

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

*by*

**RADHIKA T. P.**

**DEPARTMENT OF ENERGY SCIENCE AND ENGINEERING**

*submitted*

*In fulfillment of the requirements of the degree of*

**DOCTOR OF PHILOSOPHY**

*to the*



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**April 2026**

## സമർപ്പണം

അറിവിന്റെ ആഴങ്ങൾക്കും മനുഷ്യസ്നേഹത്തിന്റെ വിശാലതയ്ക്കുമായി,

എന്റെ വേരുകൾക്കും ചിറകുകൾക്കും — അച്ഛൻ

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## **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<sub>2</sub> emission intensities normalized to Ar (764 nm), accompanied by an increase in electron excitation temperature and electron densities approaching  $10^{15}$  cm<sup>-3</sup>. Molecular beam mass spectrometry confirmed increased yields of biologically relevant ionic species such as O<sup>+</sup>, OH<sup>+</sup>, NO<sup>+</sup>, O<sup>-</sup>, and OH<sup>-</sup>. 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

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were estimated to reach  $\sim 10^7 \text{ K s}^{-1}$ , 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  $\sim 800 \text{ V}$ ) 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

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$(2.3 \times 10^{-4} - 4.6 \times 10^{-2})$  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। पावरड 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।

# Contents

<b>CERTIFICATE</b>	<b>ii</b>
<b>DECLARATION</b>	<b>iii</b>
<b>ACKNOWLEDGEMENTS</b>	<b>iv</b>
<b>ABSTRACT</b>	<b>vii</b>
<b>सारांश</b>	<b>xi</b>
<b>List of figures</b>	<b>xxiv</b>
<b>List of tables</b>	<b>xxv</b>
<b>Abbreviations and symbols</b>	<b>xxvi</b>
<b>List of Publications</b>	<b>xxviii</b>
<b>1 INTRODUCTION</b>	<b>1</b>
1.1 Fundamental aspects of plasma . . . . .	2
1.1.1 Local Thermodynamic Equilibrium (LTE) Plasmas . . . . .	2
1.1.2 Non-Local Thermodynamic Equilibrium (non-LTE) Plasmas . . . . .	3
1.1.3 Plasma Generation and Breakdown Mechanism . . . . .	4
1.2 Classification to thermal and non-thermal plasma . . . . .	7
1.2.1 Non-Thermal Atmospheric Pressure Plasmas . . . . .	8
1.3 Challenges in Generating Atmospheric-Pressure Non-Thermal Plasmas . . . . .	10
1.4 Atmospheric Pressure Non-Thermal Plasma Sources . . . . .	14
1.4.1 Corona Discharges . . . . .	15

---

1.4.2	Dielectric Barrier Discharges (DBDs) . . . . .	16
1.4.3	Atmospheric Pressure Plasma Jets (APPJs) . . . . .	17
1.4.4	Radio-Frequency Atmospheric Pressure Plasma Jet (RF-APPJ) . . . . .	19
1.5	Literature survey and Research gap . . . . .	24
1.5.1	Electrode Configuration and Plasma Reactivity . . . . .	24
1.5.2	Power Modulation and Discharge Transitions in RF-APPJs . . . . .	28
1.5.3	Effect of DC Biasing on Discharge Regimes in RF-APPJ . . . . .	32
1.5.4	Plume Fluid Dynamics and Morphological Transitions in RF-APPJs . . . . .	35
1.6	Motivation and Scope of the Thesis . . . . .	40
1.7	Research Objectives . . . . .	41
1.8	Outline of the Thesis . . . . .	42
<b>2</b>	<b>DEVELOPMENT OF EXPERIMENTAL SETUP AND CHARACTERIZATION TECHNIQUES</b>	<b>45</b>
2.1	Development of Experimental Setup . . . . .	46
2.1.1	Plasma Jet Reactor Design and Electrode Configuration . . . . .	46
2.1.2	Gas Supply and Flow Control System . . . . .	48
2.1.3	RF Power Delivery and Matching Network . . . . .	49
2.1.4	Integration of Diagnostic Systems . . . . .	50
2.2	Plasma Characterization Techniques . . . . .	53
2.2.1	Measurement of Input Voltage, Current, and Absorbed Power . . . . .	53
2.2.2	Discharge Current and Plume Current Measurements . . . . .	58
2.2.3	Floating Potential Fluctuation Measurement Using a Single-Pin Capacitive Probe . . . . .	64
2.2.4	Optical Emission Spectroscopy: Species Identification, $T_{exc}$ and $n_e$ Estimation . . . . .	70
2.2.5	Molecular Beam Mass Spectrometry (MBMS) for Quantitative Species Analysis . . . . .	77
2.2.6	Gas Temperature Measurement Using K-type Thermocouple . . . . .	82
2.2.7	High-Speed Imaging of Plasma Plume Dynamics . . . . .	85
2.2.8	High speed Schlieren Imaging for Flow-Field and Instability Visualization . . . . .	86
<b>3</b>	<b>INFLUENCE OF AN ADDITIONAL FLOATING ELECTRODE ON PLASMA REACTIVITY</b>	<b>90</b>

---

---

3.1	Introduction and Motivation . . . . .	91
3.2	Experimental Configuration and Diagnostic Methods . . . . .	92
3.3	Optimization of Nozzle Geometry and Electrode Configuration . . . . .	93
3.3.1	Effect of Nozzle Geometry in the Presence of an Additional Floating Electrode . . . . .	94
3.3.2	Comparison Between Additional Floating and Additional Ground Electrodes . . . . .	98
3.3.3	Role of Gas Heating and Selection of Optimized Configuration . . . . .	100
3.4	Characterization of Cross-field RF APPJ with an Additional Floating Electrode	101
3.4.1	Charge Transfer Dynamics: Radial Versus Axial Transport . . . . .	101
3.4.2	Discharge Power Consumption and Energy Efficiency . . . . .	103
3.4.3	Optical Emission Characteristics and Reactive Species Enhancement . . . . .	104
3.4.4	Ion Species Composition and Plasma Chemistry Assessed by Molecular Beam Mass Spectrometry . . . . .	111
3.4.5	Floating Potential Fluctuations and Electric Field Redistribution . . . . .	114
3.4.6	Physical Mechanism of Electron Confinement and Ionization Enhancement . . . . .	115
3.5	Gas Flow Rate as a Control Parameter . . . . .	122
3.5.1	Gas Temperature Regulation by Flow Rate . . . . .	123
3.5.2	Effect of Gas Flow on Electron Excitation Temperature and Electron Density . . . . .	125
3.5.3	Reactive Species Emission under Flow and Power Control . . . . .	128
3.5.4	Operational Implications . . . . .	128
3.6	Summary: Electrode and Flow-Based Control of APPJs . . . . .	130
<b>4</b>	<b>POWER MODULATION AND DISCHARGE REGIME TRANSITIONS IN RF ATMOSPHERIC PRESSURE CROSS-FIELD PLASMA JET</b>	<b>134</b>
4.1	Introduction and Motivation . . . . .	135
4.2	Experimental Configuration and Power Modulation Strategy . . . . .	137
4.2.1	Atmospheric Pressure Plasma Jet Configuration . . . . .	137
4.2.2	Controlled Power Increment Protocol . . . . .	138
4.3	Discharge Regime Identification . . . . .	140
4.3.1	Visual Identification of Discharge Regimes Using High-Speed Imaging	140
4.3.2	Filament Nucleation and Morphological Evolution . . . . .	142

---

---

4.3.3	Electrical Signatures of Discharge Regimes . . . . .	143
4.3.4	Regime Definition Summary . . . . .	146
4.4	Plasma Parameter Evolution Across Discharge Regimes . . . . .	147
4.4.1	Electron Excitation Temperature and Electron Density . . . . .	147
4.4.2	Gas Temperature Evolution . . . . .	150
4.4.3	Coupled Evolution of Plasma Parameters . . . . .	151
4.5	Thermal Instability Framework and Governing Physics . . . . .	151
4.5.1	Physical Origin of Thermal Instability in Atmospheric-Pressure Plasmas	151
4.5.2	Quantitative Estimation of Heating and Cooling Rates . . . . .	153
4.5.3	Exclusion of Alternative Instability Mechanisms . . . . .	155
4.5.4	Connection to Observed Discharge Regimes . . . . .	156
4.6	Floating Potential Fluctuations as Electrical Signatures of Instability . . . . .	156
4.6.1	Correlation Between Floating Potential Fluctuations and Discharge Regimes	157
4.6.2	Physical Interpretation of Potential Fluctuations . . . . .	158
4.7	Role of Thermo-Field Emission in Discharge Transitions . . . . .	159
4.7.1	Thermal Instability as the Trigger for Enhanced Electron Emission . . .	159
4.7.2	Formation of Abnormal Glow and Filamentary Structures . . . . .	161
4.7.3	Ramp-Rate Dependence of Discharge Transitions . . . . .	163
4.7.4	Reactive Species Implications of Power-Modulated Discharge Regimes	165
4.8	Summary and Outlook . . . . .	168
<b>5</b>	<b>ELECTRIC FIELD-ASSISTED CONTROL OF DISCHARGE REGIMES USING POSITIVE DC BIASING IN RF CROSS-FIELD APPJ</b>	<b>171</b>
5.1	Introduction and Motivation . . . . .	172
5.2	Experimental Configuration and Diagnostic Approach . . . . .	173
5.2.1	Design and Characterization of RF-DC Decoupling Filter . . . . .	174
5.2.2	Plasma characterization methods . . . . .	178
5.3	Discharge regime evolution and baseline transition physics . . . . .	179
5.3.1	Modification of discharge current characteristics under DC bias . . . . .	180
5.4	Evolution of plasma parameters under DC bias . . . . .	183
5.4.1	Electron density and excitation temperature response to DC bias . . . . .	183
5.4.2	Floating potential fluctuations and instability signatures . . . . .	188

---

5.5	Integrated interpretation and implications for discharge control . . . . .	190
5.6	Summary and Outlook . . . . .	191
<b>6</b>	<b>THEORETICAL INSIGHT INTO HELICAL PLUMES VIA GAS FLOW DYNAMICS ANALYSIS</b>	<b>193</b>
6.1	Introduction and Motivation . . . . .	194
6.2	Experimental Configuration and Diagnostic Approach . . . . .	196
6.3	Baseline Neutral Jet Hydrodynamics Prior to Plasma Ignition . . . . .	198
6.4	Modification of Jet Flow Dynamics under Plasma Ignition . . . . .	201
6.4.1	Assessment of Buoyancy Effects Using Richardson Number . . . . .	206
6.5	Flow Instability and Vortex Development in Plasma-Driven Jets . . . . .	209
6.5.1	Analysis of Kelvin-Helmholtz Instability Growth and Vortex Onset . . . . .	209
6.5.2	Plasma Heating as an Amplifier of Kelvin-Helmholtz Growth . . . . .	211
6.5.3	Strouhal Number Analysis and Temporal Forcing of Flow Instabilities . . . . .	213
6.5.4	Baroclinic Torque and Generation of Azimuthal Vorticity . . . . .	216
6.6	Integrated mechanism deciding the plume morphology and Implications . . . . .	218
6.6.1	Coupling of Neutral Flow Instability with the Plume Morphology . . . . .	218
6.6.2	Coupling the Plume Morphology with Plasma Reactivity . . . . .	222
6.7	Summary and Outlook . . . . .	225
<b>7</b>	<b>SUMMARY AND FUTURE SCOPE OF THE THESIS</b>	<b>229</b>
7.1	Overall Summary and Major Contributions . . . . .	230
7.2	Prospects for Future Research . . . . .	234
7.3	Closing Remarks . . . . .	237
	<b>References</b>	<b>239</b>
	<b>Brief Bio-data</b>	<b>256</b>

## List of Figures

1.1	Classification of plasmas according to their characteristic electron temperature and electron density, illustrating typical regimes from laboratory to astrophysical plasmas [1] . . . . .	3
1.2	Breakdown mechanism for streamer discharge [2] . . . . .	6
1.3	Schematic representation of major applications of atmospheric pressure non-thermal plasmas in industrial, biomedical, and environmental domains. . . . .	11
1.4	Breakdown potential in various gases as a function of pressure and gap distance (p.d) [3]. Figure reproduced from its original publication Schütze et al., IEEE Trans. Plasma Sci. 1998, 26 (6), 1685; Copyright © 1998 IEEE. . . . .	12
1.5	Electron and gas temperature as a function of pressure in a plasma discharge [3]. Figure reproduced from its original publication, Schütze et al., IEEE Trans. Plasma Sci. 1998, 26 (6), 1685; Copyright © 1998 IEEE. . . . .	13
1.6	Schematic representation of typical atmospheric pressure non-thermal plasma sources: (a) Dielectric Barrier Discharge, (b) Atmospheric pressure plasma jet, and (c) Corona discharge. . . . .	15
1.7	Illustration of the frequency dependence of breakdown voltage in air, showing a reduction in breakdown threshold in the RF regime [4]. Figure reproduced from its original publication Kunhardt et al., IEEE Trans. on Plasma Sci. 2000, 26 (6); Copyright © 2000, IEEE. . . . .	20
2.1	Cross-field configuration of the APPJ along with dimensions . . . . .	47
2.2	Image of RF APPJ system under investigation . . . . .	49
2.3	Schematic of atmospheric pressure RF plasma jet experiment set up . . . . .	51
2.4	Schematic representation of the joint calibration setup used to determine the voltage and current probe calibration constants. The RF generator is connected directly to the oscilloscope through a short transmission line to obtain the reference voltage $V_r$ . The voltage probe and current transformer simultaneously measure the line voltage and current while a test load $Z_d$ provides different impedance conditions for calibration. $Z_d = 50 + jC_d$ , $C_d = 15, 27, 47$ , and $83pF$ . The procedure follows the method described in Ref. [5]. . . . .	54
2.5	Location of probes for V-I measurements . . . . .	56

2.6	Schematic showing the Voltage probe and current transformer measurement planes.	57
2.7	Schematic showing the electrical diagnostics; discharge current, discharge power via Lissajous method, and plume current, together with their respective measurement locations . . . . .	59
2.8	a) Lissajous figure for input power of 75 W b) Plot of estimated discharge power for different input voltages . . . . .	63
2.9	a) A schematic of the single pin capacitive probe geometry b) Experimental schematic with single pin capacitive probe measurement locations . . . . .	66
2.10	Voltage signal after performing FFT b) Voltage signal after applying notch filter to remove the dominant source frequency . . . . .	69
2.11	Variation in the the ratio of maximum to mean floating potential fluctuations, $V_{max}/V_{mean}$ at different axial positions with input power . . . . .	69
2.12	Time-integrated optical emission spectrum of the argon plasma jet recorded at an absorbed RF power of 75 W and argon flow rate of 3 lpm. Emission was collected at 15 mm axially and 4 mm radially from the plume center. Dominant Ar I lines, weak Ar II contributions, and reactive species such as OH, N <sub>2</sub> , and O formed due to ambient air entrainment are identified using the NIST atomic spectra database.	72
2.13	Boltzmann plot for plume ignited with input power of 75W and 3 lpm Argon flow for the estimation of electron excitation temperature . . . . .	73
2.14	Estimated electron excitation temperature ( $T_{exc}$ ) for different input powers . . .	74
2.15	Estimated electron density ( $n_e$ ) for different input powers . . . . .	76
2.16	Schematic representation of Atmospheric Pressure Plasma Jet assembly in front of the MBMS orifice for quantitative analysis of species composition in the plasma plume. MBMS schematic image taken from Malovi'c, G. et al. [6] The plasma jet was aligned perpendicular to the MBMS orifice at a fixed distance from the orifice and recorded the data in the range of 1-100 amu (m/z) . . . . .	78
2.17	Mass spectra of singly charged positive ion species obtained at an input power of 75 W and gas flow rate of 3 lpm . . . . .	79
2.18	Mass spectra of singly charged negative ion species obtained at an input power of 75 W and gas flow rate of 3 lpm . . . . .	80
2.19	Variation in positive ion species with input power with a gas flow rate of 3 lpm	80
2.20	Variation in negative ion species with input power with a gas flow rate of 3 lpm	82
2.21	Voigt fit for argon 696 line . . . . .	84
2.22	a) Schematic diagram and b) digital picture of schlieren imaging setup . . . . .	87
3.1	Schematic of the atmospheric pressure cross-field plasma jet with (a) conical and (b) cylindrical nozzle geometry with an additional floating electrode. . . . .	94

---

3.2	Plot showing the variation in the jet length in the presence of floating electrodes of different widths at different applied powers for a reactor with (a) conical nozzle and (b) cylindrical nozzle. . . . .	95
3.3	Schematic of the atmospheric pressure cross-field plasma jet with (a) an additional ground electrode and (b) single wide ground electrode . . . . .	96
3.4	Plot showing the variation in the jet length in the presence of a) an additional ground electrodes of different widths and b) a single wide ground electrode at different applied powers. . . . .	97
3.5	Plot showing the variation in the gas temperature ( $T_{gas}$ ) in the presence of additional a) floating and b) ground electrodes of different widths at different applied powers. . . . .	99
3.6	Plot of net charge transferred from the electrode gap to the external circuit versus floating ring width estimated by the series resistor and series capacitor connected to ground at input power of 75 W and gas flow of 3 lpm. The net charge Q estimated from both methods are consistent with each other and suggest a decrement of 5-35 % with a floating ring width of 3-10 mm . . . . .	102
3.7	Charge-Voltage Lissajous curves for plasma jets without additional floating electrode and with a floating electrode of width 10 mm at an input power of 70W . . . . .	104
3.8	Plot of plasma discharge power versus input power for different floating electrode widths . . . . .	105
3.9	Optical emission spectra comparing jet without and with an additional floating electrode ( $w = 10$ mm) at a) main discharge region b) nozzle c) 10 mm down the nozzle . . . . .	106
3.10	Variation in electron Excitation temperature with input power in the presence of floating electrode of different widths. Gas flow rate is 3 lpm . . . . .	107
3.11	Variation in electron density with input power in the presence of floating electrode of different widths. Gas flow rate is 3 lpm . . . . .	108
3.12	Optical emission lines of a) $OH$ b) $N_2$ and c) $O$ in the presence of floating electrodes of different widths . . . . .	109
3.13	Variation in normalized optical emission intensity of reactive oxygen and nitrogen species in the presence of the floating electrode. (Emission intensity is normalized with respect to Ar (764 nm) line). . . . .	110
3.14	Relative yield of (a) positive ion and (b) negative ion in the absence of floating electrode and in the presence of additional floating electrode of width 10 mm . . . . .	112
3.15	Variation in the ratio of maximum to mean of floating potential fluctuations with floating electrode width at different axial positions. Position 1 starts from the nozzle. . . . .	114

---

3.16	a) Main discharge region showing positive ions, excited atoms, and electrons that overcome the RF oscillations. Weak surface charging and negative ion formation may already occur near the dielectric capillary surface, although their magnitude is limited in the absence of the floating electrode. b) Electrons attract toward the floating electrode that is additionally introduced. c) Electrons accumulate on the dielectric wall enclosing the floating electrode. d) Photo-electrons generated in the positive charge cloud along with the primary electrons attract toward the floating electrode. e) These electrons repel toward the center of the glass tube under the effect of the electric field generated by the electrons accumulated on the dielectric wall and get confined within the additional floating electrode f) These confined electrons form an electron cloud and act as an electron source ahead of the ionization wave. . . . .	116
3.17	Variation in gas temperature ( $T_{gas}$ ) with input power for different widths of the additional floating electrode at a gas flow rate of 3 lpm. . . . .	122
3.18	Variation in gas temperature ( $T_{gas}$ ) with input power for different gas flow rates for the jet with an additional floating electrode of width 10 mm. . . . .	124
3.19	a) Variation in plasma jet length with gas flow rate for the cross-field plasma jet with different widths of the additional floating electrode. b) Variation in plasma jet length with Reynolds number for the cross-field plasma jet without an additional floating electrode. . . . .	125
3.20	Variation in a) electron excitation temperature ( $T_{exc}$ ) and b) electron density ( $n_e$ ) with gas flow rate for the jet with different widths of the additional floating electrode at an input power of 85 W. . . . .	126
3.21	Variation in a) electron excitation temperature ( $T_{exc}$ ) and b) electron density ( $n_e$ ) with input power for different gas flow rates for the jet with an additional floating electrode of width 10 mm. . . . .	127
3.22	Variation in normalized optical emission intensity of a) OH b) N <sub>2</sub> and c) O with input power for different gas flow rates for the jet with an additional floating electrode of width 10 mm. . . . .	129
3.23	Schematic flow chart summarizing the optimization of electrode configuration and operating parameters in a cross-field RF atmospheric-pressure cross-field plasma jet. . . . .	131
4.1	Series of images depicting the plasma plume under varying input power levels, with power increments at rates of a) 3 W/1 Sec, b) 1 W/5 Secs, and c) 1 W/10 Sec. These images visually represent the stages of initial filament formation at lower power and the subsequent glow-to-arc transition at higher power. . . . .	141
4.2	a) Input power and discharge current correlation for different power increment rates. b) Correlation between input power and discharge current at 1 W/3 S power increment rate, defining various discharge regimes. . . . .	144
4.3	Correlation of electron excitation temperature ( $T_{exc}$ ) with power for different power increment rates. . . . .	148

---

4.4	Correlation of electron density ( $n_e$ ) with power for different power increment rates.	149
4.5	Variation in Gas temperature ( $T_{gas}$ ) with input power incremented at a rate of 1W/10sec. . . . .	150
4.6	Variation in the degree of floating potential fluctuations (ratio of maximum to mean floating potential, $(V_{max}/V_{mean})$ ) for different power increment rates. . . . .	157
4.7	Series of images depicting the plasma plume during the glow-to-arc transition under varying input power levels, with power increments at rates of 3 W/1 sec . . .	161
4.8	Unified physical model illustrating the sequence of discharge transition mechanisms in the RF atmospheric-pressure plasma jet. Thermal instability drives enhanced ionization and thermo-field emission at the powered electrode, leading to filamentary abnormal glow formation. Charge accumulation on dielectric surfaces generates ponderomotive forces that suppress ion flux and electron emission, causing recovery to normal glow. Continued power increase ultimately overcomes stabilization, resulting in a irreversible glow-to-arc transition. The power increment rate controls the temporal balance between destabilizing thermal feedback and stabilizing dielectric polarization, thereby shifting transition thresholds. . . . .	164
4.9	Correlation of normalized optical emission intensity of RONS OH (308 nm) with power for different power increment rates. Optical emission intensity is normalized with respect to the Ar (764 nm) line. . . . .	166
4.10	Correlation of normalized optical emission intensity of RONS N <sub>2</sub> (337 nm) with power for different power increment rates. Optical emission intensity is normalized with respect to the Ar (764 nm) line. . . . .	167
4.11	Correlation of normalized optical emission intensity of RONS O (777 nm) with power for different power increment rates. Optical emission intensity is normalized with respect to the Ar (764 nm) line. . . . .	168
5.1	Schematic representation of the experimental setup for the positively DC-biased RF plasma jet system. . . . .	174
5.2	Correlation of cut off frequency of a low-pass filter with inductance . . . . .	175
5.3	Correlation of number of turns and radius of an air-core inductor to its inductance	176
5.4	Low pass LC filter network . . . . .	178
5.5	The variation in discharge current with DC bias voltage varying from 0-1600 V for RF power increment rate of 1 W/10 sec . . . . .	181
5.6	The variation in discharge current with DC bias voltage varying from 0-1600 V for RF power increment rate of 1 W/3 sec . . . . .	181
5.7	The variation in discharge current with DC bias voltage varying from 0-1600 V for RF power increment rate of 3 W/1 sec . . . . .	182
5.8	The variation in electron density with DC bias voltage varying from 0-1600 V for RF power increment rate of 1 W/10 sec . . . . .	184

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5.9	The variation in electron density with DC bias voltage varying from 0-1600 V for RF power increment rate of 1 W/3 sec . . . . .	184
5.10	The variation in electron density with DC bias voltage varying from 0-1600 V for RF power increment rate of 3 W/1 sec . . . . .	185
5.11	The variation in electron excitation temperature with DC bias voltage varying from 0-1600 V for RF power increment rate of 1 W/10 sec . . . . .	186
5.12	The variation in electron excitation temperature with DC bias voltage varying from 0-1600 V for RF power increment rate of 1 W/3 sec . . . . .	186
5.13	The variation in electron excitation temperature with DC bias voltage varying from 0-1600 V for RF power increment rate of 3 W/1 sec . . . . .	187
5.14	The variation in electron excitation temperature floating potential fluctuations with DC bias voltage varying from 0-1600 V for RF power increment rate of 1 W/10 sec . . . . .	188
5.15	The variation in floating potential fluctuations with DC bias voltage varying from 0-1600 V for RF power increment rate of 1 W/3 sec . . . . .	188
5.16	The variation in floating potential fluctuations with DC bias voltage varying from 0-1600 V for RF power increment rate of 3 W/1 sec . . . . .	189
6.1	Schlieren images of argon flowing into ambient air at different flow rates (1 - 10 lpm) prior to plasma ignition. . . . .	199
6.2	Measured laminar length from schlieren images for different gas flow rates before ignition of plasma . . . . .	200
6.3	Schlieren images of argon jet flow at 4 lpm, illustrating the transition from laminar to turbulent regimes in (a) plasma-off and (b) plasma-on conditions. In the plasma-on case, the discharge is operated in continuous mode at an input power of 50 W. . . . .	202
6.4	High frame rate camera images (a)-(h) and Schlieren images (i)-(p) of conical plasma plume formed by igniting the discharge with continuous RF power at 50 W, for argon gas flow rates ranging from 1 to 10 lpm. . . . .	204
6.5	High frame rate camera images (a)-(f) and Schlieren images (g)-(l) of conical plasma plume formed when the discharge is ignited with continuous RF power ranging from 30 to 80 W, at an argon flow rate of 4 lpm. . . . .	205
6.6	High frame rate camera images (a)-(h) and Schlieren images (i)-(p) of helical plasma plume formed when the discharge is ignited with pulsed RF power at 50 W, with a pulse frequency of 500 Hz and a duty cycle of 50%, for argon gas flow rates ranging from 1 to 10 lpm. . . . .	206
6.7	Intensity profile of the plasma plume from schlieren image using imageJ software (Argon flow at 4 lpm and input RF power of 50 W) . . . . .	211
6.8	Plot of theoretically estimated Kelvin-Helmholtz instability growth length and onset of initial vortex/Laminar length from schlieren image for different gas flow rates at RF input power of 50W . . . . .	212

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6.9	(a-n)Time resolved schlieren images and (o-u) High frame rate camera images of Argon plasma jet ignited at 4 lpm with continuous RF power . . . . .	214
6.10	Comparison of plasma plume length, effective potential core length, and onset position of vortex structures for conical plumes formed under continuous RF excitation at 50 W. The plot highlights the relative placement of swirl structures with respect to the luminous plasma region across different flow rates (1 - 10 lpm) . . . . .	217
6.11	Comparison of plasma plume length, effective potential core length, and onset position of vortex structures for helical plumes formed under pulsed RF excitation at 50 W. The plot highlights the relative placement of swirl structures with respect to the luminous plasma region across different flow rates (1 - 10 lpm) . . . . .	218
6.12	Flow chart illustrating the formation of swirl-structured gas flow and how swirl placement distinguishes conical plumes in continuous RF operation from helical plumes in pulsed RF operation, with representative schlieren and plume images. . . . .	220
6.13	Optical emission spectra recorded along different axial positions of the conical plume formed under continuous-mode RF excitation at 50 W input power and 4 lpm gas flow rate: (a) at the nozzle, (b) 5 mm axially down from the nozzle, and (c) 10 mm axially down from the nozzle. . . . .	221
6.14	Optical emission spectra recorded along different axial positions of the helical plume formed under pulsed RF excitation (500 Hz, 50% duty cycle) at a gas flow rate of 4 lpm: (a) at the nozzle, (b) 5 mm axially down from the nozzle, and (c) 10 mm axially down from the nozzle. . . . .	222
6.15	Normalized emission intensity of OH (308 nm) along different axial positions of conical and helical plume. . . . .	223
6.16	Normalized emission intensity of O (777 nm) along different axial positions of conical and helical plume. . . . .	223
6.17	Normalized emission intensity of $N_2$ (337 nm) along different axial positions of conical and helical plume. . . . .	224
6.18	Normalized emission intensity of $N_2$ (357 nm) along different axial positions of conical and helical plume. . . . .	224
6.19	Molecular beam mass spectrometry analysis of species composition in conical versus helical plumes. . . . .	226
7.1	A schematic overview of the major achievements and their interconnections . . . . .	233

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## List of Tables

1.1	Temperature comparison of thermal and non-thermal plasmas. . . . .	8
3.1	Charge dynamics in the presence of additional floating electrodes for different widths. . . . .	103
4.1	Correlation of normal glow-to-abnormal glow transition threshold, abnormal glow-to-normal glow transition threshold and arcing limit with power increment rate.	146
5.1	Geometrical and electrical parameters of the inductors designed for the LC filter circuit . . . . .	177
6.1	Estimated Reynolds number under different gas flow rates for different plasma discharge conditions . . . . .	207
6.2	Estimated Strouhal number under different gas flow rates for conical and helical plume morphologies . . . . .	215

# 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
$\sigma$	Conductivity
$j_e$	Current Density
$n_e$	Electron density
$T_{exc}$	Electron Excitation temperature
$\omega$	Frequency of power supply
D	Gas diffusion Coefficient
$T_{gas}$	Gas Temperature
$\Omega$	Instability Growth Factor
$\epsilon_0$	Permittivity of Vacuum

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$\omega_p$	Plasma frequency
$F_P$	Ponderomotive force
$j_e E$	Power Dissipation
$p$	Pressure
$\rho$	Density
$\gamma$	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
$\omega_i$	KHI growth rate
$\delta$	Shear layer thickness
$St$	Strouhal number
$\omega_\theta$	Baroclinic torque

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# 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).
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