uc3m | Universidad Carlos III de Madrid
Department of Aerospace Engineering

PhD Aerospace Engineering UC3M
Doctoral Meetings 2026

uc3m PHD

Numerical modeling and analysis of atmosphere-breathing electric propulsion thrusters for VLEO drag compensation

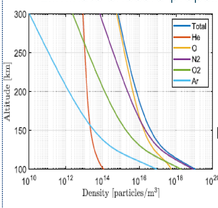
Author/PhD Student: Saumya Ranjan
Supervisor: Jiewei Zhou, Ahilan Appar

State of the Art / Motivation

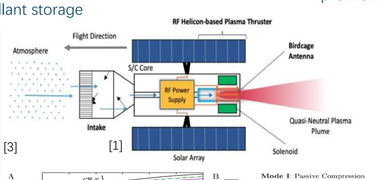
Very Low Earth Orbit (VLEO) provides significant advantages for Earth observation and communication systems, but persistent atmospheric drag causes rapid orbital decay and increased propellant consumption.

For Drag Compensation, **Atmosphere-Breathing Electric Propulsion (ABEP)** has emerged as a promising solution. ABEP systems:

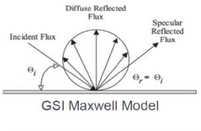
- Collect residual atmospheric species (**N_2, O...**)
- Feed them directly into an electric propulsion device
- Eliminate onboard propellant storage

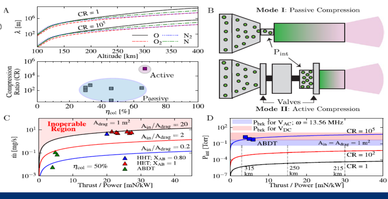


[3]



[1]





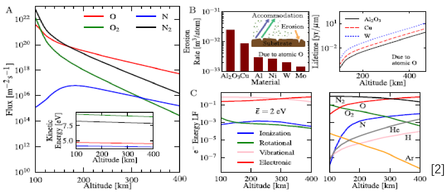
[2]

Potentiality of Using Model:

- ABEP is still at an early development stage with currently low efficiencies
- Experimental characterization is time-consuming, with scarce measurements and prescribed-composition low-velocity propellant testing
- Ground facilities remain limited in reproducing VLEO hypersonic atmospheric conditions
- At this early stage, modelling tools are particularly valuable for identifying promising thruster designs and operating conditions

ABEP Current Modeling limitations include:

- Most existing ABEP simulations rely on **low-dimensional and simplified numerical models.**
- Important **volumetric and wall-induced molecular reactions are often simplified or neglected**
- A fully coupled **intake–plasma thruster framework** is still unavailable in current modeling approaches



[2]

Objectives

The main objective of this project is to boost the efficiency of **Atmosphere-Breathing Electric Propulsion (ABEP)** systems and provide a comprehensive characterization of their performance for **VLEO drag compensation** through advanced gas/plasma modeling.

- Develop a **two-way coupled intake–plasma thruster code** with relevant plasma chemistry and realistic Gas-Surface Interaction and Plasma -Surface Interaction (**GSI/PSI**) models
- Quantify the **propellant mass flow** captured at the intake under representative orbital conditions
- Investigate a broad range of operating regimes for the main **electric propulsion technologies**
- Analyze overall **propulsive performance**, identifying dominant plasma physics and power loss mechanisms
- Determine optimal configurations for efficient **ABEP operation**

Methodology

The proposed methodology is based on extending the in-house hybrid code **HYPHEN** for coupled analyses of ABEP systems

- HYPHEN is a 2D axisymmetric hybrid PIC–fluid plasma simulation code for **plasma chamber and near-plume simulations**
- HYPHEN uses three main modules: **I-Module** for heavy species, **E-Module** for magnetized electrons, and **S-Module for the interaction of bulk with the thruster walls**, executed sequentially within a simulation loop; combining a **Particle-In-Cell (PIC)** approach for ion/neutral dynamics with a quasineutral drift-diffusion fluid model for magnetized electrons using a **Magnetic Field Aligned Mesh (MFAM)**

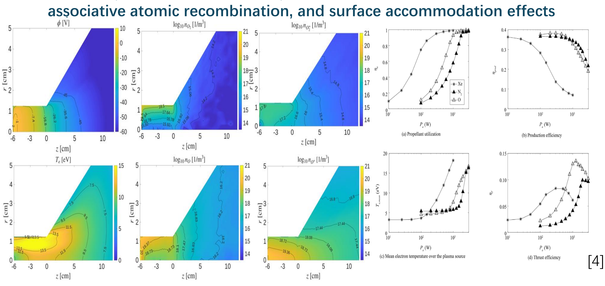
Present Limitations for Air-Breathing Simulations:

- Only singly charged ion species are currently considered
- Chemistry implementation is limited to diatomic species
- Intake flow and intake–plasma coupling are not included in the present simulations
- Empirical Models are used for GSI/PSI that are not material dependent.

Current Capabilities of HYPHEN:

Current HYPHEN capabilities partially advance ABEP modeling and enable pioneering studies of air-breathing electrodeless plasma thrusters.
Built for multi-thruster simulations: Hall-effect thrusters, Helicon / ECR thrusters, RIT (Radio-Frequency Ion Thruster)

- Supports multispecies plasma transport and chemistry
- Comprehensive air plasma model accounting for elastic/Coulomb collisions, ionization, dissociation, and electronic-vibrational-rotational excitations
- Includes plasma–wall interaction processes such as **ion recombination, associative atomic recombination, and surface accommodation effects**



[4]

Course of action **:**

1) An extensive **literature review** will first establish the state of the art in ABEP design and modeling, focusing on:

- **Surface materials and properties**
- **Plasma–wall interaction processes**
- **Volumetric reactions and cross-section data**
- **Intake and atmosphere-breathing thruster designs**
- Available **experimental measurements**

3) The upgraded framework will then be applied to representative **VLEO intake simulations** to evaluate:

- **Mass flow**
- **Collection efficiency**
- **Compression ratio**

under different intake geometries, orbital conditions, and material configurations.

2) Next, material-dependent PSI models will be developed using molecular dynamics simulations to characterize reflection, accommodation, and surface reaction processes for neutral and charged species.
In parallel, the plasma model will be extended through improved **multispecies air chemistry**, including:

- **Multiply charged ions** (become important at high powers, where more competitive performances are achieved)
- **Asymmetric non-diatomic species** (for example NO, N_2O, NO_2), can be produced through associative reactions at the walls)
- **Heavy-species reactions**
- Dedicated **collision operators** (capturing the anisotropic scattering patterns)

4) Finally, simulations of representative **Hall Effect Thrusters (HET)** and **RF Ion Thrusters (RIT)** will be performed to analyze **plasma discharge physics**, **plasma composition and chemistry**, and overall **propulsive performance**, by **two-way coupled intake–thruster simulations** to characterize the interaction between **intake flow** and **plasma discharge**.

Preliminary Research/Results

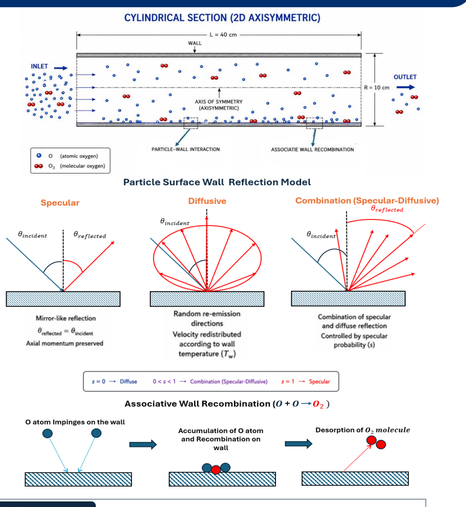
Cylindrical Intake Configuration for VLEO Atmosphere-Breathing Propulsion

- Simulations of simplified cylindrical intake geometries were performed using the current capabilities of HYPHEN
- These preliminary studies provide insight into intake flow behavior and help identify the present capabilities and limitations of HYPHEN for ABEP-related applications
- Current HYPHEN predictions are also benchmarked against intake models reported in the literature
- Present simulations consider atomic oxygen (O) injection at the intake inlet.
- Incoming flow conditions were obtained from the NRLMSISE-00 atmospheric model database database reported by Romano et al

Simulation Parameters & Results for Cylindrical Section

Parameter	Value
Orbit altitude	150 km
Injection velocity (V_{in})	7818.2 m/s
Injection temperature (T_{in})	582 K (≈0.05 eV)
Mass flow ($\dot{m}$)	6.74×10−8 kg/s
Wall temperature (T_{wall})	300 K
Intake geometry	Cylindrical
Intake length	0.40 m
Intake radius	0.05 m

Specular Reflection Probability(s)	Collection Efficiency (ηc) $\frac{\dot{m}_{out}}{\dot{m}_{in}}$	Compression Ratio $CR = \frac{n_{out}}{n_{in}}$	O_2 outlet mass fraction
0.00 *(Diffuse)*	80.64%	3.52	20.86%
0.25	85.51%	3.18	17.70%
0.50	89.48%	2.78	14.50%
0.75	92.56%	2.17	10.47%
1.00 *(Specular)*	95.45%	1.59	6.15%



Acknowledgement

PhD was initially funded by the Aerospace Department at UC3M. In the subsequent years, it will be funded the UC3M's research program, under the call "Ayudas a departamentos de la universidad para el fomento de la igualdad de género en el colectivo predoctoral de la universidad"

References:

1. *Romano, F. et al. (2017). Performance Evaluation of a Novel Inductive Atmosphere- Breathing EP System*
2. *Woodley, Adrian & Horstman, Ethan & Keidar, Michael & Underwood, Thomas. (2024). Requirements for air-breathing electric propulsion in low-altitude orbits. Journal of Electric Propulsion. 3. 10.1007/s44205-024-00095-w. .*
3. Crandall, Patrick & Wirz, Richard. (2022). Air-breathing electric propulsion: mission characterization and design analysis. Journal of Electric Propulsion. 1. 12. 10.1007/s44205-022-00009-8.
4. Zhou, Jiewei & Taccogna, Francesco & Fajardo, Pablo & Ahedo, Eduardo. (2024). A study of an air-breathing electrodeless plasma thruster discharge.

PhD Student: - sranjan@ing.uc3m.es
Supervisor: jzhou@pa.uc3m.es
aappar@ing.uc3m.es

uc3m PHD