Plasma Jets in Vacuum: A Comprehensive Review of Generation, Characterization, and Applications

1. Introduction: The Plasma State in a Vacuum Environment

Plasma, often referred to as the fourth state of matter, is a partially or fully ionized gas characterized by a unique collective behavior driven by the electromagnetic interactions of its constituent charged particles.[1] Yet behaves similar to liquids. While plasmas exist across a vast range of pressures and temperatures, their generation and study in a vacuum or low-pressure environment present distinct advantages. In these conditions, the reduced frequency of particle collisions allows for greater control over the plasma's fundamental properties, including electron temperature, ion energy, and species composition.[1] This intrinsic level of control and precision is why vacuum-based plasma jets have become indispensable in a variety of specialized fields, from deep-space propulsion to advanced materials processing.

The intellectual landscape of plasma jet research is not a monolithic discipline but an interdisciplinary convergence of fundamental physics and applied engineering. The core principles governing plasma generation and the diagnostic techniques used for their characterization are remarkably consistent across disparate application areas. For example, the challenges in understanding plasma-material interactions central to mitigating erosion in a Hall thruster are conceptually analogous to those faced when modifying the surface of a polymer with a low-pressure jet. The diagnostic tools employed, such as Optical Emission Spectroscopy (OES) and Langmuir probes, are shared across these applications, providing a unifying methodology for researchers. This synergy implies that breakthroughs in one field, such as the development of predictive erosion models for spacecraft thrusters, have direct and profound implications for other areas like semiconductor manufacturing or biomedical engineering.

This review is structured to mirror the logical progression of plasma jet research. The subsequent sections will first explore the principles and mechanisms of plasma jet generation in vacuum, tracing their historical evolution from early industrial uses to modern high-technology systems. This is followed by a comprehensive overview of the sophisticated diagnostic techniques and computational models used to characterize these plasma plumes. Finally, the report will examine the diverse and evolving applications of vacuum plasma jets, including space propulsion, materials processing, and biomedicine. The final section will synthesize these themes to identify conflicting viewpoints, critical knowledge gaps, and promising avenues for future research.

2. Principles and Mechanisms of Plasma Jet Generation in Vacuum

The generation of plasma jets in vacuum or low-pressure conditions has evolved significantly over time, progressing from high-temperature, high-power sources for industrial applications to precisely controlled, non-thermal systems for advanced engineering. Early research, dating to the mid-20th century, focused on the use of plasma jets as intense heat sources for processes like welding, cutting, and thermal spray-coating.[2] Devices such as the magneto-plasma compressor (MPC) were initially developed by Russian scientists for plasma fusion research before being miniaturized for other uses, including supersonic flow control and surface modification.[4] This historical shift from brute-force thermal applications to nuanced, non-equilibrium systems lays the groundwork for the diverse range of modern plasma sources.

2.1 A Foundational Review of Plasma Propulsion in Vacuum

Vacuum-based plasma jets are a cornerstone of electric propulsion, a field that sacrifices high thrust for a much higher propellant efficiency, or specific impulse (Isp).[5] The design and operation of these thrusters reflect a complex interplay of electric, magnetic, and fluid dynamics.

2.1.1 Gridded Ion Thrusters

Gridded ion thrusters represent a highly efficient class of electric propulsion systems. Their operation relies on the separation of plasma generation and ion acceleration into distinct stages. An inductively coupled plasma (ICP) discharge is typically used to generate a plasma within a discharge chamber, where a neutral propellant, most commonly xenon, is ionized.[6] The key to thrust generation is the subsequent acceleration of these ions. A set of biased grids, consisting of a positively charged screen grid and a negatively charged accelerator grid, creates a strong electrostatic potential that accelerates the ions to high velocities, producing a directional beam and generating thrust.[5] The high charge-to-mass ratio of the ions allows for a relatively small potential difference to impart a high exhaust velocity, which, in turn, translates to an exceptionally high specific impulse.[5] Some advanced designs, such as the NEXIS thruster fabricated by JPL, have demonstrated a design lifetime of over 100,000 hours and a specific impulse exceeding 7000 s.[7] Gridded ion thrusters are categorized as electrostatic thrusters because they primarily use the Coulomb force to accelerate the ions.[5]

2.1.2 Hall-Effect Thrusters

Hall-effect thrusters (HETs), also known as stationary plasma thrusters (SPTs), are another leading technology in electric propulsion. They are distinct from gridded ion thrusters in their acceleration mechanism. A Hall thruster forms and sustains plasma within an annular ceramic discharge chamber using a unique configuration of crossed electric and magnetic fields.[8] An external power supply establishes an electric field along the thruster's axis, while a set of solenoids generates a magnetic field that points radially. Electrons, emitted from an external cathode, are trapped by the radial magnetic field and forced into a gyrating azimuthal "Hall" drift inside the discharge chamber.[8] Neutral propellant, typically xenon, is fed through an anode and ionized by collisions with these trapped, high-energy electrons. The resulting ions are then accelerated into the thruster exhaust by the axial electric field. A critical design feature is that the magnetic field is strong enough to confine the light electrons but too weak to magnetize the much heavier ions, allowing the ions to be accelerated out of the chamber, generating thrust.[8]

A primary challenge with Hall thrusters has historically been wall erosion caused by plasma sputtering, which degrades performance and ultimately limits the thruster's lifespan.[8] Research reveals a complex, coupled feedback loop: the sputtering rate is highly sensitive to the near-wall plasma conditions, such as ion density and energy, but the sputtering process itself changes the wall's surface composition and secondary electron yield, which in turn alters the plasma properties.[8] This non-linear interaction makes predictive computational modeling a formidable challenge.[9] A major technological advancement has been the development of "magnetic shielding" technology, which effectively separates the energetic ions from the discharge chamber walls. This breakthrough breaks the detrimental feedback loop, leading to significantly extended thruster lifetimes and the emergence of

"Zero-Erosion™" thruster lines.[8]

2.2 Vacuum Plasma Sources for Non-Propulsion Applications

Beyond space propulsion, low-pressure plasma systems are essential for industrial processes that demand meticulous control. The semiconductor manufacturing industry, in particular, relies heavily on these systems for techniques such as plasma-enhanced chemical vapor deposition (PECVD) and reactive ion etching (RIE).[1] The ability to precisely regulate the gas composition, pressure, and power in a vacuum chamber allows for the controlled growth of thin films and the selective removal of material with angstrom-level precision. This level of control is crucial for fabricating the complex microelectronic circuits that power modern technology.[1]

2.3 Low-Pressure vs. Atmospheric-Pressure Plasma Jets: A Comparative View

While this review focuses on vacuum-based systems, a central intellectual debate in the field concerns the relative merits of low-pressure versus atmospheric-pressure plasma jets (APPJs).[12] This is not a trivial distinction but a fundamental trade-off that defines the appropriate application space for each technology. Low-pressure plasma systems offer unparalleled control, species homogeneity, and a high concentration of active species.[15] However, they are inherently complex, requiring expensive vacuum chambers, pumps, and robotic assemblies, which limits their scalability and makes them unsuitable for treating large or irregularly shaped objects.[1] In contrast, APPJs are often simpler, more portable, and can treat objects of any size and configuration without the constraints of a vacuum chamber.[12] However, their performance and repeatability are often compromised by uncontrolled interactions with the surrounding ambient air, which can introduce impurities and alter the plasma chemistry in an unpredictable manner.[13] This tension between precision and practicality is a recurring theme in the literature and a key factor in the selection of plasma technology for a given application.

The following table summarizes the key distinctions between these two dominant plasma jet configurations.

Table 1: Comparison of Low-Pressure and Atmospheric-Pressure Plasma Jets

Characteristic	Low-Pressure Plasma Jets	Atmospheric-Pressure Plasma Jets (APPJs)
Typical Operating Pressure	Millitorr to microns (<1 atm) [1]	Atmospheric pressure (760 Torr) [12]
Equipment Complexity	High; requires vacuum chambers, pumps, and control systems [1]	Low; portable devices are common [12]
Cost	High; due to complex equipment [12]	Lower; due to simpler setup
Scalability	Limited by vacuum chamber dimensions [12]	Highly scalable for large or complex objects [12]
Reactive Species Control	High; precise control of gas composition is possible [16]	Moderate to Low; susceptible to ambient air contamination [13]
Repeatability/Stability	High; fewer particle collisions allow for stable and reproducible conditions [1]	Can be a challenge; sensitive to ambient conditions and gas impurities [13]
Primary Applications	Semiconductor fabrication, thin-film deposition, advanced materials science [1]	Biomedical applications (sterilization), surface activation, environmental remediation [13]

3. Characterization of Plasma Plumes in Low-Pressure Environments

The ability to accurately characterize the fundamental properties of a plasma jet is essential for both optimizing its performance and validating the theoretical and computational models that seek to describe its behavior. The hostile and sensitive nature of plasma in a vacuum environment imposes severe constraints on diagnostic techniques, often requiring non-intrusive methods.[17] The literature highlights a variety of experimental and computational approaches used to overcome these challenges.

3.1 Experimental Diagnostic Techniques

A prerequisite for gaining a comprehensive understanding of plasma dynamics is the simultaneous measurement of multiple parameters, such as density, temperature, and velocity, with high spatiotemporal resolution.[17]

3.1.1 Langmuir Probes

The Langmuir probe is a foundational and widely used diagnostic tool for measuring local plasma properties. By analyzing the current-voltage (I–V) curve obtained from a conductive probe immersed in the plasma, researchers can determine key parameters such as electron temperature, electron density, and plasma potential.[18] Despite its utility, the Langmuir probe faces significant challenges in real-world applications. The presence of radiofrequency (RF) fields can influence the probe's sheath impedance, complicating measurements.[20] Furthermore, probe contamination is a pervasive problem, especially in processes like chemical vapor deposition, where impurities can adsorb onto the probe surface over time, leading to inaccurate measurements of electron temperature.[19] Advanced techniques, such as combining Langmuir probes with OES, have been proposed to mitigate these issues and provide more reliable data.[19]

3.1.2 Optical Emission Spectroscopy (OES)

As a non-intrusive alternative, Optical Emission Spectroscopy (OES) is a powerful diagnostic tool that analyzes the light emitted by the plasma.[21] Every element and molecule has a unique spectral signature, and by analyzing the wavelength and intensity of emitted light, OES can identify the excited species present in the plasma and estimate the electron excitation temperature.[21] This technique was used to characterize the plume of a helicon-based inductive plasma thruster (IPT), where the dominance of Ar I emission spectral lines confirmed that the thruster was operating in an inductively coupled plasma mode.[22] OES is also critical for identifying the reactive species, such as hydroxyl (

OH) radicals, that are responsible for the efficacy of plasma jets in biomedical and surface modification applications.[24]

3.1.3 Advanced Imaging and Other Techniques

To capture the dynamic nature of plasma jets, advanced imaging techniques are often employed. Fast imaging using intensified charge-coupled device (ICCD) cameras provides spatiotemporal resolution, allowing researchers to visualize the propagation of plasma "bullets" and estimate their velocity.[21] Electrical diagnostics, including voltage probes and current sensors, are used to characterize the discharge behavior and measure parameters such as plume current, which can be used to estimate plasma density.[21] Additionally, in the context of plasma propulsion, a Pitot probe can be used to assess the flow regime of the plume, with one study finding that a helicon-based thruster likely operates in a rarefied or transitional flow regime due to its low temperature and pressure.[22]

3.2 Modeling and Simulation of Plasma Dynamics

Computational models are essential for interpreting experimental data and predicting the complex behavior of plasma jets. They provide a window into the underlying physics that cannot be observed with diagnostics alone.

The literature distinguishes between two main modeling approaches. Fluid models, which assume that the particle velocity distribution function is close to a Maxwellian, are computationally fast and effective for simulating macroscopic quantities like density and mean velocity.[27] However, they often fail to capture non-equilibrium effects. Conversely, particle simulations, such as Particle-in-Cell Monte Carlo (PIC-MCC) and Direct Kinetic (DK) models, are able to simulate the non-equilibrium nature of the discharge plasma with a much higher fidelity.[27] The challenge with these methods is that they can be computationally intensive and may suffer from statistical noise, particularly in low-density regions.[27] The development of advanced algorithms, such as the Temporal Multi-scale Algorithm (TMA), is aimed at efficiently coupling the wide disparity of characteristic time scales between light species (electrons) and heavy species (neutrals) to improve computational efficiency and accuracy.[28]

Table 2: Key Plasma Parameters and Corresponding Diagnostic Techniques

Plasma Parameter	Diagnostic Technique(s)	Primary Function/Application
Electron Temperature (Te)	Langmuir Probe, OES	Fundamental plasma property, relates to ionization efficiency [19]
Electron Density (ne)	Langmuir Probe, Electrical Diagnostics	Indicates plasma ionization level and potential for material interaction [19]
Reactive Species (e.g., radicals)	OES	Identification of key chemical agents for surface modification and biomedical applications [21]
Plume Velocity	ICCD Camera, Electrical Diagnostics, Pitot Probe	Quantifies thrust in propulsion systems; relates to fluid dynamics [21]
Discharge Current and Voltage	Electrical Diagnostics	Characterizes overall power consumption and discharge stability [21]
Plasma Potential	Langmuir Probe	Determines the electric field and energy of ions bombarding a surface [18]

4. Evolving Applications of Vacuum Plasma Jets

The unique characteristics of plasma jets in a vacuum environment—particularly their high efficiency and controlled reactivity—have enabled a wide range of applications that continue to expand.

4.1 Space Propulsion: The Drive for High-Efficiency Missions

Plasma jets have revolutionized space propulsion by enabling missions that would be impractical with conventional chemical rockets. The two most prominent technologies, Hall thrusters and gridded ion thrusters, are both highly efficient but occupy slightly different performance niches.

4.1.1 Comparison of Hall and Ion Thrusters

The selection of a thruster for a specific mission often comes down to a trade-off between thrust-to-power ratio and specific impulse. At constant power, Hall thrusters generally have a higher thrust-to-power ratio and lower specific impulse, while gridded ion thrusters offer a higher specific impulse, efficiency, and total impulse capability (lifetime).[10] This distinction dictates their respective applications: Hall thrusters are often preferred for satellite orbit control and station-keeping, which require more thrust for maneuvering, while gridded ion thrusters are the choice for long-duration, deep-space missions that require a very high change in velocity (

Δv) and propellant efficiency.[10] The advent of magnetic shielding has narrowed the gap in lifetime, allowing Hall thrusters to also be considered for certain deep-space applications.

Table 3: Performance and Life Characteristics of Hall and Ion Thrusters

Characteristic	Hall Thrusters	Gridded Ion Thrusters
Thrust	0.1–1 N (typical) [9], up to 5.4 N (lab) [31]	40–600 mN (typical) [31]
Specific Impulse (Isp)	1000–3000 s (typical) [31], up to 3400 s (advanced) [10]	up to 7000 s (advanced) [7]
Efficiency	45–60% (typical) [31]	Not specified, but generally higher than Hall thrusters [10]
Demonstrated/Projected Lifetime	10,000 hours (typical) [9], 10,000–30,000 hours	100,000+ hours (advanced) [7]

	(magnetic shielded) [10]	

4.2 Materials Processing and Surface Modification

Low-pressure plasma has been used for decades to precisely alter the surface properties of materials without affecting their bulk characteristics.[16] The mechanisms involve the interaction of the plasma's reactive species with the material surface.

4.2.1 Mechanisms and Applications

Plasma treatment in a vacuum can be used for surface cleaning, etching, activation, and deposition.[1] The precise effect is determined by the chemistry of the reactive species present, which can be meticulously controlled by the choice of a noble or reactive process gas (e.g., argon, oxygen, nitrogen) in the vacuum chamber.[16] For example, plasma-induced oxidation using an oxygen-containing gas can significantly increase a polymer's surface energy, thereby enhancing its wettability and improving the adhesion of coatings, inks, and adhesives.[16] Low-pressure plasma has also been employed to create high-temperature-resistant ceramic coatings and develop self-lubricating surfaces, which was previously considered impossible.[2]

4.3 Biomedical and Clinical Applications

Non-thermal (cold) plasma is preferred for biomedical applications because its low gas temperature allows for the treatment of heat-sensitive biological tissues without causing thermal damage.[18]

4.3.1 Sterilization and Wound Healing

The sterilization effect of low-pressure plasma is multifaceted and highly effective, leveraging a combination of physical and chemical mechanisms to inactivate a wide range of pathogens.[33] The sterilization is based on the high reactivity of plasma particles (free electrons, ions, and radicals), which damage the organic molecules of microorganisms.[33] The ultraviolet (UV) light present in low-pressure plasma damages the DNA of bacteria and viruses, rendering them inactive, while the high kinetic energy of ions and electrons physically sputters off contaminants from the surface of instruments.[33] A key advantage of low-pressure plasma sterilization is its ability to penetrate the smallest cracks and cavities in complex medical devices, ensuring thorough disinfection.[33]

In wound healing, low-temperature cold plasma (LTCP) has emerged as a promising new therapy. Clinical and experimental studies have demonstrated that LTCP can accelerate the healing of chronic and acute wounds.[34] The proposed mechanism involves the suppression of pro-inflammatory cytokines (such as TNF-$ \alpha

,IL−6,andIL−1 \beta $) and the promotion of tissue repair-related factors (such as VEGF, bFGF, and COL-I).[34] Additionally, LTCP treatment has been shown to alter the skin microbiome, reducing the relative abundance of harmful bacteria while increasing beneficial ones.[34]

5. Unresolved Debates, Gaps in Literature, and Future Research Directions

Despite significant advancements, the field of plasma jets in vacuum is not without its challenges and unresolved questions. A critical analysis of the current literature reveals several key areas where further research is needed.

5.1 Fundamental and Applied Debates

5.1.1 The Erosion-Modeling Problem

The physics of plasma-induced erosion in Hall thrusters remains a topic of intense study. While experimental data on erosion rates and performance degradation has been collected over thousands of hours, a complete understanding has thus far eluded researchers.[9] A core issue is the highly coupled, non-linear feedback loop between plasma properties and the evolving wall surface. The sputtering rate is a function of the near-wall plasma, but the process of sputtering itself alters the surface, which in turn changes the plasma conditions.[8] Current computational models are not yet predictive, as they are highly sensitive to tunable parameters and cannot accurately simulate the impact of microsecond-scale events over thousands of hours without being adjusted to match experimental data.[8]

5.1.2 Standardization and Reproducibility

A notable gap in the literature is the lack of a clear, systematic comparison between different plasma jet devices and the effects of various noble gases (e.g., argon vs. helium) on performance and reactive species generation.[14] While many studies exist, they often use different power supplies, electrode geometries, and operational parameters, making it difficult to generalize findings. For example, a comparison of He and Ar APPJs driven by microsecond pulses showed significant differences in discharge current, luminous intensity, and jet length due to the distinct physical properties of the gases, particularly their ionization energies and metastable states.[36] A more comprehensive and standardized approach to these comparative studies is needed to improve the generalizability and reproducibility of research findings.

5.1.3 The Physics of Plasma-Target Interaction

The precise mechanisms of reactive species transport and their interactions with a target surface, particularly at a plasma-liquid interface, are not yet fully understood.[13] Computational models have shown that the physical properties of the gas, such as its molecular weight, can significantly influence transport efficiency. For instance, the heavier molecular weight of argon allows its reactive species to sufficiently contact a water surface, leading to a higher transportation efficiency than helium, which is much lighter and tends to float upwards, inhibiting transportation.[37] The interplay between gas flow, well geometry, and shielding gases further complicates the process.[37] A better understanding of these transport phenomena is critical for optimizing plasma sources for specific applications like sterilization and wound healing.

5.2 Critical Gaps and Suggestions for Future Work

The future of plasma science lies in addressing the limitations of current research, particularly through the synergy of advanced modeling and next-generation diagnostics.

- **Integrated Models:** Future research must focus on developing high-fidelity, predictive models that can integrate the complex physics of plasma, fluid dynamics, and material interactions.[27] This requires a move toward multi-scale, hybrid models that combine the computational efficiency of fluid approaches with the kinetic accuracy of particle simulations.[28] The goal is to bridge the gap between microscopic physical processes and macroscopic device performance, which is essential for engineering future plasma systems.
- **Advancements in Diagnostics:** To validate these sophisticated models, there is a pressing need for advanced, multi-channel diagnostic systems with higher spatiotemporal resolution. These systems must be able to simultaneously measure a broader range of plasma parameters and species, including the high-energy "tail" of the electron energy distribution function, which is critical for understanding ionization and excitation processes.[17] Such diagnostics would provide the detailed experimental data required to build and verify truly predictive models.
- **New Applications and Scalability:** The field should continue to explore underexplored applications, such as the use of plasma in gynaecological oncology, as suggested by the literature.[35] There is also potential for plasma to play a role in next-generation environmental and energy solutions, such as waste treatment and fusion energy generation.[1] Future work should also investigate the scalability of plasma jets to higher power levels for ambitious projects like deep-space human exploration.[10]

6. Conclusion

The review demonstrates that plasma jets in vacuum are a versatile and powerful technology, underpinning significant advancements across a diverse range of fields. From the high-efficiency propulsion of spacecraft to the precise modification of surfaces for industrial and biomedical applications, the unifying thread is the ability to harness and control the unique properties of plasma in a low-collision environment.

While remarkable progress has been made in the development of these systems and their applications, fundamental challenges remain. The inability to create truly predictive computational models for phenomena like Hall thruster erosion and the lack of standardized, comparative studies of different jet configurations highlight the field's most critical knowledge gaps. The future of this discipline hinges on a more profound, integrated understanding of the underlying physics. This can only be achieved through a convergence of advanced, high-resolution diagnostic techniques capable of capturing the transient and non-equilibrium nature of plasma, and the development of sophisticated multi-scale computational models that can accurately simulate these complex systems. The synergy of these two approaches will enable a new era of innovation, leading to more efficient, durable, and versatile plasma jet technologies.

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