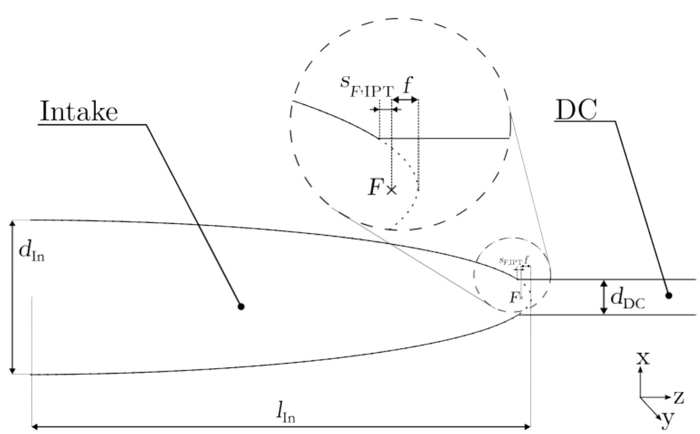


Fig. 1. Functional schematic of the parabolic intake, showing intake diameter d_{In}, intake length l_{In}, discharge channel diameter d_{DC}, and focal point position F inside the discharge channel with the focal length f and vertex-to-focal point distance $s_{F,\mathrm{IPT}}$

The location of the focal point F relative to the DC is critical. Romano [4] tested three configurations: one in front of the DC intake vertex, one at the vertex, and one inside the DC. The most efficient setup was with F inside the DC, using a focal length f of 5.5 mm and a d_{DC} of 37 mm, achieving an $s_{F,\mathrm{IPT}}$ of 10 mm. Increasing $s_{F,\mathrm{IPT}}$ could further improve efficiency but would reduce intake area, limiting particle collection and pressure.

3 Methodology

In rarefied gas conditions, the Navier-Stokes equations are inapplicable, necessitating the use of the Direct Simulation Monte Carlo (DSMC) method for ABEP system simulations instead of continuum methods like Computational Fluid Dynamics (CFD). These simulations are conducted using the three-dimensional open-source particle code PICLas [8], which incorporates the DSMC method [9].

The simulations conducted in this work rely on atmospheric data provided by the NRLMSISE-00 model [10], a widely accepted standard in space research for modeling lower thermospheric conditions. Previous ABEP studies have used this model, including work by Romano [4] and Kun [6]. This study uses atmospheric data under low-activity conditions based on ISO-14222 [11] and ECSS [12] standards (F10.7 = 65, $\mathrm{A_P} = 0$). A fully specular intake material is assumed to focus on geometric and environmental factors. The effect of the specularity assumption of 100% is discussed in detail in [4, 7].

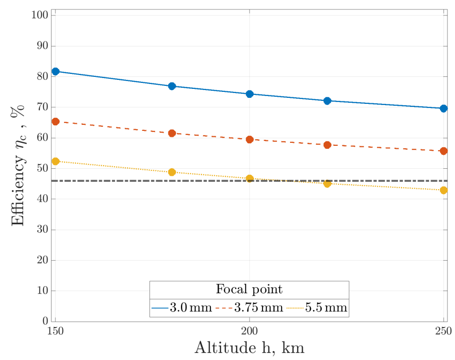
Simulations examine altitudes from 150 km to 250 km. The lower limit of 150 km is selected to avoid increased drag, which raises thruster power demands and thermal loads [4]. While there is no strict upper limit, at higher altitudes it becomes increasingly difficult to collect enough particles to sustain thruster operation at a reasonable specific impulse, and the benefits of close proximity to the Earth's atmosphere are lost. Additionally, numerical resources are limited, so 250 km was chosen as the upper limit here. A minimum pressure of 0.1 Pa, sufficient to ignite the ABEP thruster IPT, is assumed based on experimental results from the University of Stuttgart [2]. However, it is possible that a lower threshold pressure may be required.

Rotational symmetry of the intake allows for 2D axisymmetrical simulations in PICLas. Results are averaged across the DC radius at a z-position 164 mm downstream of the intake-DC intersection, considering variations in altitude and geometry.

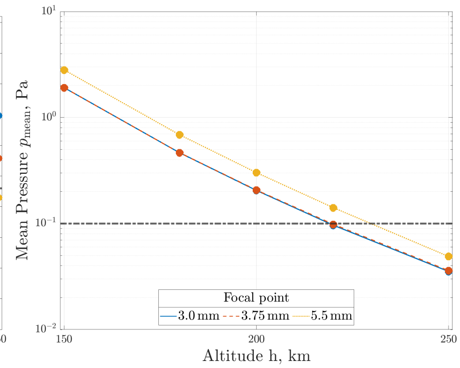
4 Simulation Results

4.1 Focal Length

The position of the focal point F significantly impacts performance. This study examines three focal lengths inside the DC for a DC diameter of 25 mm: f = [3 mm, 3.75 mm, 5.5 mm], corresponding to $s_{F,\mathrm{IPT}}$ = [10.02 mm, 6.67 mm, 1,602 mm]. A focal length of 3 mm was chosen to match earlier IRS research



(a) Efficiency



(b) Mean Pressure

Fig. 2. Efficiency and pressure levels for three different focal lengths distances at a DC diameter of 25 mm and a length of 1000 mm, with the black line showing the current efficiency limit for diffuse intakes (a) and the expected minimum pressure required for ignition of the thruster inside the DC (b)

on a DC37 configuration, while 3.75 mm was tested to evaluate the impact of a slightly larger intake area.

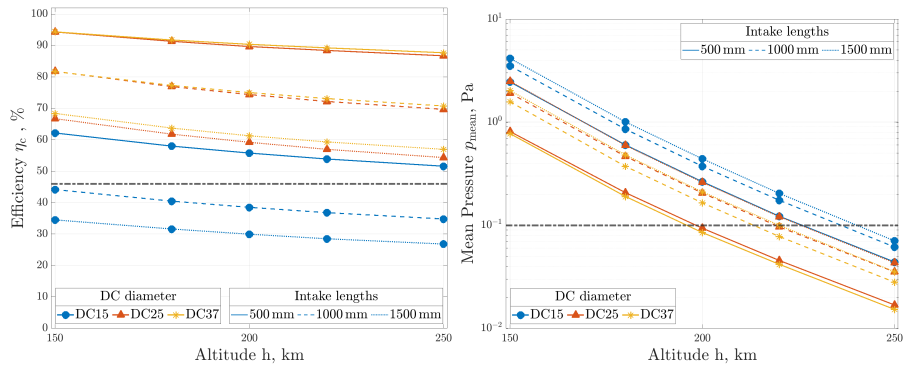
Fig. 2 compares efficiency (a) and mean pressure (b). Smaller focal lengths lead to higher efficiencies at all altitudes due to better particle focusing, with 5.5 mm performing worse than diffuse intake designs (46 % [13]). Even a 0.75 mm increase of the focal length significantly reduces efficiency. Ignition pressure is reached at similar altitudes for all focal lengths: 220 km for 3.0 mm and 3.75 mm, and 230 km for 5.5 mm. Despite small pressure losses, shorter focal lengths significantly improve efficiency, making 3 mm the optimal focal length for DC25.

4.2 DC Diameter

The comparison of DC diameters used a focal length of 5.5 mm for DC37, 3 mm for DC25, and 3 mm for DC15. A shorter focal length for DC15 was avoided as it reduced the intake area, limiting particle collection.

Fig. 3 (a) shows DC25 and DC37 achieving similar efficiencies, reaching up to 94 % for a 500 mm intake length. DC15 performs significantly worse, with its 3 mm focal length resulting in lower efficiencies than DC25's 5.5 mm focal length, even below diffuse designs. This highlights the need for shorter focal lengths for smaller DCs to increase $s_{F,\text{IPT}}$ and outperform diffuse designs.

Fig. 3 (b) shows DC15 achieving the highest mean pressure across all intake lengths, while DC25 and DC37 show similar pressures, with DC25 slightly higher for longer intakes. As noted in [7], efficiency and pressure depend on the molecular speed ratio, with higher thermal velocities reducing particle focusing for longer intakes. DC37 excels at particle focusing, while DC25 produces more collisions, leading to higher pressure at longer intakes. Differences between DC25 and DC37 are attributed to slight variations in $s_{F,\text{IPT}}$.

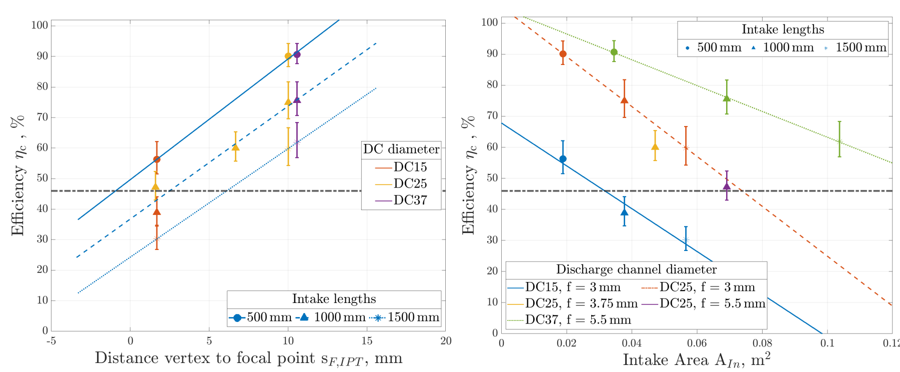


(a) Efficiency (b) Mean Pressure

Fig. 3. Efficiency and pressure levels for three different DC diameters and three different intake length over altitude, with the black line showing the current efficiency limit for diffuse intakes (a) and the expected minimum pressure required for ignition of the thruster inside the DC (b)

4.3 Comparison over Geometry

The previous results indicate a strong relationship between efficiency and $s_{F,\mathrm{IPT}}$ as the results for DC25 and DC37 were similar with comparable $s_{F,\mathrm{IPT}}$. Therefore Fig. 4 (a) presents a comparison of all simulation results based on the vertex-to-focal point distance, $s_{F,\mathrm{IPT}}$, with error bars showing efficiency variations across altitudes. DC diameters are color-coded, and additional DC25 results for a 1000 mm intake length at $f = 3.75$ mm and $f = 5.5$ mm are included. For a given intake length, efficiency shows a linear dependency on $s_{F,\mathrm{IPT}}$, confirm-



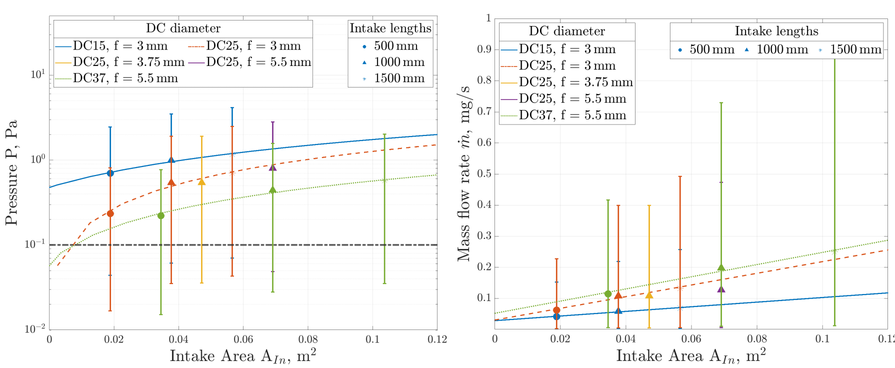
(a) Efficiency over $s_{F,\mathrm{IPT}}$ (b) Efficiency over intake area

Fig. 4. Efficiency for three different DC diameters with different focal lengths and three different intake length over $s_{F,\mathrm{IPT}}$ and intake area, with the black line showing the current efficiency limit for diffuse intakes

ing that smaller focal lengths f, which increase $s_{F,\mathrm{IPT}}$, are essential for higher efficiency.

Efficiency is also analyzed as a function of intake area, which is influenced by all geometric factors. Fig. 4 (b) illustrates the results, with markers representing intake lengths and colors indicating DC diameters and focal lengths. A fitted curve demonstrates a linear relationship between efficiency and intake area across different configurations. The results indicate that DC37 consistently outperforms DC15 and DC25 in terms of efficiency. While DC25 achieves relatively high efficiency at smaller intake areas, its performance declines with longer intake lengths. This decline is expected, as focusing particles into a smaller discharge channel becomes more challenging with increased intake length. This effect is even more pronounced for DC15, where the non-optimal focal length further amplifies the limitations of the smaller discharge channel. Specular intakes outperform diffuse designs for smaller intake areas, but their advantage diminishes as intake area increases.

Efficiency alone, however, is not the sole consideration; sufficient pressure for thruster ignition must also be achieved. The ignition threshold in this study is set at 0.1 Pa, based on experimental results [2], though a lower threshold may be possible. Fig. 5 (a) shows the mean pressure in the DC, with a dotted line marking the 0.1 Pa ignition threshold. A linear fit indicates that pressure is highest for DC15 and lowest for DC37. Nonetheless, none of the configurations consistently meet the ignition threshold across all altitudes, as error bars reveal instances where pressure falls below 0.1 Pa. The altitude at which ignition pressure is reached depends on the specific intake system. However, the results suggest that as the DC diameter decreases, the number of collected particles does not decrease proportionally, leading to a higher particle flux and, consequently, greater pressure.



(a) Mean Pressure (b) Mass flow rate

Fig. 5. Pressure and mass flow rate for three different DC diameters and three different intake length over intake area

Fig. 5(b) presents the mass flow rate inside the DC, which shows a strong dependence on atmospheric conditions and altitude, as evidenced by the large error bars. Despite this variability, a clear linear trend in the mean mass flow rate across all altitudes is observed, suggesting that, for a given altitude, both mass flow rate and pressure scale linearly with the intake area. DC37 and DC25 have similar slopes for this linear relationship, while DC15 shows a less steep slope. This variation aligns with the previously discussed influence of focal length f and the resulting higher $s_{F,\mathrm{IPT}}$ values for DC25 and DC37, which improves their mass flow rate performance compared to DC15.

5 Conclusion

This simulative study of different ABEP intake geometries examines the impact of intake length, discharge channel diameter, and focal length on collection efficiency, pressure, and mass flow rates. Results indicate a linear relationship between the vertex-to-focal point distance ($s_{F,\mathrm{IPT}}$) and collection efficiency, with larger $s_{F,\mathrm{IPT}}$ resulting in higher efficiencies. For a 25 mm DC, a 3 mm focal length, resulting in $s_{F,\mathrm{IPT}} = 10$ mm, achieves efficiencies up to 94 % for a 500 mm intake length. In contrast, DC15 performs poorly due to its non-optimal larger focal length, highlighting the importance of small focal lengths for high efficiency.

Pressure within the DC is strongly influenced by geometry, with smaller DCs (e.g., DC15) producing higher pressures due to increased particle collisions but lower efficiencies, especially for longer intakes. This trade-off highlights the need to balance collection efficiency and pressure to optimize thruster performance.

Mass flow rate also has a linear dependency on intake area, mirroring the efficiency trend. DC37 and DC25 show similar slopes, while DC15 has a shallower slope due to its suboptimal focal length. Larger DC diameters, combined with optimal focal lengths, improve particle focusing, resulting in higher efficiencies and mass flow rates.

In conclusion, larger DC diameters and shorter focal lengths maximize efficiency and mass flow rates, while higher pressures are achieved with smaller DCs due to increased particle collisions. Among the configurations studied, a DC diameter of 25 mm with a 3 mm focal length offers the best balance between efficiency and pressure.

Acknowledgments

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