STUDY OF DISCHARGE DYNAMICS AND CONTROL PARAMETERS IN A RADIO-FREQUENCY ATMOSPHERIC PRESSURE PLASMA JET

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INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

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DEPARTMENT OF ENERGY SCIENCE AND ENGINEERING

submitted

lnfulfillment of the requirements of the degree of

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സമർപ്പണം

അറിവിന്റെ ആഴങ്ങൾക്കും മനുഷ്യസ്നേഹത്തിന്റെ വിശാലതയ്ക്കുമായി,

എന്റെ വേരുകൾക്കും ചിറകുകൾക്കും — അച്ഛച്ഛന്

CERTIFICATE

This is to certify that the thesis titled **Study Of Discharge Dynamics And Control Parameters In A Radio-frequency Atmospheric Pressure Plasma Jet**, submitted by **Ms. Radhika T. P.**, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work done by her under my supervision and guidance.

In my opinion, the thesis has reached the standard of fulfilling the requirement of all the regulations regarding the degree. The results contained in this thesis have not been submitted, in part or in full, to any other university or institute to award any degree or diploma.

New Delhi
February 2026

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DECLARATION

This is to certify that the thesis entitled "**Study of Discharge Dynamics and Control Parameters in a Radio-Frequency Atmospheric Pressure Plasma Jet**" is an original work carried out by me under the supervision of **Prof. Satyananda Kar**. To the best of my knowledge and belief, this thesis contains original research results and has not been submitted, either in part or in full, to any other university or institution for the award of any degree or diploma.

All sources of information and assistance used in this work have been duly acknowledged through appropriate citations and references, in accordance with accepted academic practices.

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ABSTRACT

Atmospheric pressure plasma jets (APPJs) enable the generation of reactive oxygen and nitrogen species (RONS) at near-ambient temperature without vacuum infrastructure and are therefore attractive for plasma medicine, surface engineering, and environmental applications. However, their practical utilization remains limited by insufficient control over discharge stability, plasma reactivity, and plume morphology under highly collisional atmospheric conditions. Strong coupling between electron kinetics, gas heating, sheath dynamics, and neutral flow frequently leads to thermal instability, abrupt discharge transitions, and nonuniform plasma-ambient interaction. This thesis establishes physics-based strategies for precise and independent control of discharge dynamics, plasma parameters, and plume morphology in radio-frequency (RF) atmospheric pressure plasma jets.

Four complementary control pathways are systematically investigated: (i) electrode configuration optimization using an additional floating electrode, (ii) modulation of RF power increment rate to regulate discharge transitions, (iii) application of positive DC bias to independently control sheath dynamics and electron emission, and (iv) elucidation of plume fluid dynamics and morphology using high-speed Schlieren imaging.

In the first part, the influence of an additional floating electrode on a cross-field RF plasma jet is examined. Copper floating electrodes with widths ranging from a few millimeters to 10 mm were positioned downstream of the grounded electrode along the jet propagation path. The floating electrode significantly reduced the threshold RF power required for plasma propagation across

the nozzle and increased the achievable jet length. For cylindrical nozzles, a plume length of approximately 22 mm was obtained at an absorbed power of $\sim$75 W without the floating electrode, which increased to nearly 26 mm with a 10 mm floating electrode. In contrast, conical nozzles required substantially higher absorbed power ($\sim$54 W) to cross the nozzle and reach a saturated plume length of only $\sim$16 mm at 75 W. Charge transfer analysis revealed redistribution of current pathways, with reduced radial charge transfer to the grounded electrode and enhanced axial charge transport toward the plume, indicating improved downstream electron availability. Optical emission spectroscopy showed pronounced enhancement of OH, O, and N_2 emission intensities normalized to Ar (764 nm), accompanied by an increase in electron excitation temperature and electron densities approaching 10^{15} cm^{-3}. Molecular beam mass spectrometry confirmed increased yields of biologically relevant ionic species such as O^+, OH^+, NO^+, O^-, and OH^-. While enhanced ionization increased plasma reactivity, gas temperature exceeded 430 K at high power. Controlled variation of gas flow rate from 1.5 to 9 lpm reduced gas temperature from approximately 438 K to 402 K while maintaining elevated reactivity, demonstrating that combined optimization of electrode geometry, flow rate, and input power enables enhanced plasma performance with controlled thermal loading.

The second part addresses dynamic control of discharge transitions through modulation of RF power increment rate. Seven ramp protocols (3 W/1 s, 2 W/1 s, 1 W/1 s, 1 W/2 s, 1 W/3 s, 1 W/5 s, and 1 W/10 s) were investigated. Electrical diagnostics revealed distinct discharge phases with increasing power: normal glow, abnormal glow, and glow-to-arc transition. Slower ramping promoted earlier onset of abnormal glow at lower absorbed power, whereas faster ramping delayed transitions to significantly higher power levels. The abnormal glow regime exhibited sharp increases in discharge current, electron density, excitation temperature, and RONS emission, indicating enhanced ionization driven by gas-heating-induced thermal instability. Gas heating rates

were estimated to reach $\sim 10^7$ K s^{-1}, exceeding diffusion-driven cooling and triggering positive feedback between ionization and temperature. Transient filament formation was observed on the powered electrode during abnormal glow, attributed to ion-induced thermo-field emission. At lower power levels, ponderomotive forces associated with dielectric charging suppressed thermofield emission and prevented premature glow-to-arc transition. These results establish power ramp rate as a powerful dynamic control parameter for accessing transient high-reactivity regimes while improving operational safety and energy efficiency.

The third part introduces positive DC biasing (0-1600 V) as an independent control knob to regulate sheath dynamics and electron emission. A custom-designed LC low-pass filter with an effective cutoff frequency of approximately 1.45 MHz enabled safe superposition of DC bias without RF interference. Increasing DC bias systematically reduced the steep current rise and saturation associated with abnormal glow formation across all ramp protocols. Electron density and excitation temperature exhibited non-monotonic behaviour: moderate bias (up to $\sim$800 V) enhanced electron energetics, whereas higher bias suppressed ion-driven thermofield emission and increased electron loss to the electrode, resulting in a 30-50% reduction in peak electron density. Floating potential fluctuation amplitudes decreased with increasing bias, indicating suppression of discharge instabilities. These observations demonstrate that DC bias directly modulates local sheath fields and electron injection mechanisms, enabling stabilization of discharge operation and tunable control over plasma energetics independent of RF power delivery.

The fourth part focuses on plume fluid dynamics and morphology using high-speed Schlieren imaging at 2500 fps. Baseline argon jets exhibited laminar cores followed by shear-driven transition to turbulence, with laminar length decreasing as flow rate increased from 1 to 10 lpm. Plasma ignition shortened the laminar region despite reduced Reynolds number due to gas heating, indicating that the Reynolds number alone does not govern stability. Richardson number analysis

(2.3×10^{-4} - 4.6×10^{-2}) confirmed negligible buoyancy influence. Kelvin-Helmholtz instability growth lengths derived from refractive index gradients quantitatively matched experimentally observed vortex onset positions. Under continuous RF excitation, Strouhal numbers clustered near resonance ($St \approx 0.29$), producing coherent downstream swirl structures and stable conical plumes. Under pulsed RF excitation (500 Hz, 50% duty cycle), effective $St > 0.5$ disrupted the laminar core and triggered immediate vortex formation at the nozzle. Strong baroclinic torque arising from misaligned pressure and density gradients twisted these vortices into azimuthal motion, generating stable helical plumes. Optical emission spectroscopy and molecular beam mass spectrometry demonstrated enhanced RONS production, extended interaction length, and improved spatial uniformity in helical plumes, while pulsed operation reduced thermal loading for temperature-sensitive applications.

Collectively, this thesis establishes integrated strategies for controlling discharge dynamics, plasma reactivity, and plume morphology in RF atmospheric pressure plasma jets. By combining electrode engineering, power modulation, sheath field control, and flow instability management, the work enables rational design of plasma sources with improved stability, tunable reactivity, and optimized spatial coupling, advancing the deployment of APPJs in advanced biomedical, materials, and environmental technologies.

सारांश

वायुमंडलीय दाब प्लाज़्मा जेट (Atmospheric Pressure Plasma Jets, APPJs) बिना वैक्यूम अवसंरचना के लगभग परिवेशीय तापमान पर रिएक्टिव ऑक्सीजन एवं नाइट्रोजन प्रजातियाँ (Reactive Oxygen and Nitrogen Species, RONS) उत्पन्न करने में सक्षम होते हैं। इस कारण वे प्लाज़्मा चिकित्सा, सतह अभियांत्रिकी तथा पर्यावरणीय अनुप्रयोगों के लिए अत्यंत उपयोगी माने जाते हैं। तथापि, अत्यधिक टकराव वाली वायुमंडलीय परिस्थितियों में डिस्चार्ज स्थिरता, प्लाज़्मा अभिक्रियाशीलता तथा प्लूम संरचना पर अपर्याप्त नियंत्रण के कारण इनका व्यावहारिक उपयोग अब भी सीमित है। इलेक्ट्रॉन गतिकी, गैस ताप, शीथ डायनेमिक्स तथा न्यूट्रल प्रवाह के बीच प्रबल युग्मन प्रायः ऊष्मीय अस्थिरता, अचानक डिस्चार्ज संक्रमण तथा असमान प्लाज़्मा-परिवेश अंतःक्रिया को जन्म देता है। यह शोधप्रबंध रेडियो-फ्रीक्वेंसी (RF) चालित वायुमंडलीय दाब प्लाज़्मा जेट्स में डिस्चार्ज डायनामिक्स, प्लाज़्मा मापदंडों तथा प्लूम संरचना के सटीक और स्वतंत्र नियंत्रण हेतु भौतिकी-आधारित रणनीतियाँ प्रस्तुत करता है।

इस शोध में चार पूरक नियंत्रण विधियों का व्यवस्थित अध्ययन किया गया है: (1) अतिरिक्त फ्लोटिंग इलेक्ट्रोड के माध्यम से इलेक्ट्रोड विन्यास का अनुकूलन, (2) डिस्चार्ज संक्रमण को नियंत्रित करने हेतु RF पावर वृद्धि दर का मॉड्यूलेशन, (3) शीथ डायनामिक्स एवं इलेक्ट्रॉन उत्सर्जन को स्वतंत्र रूप से नियंत्रित करने के लिए पॉजिटिव DC बायस का उपयोग, तथा (4) हाई-स्पीड श्लीरेन इमेजिंग द्वारा प्लूम फ्लूइड डायनामिक्स एवं संरचना का विश्लेषण।

प्रथम भाग में क्रॉस-फील्ड RF प्लाज़्मा जेट में अतिरिक्त फ्लोटिंग इलेक्ट्रोड के प्रभाव का अध्ययन किया गया है। ग्राउंडेड इलेक्ट्रोड के डाउनस्ट्रीम में जेट प्रसार पथ के साथ कुछ मिलीमीटर से 10 mm चौड़ाई के कॉपर फ्लोटिंग इलेक्ट्रोड लगाए गए। फ्लोटिंग इलेक्ट्रोड की उपस्थिति से नोज़ल पार करने के लिए आवश्यक थ्रेशहोल्ड RF पावर में उल्लेखनीय कमी आई तथा अधिकतम प्राप्त करने योग्य जेट लंबाई में वृद्धि हुई। बेलनाकार नोज़ल के लिए लगभग 34 W अवशोषित शक्ति पर प्लूम लंबाई लगभग 22 mm से बढ़कर 10 mm फ्लोटिंग इलेक्ट्रोड के साथ लगभग 26 mm हो गई। चार्ज ट्रांसफर

विश्लेषण से ग्राउंडेड इलेक्ट्रोड की ओर रेडियल चार्ज ट्रांसफर में कमी तथा प्लूम की ओर अक्षीय चार्ज परिवहन में वृद्धि देखी गई, जो डाउनस्ट्रीम क्षेत्र में बेहतर इलेक्ट्रॉन उपलब्धता को दर्शाता है। ऑप्टिकल एमिशन स्पेक्ट्रोस्कोपी तथा मॉलिक्यूलर बीम मास स्पेक्ट्रोस्कोपी द्वारा जैविक रूप से महत्वपूर्ण आयनिक प्रजातियों जैसे O^+, OH^+, NO^+, O^-, OH^- की बढ़ी हुई उपस्थिति की पुष्टि हुई। उच्च पावर पर गैस ताप 430 K से अधिक हो गया, जिसे गैस फ्लो रेट को 1.5 से 9 lpm तक बढ़ाकर लगभग 402 K तक कम किया गया, जिससे नियंत्रित थर्मल लोडिंग के साथ उच्च अभिक्रियाशीलता बनी रही।

द्वितीय भाग में RF पावर वृद्धि दर को परिवर्तित कर डिस्चार्ज संक्रमण का गतिशील नियंत्रण प्रदर्शित किया गया। विभिन्न रैंप प्रोटोकॉल के अंतर्गत नॉर्मल ग्लो, एबनॉर्मल ग्लो तथा ग्लो-टू-आर्क संक्रमण देखे गए। धीमी रैंपिंग पर कम अवशोषित पावर पर ही एबनॉर्मल ग्लो की शुरुआत हुई, जबकि तेज़ रैंपिंग से संक्रमण उच्च पावर तक विलंबित हुआ। एबनॉर्मल ग्लो अवस्था में इलेक्ट्रॉन घनत्व, ताप तथा RONS उत्सर्जन में तीव्र वृद्धि हुई, जो ऊष्मीय अस्थिरता द्वारा प्रेरित आयनीकरण को दर्शाता है। पावर्ड इलेक्ट्रोड पर क्षणिक फिलामेंट निर्माण आयन-प्रेरित थर्मो-फील्ड एमिशन से संबंधित पाया गया।

तृतीय भाग में पॉजिटिव DC बायस (0-1600 V) द्वारा शीथ फील्ड एवं इलेक्ट्रॉन इंजेक्शन का स्वतंत्र नियंत्रण प्रदर्शित किया गया। लगभग 1.45 MHz कटऑफ वाले LC फ़िल्टर द्वारा RF हस्तक्षेप रहित बायस सुपरपोज़िशन संभव हुआ। मध्यम बायस पर इलेक्ट्रॉन एनर्जेटिक्स में वृद्धि हुई जबकि उच्च बायस पर इलेक्ट्रॉन हानि बढ़ी और पीक इलेक्ट्रॉन घनत्व में 30-50% तक की कमी आई। फ्लोटिंग पोटेंशियल फ्लक्चुएशन में कमी से डिस्चार्ज स्थिरता में सुधार स्पष्ट हुआ।

चतुर्थ भाग में 2500 fps पर श्लीरेन इमेजिंग द्वारा फ्लो डायनामिक्स का अध्ययन किया गया। निरंतर RF में स्थिर शंक्वाकार प्लूम तथा पल्स्ड RF (500 Hz, 50% ड्यूटी साइकिल) में स्थिर हेलिकल प्लूम उत्पन्न हुए। केल्विन–हेल्महोल्ट्ज़ अस्थिरता तथा बारोक्लिनिक टॉर्क को स्वर्ल निर्माण के मुख्य कारण के रूप में पहचाना गया। हेलिकल प्लूम में बेहतर मिक्सिंग, लंबा इंटरैक्शन पाथ तथा उच्च RONS उत्पादन पाया गया।

समग्र रूप से यह शोधप्रबंध RF वायुमंडलीय दाब प्लाज़्मा जेट्स में डिस्चार्ज स्थिरता, अभिक्रियाशीलता तथा प्लूम संरचना के नियंत्रित संचालन हेतु एक एकीकृत भौतिक ढांचा प्रस्तुत करता है, जो उन्नत जैवचिकित्सीय, पदार्थ संशोधन तथा पर्यावरणीय अनुप्रयोगों के लिए प्रभावी प्लाज़्मा स्रोतों के विकास में सहायक होगा।

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Abbreviations and Symbols

Abbreviations

AC	Alternating current
APNTP	Atmospheric Pressure non-thermal plasma
APP	Atmospheric Pressure Plasma
APPJ	Atmospheric Pressure Plasma Jet
CAP	Cold Atmospheric Pressure Plasma
DBD	Dielectric Barrier Discharge
DC	Direct current
EEDF	Electron Energy Distribution Function
FFT	Fast Fourier Transform
GAT	Glow-to-Arc Transition
KHI	Kelvin-Helmholtz Instability
RF	Radio Frequency
RONS	Reactive Oxygen and Nitrogen Species

Symbols

N_A	Avogadro Number
σ	Conductivity
j_e	Current Density
n_e	Electron density
T_{exc}	Electron Excitation temperature
ω	Frequency of power supply
D	Gas diffusion Coefficient
T_{gas}	Gas Temperature
Ω	Instability Growth Factor
ϵ_0	Permittivity of Vacuum

ω_p	Plasma frequency
F_P	Ponderomotive force
$j_e E$	Power Dissipation
p	Pressure
ρ	Density
γ	Ratio of specific heat capacity
k_i	sensitivity of the ionization rate to electron temperature
C_p	Specific heat capacity
F_p	Ponderomotive force
R_e	Reynolds number
R_i	Richardson number
L_{KH}	KHI growth length
ω_i	KHI growth rate
δ	Shear layer thickness
St	Strouhal number
ω_θ	Baroclinic torque

List of Publications

Journal Articles

1. **Radhika T. P.**, and S. Kar, Effect of an additional floating electrode on radiofrequency cross-field atmospheric pressure plasma jet, *Scientific Reports*, 13, 10.1038/s41598-023-37805-7 (2023).

2. **Radhika T. P.**, and S. Kar, Glow-to-arc discharge transitions in a radio frequency atmospheric pressure plasma jet, *Physics of Fluids*, 36(8) (2024).

3. **Radhika T. P.**, and S. Kar "Gas Flow Rate Influence on Gas Temperature Regulation in a Reinforced Radio-Frequency Cross-Field Atmospheric Pressure Plasma Jet" Asian J. Phys Vol. 34(3 & 4) 167-178 (2025).

4. **Radhika T. P.**, A. B. Mallick, V. Kumar, M. Kumar, & S. Kar, Study of gas flow dynamics of helical plumes in a radiofrequency atmospheric pressure plasma jet. *Physics of Fluids*, 38(1) (2026).

5. **Radhika T. P.**, and S. Kar "Influence of Positive DC Bias on Discharge Regimes and Plasma Parameters in Radio Frequency Atmospheric Pressure Plasma Jets" *Phys. Plasmas* 33, 012114 (2026).

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1. **Radhika T. P.**, and S. Kar, An exploratory study on discharge transitions and stability of radio frequency atmospheric pressure plasma jet, in *2024 IEEE International Conference on Plasma Science (ICOPS)*, IEEE (2024).