Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Vacuum Test Facilities for Spacecraft Propulsion Systems: A Review and Operational Capability Assessment of a Medium-Scale University Facility

Afroz Javed

afrozjaved@gmail.com

Sivas Bilim ve Teknoloji Universitesi https://orcid.org/0009-0000-8817-7094

Mustafa Ali AKDUMAN

Sivas Bilim ve Teknoloji Universitesi https://orcid.org/0009-0008-5432-5106

İsmail TUNÇİL

Sivas Bilim ve Teknoloji Universitesi https://orcid.org/0000-0001-6910-1019

Systematic Review

Keywords: Space propulsion, Vacuum test facilities, Altitude simulation, Spacecraft propulsion testing, Neutral-gas-based propulsion, Cold-gas thrusters, Vacuum chamber analysis, Pulse mode testing

Posted Date: August 27th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10825290/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: The authors declare no competing interests.

Abstract

Ground based experimental verification of spacecraft propulsion systems under rarefied conditions is essential for minimizing facility effects and accurately characterizing propulsion performance. This study reviews propulsion oriented vacuum test facilities and examines the differing requirements of neutral-gas-based and plasma-based propulsion systems. Particular attention is given to medium scale facilities suitable for university level propulsion research. A comparative assessment of international and Turkish facilities is followed by an analytical evaluation of the 3.55 m³ propulsion vacuum chamber at Sivas Bilim ve Teknoloji Üniversitesi (SBTÜ), which achieves a minimum pressure of approximately 3 Pa. A mass conservation model is developed to determine the pressure evolution and operating limits of a mechanically pumped chamber under continuous and intermittent gas injection. The results show that continuous operation is governed primarily by pumping speed, whereas intermittent operation permits substantially higher mass flow rates for finite operating durations by utilizing the chamber volume as a temporary gas-storage capacity. Representative calculations further demonstrate the corresponding thrust levels that can be accommodated by the facility. The proposed methodology provides a general framework for estimating operating limits and planning propulsion experiments in medium-scale vacuum test facilities.

1. Introduction

The rapid growth of satellite-based communication, Earth observation, navigation, scientific exploration, and national-security missions has substantially increased the demand for reliable spacecraft propulsion systems. In addition to spacecraft, low-thrust propulsion devices are widely employed in launch vehicles, upper stages, ballistic missiles, and re-entry vehicles when aerodynamic control surfaces become ineffective. These propulsion systems perform critical functions including attitude control, orbit maintenance, station keeping, orbit transfer, rendezvous, collision avoidance, and precision trajectory correction, making their reliable operation essential to mission success [1–7].

Since spacecraft propulsion systems operate in rarefied atmospheric or near-vacuum environments, their performance cannot be adequately evaluated under normal laboratory conditions. Ground-based testing therefore requires vacuum facilities capable of reproducing reduced-pressure environments while minimizing facility effects that may influence measured thrust, specific impulse, plume development, contamination, thermal loading, and lifetime characteristics [8–12]. Vacuum chambers consequently constitute an essential component of spacecraft propulsion research, technology development, and qualification programs.

The vacuum requirements of propulsion test facilities vary considerably according to the mechanism by which thrust is generated. Neutral-gas-based propulsion systems generate thrust primarily through the gas-dynamic acceleration and expansion of a predominantly neutral working fluid, whereas plasma-based propulsion systems generate thrust primarily by accelerating charged particles using electric and/or electromagnetic fields. These fundamentally different propulsion mechanisms result in markedly

different sensitivities to background pressure and, consequently, to the vacuum conditions required during ground testing. Propulsion test facilities therefore span a wide range of chamber volumes, pumping capacities, and achievable vacuum levels, from compact laboratory installations to large national-scale space-simulation facilities.

The construction and operation of large propulsion vacuum facilities require extensive infrastructure, specialized pumping systems, and significant operational resources. Such facilities are therefore generally concentrated within national space agencies, defense organizations, and major research laboratories. In contrast, medium-scale university facilities provide a more accessible platform for propulsion research, prototype validation, instrumentation development, and graduate education. Although their vacuum capability is more limited, these facilities can support a significant range of experiments involving neutral-gas-based propulsion systems and occupy an important position between small laboratory vacuum systems and large national test centers.

This issue is particularly relevant in Türkiye, where dedicated propulsion-testing infrastructure remains concentrated primarily within government and defense organizations, while comparatively few universities operate dedicated propulsion vacuum facilities. As national investment in space technologies continues to expand, university-scale experimental infrastructure can play an increasingly important role in supporting indigenous propulsion research, workforce development, and academic–industrial collaboration.

The present study reviews propulsion-oriented vacuum test facilities reported in the literature and examines the relationship between chamber volume, achievable vacuum level, and intended propulsion application. Particular emphasis is placed on medium-scale facilities that bridge the gap between small laboratory chambers and large national test centers. A comparative assessment of representative international and Turkish facilities is followed by an analytical evaluation of a university-scale propulsion vacuum chamber with an internal volume of 3.55 m^3 and a minimum operating pressure of 3 Pa. Analytical models are developed to establish the continuous and intermittent operating limits of the facility and to quantify its practical testing capability, including representative thrust levels. The study provides a generalized framework for assessing medium-scale vacuum chambers for neutral-gas-based propulsion research, altitude-simulation experiments, and related spacecraft propulsion investigations.

2. Vacuum Testing Requirements for Space Propulsion Systems

Spacecraft propulsion systems operate over a wide range of ambient pressures, extending from the upper atmosphere to the near-vacuum conditions encountered in Earth orbit and deep space. Consequently, realistic ground testing requires vacuum facilities capable of reproducing, as closely as practical, the pressure environment relevant to the intended application. The required vacuum level, however, depends fundamentally on the nature of the propulsive medium and the mechanism by which exhaust momentum is generated. From the perspective of ground testing, spacecraft propulsion systems may therefore be broadly classified into neutral-gas-based propulsion systems and plasma-

based propulsion systems. The two classes employ fundamentally different thrust generation mechanisms and consequently exhibit markedly different sensitivities to background pressure.

2.1 Neutral-Gas-Based Propulsion Systems

In neutral-gas-based propulsion systems, thrust is produced primarily by accelerating a predominantly neutral working fluid through a nozzle. Pressure and/or thermal energy supplied to the propellant are converted into directed kinetic energy during expansion, with the resulting exhaust velocity governed by the thermodynamic state of the propellant, nozzle geometry, and ambient pressure. Consequently, the surrounding pressure can influence nozzle expansion and, under sufficiently high backpressure, the resulting propulsion performance.

This category includes cold-gas thrusters, warm-gas thrusters, monopropellant and bipropellant chemical thrusters, resistojets, and arcjets. Although these systems differ in the manner in which propellant energy is generated, through stored pressure, electrical heating, or chemical reaction—they ultimately produce thrust predominantly through the gas-dynamic acceleration and expansion of the working fluid.

2.2 Plasma-Based Propulsion Systems

Plasma-based propulsion systems generate thrust primarily by accelerating charged particles rather than by relying on conventional gas-dynamic expansion of a neutral working fluid. Electric and/or magnetic fields are employed to generate, control, and accelerate the charged propulsive species, producing exhaust velocities substantially higher than those typically obtained from neutral-gas expansion.

This category includes Hall-effect thrusters, gridded ion engines, pulsed plasma thrusters, field-emission electric propulsion (FEEP), and electrospray thrusters. Because the operation of these systems depends strongly on charged-particle dynamics and plasma processes, residual neutral gas can significantly influence their performance through mechanisms such as neutral-gas ingestion, charge-exchange collisions, discharge modification, and plume interactions.

2.3 Vacuum Facility Effects

A major challenge in ground-based propulsion testing is the occurrence of facility effects, whereby the characteristics of the vacuum chamber influence the measured performance of the propulsion system. Facility effects arise when the chamber environment deviates from the intended flight conditions owing to limited chamber volume, insufficient pumping capacity, elevated background pressure, or interactions between the exhaust plume and the test facility. These effects may introduce errors in measured thrust, specific impulse, plume characteristics, and other diagnostic measurements [9, 10].

Facility effects become particularly significant when the background pressure is sufficiently high to influence exhaust expansion or when the chamber dimensions are small relative to the plume size.

Under such conditions, plume-wall interactions, reflected particles, sputtered material, and recirculating gases may re-enter the measurement region, introducing uncertainties in thrust measurements, plume diagnostics, contamination assessments, and lifetime investigations [13].

The severity of facility effects depends strongly on the propulsion technology under investigation. Plasma-based propulsion systems are especially sensitive because residual neutral gas can modify plasma behavior through background-gas ingestion and charge-exchange collisions [11, 14, 15], whereas neutral-gas-based propulsion systems are generally less sensitive to background gas, provided that the chamber pressure remains sufficiently low to avoid significant backpressure and plume-interaction effects. Hence, the design of propulsion test facilities emphasizes appropriate chamber volume, pumping speed, and flow management to minimize facility effects. The specific vacuum requirements of representative propulsion systems are discussed in the following section.

2.4 Vacuum Requirements of Representative Space Propulsion Systems

The vacuum requirements of propulsion test facilities depend strongly on the propulsion mechanism and the associated sensitivity to ambient pressure. For neutral-gas-based propulsion systems, the primary objective of vacuum testing is to reduce ambient backpressure sufficiently to permit exhaust expansion representative of the intended flight environment. In contrast, plasma-based propulsion systems require substantially lower background pressures because residual neutral gas can influence plasma behavior through mechanisms such as neutral-gas ingestion, charge-exchange collisions, plume recirculation, and plasma - wall interactions. Consequently, the vacuum requirements of the two propulsion classes can differ by several orders of magnitude.

The typical vacuum environments required for representative spacecraft propulsion systems are summarized in Table 1. The pressure ranges and performance characteristics have been compiled from standard spacecraft propulsion references, including Sutton and Biblarz [1], Humble et al. [7], Goebel and Katz [4], and Jahn and Choueiri [5], together with published experimental investigations of electric-propulsion testing and facility effects [9, 16]. These values should be regarded as representative testing environments rather than absolute operational limits, since the required chamber pressure ultimately depends on the propulsion-system design, propellant mass flow rate, test objectives, and desired measurement accuracy.

Table 1
Representative spacecraft propulsion systems and typical vacuum-testing requirements.

Propulsion System	Thrust Range	Isp (s)	Typical Application	Test Pressure (Pa)	Typical Facility
Cold-gas	0.1 mN – 100 N	40–80	Attitude control, CubeSats, RCS	10–500	Small/medium laboratory
Monopropellant	0.1–500 N	180–260	Attitude control, orbit correction, launch vehicle RCS	1–100	Medium university/national
Bipropellant	1–5000 N	280–340	Orbit transfer, apogee maneuvers	0.1–50	Medium/large
Resistojets	1 mN–5 N	150–350	Small satellites	0.1–50	Medium laboratory
Arcjets	0.05–5 N	300–700	Orbit transfer, station keeping	10^{-2}–10^{-4}	Large EP
Hall thrusters	5 mN–5 N	1000–2500	Station keeping, orbit raising, deep space	10^{-3}–10^{-5}	Large cryopumped EP
Ion engines	1 mN–1 N	2000–5000	Deep space, precision orbit control	10^{-4}–10^{-6}	Large UHV
PPTs	10 μN-10 mN	500–1500	Small satellites, CubeSats	10^{-2}–10^{-5}	Medium/large EP
Electrosprays	1 μN–10 mN	500–3000	Formation flying, drag-free control	10^{-4}–10^{-6}	High-vacuum micropropulsion
FEEP	1 μN–1 mN	3000–10000	Ultra-precise attitude control	10^{-5}–10^{-7}	Specialized UHV

It can be observed that the vacuum requirements of propulsion test facilities vary considerably according to the underlying propulsion mechanism. Neutral-gas-based propulsion systems primarily require reduced ambient pressure to reproduce nozzle expansion conditions encountered at high altitude and in space. In principle, maximum nozzle performance is achieved when the exhaust expands to the ambient pressure. However, reproducing the near-vacuum conditions of space would require extremely large nozzle expansion ratios. Practical spacecraft thrusters employ much smaller area ratios because of constraints imposed by nozzle length, structural mass, packaging volume, manufacturing complexity, and diminishing performance gains. Sutton and Biblarz report that only marginal increases in exhaust velocity are obtained by increasing the nozzle area ratio beyond approximately 1000, while expansion ratios greater than about 350 are generally impractical for flight systems [1]. Published cold-gas and resistojet thrusters typically employ nozzle area ratios between approximately 60 and 250 [17–19]. Consequently, these propulsion systems discharge at pressures substantially higher than the

surrounding space environment and can therefore be tested in facilities operating at pressures of several pascals to several hundred pascals without significant degradation of performance measurements.

In contrast, plasma-based propulsion systems accelerate charged particles using electrostatic and/or electromagnetic fields rather than by gas expansion through a nozzle. Their performance is therefore highly sensitive to the presence of residual neutral gas within the vacuum chamber. Elevated background pressures can modify ionization and acceleration processes, alter discharge characteristics, increase plume divergence, and influence measured thrust and specific impulse. Furthermore, charge-exchange collisions between energetic ions and background neutrals generate secondary ions that are absent under true space conditions and constitute one of the principal facility effects in electric-propulsion testing [20, 21]. Chamber walls, finite pumping capacity, and plume recirculation may further influence plasma behavior, contamination levels, and plume development [22, 23]. For these reasons, facilities used for testing plasma-based propulsion systems are typically operated at pressures several orders of magnitude lower than those required for neutral-gas-based propulsion systems, commonly in the range of 10^{-3}-10^{-5} Pa during operation and, in some cases, even lower [24, 25].

The preceding discussion explains the broad range of vacuum requirements summarized in Table 1 and illustrates why propulsion test facilities differ substantially in chamber volume, pumping capacity, and achievable operating pressure. These differing requirements have led to the development of specialized facilities optimized for particular classes of propulsion systems. The following section reviews representative propulsion vacuum test facilities reported in the literature and compares their capabilities with respect to chamber volume, achievable vacuum level, and intended application.

3. Major International Propulsion Vacuum Test Facilities

The wide range of vacuum requirements discussed in the previous section has led to the development of propulsion test facilities spanning several orders of magnitude in chamber volume, pumping capacity, and achievable pressure. These facilities have been established by national space agencies, defense organizations, research laboratories, and universities to support propulsion development, qualification, plume characterization, and endurance testing.

Representative facilities reported in the literature range from compact university laboratories intended for experimental investigations to large national-scale installations equipped with extensive cryogenic pumping systems and advanced diagnostic instrumentation. Their characteristics are largely dictated by the propulsion technologies for which they were designed, with electric-propulsion facilities generally emphasizing ultra-low background pressures and high pumping speeds, while facilities intended for chemical and electrothermal propulsion systems often prioritize altitude simulation, plume development, and thrust measurement.

The following survey presents representative international propulsion vacuum test facilities with emphasis on chamber dimensions, achievable vacuum levels, and intended applications. The objective is not to provide an exhaustive catalog of all existing facilities, but rather to illustrate the diversity of

propulsion-testing infrastructure currently in operation and to establish a basis for comparison with the facilities available in Türkiye.

3.1 Ground Simulation and Vacuum Test Infrastructure at TsNIIMash (Russia)[26]

The TsNIIMash has been one of the pioneering organizations in the development of propulsion vacuum-test infrastructure since its establishment in 1946. Over several decades, the institute has developed a series of dedicated vacuum facilities supporting the qualification and performance evaluation of satellite propulsion systems under simulated high-altitude and space-vacuum conditions. Rather than relying on a single universal chamber, TsNIIMash employs multiple test stands of varying dimensions to accommodate propulsion systems with different thrust levels, geometries, and experimental objectives.

For satellite-propulsion testing, the facilities are capable of maintaining an operating pressure of approximately 1×10^{-4} Torr during a nominal propellant mass flow rate of 0.02 g/s. These operating conditions are achieved using high-vacuum pumping systems providing effective pumping speeds between 10,000 and 15,000 L/s, referenced at a pressure of 1×10^{-5} torr under no-flow conditions.

The principal propulsion-test chambers include:

- **Stand 1**: Cylindrical chamber, 2.8 m diameter × 4.2 m length.
- **Stand 1M**: Cylindrical chamber, 1.0 m diameter × 7.0 m length.
- **Stand 2**: Cylindrical chamber, 3.0 m diameter × 4.0 m length.
- **Stand 1/2**: Cylindrical chamber, 1.5 m diameter × 4.0 m length.
- **VKK-16**: Large-scale simulation chamber, 2.5 m diameter × 8.5 m length.

The availability of multiple chambers with different dimensions demonstrates the modular approach adopted at TsNIIMash, whereby the facility configuration is selected according to the propulsion system under investigation. This approach provides operational flexibility while maintaining the vacuum conditions necessary for satellite propulsion development and qualification.

3.2 NASA Glenn Research Center (USA) – Electric Propulsion Research Building [27]

The NASA Glenn Research Center (formerly the Lewis Research Center) operates one of the world's most comprehensive collections of vacuum test facilities dedicated to electric propulsion research. The laboratory has developed multiple specialized vacuum chambers to support the development, characterization, qualification, and endurance testing of a wide range of electric propulsion systems, including hollow cathodes, pulsed plasma thrusters, ion engines, electrodeless thrusters, Hall-effect thrusters, and high-power electric propulsion devices. Rather than relying on a single facility, NASA Glenn

employs chambers of different sizes and pumping capacities, each optimized for a particular class of propulsion system.

The smaller research facilities are primarily intended for component development and laboratory-scale investigations. VF-1 is a cylindrical chamber measuring 1.5 m in diameter and 4.5 m in length, capable of achieving a base pressure of 3×10^{-7} torr with a nominal pumping speed of 40,000 L/s. The chamber is equipped as a fully automated hollow-cathode test facility. VF-2, having dimensions of 1.0 m diameter × 1.8 m length, supports pulsed plasma thrusters, electrodeless thrusters, and low-flow electric propulsion devices, operating at a base pressure of 1×10^{-6} torr with a pumping speed of approximately 1,950 L/s. VF-3, with dimensions of 1.5 m × 4.5 m, is dedicated to pulsed plasma thruster investigations and incorporates an integrated thrust-measurement system together with temperature control down to -100°C. The chamber achieves a base pressure of 4×10^{-7} torr and provides a pumping speed of approximately 80,000 L/s.

For higher-power propulsion systems, NASA Glenn operates several medium- and large-scale facilities. VF-7 is a 3.0 m diameter × 5.0 m long cylindrical chamber designed for high-power electric propulsion experiments, incorporating dedicated xenon feed systems and achieving a base pressure of 1×10^{-7} torr with a pumping speed of approximately 125,000 L/s. VF-11, measuring 2.2 m in diameter and 8.25 m in length, serves as an ion-propulsion test facility with integrated xenon supply capability and maintains a base pressure of 1×10^{-7} torr. VF-16, with dimensions of 2.75 m diameter × 8.5 m length, is equipped with cryogenic pumping systems capable of producing an ultimate pressure of approximately 7×10^{-8} torr, making it suitable for electrostatic propulsion testing.

The largest installation, VF-5 [28, 29], represents NASA Glenn's principal high-power electric propulsion test facility. The chamber is a horizontal cylinder 5.0 m in diameter and 20.0 m in length, corresponding to an internal volume of approximately 392 m^3. It achieves an ultimate pressure of 1×10^{-7} mbar and provides a xenon pumping speed approaching 700,000 L/s, enabling the chamber to maintain operating pressures of approximately 2×10^{-5} torr during high-flow testing. The facility supports qualification and performance evaluation of high-power Hall-effect thrusters, anode-layer thrusters, multi-thruster clusters, and electric propulsion systems operating in the 50 kW power class.

The wide range of chamber sizes and pumping capacities available at NASA Glenn illustrates the progressive scaling of electric-propulsion research infrastructure, from laboratory-scale component investigations to full-scale qualification of high-power propulsion systems. The facilities collectively demonstrate the stringent vacuum and pumping requirements associated with modern electric propulsion research.

3.3 Arnold Engineering Development Complex: 12V Space Chamber [30]

The 12V Space Chamber at the Arnold Engineering Development Complex is a thermal-vacuum facility that can be configured for spacecraft environmental testing as well as electric propulsion plume

characterization and integration studies. The facility combines high vacuum capability with thermal control and solar simulation, enabling ground-based reproduction of the space environment for propulsion-system evaluation.

The chamber is vertically oriented with an internal diameter of 3.66 m and a height of 10.67 m, corresponding to an internal volume of approximately 112 m^3. A full liquid nitrogen thermal shroud provides chamber wall temperatures down to 77 K, while an optional gaseous-helium liner enables thermal conditions approaching 10 K. An off-axis xenon-arc solar simulator is also available to produce a uniform one-solar-constant irradiance over the test volume for combined thermal-vacuum testing.

High-vacuum conditions are established using mechanical roughing pumps, Roots blowers, and a 36-inch diffusion pump equipped with cryogenic traps, allowing the chamber to achieve a base pressure below 1×10^{-7} torr. When configured for electric propulsion testing, the facility provides a xenon pumping speed exceeding 2×10^6 L/s, maintaining chamber pressures at or below 1×10^{-6} torr during thruster operation. The chamber is equipped with plume diagnostic instrumentation, including Langmuir probes and radio-frequency (RF) horns, for plasma characterization, plume-divergence measurements, and electromagnetic compatibility investigations.

The combination of thermal-vacuum capability, solar simulation, and exceptionally high xenon pumping capacity makes the 12V Space Chamber well suited for the performance evaluation, plume characterization, and environmental qualification of high-power electric propulsion systems

3.4 University of Michigan – Plasmadynamics and Electric Propulsion Laboratory (PEPL), USA [12]

The Plasmadynamics and Electric Propulsion Laboratory operates the Large Vacuum Test Facility (LVTF), one of the leading university-based research facilities dedicated to electric propulsion. The laboratory supports the development and experimental characterization of Hall-effect thrusters, CubeSat propulsion systems, nested Hall thrusters, and emerging electric propulsion technologies utilizing alternative propellants such as iodine and water.

The LVTF consists of a cylindrical vacuum chamber measuring 6.0 m in diameter and 9.0 m in length. The facility achieves an ultimate pressure of approximately 2×10^{-7} torr, while typical operating pressures during active thruster testing are maintained in the 10^{-6} torr range to minimize facility effects and enable representative electric-propulsion performance measurements.

In addition to fundamental academic research, the facility serves as a collaborative platform for government and industrial propulsion-development programs. Its combination of large chamber volume, high-vacuum capability, and advanced diagnostic instrumentation has made the LVTF an important experimental facility for the development and qualification of next-generation electric propulsion systems.

3.5 German Aerospace Center (DLR), Göttingen – High-Vacuum Plume Test Facility for Chemical Thrusters (STG-CT) [31]

The German Aerospace Center operates the High-Vacuum Plume Test Facility for Chemical Thrusters (STG-CT) at Göttingen for the experimental investigation of exhaust-plume characteristics from chemical and electrothermal propulsion systems. The facility is specifically designed to reproduce free-plume expansion under high-vacuum conditions while minimizing interference from chamber-wall reflections, making it well suited for plume diagnostics and validation of computational flow models.

The facility consists of a cylindrical vacuum chamber with an internal volume of approximately 10 m^3 and achieves a background pressure below 1×10^{-3} Pa under standby and cold-flow operating conditions. The chamber incorporates a liquid-helium cryogenic cold-wall system operating at approximately 4.2 K, which rapidly cryopumps condensable exhaust species such as nitrogen, water vapor, and carbon dioxide. This configuration effectively suppresses gas recirculation and wall-reflection effects, thereby providing a test environment that closely approximates free expansion into space.

The STG-CT facility supports the testing of cold-gas thrusters, monopropellant and bipropellant attitude-control thrusters, and low-power resistojets. Its emphasis on minimizing plume interference makes it particularly valuable for detailed studies of exhaust-plume structure, species distribution, and near-field plume behavior.

3.6 AEROSPAZIO Tecnologie – Large Vacuum Test Facility (Italy) [32]

The AEROSPAZIO Tecnologie operates a Large Vacuum Test Facility (LVTF) developed to support the ground qualification and performance evaluation of high-power electric propulsion systems under simulated space conditions. The facility was originally described by Scortecci[32][32] and was conceived as an independent European test infrastructure for electric-propulsion development, combining a large test volume with high xenon pumping capability.

The facility consists of a horizontal stainless-steel vacuum chamber measuring 3.8 m in diameter and 11.5 m in length, providing an internal volume of approximately 130 m^3. Initial evacuation is accomplished using a turbodrag pumping system comprising a 1000 L/s turbomolecular pump backed by a 30 m^3/h dry pump, allowing the chamber to reach pressures of approximately 10^{-5} mbar without the use of cryogenic pumping. Final evacuation is achieved using a dedicated cryogenic pumping system with a nominal pumping speed of approximately 20,000 L/s for air, producing an ultimate static pressure in the 10^{-7} mbar range.

For electric-propulsion operation, the facility employs a modular high-capacity cryopumping system specifically optimized for xenon exhaust. Under thruster operating conditions, the effective xenon

pumping speed ranges between 175,000 and 215,000 L/s, enabling stable low-background-pressure testing of high-power electric propulsion devices while minimizing facility effects arising from residual propellant gas.

The combination of a large chamber volume, dedicated xenon cryopumping system, and flexible pumping architecture makes the AEROSPAZIO Tecnologie LVTF an important European facility for the development, qualification, and experimental investigation of advanced electric propulsion systems.

3.7 David Fearn Electric Propulsion Laboratory, University of Southampton (United Kingdom) [33]

The University of Southampton operates the David Fearn Electric Propulsion Laboratory, a university-based research facility dedicated to the development and long-duration testing of electric propulsion systems. The laboratory is designed to provide a flexible thermal-vacuum environment for propulsion research, supporting repeated operational cycling, endurance testing, and comprehensive instrumentation of experimental thrusters.

The facility comprises a main cylindrical vacuum chamber measuring 2.0 m in diameter and 4.0 m in length, together with a 0.75 m diameter × 0.7 m long loading chamber. The two chambers are separated by a pneumatically actuated gate valve, allowing rapid exchange of test hardware without venting the main vacuum chamber, thereby reducing preparation time between successive experiments. The loading chamber is evacuated using a Leybold TURBOVAC MAG W700 iP turbomolecular pump backed by an Edwards XDS 35i dry scroll pump.

The vacuum system provides pressure measurement over the range of 5×10^{-9} to 1000 mbar, enabling experiments covering both high-vacuum and moderate-vacuum operating conditions. During resistojet endurance investigations, the chamber was operated at pressures of approximately 10^{-1} mbar (10 Pa) or lower. This operating regime demonstrates that, unlike plasma-based electric propulsion systems requiring ultra-high vacuum throughout testing, electrothermal propulsion devices such as resistojets can be evaluated successfully at comparatively higher chamber pressures while still maintaining representative thermal-vacuum conditions.

The facility illustrates the versatility of modern university laboratories in supporting electric and electrothermal propulsion research through modular chamber design, efficient vacuum operation, and long-duration experimental capability.

3.8 Lanzhou Institute of Physics (LIP) / CAST (China) [34]

The Lanzhou Institute of Physics (LIP) of the China Academy of Space Technology (CAST) operates a dedicated electric propulsion test facility for the qualification, performance evaluation, and lifetime assessment of spacecraft electric propulsion systems. The facility has been extensively employed for the development and long-duration validation of Chinese gridded ion thrusters and Hall-effect thrusters developed for satellite propulsion and the Tiangong Space Station programme.

The facility incorporates a dual-zone vacuum chamber configuration consisting of a cylindrical accessory chamber measuring 2.0 m in diameter and 2.0 m in length, in which the thruster is installed, coupled to a larger main plume chamber measuring 4.5 m in diameter and 10.0 m in length. This arrangement provides adequate space for free plume expansion while reducing the influence of chamber-wall interactions on plume diagnostics and performance measurements.

The vacuum system achieves an ultimate pressure of approximately 1×10^{-7} mbar under no-flow conditions. During active thruster operation, six internal cryopumps maintain an operating pressure of approximately 1×10^{-4} Pa, providing the low-background-pressure environment required for high-power electric propulsion testing and minimizing facility effects associated with residual neutral gas.

A distinguishing feature of the facility is its capability for long-duration endurance testing, having supported qualification campaigns exceeding 6,500 hours for Chinese LIPS-200 and LIPS-300 gridded ion thrusters, in addition to the evaluation of high-power Hall-effect thrusters for space applications. The combination of a dual-chamber configuration, high cryopumping capacity, and long-duration operational capability makes the facility one of China's principal research infrastructures for electric propulsion development.

3.9 Joint Laboratory of Plasma Propulsion (JLPP), Beihang University (China) [35]

The Joint Laboratory of Plasma Propulsion (JLPP) at Beihang University has established a comprehensive vacuum-testing infrastructure to support research on a broad range of spacecraft propulsion technologies. Rather than relying on a single experimental facility, the laboratory operates several specialized vacuum chambers optimized for different propulsion concepts, power levels, and thermal-vacuum environments. Collectively, these facilities support experimental investigations of Hall-effect thrusters, pulsed plasma thrusters (PPTs), magnetoplasmadynamic (MPD) thrusters, ion thrusters, arcjets, helicon thrusters, air-breathing electric propulsion (ABEP), VASIMR concepts, colloidal thrusters, and cold-gas propulsion systems.

The principal research facility is the DWB-2500 Vacuum Chamber, a cylindrical chamber measuring 2.5 m in diameter and 5.5 m in length. The chamber achieves a base pressure below 1×10^{-5} Pa and maintains an operating pressure better than 4×10^{-5} Pa through the use of cryopumps and liquid-nitrogen shrouds. It serves as the primary experimental platform for the development and characterization of Hall-effect thrusters, pulsed plasma thrusters, magnetoplasmadynamic thrusters, and air-breathing electric propulsion concepts.

To support thermal-vacuum qualification, the laboratory also operates a high- and low-temperature thermal-vacuum chamber measuring 0.8 m in diameter and 1.0 m in length. The facility maintains a pressure of approximately 1.3×10^{-3} Pa while providing a controllable temperature range from − 196°C to + 150°C, enabling thermal-vacuum testing of pulsed plasma thrusters, colloidal thrusters, and other propulsion components under representative space-environment conditions.

A comprehensive propulsion vacuum chamber, measuring 2.5 m in diameter and 5.5 m in length, is employed for experimental investigations of a wide variety of propulsion systems. Equipped with four rotary-vane pumps, one Roots pump, and two oil-diffusion pumps, the chamber achieves an ultimate pressure of approximately 1×10^{-4} Pa and has been used for testing MPD thrusters, arcjets, pulsed plasma thrusters, ion thrusters, VASIMR concepts, and cold-gas propulsion systems.

The laboratory further operates the MPC-1500 (Molecular Pump Chamber-1500), a compact facility measuring 1.5 m in diameter and 1.5 m in length. Equipped with two mechanical pumps and two molecular pumps, the chamber achieves an ultimate pressure of approximately 2×10^{-4} Pa and is primarily dedicated to the investigation of helicon thrusters and air-breathing electric propulsion systems.

The availability of multiple specialized vacuum chambers allows JLPP to support experimental research across an exceptionally broad spectrum of electric and auxiliary propulsion technologies. This modular laboratory infrastructure provides considerable flexibility for propulsion development, component qualification, and technology demonstration within a university research environment.

3.10 JAXA Electric Propulsion Endurance Test Facility (Japan) [36]

The Japan Aerospace Exploration Agency operates a dedicated Electric Propulsion Endurance Test Facility for the long-duration ground verification and qualification of microwave-discharge ion engines. The facility has been developed to support continuous, automated endurance testing under representative space-vacuum conditions, enabling extended operational campaigns for spacecraft electric propulsion systems.

The facility consists of a cylindrical vacuum chamber measuring 2.0 m in diameter and 5.0 m in length, corresponding to an internal volume of approximately 15.7 m^3. The chamber is evacuated using four 800-mm cryogenic pumps, which maintain a dynamic background pressure below 2×10^{-4} Pa during active thruster operation. To minimize facility effects arising from plume backscattering, the chamber incorporates a titanium shroud together with a dedicated beam dump maintained at approximately −40°C, providing efficient absorption of plasma exhaust and reducing reflected particle flux.

The facility is specifically configured for automated endurance evaluation of microwave discharge ion engines, allowing continuous long duration operation with comprehensive monitoring of thruster performance. Its specialized vacuum system and plume management design make it particularly suitable for lifetime qualification and reliability assessment of electric propulsion systems intended for long-duration space missions.

3.11 JAXA Akiruno Experiment Laboratory (Japan) [37]

The Akiruno Experiment Laboratory of the Japan Aerospace Exploration Agency provides a dedicated experimental facility for the development and performance evaluation of electrothermal propulsion

systems. Unlike large electric-propulsion test facilities designed to achieve ultra-high vacuum, the laboratory is configured specifically for resistojet investigations, where comparatively higher chamber pressures are sufficient for propulsion characterization.

The facility utilizes a vacuum chamber with an internal volume of approximately 6 m^3, evacuated by two ULVAC explosion-proof vacuum pumps with individual pumping capacities of 1600 L/min. The pumping system produces an ultimate pressure of approximately 5 kPa, which has been demonstrated to be adequate for experimental studies of hydrogen resistojets despite being considerably higher than the vacuum levels typically required for plasma-based electric propulsion.

To support accurate propulsion performance measurements, the chamber incorporates a double-pendulum thrust stand equipped with a 5 N load cell, providing a thrust measurement accuracy of approximately ± 27.6 mN. The experimental facility also includes a dedicated low-mass-flow hydrogen feed system incorporating redundant pneumatic isolation valves and a precision mass-flow meter to ensure stable and repeatable propellant delivery during testing.

The Akiruno facility illustrates that electrothermal propulsion systems, particularly resistojets, can be effectively characterized without the ultra-high-vacuum conditions demanded by Hall-effect thrusters and ion engines. This distinction highlights the wide variation in vacuum requirements among different classes of spacecraft propulsion systems.

3.12 ISAS Large Space Science Chamber (Japan) [38]

The Large Space Science Chamber at the Institute of Space and Astronautical Science (ISAS), Japan, is a dedicated vacuum facility for the experimental investigation of electric propulsion systems and space plasma phenomena. The chamber has been extensively employed for the characterization of Hall-effect thrusters and other low- to medium-power electric propulsion devices, with particular emphasis on plume diagnostics, discharge stability, and magnetic field optimization.

The facility consists of a horizontal cylindrical vacuum chamber measuring 2.5 m in diameter and 5.0 m in length, corresponding to an internal volume of approximately 24.5 m^3. The vacuum system employs a dedicated xenon cryopump in conjunction with a liquid-nitrogen cryogenic shroud, providing efficient removal of propellant gases and maintaining a dynamic background pressure of approximately 7.9×10^{-4} Pa during active thruster operation. The combination of cryogenic pumping and thermal shielding minimizes facility effects arising from residual propellant gas and plume recirculation.

The chamber is equipped to support advanced plasma diagnostics and has been used to investigate the discharge characteristics, magnetic-field configuration, and plume properties of 100 W class Hall-effect thrusters. Its combination of high-vacuum capability, efficient xenon pumping, and comprehensive diagnostic instrumentation makes the facility well suited for the development and experimental evaluation of low- and medium-power electric propulsion systems.

The reviewed facilities illustrate how propulsion-testing infrastructure has evolved to meet the diverse requirements of chemical and electric propulsion systems. While large national laboratories continue to dominate qualification and endurance testing, smaller research-oriented facilities remain essential for technology development, experimental investigations, and academic research. This distinction is particularly relevant when considering the current state of propulsion vacuum-testing infrastructure in Türkiye, where capabilities are distributed among defense organizations, research institutions, and a limited number of universities. The following section presents a survey of the principal propulsion vacuum test facilities currently available in the country.

4. Vacuum Test Infrastructure for Space Propulsion Research in Türkiye

Türkiye has developed a growing vacuum-testing infrastructure supporting both spacecraft environmental qualification and propulsion-system development. Existing facilities can generally be divided into thermal-vacuum systems used for spacecraft environmental testing and propulsion-oriented vacuum chambers designed for the evaluation of rocket and spacecraft thrusters under reduced pressure conditions.

Although Thermal-vacuum testing facilities are available at institutions such as İstanbul Technical University (ITU) [39], TÜBİTAK UZAY [40], and TUSAŞ [41], these systems are primarily intended for spacecraft environmental qualification and are therefore outside the scope of the present review. The discussion that follows is restricted to vacuum facilities specifically employed for propulsion-system development, characterization, and altitude-simulation testing.

Currently, the principal propulsion-oriented vacuum test facilities reported in the open literature are located at ROKETSAN, Boğaziçi University, and Sivas Bilim ve Teknoloji Üniversitesi. These facilities provide capabilities ranging from electric-propulsion experimentation to cold-gas thruster development and altitude-simulation research.

4.1 ROKETSAN Propulsion Vacuum Test Facility [42]

ROKETSAN has developed a dedicated vacuum test facility for the experimental evaluation of spacecraft cold-gas propulsion systems. The facility, designed and manufactured using national resources and Turkish subcontractors, incorporates a vacuum chamber with an internal volume of approximately 3.1 m^3. The chamber is evacuated using a dedicated pumping system capable of achieving pressures as low as 5 Pa, thereby enabling the simulation of high-altitude and near-space operating environments. Real-time pressure and temperature instrumentation are integrated within the chamber to monitor environmental conditions during testing.

The facility supports complete propulsion-system performance characterization, including measurements of chamber pressure, propellant temperature, mass flow rate, and thrust. The reported

experimental campaign involved a 10 N-class cold-gas thruster operating at a nominal chamber pressure of 1 MPa, with the vacuum chamber maintained at approximately 200 Pa during testing. A dedicated thrust frame and precision load-cell system permit accurate thrust measurements while minimizing mechanical interference. The facility is therefore well suited for the development, validation, and performance assessment of cold-gas attitude-control and reaction-control propulsion systems for spacecraft applications.

4.2 Boğaziçi University Space Technologies Laboratory (BUSTLab) [43]

The Boğaziçi University Space Technologies Laboratory (BUSTLab) operates a dedicated vacuum facility for the development and testing of spacecraft electric propulsion systems. The primary test chamber is a cylindrical vacuum vessel measuring 1.5 m in diameter and 2.7 m in length, providing a controlled environment for propulsion experiments and performance characterization. The facility is designed to simulate the low-pressure conditions encountered in low Earth orbit and supports the testing of electric propulsion systems utilizing xenon and argon propellants.

The vacuum system incorporates a mechanical roughing pump capable of maintaining pressures on the order of 1×10^{-3} torr. Following the integration of a cryogenic pumping system and associated cooling infrastructure, ultimate pressures approaching 1×10^{-8} torr can be achieved, enabling experiments that require high-vacuum conditions and reduced facility effects. The chamber is equipped with an internal experimental platform that provides a rigid mounting interface for propulsion hardware, diagnostic instrumentation, and auxiliary test equipment. The facility supports research activities related to electric propulsion development, thruster performance evaluation, plume characterization, and technology maturation for spacecraft applications.

4.3 Sivas Bilim ve Teknoloji Üniversitesi Vacuum Test Facility

The Sivas Bilim ve Teknoloji Üniversitesi Vacuum Test Facility is a medium-scale vacuum chamber developed for altitude-simulation experiments and propulsion-system research. This facility consists of a custom-designed stainless-steel vacuum chamber with internal dimensions of 1.35 m × 1.35 m × 1.95 m, corresponding to an internal volume of approximately 3.55 m³. The chamber incorporates multiple instrumentation ports, electrical and fluid feedthroughs, optical viewing windows, internal illumination, programmable pressure-control capability, and automated venting and safety systems.

Vacuum generation is provided by four Busch Zebra RH0090 oil-sealed rotary vane pumps operating in parallel. Each pump has a nominal pumping speed of 80 $m^3\ h^{-1}$, resulting in a combined pumping capacity of approximately 320 $m^3\ h^{-1}$. The pumps utilize mineral oil lubrication and are suitable for operation with air, water vapor, and a wide range of non-corrosive process gases, including nitrogen, oxygen, and noble gases. The pumping system was specified by the manufacturer to achieve a minimum operating pressure of 3 Pa, which was subsequently demonstrated during facility commissioning.

Pressure measurement is performed using three Pfeiffer CCR-series capacitance diaphragm gauges (Baratron type) covering different pressure ranges: CCR361 (1000 Torr full scale), CCR363 (10 Torr full scale), and CCR365 (0.1 Torr full scale). The use of multiple gauges enables accurate pressure measurement from atmospheric conditions to the facility's minimum operating pressure. In particular, the CCR365 gauge has a full-scale range of 0.1 Torr (13.3 Pa), allowing reliable measurement of chamber pressures near the demonstrated minimum pressure of 3 Pa.

The facility is equipped with a computer-based control system that continuously monitors chamber pressure and regulates the operation of the vacuum pumps and control valves. This system permits the chamber pressure to be maintained at any prescribed value within the operating range rather than merely achieving the minimum attainable pressure. Such pressure-hold capability is particularly valuable for altitude-simulation studies and propulsion-system testing, where a constant backpressure corresponding to a specified flight altitude may be required. By operating at elevated controlled pressures, the facility can accommodate substantially higher propellant mass flow rates while maintaining stable test conditions.

The chamber is additionally equipped with high-current electrical feedthroughs rated up to 470 A and 8 kV DC, signal feedthroughs, fluid pass-through connections, and multiple reserve ports for future instrumentation and facility expansion. Owing to its volume, pumping capacity, programmable pressure-control capability, and moderate-vacuum performance, the facility is suitable for investigations involving cold-gas thrusters, warm-gas thrusters, resistojets, reaction-control systems, nozzle-flow experiments, and other propulsion technologies requiring controlled low-pressure environments.

The survey indicates that Türkiye possesses a diverse, albeit limited, propulsion-testing infrastructure encompassing both industrial and university-based facilities. These facilities occupy different positions within the spectrum of propulsion-testing capability, ranging from electric-propulsion experimentation to cold-gas thruster development and altitude-simulation research. Their characteristics suggest that meaningful propulsion research can be conducted without necessarily relying on the large national-scale facilities commonly associated with electric-propulsion qualification. To place these observations in a broader context, the following section compares Turkish and international facilities in terms of chamber volume, vacuum capability, and intended application, with particular attention given to the niche occupied by medium-scale university vacuum chambers.

5. Comparative Analysis of Propulsion Vacuum Test Facilities

The propulsion vacuum test facilities reviewed in the preceding sections exhibit significant variation in chamber dimensions, vacuum performance, pumping capacity, and intended applications. While the individual facility descriptions highlight the capabilities of specific installations, a comparative assessment provides a broader understanding of the design philosophies adopted for different classes of propulsion systems. Among the various facility parameters, chamber volume and achievable vacuum level are particularly important because they govern background pressure, facility effects, plume

expansion, pumping requirements, and ultimately the range of propulsion systems that can be accommodated. Figure 1 compares representative international and Turkish propulsion vacuum facilities using chamber volume and ultimate vacuum pressure as the principal comparison parameters.

Figure 1 reveals that propulsion vacuum facilities occupy a wide range of chamber volumes and attainable vacuum levels, reflecting the diverse requirements of different propulsion technologies. Although larger facilities generally possess greater pumping capacities and provide improved mitigation of facility effects, no direct correlation exists between chamber volume and achievable vacuum pressure. Instead, facility characteristics are primarily determined by the propulsion systems for which they are intended. Facilities dedicated to electric propulsion are concentrated in the ultra-high-vacuum region because of the stringent background-pressure requirements associated with Hall-effect thrusters, ion engines, and other plasma-based propulsion devices. In contrast, facilities designed for cold-gas thrusters, resistojets, monopropellant and bipropellant thrusters, and altitude simulation generally operate at substantially higher pressures. The comparison further shows that medium-scale university facilities occupy an important intermediate region, providing sufficient capability for propulsion research and technology development while avoiding the complexity and cost associated with large national test facilities.

Facility Key: (1) TsNIIMash–Stand 1; (2) TsNIIMash–Stand 1M; (3) TsNIIMash–Stand 2; (4) TsNIIMash–VKK-16; (5) TsNIIMash–Stand 1/2; (6) NASA Glenn VF-1; (7) NASA Glenn VF-2; (8) NASA Glenn VF-3; (9) NASA Glenn VF-5; (10) NASA Glenn VF-7; (11) NASA Glenn VF-11; (12) NASA Glenn VF-16; (13) AEDC 12V Space Chamber; (14) University of Michigan Large Vacuum Test Facility (LVTF); (15) DLR Göttingen STG-CT Facility; (16) Aerospazio Tecnologie Large Vacuum Test Facility (LVTF); (17) University of Southampton Vacuum Test Facility; (18) Large-scale Ion Propulsion (LIP) Facility, China; (19) JLPP DWB-2500; (20) JLPP TVC; (21) JLPP CVC; (22) JLPP MPC-1500; (23) JAXA Electric Propulsion Test Facility; (24) JAXA Akiruno Vacuum Test Facility; (25) ISAS Large Space Science Chamber; (26) Boğaziçi University Space Technologies Laboratory (BUSTLab); (27) ROKETSAN Cold Gas Propulsion Test Facility; and (28) Sivas Bilim ve Teknoloji Üniversitesi (SBTÜ) Vacuum Test Facility.

5.1 Suitability of Medium-Scale Vacuum Chambers for Nozzle-Based Propulsion Systems

The comparative assessment presented in the previous section demonstrates that propulsion vacuum test facilities span a wide range of chamber volumes and achievable vacuum levels. This diversity reflects the differing requirements of neutral-gas-based and plasma-based propulsion systems. Large national facilities are primarily designed to support plasma-based propulsion systems qualification, plume characterization, and long-duration endurance testing under high and ultra-high vacuum conditions. In contrast, medium scale facilities occupy an important niche for the experimental investigation of neutral-gas-based propulsion systems.

As discussed in Section 2, practical spacecraft thrusters employing nozzle expansion typically operate with moderate nozzle expansion ratios and exhaust pressures substantially higher than the surrounding space environment. Consequently, meaningful performance characterization does not generally require reproduction of the extremely low background pressures needed for plasma-based propulsion systems. Instead, vacuum chamber pressures ranging from a few pascals to several hundred pascals are often sufficient to minimize ambient backpressure effects while providing representative nozzle-flow conditions.

The facility survey further shows that university scale vacuum chambers commonly operate within this pressure range while offering significantly lower infrastructure cost and operational complexity than national-scale electric-propulsion facilities. Such chambers are therefore well suited for propulsion-system development, nozzle-flow investigations, thrust characterization, altitude-simulation experiments, and educational research involving neutral-gas-based propulsion technologies.

These observations motivate the analytical assessment presented in the following section, where the operating limits of a representative medium scale vacuum chamber are quantified in terms of continuous operating capability, intermittent operation, allowable propellant mass flow rate, and achievable thrust levels.

6. Analytical Assessment of the Representative Vacuum Chamber

The preceding sections established that medium-scale vacuum chambers are well suited for the experimental investigation of neutral-gas-based propulsion systems. However, the practical operating limits of such facilities are governed by the interaction between the propellant mass flow rate, chamber volume, pumping capacity, and allowable background pressure. These parameters determine whether a propulsion system can be operated continuously at a prescribed vacuum level or only for a finite duration before the chamber pressure exceeds the permissible limit.

To quantify these operating limits, a generalized mathematical model is developed based on conservation of mass for a pumped vacuum chamber. The resulting analytical expressions are applicable to any vacuum facility operating with continuous gas injection and mechanical pumping, independent of chamber size or propulsion system. The equations are subsequently applied to the representative vacuum chamber described in Section 4 to determine its continuous and intermittent operating capabilities for representative propulsion gases.

The analysis is presented in four parts. Section 6.1 derives the governing equations describing pressure evolution in a mechanically pumped vacuum chamber. Sections 6.2 and 6.3 apply these equations to evaluate the continuous and intermittent operating limits of the representative facility in terms of allowable propellant mass flow rates and pulse durations. Finally, Section 6.4 translates these operating limits into representative thrust capabilities for typical nozzle-based propulsion systems, providing a practical assessment of the propulsion-testing envelope of the SBTÜ vacuum chamber.

6.1 Governing Equations for Pressure Evolution in a Pumped Vacuum Chamber

The operational capability of a propulsion vacuum test facility is governed by the dynamic balance between the rate at which propellant gases are introduced into the chamber during thruster operation and the rate at which these gases are removed by the vacuum pumping system. This balance determines both the steady-state pressure attained during continuous operation and the transient pressure variation that occurs during intermittent operation. A generalized mathematical model applicable to both operating modes is therefore developed in this section.

The analysis is based on the ideal-gas relationship together with conservation of mass for a well-mixed vacuum chamber of constant volume. The gas within the chamber is assumed to remain at a uniform temperature, while the pumping speed is considered constant over the operating pressure range of interest. These assumptions are appropriate for the present first-order engineering analysis and provide analytical expressions that are readily applicable to propulsion vacuum test facilities of different sizes and pumping capacities.

The Operational time can be evaluated by analyzing the Ideal gas equation

$$PV = n\,RT\,(1)$$

Where *P* is the pressure in vacuum chamber *V* is its volume n is number of moles present in the vacuum chamber *R* is universal gas constant and *T* is the temperature of gases in the vacuum chamber. Assuming that the temperature remains constant the pressure in vacuum chamber can change only due to the change in number of moles in the chamber which can occur by the injection of gases while testing a thruster and removal of gases through the operation of the vacuum pumps. Differentiating the ideal gas equation with respect to time we get

$$V\frac{dP}{dt} = RT\frac{dn}{dt}(2)$$

Where dP/dt represents the rate of pressure change with time and dn/dt is the rate of change of number of moles. The rate of change of number of moles can be expressed as

$$\frac{dn}{dt} = \frac{\dot{m}}{M} - \frac{\rho\,S}{M}(3)$$

The first term on right hand side shows the rate of addition of number of moles from the operation of thruster with a mass flow rate exhaust of $\dot{m}$ and molecular weight of *M*. the second term shows the rate of removal of moles by the vacuum pumps. With ρ denoting the density of gas inside the vacuum chamber, and *S* as volumetric rate of gas removal by the pumps in m^3/s. Using ideal gas equation again for the density in this equation the rate of change of moles can be shown as

$$\frac{dn}{dt} = \frac{\dot{m}}{M} - \frac{PS}{RT}(4)$$

Using this equation, the rate of change of pressure can be expressed as

$$\frac{dP}{dt} = \frac{RT\dot{m}}{MV} - \frac{S}{V}P \quad (5)$$

For a steady operation dP/dt must be equal to zero. And in this case the steady state pressure can be expressed as

$$P_{SS} = \frac{RT\dot{m}}{MS} \quad (6)$$

In Eq. (6), R = 8.314 J/mol K, T is expressed in Kelvin, $\dot{m}$ in kg/s, *M* in kg/mol, *S* in m^3/s and the resulting steady-state pressure P_{SS} is obtained in Pa.

The thruster mass flow rate can be expressed as

$$\dot{m} = \frac{MSP_{SS}}{RT} \quad (7)$$

To analyze the transient behavior of the pressure in vacuum chamber with thruster mass flow rate, it can be noticed that Eq. (5) is a first order linear differential equation and it can be solved to show the variation of pressure with time as

$$P(t) = \frac{RT\dot{m}}{MS} + \left(P_0 - \frac{RT\dot{m}}{MS}\right) e^{-\frac{S}{V}t} \quad (8)$$

Here P_0 is the pressure at time *t = 0*. The time taken to reach a final pressure of $P(t)$ when the thruster is exhausting and pumps are also running can be expressed as

$$t = -\frac{V}{S} ln\left(\frac{P(t)-P_{SS}}{P_0-P_{SS}}\right) \quad (9)$$

The governing equations obtained above provide a general description of pressure evolution in a pumped vacuum chamber subjected to continuous gas injection. Eq. (6) establishes the steady-state chamber pressure corresponding to a specified propellant mass flow rate, while Eq. (7) determines the maximum allowable mass flow rate for a prescribed operating pressure. Equations (8) and (9) describe the transient approach to equilibrium and enable the time required to reach any specified chamber pressure to be determined.

Throughout the present analysis, the operational capability of the vacuum chamber is expressed in terms of propellant mass flow rate rather than thrust. While the mass flow rate is determined directly by the vacuum pumping capacity and chamber operating conditions, the thrust produced by a propulsion system also depends on factors such as chamber pressure, nozzle geometry, expansion ratio, operating temperature, nozzle efficiency, and propellant thermodynamic properties. Consequently, the mass-flow-rate limits derived in this study provide a generalized and facility-independent measure of vacuum-chamber capability that is applicable to a broad range of nozzle-based propulsion systems. The governing equations developed above are applied in the following subsections to evaluate the

continuous and intermittent operating limits of a representative medium-scale propulsion vacuum chamber.

These analytical expressions form the basis for evaluating the operating limits of propulsion vacuum test facilities. In the following subsections, they are applied to two practically important operating modes, which are, continuous operation, in which the chamber pressure is maintained at a specified steady value during sustained thruster firing, and intermittent operation, in which the chamber is initially evacuated to its lowest attainable pressure and the thruster is operated only until a prescribed maximum chamber pressure is reached.

6.2 Continuous Operation Mode

During continuous operation, the chamber pressure gradually approaches a steady-state value at which the rate of propellant injection from the thruster equals the rate of gas removal by the vacuum pumping system. Under this condition, the chamber pressure remains constant and is given by Eq. (6). The governing relation indicates that the steady-state pressure increases with propellant mass flow rate and gas temperature, while it decreases with pumping speed and molecular weight. Consequently, for a prescribed operating pressure, higher mass flow rates can be accommodated either by increasing the pumping speed or by using propellants with higher molecular weight. Rearrangement of Eq. (6) yields Eq. (7), which directly determines the maximum allowable continuous mass flow rate for a specified chamber operating pressure.

Both the steady-state mass flow rate and the transient pressure response depend on the gas temperature within the vacuum chamber. In practice, however, the exhaust gases discharged from the thruster undergo rapid expansion into the low-pressure chamber environment and exchange heat with the chamber walls, making the effective gas temperature difficult to predict without detailed gas-dynamic and heat-transfer analyses. Such analyses are beyond the scope of the present study. Accordingly, a representative chamber-gas temperature equal to the ambient laboratory temperature (T = 300 K) is assumed for all calculations presented herein.

Figure 2 illustrates the steady-state relationship between the allowable propellant mass flow rate and chamber pressure for representative propellant gases, assuming a pumping speed of 0.089 m³/s and a chamber-gas temperature of 300 K. The results demonstrate that the allowable mass flow rate is directly proportional to the molecular weight of the propellant. Since the vacuum pumping system removes an approximately constant volumetric flow rate, the corresponding molar flow rate remains nearly constant, while the allowable mass flow rate increases with molecular weight. Therefore xenon permits the highest continuous mass flow rate, followed by butane, argon, nitrogen, and helium.

Figure 2 confirms the linear relationship predicted by Eq. (7) between the allowable continuous mass flow rate and the selected steady-state chamber pressure. For all propellant gases, increasing the permissible operating pressure allows proportionally higher continuous mass flow rates to be sustained

by the vacuum pumping system. At any given operating pressure, the allowable mass flow rate increases with molecular weight because the vacuum pumps remove a nearly constant volumetric flow of gas. And hence heavier propellants such as xenon and butane permit substantially higher continuous mass flow rates than lighter gases such as helium, even though the corresponding molar flow rates remain nearly the same.

An important observation from Eq. (7) and Fig. 2 is that the chamber volume does not influence the steady-state operating condition. The maximum continuous mass flow rate is determined solely by the pumping speed, gas properties, operating temperature, and the selected chamber pressure. Chamber volume affects only the transient response of the chamber pressure, that is, the time required to reach the steady-state condition. Nevertheless, the physical dimensions of the chamber remain important for practical propulsion testing, as they influence plume expansion, interactions between the exhaust plume and chamber walls, diagnostic accessibility, and the minimization of facility effects.

6.3 Intermittent (Pulse) Operation Mode

The steady-state analysis presented in the previous section demonstrates that continuous operation is fundamentally limited by the pumping capacity of the vacuum facility. For a specified operating pressure, the allowable propellant mass flow rate cannot exceed the value predicted by Eq. (7). In practice, however, many propulsion experiments do not require continuous thruster operation. Performance parameters such as thrust, specific impulse, plume structure, and valve characteristics can often be measured during relatively short firing intervals. Under such conditions, the vacuum chamber may first be evacuated to its lowest attainable pressure, after which the thruster is operated only until a prescribed maximum chamber pressure is reached. This operating strategy, commonly referred to as intermittent or pulse-mode operation, significantly expands the range of propellant mass flow rates that can be investigated using a given vacuum facility.

The pressure variation within the vacuum chamber during pulse operation is described by Eq. (8), which may be rewritten as

$$P\left(t\right) = P_{SS} + \left(P_0 - P_{SS}\right) e^{-\frac{t}{\tau}} \quad (10)$$

where the characteristic response time is

$$\tau \; = \frac{V}{S} (11)$$

The characteristic response time, $\tau \; = V/S$ represents the time scale over which the chamber pressure approaches its steady-state value. It depends solely on the chamber volume and the effective pumping speed and is independent of the propellant gas or its mass flow rate. Larger chamber volumes increase the response time by storing a greater quantity of gas before a significant pressure rise starts occurring, whereas higher pumping speeds reduce the response time by removing gas more rapidly. For the SBTÜ vacuum chamber, having a volume of 3.55 m³ and an effective pumping speed of 0.089 m³/s,

the response time is $\tau = 3.55/0.089 = 39.9\ s$ indicating that the chamber pressure responds on a characteristic time scale of approximately 40 s.

Equation (9) can be used to determine the allowable operating time of a thruster when the chamber pressure is permitted to increase from an initial pressure P_0 to a specified maximum pressure P_{max}. Rearranging Eq. 10 yields

$$t = -\tau\ ln\left(\frac{P_{max}-P_{SS}}{P_0-P_{SS}}\right) (12)$$

Where P_{SS} can be obtained using Eq. (6).

Equation (12) provides the allowable operating time for a prescribed maximum chamber pressure. The pulse duration is governed by the chamber volume, pumping speed, propellant mass flow rate, molecular weight, gas temperature, initial chamber pressure, and the selected maximum operating pressure. Collectively, these parameters determine the rate at which the chamber pressure approaches the prescribed pressure limit during thruster operation.

The allowable operating durations for intermittent operation of the SBTÜ vacuum chamber using argon as a representative propellant are presented in Table 2. For each selected propellant mass flow rate, the corresponding steady-state chamber pressure was first calculated using Eq. (6). The allowable pulse duration was then determined from Eq. (12) by assuming that the chamber is initially evacuated to 3 Pa and allowing the chamber pressure to increase to prescribed limiting values of 100, 200, 300, 400, and 500 Pa.

The results demonstrate that the steady-state pressure associated with a given mass flow rate is often considerably higher than the selected chamber-pressure limit. Under continuous operation, such conditions would therefore be unacceptable because the chamber would eventually stabilize at a pressure well above the allowable value. However, under intermittent operation, the chamber pressure increases only gradually toward its steady-state value. Thus, the thruster may be operated for a finite but practically useful duration before the chamber pressure reaches the prescribed limit.

This behavior substantially extends the operating envelope of the facility. For example, a propellant mass flow rate of 1.0 g/s corresponds to a steady-state pressure of approximately 701 Pa, which exceeds all of the selected pressure limits. Nevertheless, the chamber can still accommodate pulse durations of approximately 6 s, 13 s, 22 s, 34 s, and 50 s for limiting vacuum chamber pressures of 100, 200, 300, 400, and 500 Pa, respectively. Similar trends are observed throughout the table, indicating that intermittent operation permits significantly higher propellant mass flow rates than would be possible under continuous operation while maintaining acceptable vacuum chamber-pressure limits.

Table 2
Steady-state chamber pressures and allowable pulse durations for intermittent operation of the SBTÜ vacuum chamber with argon as the representative propellant.

S. No.	$\dot{m}$ (g/s)	P_{cS} (Pa)	Pulse duration (s) at limiting chamber pressure				
			100 Pa	200 Pa	300 Pa	400 Pa	500 Pa
1	0.15	105	118.6				
2	0.20	140	42.7				
3	0.25	175	33.0				
4	0.30	210	25.2	119.2			
5.	0.35	246	20.4	66.7			
6.	0.40	281	17.2	49.3			
7.	0.45	316	14.8	39.6	119.4		
8.	0.50	351	13.0	33.4	76.8		
9.	0.55	386	11.7	28.8	59.7		
10.	0.60	421	10.5	25.4	49.5	119.5	
11.	0.65	456	9.6	22.8	42.5	83.4	
12.	0.70	491	8.8	20.6	37.4	67.0	
13.	0.75	526	8.2	18.9	33.5	56.8	119.6
14.	0.80	561	7.6	17.4	30.3	49.6	88.2
15.	0.85	596	7.1	16.1	27.7	44.1	72.6
16.	0.90	631	6.7	15.0	25.5	39.9	62.5
17.	0.95	666	6.3	14.1	23.7	36.4	55.2
18.	1.00	701	6.0	13.2	22.1	33.5	49.6

These results demonstrate that intermittent operation substantially extends the experimental capability of medium-scale propulsion vacuum facilities. While continuous operation is ultimately limited by the pumping capacity of the facility, pulse-mode operation permits significantly higher propellant mass flow rates to be investigated for durations sufficient to obtain thrust measurements, characterize plume

behavior, and evaluate propulsion-system performance. This operating strategy is particularly attractive for cold-gas thrusters, warm-gas thrusters, resistojets, and reaction-control propulsion systems, where the required firing durations are typically much shorter than the characteristic chamber response time.

6.4 Representative Thrust Levels

The analyses presented in the preceding sections establish the allowable propellant mass flow rates for continuous and intermittent operation of the SBTÜ propulsion vacuum chamber. Although these limits are generally applicable to nozzle-based propulsion systems, propulsion performance is more commonly expressed in terms of thrust. Unlike mass flow rate, however, thrust is not solely determined by the propellant flow rate, but also depends on the nozzle expansion characteristics and propellant thermodynamic properties. For an ideal nozzle, thrust may be expressed as

$$F = \dot{m} C_F c^* \quad (13)$$

where C_F is the thrust coefficient and c^* is the characteristic velocity. The thrust coefficient depends primarily on the nozzle expansion ratio and the resulting exit-to-chamber pressure ratio, whereas the characteristic velocity is governed by the combustion or gas temperature and the molecular weight of the working fluid.

Since the present work focuses on vacuum-chamber capability rather than detailed nozzle design, representative operating conditions were selected to estimate the order of magnitude of thrust levels that can be accommodated by the facility. A representative thrust coefficient of $C_F = 1.7$, corresponding to moderately expanded cold-gas nozzles, was adopted from Sutton and Biblarz[1]. Assuming a chamber temperature of 300 K, the calculated characteristic velocities for several commonly used cold-gas propellants are 1215, 436, 384, and 212 m/s for helium, nitrogen, argon, and xenon, respectively.

Using the maximum allowable propellant mass flow rates corresponding to intermittent operation with a maximum chamber pressure of 500 Pa and a minimum operating duration of 10 s, the representative maximum thrust levels listed in Table 3 were obtained.

Table 3
Representative maximum thrust levels for intermittent operation of the SBTÜ propulsion vacuum chamber (300 K cold-gas operation, $C_F = 1.7$).

Propellant	Characteristic velocity c^* (m/s)	Representative maximum thrust (N)
Helium (He)	1215	0.66
Nitrogen (N_2)	436	1.60
Argon (Ar)	384	2.10
Xenon (Xe)	212	3.80

The values presented in Table 3 are intended only to provide representative thrust levels corresponding to the mass-flow-rate limits derived in the preceding sections. The exact thrust produced by a particular propulsion system depends on its chamber pressure, nozzle geometry, expansion ratio, operating temperature, and propellant properties, and should therefore be calculated for the specific thruster under consideration.

An important observation is that the minimum thrust that can be investigated is not limited by the vacuum chamber. From the standpoint of chamber pressure, progressively lower propellant mass flow rates simply produce lower steady-state pressures and longer allowable operating times. Consequently, the lower limit of measurable thrust is governed primarily by the sensitivity and resolution of the thrust-measurement system rather than by the vacuum facility itself. Conversely, the maximum thrust that can be investigated is constrained by the allowable propellant mass flow rate, which is determined by the chamber pumping speed, operating pressure, and selected mode of operation.

7. Conclusions

A comprehensive review of propulsion vacuum test facilities reported in the literature and examined the vacuum requirements associated with different classes of spacecraft propulsion systems, is presented in this paper. Particular emphasis has been placed on the distinction between nozzle-based propulsion systems, in which thrust is generated through gas expansion in a nozzle, and electromagnetic propulsion systems, in which charged particles are accelerated directly by electric and/or magnetic fields. These fundamentally different thrust-generation mechanisms lead to markedly different requirements for ground-based vacuum testing. A survey of representative international facilities, together with the propulsion vacuum-test infrastructure available in Türkiye, has been presented to place the SBTÜ propulsion vacuum chamber within the broader context of contemporary spacecraft propulsion testing.

The review demonstrates that the vacuum requirements of propulsion test facilities are governed primarily by the propulsion principle rather than by chamber size alone. While plasma-based propulsion systems require high to ultra-high vacuum environments to minimize facility effects arising from residual

neutral gas and plasma interactions, neutral-gas-based propulsion systems can be effectively evaluated at substantially higher chamber pressures.

A generalized analytical methodology has been developed to evaluate the operating limits of propulsion vacuum chambers under both continuous and intermittent operating modes. Based on conservation of mass within a mechanically pumped vacuum chamber, the steady-state formulation establishes the maximum propellant mass flow rate that can be sustained continuously at a specified chamber pressure, while the transient formulation predicts the allowable pulse duration as a function of chamber volume, pumping speed, propellant properties, operating temperature, and selected pressure limits. The analysis demonstrates that pumping speed primarily governs the continuous operating capability of a facility, whereas chamber volume controls its transient pressure response during intermittent operation.

Application of the analytical methodology to the SBTÜ propulsion vacuum chamber demonstrates that the facility provides an effective experimental platform for the development and characterization of neutral-gas-based propulsion systems. It is also shown that pulse-mode operation substantially extends practical operating envelope of the vacuum chamber, by permitting significantly higher propellant mass flow rates than can be accommodated during continuous operation.

Representative thrust estimates indicate that, under typical cold-gas operating conditions, the facility can accommodate thrust levels approaching several newtons during intermittent operation, demonstrating that medium-scale university facilities are suitable not only for very-low-thrust devices but also for a substantial class of practical neutral-gas-based spacecraft propulsion systems.

Although the analytical methodology has been demonstrated using the SBTÜ propulsion vacuum chamber, it is independent of any particular facility configuration and may be applied to other propulsion vacuum chambers to estimate continuous operating limits, allowable pulse durations, representative thrust capabilities, and overall testing envelopes. It is therefore expected that the analytical framework developed in this work will provide a practical and scalable tool for the design, assessment, and operation of propulsion vacuum test facilities, particularly those supporting university scale spacecraft propulsion research and technology development.

Declarations

Funding

This work was carried out as part of the "Propulsion Research Center" project supported by the Scientific Research Projects Coordination Unit (BAP) of Sivas Bilim ve Teknoloji Üniversitesi (Project No. 2024-GÜAP-Hav-0001).

References

1. Sutton GP, Biblarz O (2017) Rocket Propulsion Elements, 9th edn. Wiley

2. Fortescue P, Swinerd G, Stark J (2011) Spacecraft Systems Engineering. Wiley
3. Wertz JR, Larson WJ (1999) Space Mission Analysis and Design. Microcosm
4. Goebel DM, Katz I (2008) *Fundamentals of Electric Propulsion: Ion and Hall Thrusters*, JPL/Caltech
5. Jahn RG, Choueiri EY (2003) Electric Propulsion. Encyclopedia of Physical Science and Technology
6. Fleeman EL (2012) Tactical Missile Design. AIAA
7. Humble R, Henry G, Larson W (1995) Space Propulsion Analysis and Design. McGraw-Hill
8. Zarchan P (2012) *Tactical and Strategic Missile Guidance*, AIAA
9. Dankanich JW, Walker M, Swiatek MW, Yim JT (2017) Recommended Practice for Pressure Measurements and Calculation of Effective Pumping Speed in Electric Propulsion Testing, *Journal of Propulsion and Power*, Vol. 33, No. 3, 2017, pp. 668–680. https://doi.org/10.2514/1.B35478
10. Randolph T, Kim V, Kaufman H, Kozubsky K, Zhurin V, Day M (1993) Facility Effects on Stationary Plasma Thruster Testing, *Proceedings of the 23rd International Electric Propulsion Conference*, IEPC-93-093, Seattle, WA, Sept
11. Walker MLR, Gallimore AD (2004) *Performance Characteristics of a Cluster of 5 kW Laboratory Hall Thrusters*. 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA Paper 2004–3767
12. Walker MLR, Gallimore AD (2005) Neutral density map of Hall thruster plume expansion in a vacuum chamber. Rev Sci Instrum 76(5). Article 053509. https://doi.org/10.1063/1.1915011
13. Rovey JL, Walker MLR, Peterson PY, Gallimore AD (2004) *Evaluation of a Magnetically Filtered Faraday Probe for Measuring the Ion Current Density Profile of a Hall Thruster*. 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA Paper 2004–3948
14. Hofer RR, Peterson PY, Gallimore AD (2001) *Characterizing Vacuum Facility Backpressure Effects on the Performance of a Hall Thruster*. 27th International Electric Propulsion Conference, IEPC Paper 01–045
15. Polk JE, Pancotti A, Haag T, King S, Walker M, Blakely J, Ziemer J (2017) Recommended Practice for Thrust Measurement in Electric Propulsion Testing. J Propul Power 33(3):539–555. https://doi.org/10.2514/1.b35564
16. Mazouffre S Electric Propulsion for Satellites and Spacecraft: Established Technologies and Novel Approaches. Plasma Sources Sci Technol, 25, 3, 2016, Article 033002. https://doi.org/10.1088/0963-0252/25/3/033002
17. Mankavi F, Rezaeiha A Design and Development of a Low Power Laboratory Resistojet, *Proceedings of the Asian Joint Conference on Propulsion and Power (AJCPP 2012)*, Xi'an, China, 1–4 March 2012, Paper AJCPP2012-027
18. Kim SC (1994) Calculations of low-Reynolds-number resistojet nozzles. J Spacecr Rockets 31(2):325–327
19. Romei F, Grubišić AN (2019) Numerical study of a novel monolithic heat exchanger for electrothermal space propulsion. Acta Astronaut 159:8–16

20. Piragino A et al (2021) Background Pressure Effects on the Performance of a 20 kW Magnetically Shielded Hall Thruster Operating in Various Configurations. Aerospace, 8, 3, Article 69
21. Huang W, Kamhawi H, Haag T (2013) *Effect of background pressure on the performance and plume of the HiVHAc Hall thruster*(IEPC-2013-058). 33rd International Electric Propulsion Conference, Washington, D.C., United States. https://ntrs.nasa.gov/citations/20140011170
22. Walker MLR (2005) *Effects of Facility Backpressure on the Performance and Plume of a Hall Thruster*, Georgia Institute of Technology, PhD dissertation
23. Jovel DR, Cabrera JD, Walker MLR (2024) Current pathways model for hall thruster plumes in ground-based vacuum test facilities: measurements and observations. J Electr Propuls 3:35. https://doi.org/10.1007/s44205-024-00097-8
24. MacDonald-Trenteburn N, Pratt Q, Nakles M, Pilgrim N, Holmes M, Hargus W Jr (2019) Background pressure effects on ion velocity distributions in an SPT-100 Hall thruster. J Propul Power. https://doi.org/10.2514/1.B37133
25. Cai C, Boyd ID, Sun Q (2006) Rarefied background flow in a vacuum chamber equipped with one-sided pumps. J Spacecr Rockets 43(3):523–534. 10.2514/1.19178
26. Garkusha VI, Grishin SD, Mironov SG, Savitsev VV, Semenkin AV (1995) Electric propulsion activity in TsNIIMash, in Proc. 24th International Electric Propulsion Conference (IEPC), Moscow, Russia, Sep. Paper IEPC-95-09, pp. 75–86
27. NASA Glenn Research Center *Electric Propulsion Research Building (EPRB) NASA GRC, available at*. https://www.nasa.gov/centers-and-facilities/glenn/electric-propulsion-research-building/ accessed 07/07/2026
28. Grisnik SP, Parkes JE (1994) *A large high vacuum, high pumping speed space simulation chamber for electric propulsion* (NASA Technical Memorandum 106453 / IEPC-93-151). NASA Lewis Research Center. https://ntrs.nasa.gov/citations/19940021639
29. Manzella DH, Jankovsky RS, Hofer RR (2002) Laboratory model 50kW Hall thruster, in *Proc. 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Indianapolis, IN, USA, Jul. Paper AIAA-2002-3676
30. Complex AED, TN, USA (2026) 12V Space Chamber Facility Fact Sheet, Air Force Test Center, United States Air Force, Arnold AFB, [Online]. Available: https://www.arnold.af.mil/About-Us/Fact-Sheets/Display/Article/409309/12v-space-chamber/ accessed on 11.06.2026
31. Dettleff G, Plahn K (1998) The DLR High Vacuum Plume Test Facility Göttingen. Aerosp Sci Technol 2(5):329–337. https://doi.org/10.1016/S1270-9638(98)80006-2
32. Scortecci F (2003) A new large vacuum test facility for high power electric propulsion testing, in *Proc. 28th International Electric Propulsion Conference*, Toulouse, France, Mar. Paper IEPC-03-329
33. Robinson M, Grubišić A, Rempelos G, Romei F, Ognulesi C, Ahmed S (2019) Endurance testing of the additively manufactured STAR resistojet. Mater Design 180:107907. https://doi.org/10.1016/j.matdes.2019.107907

34. Sun M, Geng H, Zheng Y (2021) The 6,500-H life test results of 30 cm diameter ion thruster. J Aerosp Technol Manag 13:e0521. 10.1590/jatm.v13.1202
35. Joint Laboratory of Plasma Propulsion (2026) Vacuum chamber infrastructure and technical specifications, Joint Laboratory of Plasma Propulsion (JLPP), Beihang University, Beijing, China, Lab. Facility Review. [Online]. Available: https://jlpp.buaa.edu.cn/index.php/research-publications/facilities/vaccum-chamber/ accessed 11/06/
36. Kuninaka H, Nishiyama K, Funaki I, Shimizu Y, Yamada T, Kawaguchi J (2006) Assessment of Plasma Interactions and Flight Status of the HAYABUSA Asteroid Explorer Propelled by Microwave Discharge Ion Engines, *IEEE Transactions on Plasma Science*, vol. 34, no. 5, pp. 2125–2132, Oct. 10.1109/TPS.2006.876513
37. Coral G, Kinefuchi K, Nakata D, Tsukizaki R, Nishiyama K, Kuninaka H (2021) Design and testing of additively manufactured high-efficiency resistojet on hydrogen propellant. Acta Astronaut 181:114–127
38. Watanabe H, Cho S, Kubota K (2019) Performance Evaluation of a 100-W Class Hall Thruster, in *Proc. 36th International Electric Propulsion Conference*, Vienna, Austria, Sep. Paper IEPC-2019-447
39. https://uzay.itu.edu.tr/en/research/laboratories/space-systems-design-and-test-laboratory accessed on 4/6/26
40. https://uzay.tubitak.gov.tr/entegrasyon-ve-test-altyapimiz/isil-vakum-test-altyapilari/ accessed on 5/6/26
41. Isik HG, Uygur AB, Ömür C, Akın D, Sancak M A new thermal vacuum test chamber built in turkey, 2013 6th International Conference on Recent Advances in Space Technologies (RAST), Istanbul, Turkey, 2013, pp. 531–535. 10.1109/RAST.2013.6581267
42. Özden A, Baran Ö, Aksel M, Ak M (2021) SU2 REAL GAS MODELS' PERFORMANCE PREDICTIONS ON A COLD GAS THRUSTER. J Therm Sci Technol 41(1):77–88. https://doi.org/10.47480/isibted.979351
43. https://bogazicispacetechlab.github.io/facility/ accessed on 04/06/26

Figures

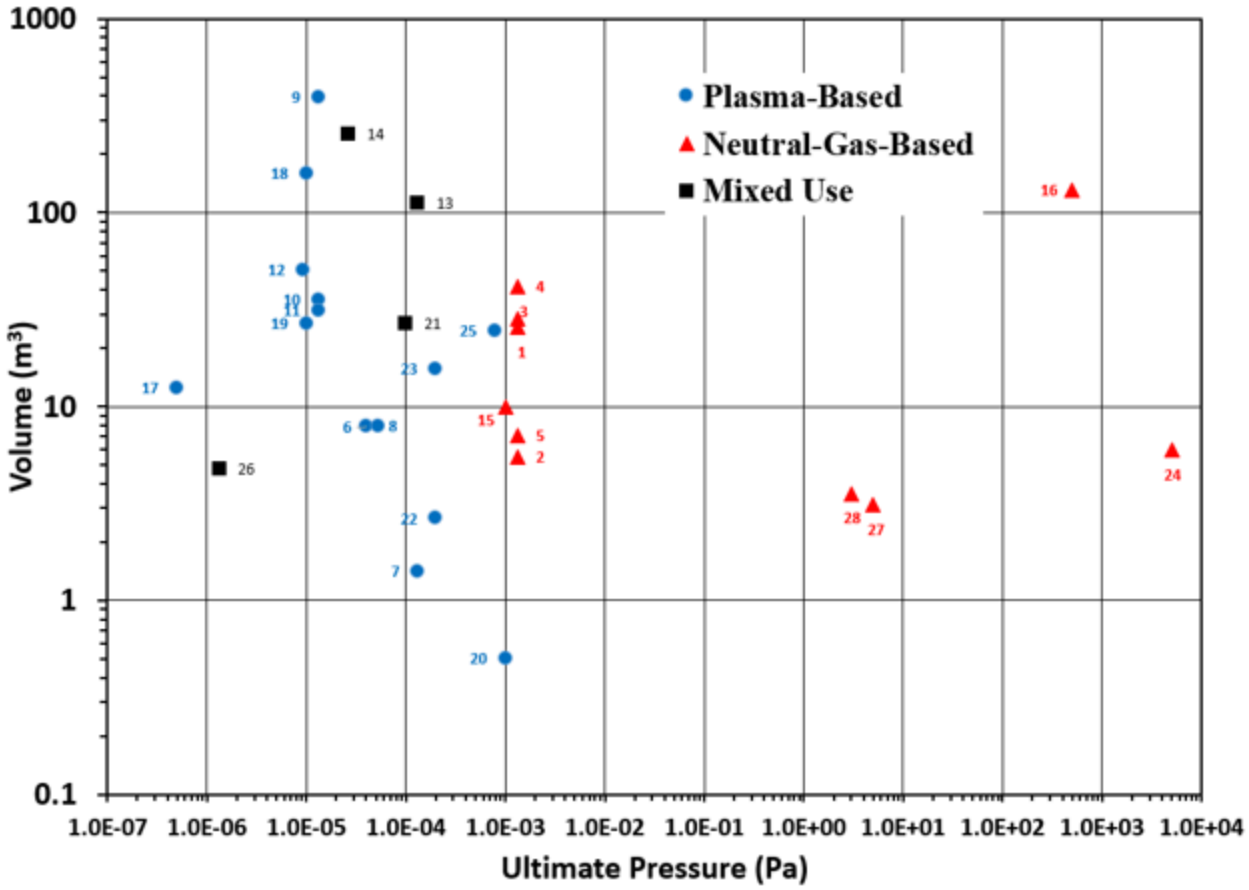


Figure 1

Comparison of major international and Turkish propulsion vacuum test facilities according to chamber volume and ultimate vacuum pressure. Blue circles represent facilities primarily dedicated to plasma-based propulsion testing, red triangles indicate facilities used for neutral-gas-based propulsion systems, and black squares denote mixed-use facilities.

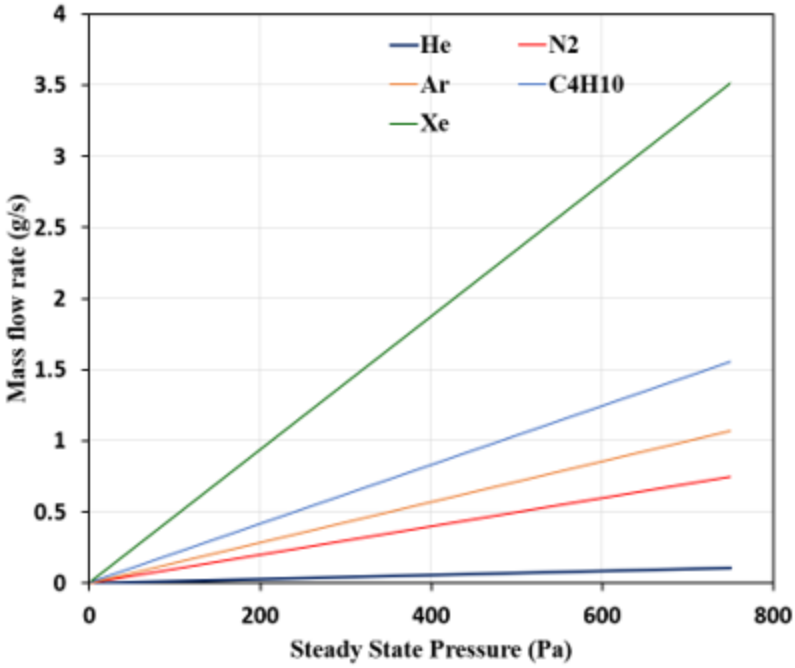


Figure 2

Mass flow rates of various gases for a given value of steady state pressure