Setup and characterization of a novel facility for air-breathing electric thrusters

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Very low Earth orbits (VLEO) enable higher-resolution Earth observation and reduced communication latency but introduce significant atmospheric drag. The ERC-funded BREATHE project addresses this challenge through the development of air-breathing electric propulsion (ABEP) systems, utilizing collected atmospheric particles as propellant to generate thrust for drag compensation. However, ground testing of ABEP systems remains complex due to difficulties in replicating a representative VLEO environment. This work presents a novel test facility and verification appraoch for ABEP systems, leveraging independent control of injected mass flow rate and thruster ionization chamber pressure. This approach will allow for on-ground testing of ABEP systems in air-breathing mode. together with the measurement of their transmission probability. The paper outlines the experimental campaign performed to characterize the facility and its performance in measuring transmission probabilities of cylindrical ducts.

I. Introduction

Operating in very low Earth orbit (VLEO), defined as altitudes below 400 km, offers significant advantages for Earth observation, telecommunication missions, and sustainable space operations. These benefits include enhanced orbital accessibility, improved sensor resolution, and accelerated space debris decay, to mention few.[1] However, the increased atmospheric drag at these altitudes severely limits satellite lifetime. To overcome this limitation while eliminating dependence on limited onboard propellant, air-breathing electric propulsion (ABEP) systems have emerged as a promising solution. Several research and development efforts have already been pursued in this field.[2] The ABEP concept integrates an atmospheric intake system with an electric thruster. The intake collects rarefied atmospheric particles encountered by the spacecraft, while the electric thruster ionizes and accelerates these particles to generate thrust for continuous orbit maintenance. Despite its theoretical promise, full drag compensation using ABEP systems has not yet been experimentally demonstrated in a representative ground-test environment at the time of writing.

In this framework, the BREATHE project aims to develop an innovative testing approach[5–7] for the verification of ABEP systems. The present paper describes the facility designed to allow for on-ground testing of ABEP systems in air-breathing mode and for measuring their transmission probability during operation. Moreover, the paper presents the test campaign performed to characterize the BREATHE facility and its performance in probing variations in transmission probabilities. Section II describes the BREATHE

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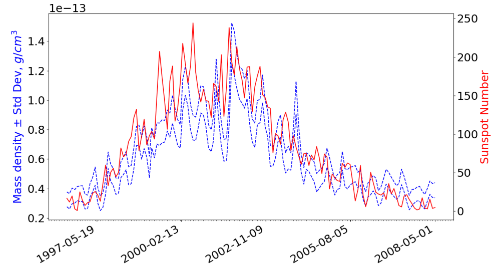


Figure 1: Space-averaged mass density and solar activity during the 23rd solar cycle at 250 km altitude.

facility and the verification strategy. Specifically, Sec. A provides details of the vacuum facility, Sec. B elaborates on the testing strategy to verify ABEP systems on-ground, Sec. C shows the results obtained in the preliminary test campaign.

II. BREATHE facility and verification strategy

The performance of an ABEP system operating in VLEO depends on the properties of the atmospheric flow collected by its intake. Key parameters include atmospheric composition, density and temperature. These properties vary substantially with orbital altitude and solar activity levels. Fig. 1 illustrates this variability, showing the space-averaged total mass density at 250 km altitude throughout the 23rd solar cycle, including one standard deviation range, alongside the corresponding solar activity profile.

VLEO consists primarily of molecular nitrogen, atomic oxygen, and molecular oxygen, characterized by low particle densities in the range of 1e14/1e16 m^{-3}.[3,6] This rarefied composition presents two fundamental challenges for Air-Breathing Electric Propulsion (ABEP) systems: material compatibility and efficient thruster operation.

The material compatibility challenge imposes severe constraints due to the presence of atomic oxygen, which causes degradation of spacecraft materials. The thruster operation challenge is related to the properties of atmospheric particles compared to xenon, the conventional propellant utilized in electric propulsion systems. Furthermore, the thruster must operate effectively at the low densities available at these orbits.

These challenges come with the difficulties in recreating a representative ground-test environment that accurately simulates the dynamically changing harsh conditions of VLEO. At the time of writing, only three institutions—Busek, JAXA, and SITAEL—have conducted complete end-to-end ground testing of ABEP technology.[2] However, none of these systems has yet demonstrated the capability to achieve full drag compensation.

A. Verification strategy

The novel experimental approach involved the design of a novel vacuum facility,[5–7] which will also allow to measure the thruster transmission probability Θ_{Th}, i.e. the probability that a particle will eventually escape from the thruster exhaust. Fig. 2 presents a qualitative schematic of the experimental setup, illustrating both the facility configuration and its operational equivalence to in-orbit thruster requirements.

In typical VLEO altitudes the Knudsen number, defined as the ratio between the molecular mean free path and the characteristic length of the problem, is larger than 10 and in the order of 100.[3] Therefore, intermolecular collisions are negligible. In orbit, the intake acts as a molecular trap for the collected atmospheric flow, increasing particle density at the ionization region and minimizing the unprocessed gas bouncing back from the thruster wall to the intake entrance. During this collection process, the majority of neutral particles undergo wall scattering, resulting in thermal accommodation to the thruster wall temperature.

This orbital condition can be replicated on-ground utilizing a propellant distributor that injects a precisely controlled flow rate equivalent to the collected one downstream the intake during orbital operation. The experimental setup for ABEP testing incorporates a turbomolecular pump with tunable pumping speed at the outlet simulating the backflow, to reproduce the orbital escape of the backstream particles. The other

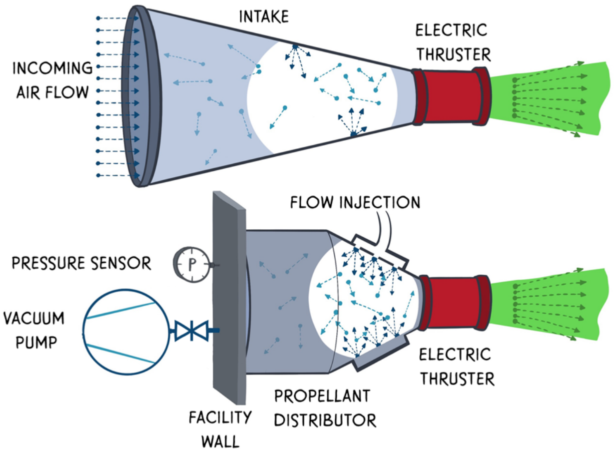
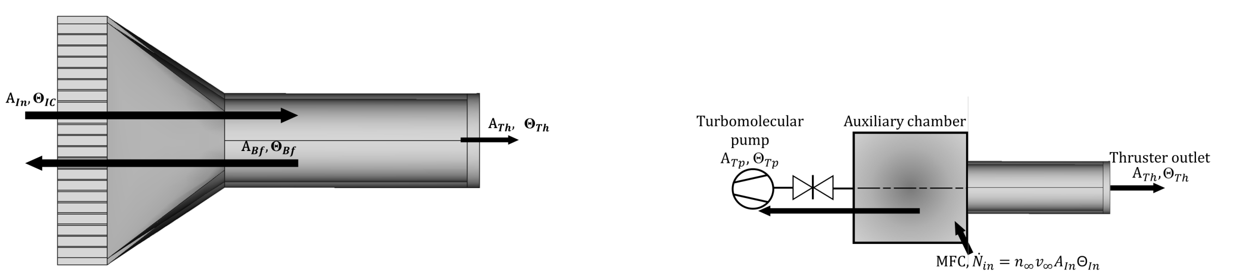


Figure 2: Schematic representation of intake flow compression (top) and the setup for ABEP testing (bottom).

outlet corresponds to the thruster exhaust. The pressure within the propellant distributor varies according to both the injected flow rate and the turbomolecular pump's pumping speed, regulated via a throttle valve, therefore enabling independent control of the thruster's operating pressure and injected mass flow rate. This aspect is what enables the testing of the ABEP system in air-breathing mode. By closing the thruster outlet with a sealing flange, the dependence of the pressure on the flow rate and the pumping speed of the turbomolecular pump can be characterized. Then, during thruster operation, the measurement of the distributor backpressure will allow to assess the flux through the open section and, consequently, the fraction of propellant processed in the thruster.

The capability of the experimental facility to accurately simulate VLEO conditions within the thruster can be formally demonstrated through a zero-dimensional (0D) theoretical model.[6,7]



(a) Thruster geometry considered for the 0D model particle flow balance.

(b) Auxiliary chamber geometry considered for the 0D model particle flow balance.

Figure 3: Control volumes utilized in the 0D balance.

Two distinct particle flow balance equations are derived, corresponding to: (i) in-flight conditions within the ionization chamber propulsion system (Fig. 3a), and (ii) on-ground testing conditions within the auxiliary chamber (Fig. 3b). Both formulations adhere to the following assumptions:[5–7] free molecular flow regime, fully diffusive wall reflections, fixed wall temperature, and purely thermal mass flux with zero macroscopic velocity. For the two equations, the ionization chamber number density is represented by N and the averaged flow velocity towards a certain direction is given as

$$v_{Th} = \sqrt{\frac{k_B T}{2\pi m_p}}. \tag{1}$$

The particle flow continuity equation for the thruster control volume is expressed as

$$V\frac{\partial N}{\partial t} = \dot{N}_{\rm In} - N v_{\rm Th}\left[A_{\rm Bf}\Theta_{\rm Bf} + A_{\rm Th}\Theta_{\rm Th}\right], \quad (2)$$

where the first term on the right represents the incoming asymptotic flow accepted by the intake, n_∞ v_∞ A_{In} Θ_{In}, with A_{In} the open front area of the intake, n_∞ v_∞ the free stream conditions (e.g. number density and velocity), and Θ_{Th} the thruster transmission probability. The second term corresponds to the backflow of thermalized particles toward the intake entrance, dependent on the backflow area A_{Bf} and the backflow transmission probability Θ_{Bf}. The last term is the flow of thermalized particles toward the thruster, dependent on the thruster outlet area A_{Th} and the thruster transmission probability Θ_{Th}.

Equivalently, the particle flow continuity equation for the chamber control volume is expressed as

$$V\frac{\partial N}{\partial t} = \dot{N}_{\rm In} - N\left[S_{l/s}\cdot 10^{-3} + v_{\rm th}A_{\rm Th}\Theta_{\rm Th}\right], \quad (3)$$

where, in this case, the first term on the right represents the injected mass flow rate controlled via a mass flow controller, the second term corresponds to the backflow of thermalized particles toward the turbomolecular pump, controlled through its pumping speed $S_{l/s}$ (in liters per second), and the last term is the flow of thermalized particles that leaves the thruster.

To ensure equivalence between the on-ground testing and the in-orbit behavior, allowing to test the ABEP system in air-breathing mode, the two governing equations must be matched. The experimental setup enables this by reproducing the intake-dependent terms as follows: (i) the forward mass flow rate accepeted by the intake at the thruster entrance is controlled via the mass flow controller, (ii) the backflow from the thruster to the intake entrance is reproduced by varying the throttle valve aperture, i.e. the pumping speed of the turbo.

The quantification of the thruster transmission probability, Θ_{Th}, can be achieved by measuring the additional mass flow rate required to maintain the same chamber pressure when the thruster is placed at the interface between the two chambers compared to the configuration with the thruster outlet sealed. Moreover, for the case of the thruster being not operating, once the relationship between pressure, flow rate, and the turbomolecular pump's pumping speed has been characterized, Θ_{Th} can also be estimated by comparing experimentally measured pressures from chamber sensors with predictions from theoretical models, such as zero-dimensional (0D) flow balance equations or Direct Simulation Monte Carlo (DSMC) simulations.

The approach described enables the testing of ABEP systems in air-breathing mode on-ground.

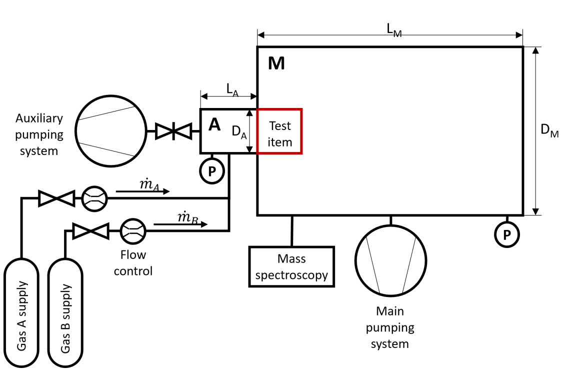
B. BREATHE facility

The BREATHE facility is schematically depicted in Fig. 4a. The facility includes a main chamber (M) and an auxiliary chamber (A). The main chamber is equipped with three turbomolecular pumps, while the auxiliary chamber with a single turbomolecular pump together with a throttle valve that allows to tune pumping speed. The two chambers are made in stainless steel 304L, with the following dimensions:

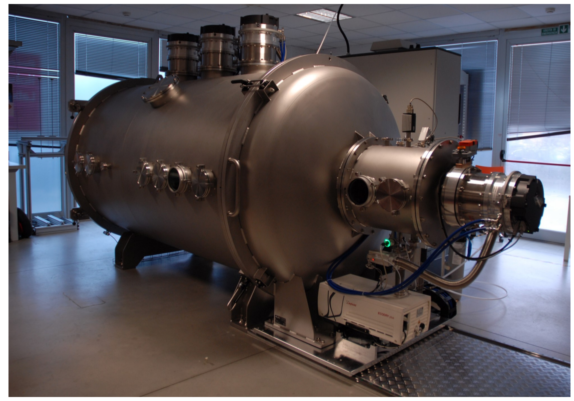
- A main large vessel 2.5m long with a 1.5m diameter.
- A smaller chamber 0.5m long with a 0.5m diameter.

A control system manages two distinct gas supplies for the injection of N2/O2 mixtures or N2/Ar mixture. The use of argon as a propellant has been proposed by BUSEK,[8] due to its similarities with the atomic oxygen present in the upper atmosphere. Although argon is not fully representative, it can simplify the analysis of prototype performance, as no dissociation needs to be considered. The same control system allows the control of the throtlle valve aperture in the auxiliary chamber. A Residual Gas Analyzer (RGA) enables the identification and quantification of the species present in the vacuum chamber. The prototypes of ABEP systems will be placed at the interface between the two chambers.

Figure 4b depicts the facility available in the laboratory of the Sant'Anna School of Advanced Studies. To further investigate the thruster performance, the main chamber is dedicated to plasma diagnostics, featuring a moving arm with Faraday probes, Langmuir probes, and a retarding potential analyser (RPA) to characterize the thruster plume.[10]



(a) Schematics representation of the BREATHE facility.



(b) The BREATHE facility.

Figure 4: BREATHE facility: (a) schematic representation and (b) actual installation.

C. Facility characterization

To assess the chamber's capability of measuring transmission probabilities and their relative variations, an experimental campaign was conducted using cylindrical ducts of different aspect ratios, defined as the ratio between the length of the duct and its radius. For this geometry, the transmission probabilities are obtained from the solutions of the Clausing's integral equation[4] for thermalized molecular flow. Solutions are depicted in Figure 5.

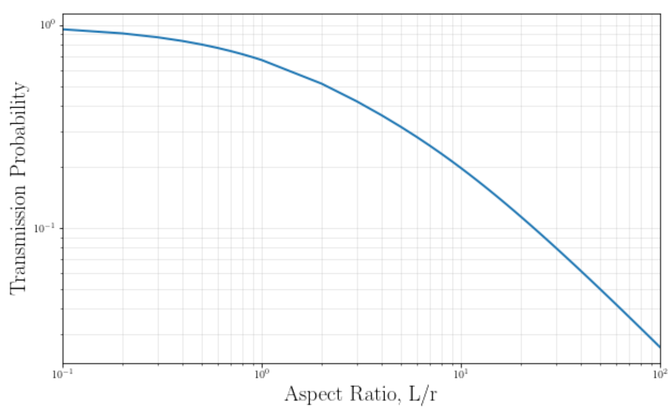


Figure 5: Transmission probability versus aspect ratio from Clausing's numerical solution.[4,9]

Cylindrical ducts with aspect ratios of 1, 2, 4 and 8 were installed at the chamber interface, with a fixed inner radius of 4 cm. For these aspect ratios, the expected transmission probabilities are reported in Tab. 1.

AR	Θ_{AR}
1	0.67
2	0.51
4	0.36
8	0.22

Table 1: Transmission probabilities for the tested cases.

Because of uncertainties in the measurements of the pressure sensor and the presence of suspected offsets indicating a lack of proper calibration, only normalized pressure values and relative variations in transmission probabilities were considered. Fig. 6 shows the experimental setup with the cylindrical duct of aspect ratio 4, representing the test item in Fig. 4 at the interface between the two vessels. Fig. 7 presents the normalized

Figure 6: Setup with tube of aspect ratio 4 at the auxiliary chamber interface.

pressure values for a 10 sccm nitrogen flow rate across the different aspect ratio configurations and the closed flange reference case. As expected, higher aspect ratios resulted in increased auxiliary chamber pressures

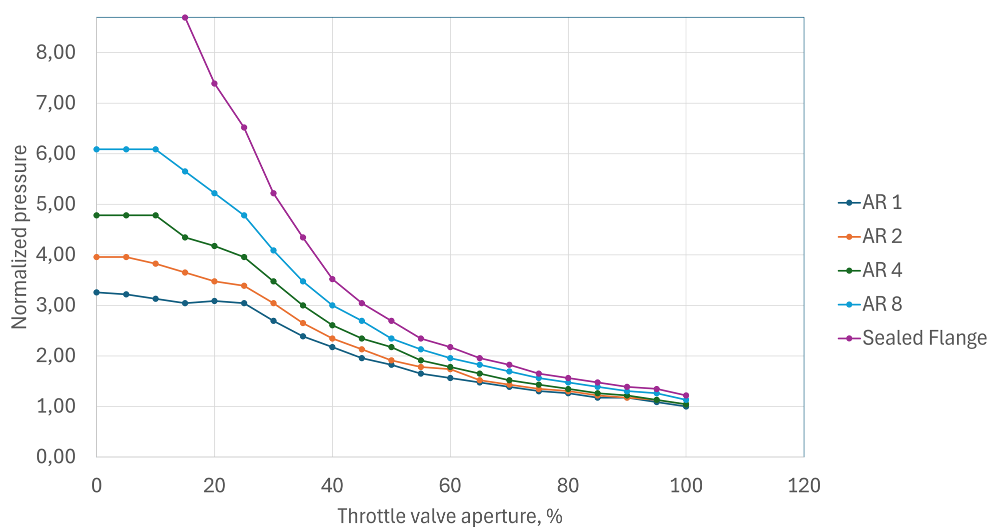


Figure 7: Normalized pressure measurements for various aspect ratios and throttle valve apertures at 10 sccm N_2 flow rate.

due to reduced transmission probability. The closed flange configuration provided the highest pressures. From the normalized pressures, relative variations in transmission probabilities can be determined in terms of pressure ratio measurements. Fig. 8 shows the ratio between $\Theta_{AR4}/\Theta_{AR1}$ as calculated from the theory of Clausing and the values obtained from the measured pressure at various throttle valve aperture. Numerical solutions of Clausing's integral equation predicts a transmission probability ratio $\Theta_{AR4}/\Theta_{AR1}$ of 0.54 and the

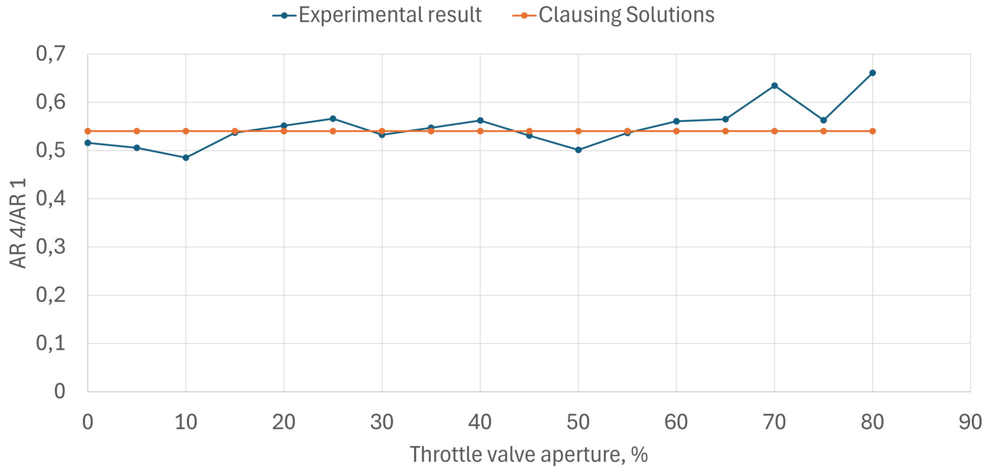


Figure 8: Relative transmission probability variations $\Theta_{AR4}/\Theta_{AR1}$.

experimental data show a mean value of 0.55. Tab. 2 summarizes the results obtained for the transmission probability ratios, defined as $\Theta_{ARi}/\Theta_{AR1}$. Experimental results are in good agreement with the measured ones across all the tested configurations. This feature will be extremely important for determining not only

AR	Θ_{AR}	Θ^i_{AR}/Θ_1 (theoretical)	Θ^i_{AR}/Θ_1 (experiments)	σ_{AR}
1	0.67			
2	0.51	0.76	0.78	0.06
4	0.36	0.54	0.55	0.04
8	0.22	0.33	0.34	0.04

Table 2: Relative transmission probaility variations across different experimental configurations.

the absolute value of transmission probability of the thruster in a certain condition, but possibly also its variations during operation, especially when considering ABEP ignition.

III. Conclusion

This work presented the development and experimental validation of a novel ground-testing facility for air-breathing electric propulsion systems operating in Very Low Earth Orbit. After a description of the innovative testing approach underlying the BREATHE facility design, results from a preliminary test campaign performed to characterize the chamber are presented.

Experimental results confirmed the facility's ability to detect transmission probability relative variations.

Future work will focus on investigating additional aspect ratios and gas species. Moreover, implementation of the complete plasma diagnostics suite (Faraday probes, Langmuir probes, and RPA) will enable comprehensive thruster plume characterization during air-breathing operation.

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