

# **INVESTIGATIONS OF SHEATH FORMATION DURING PLASMA-SURFACE INTERACTION**

**RAJAT DHAWAN**



**DEPARTMENT OF PHYSICS  
INDIAN INSTITUTE OF TECHNOLOGY DELHI  
October 2022**



© Indian Institute of Technology Delhi (IITD), New Delhi, 2022



**INVESTIGATIONS OF SHEATH FORMATION DURING  
PLASMA-SURFACE INTERACTION**

**by**

**RAJAT DHAWAN**

**Department of Physics**

**Submitted**

**in fulfillment of the requirements of the degree of Doctor of Philosophy**

**to the**



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**October 2022**



***Dedicated to***

***my family and loved ones***

***&***

***those***

***whoever inspired and encouraged me***



# Certificate

---

This is to certify that the thesis entitled “**Investigations of Sheath Formation during Plasma-Surface Interaction**” being submitted by **Mr. Rajat Dhawan** is worthy of consideration for the award of the degree of Doctor of Philosophy and is a record of the original bonafide research work carried out by him under my guidance and supervision, and that the results contained in it have not been submitted in part or full to any other university or institute for award of any degree / diploma.

I certify that he has pursued the prescribed course of research. I approve the thesis for the award of the degree of Doctor of Philosophy.

**Hitendra K. Malik**

Professor

Department of Physics

Indian Institute of Technology Delhi

INDIA



## Acknowledgements

---

At the final completion of the thesis, I must first thank God, the All-Powerful, who has given me innumerable blessings, insights, and opportunities. This work would not have been possible without invaluable guidance and support of my supervisor, **Prof. Hitendra K. Malik**. I am extremely appreciative that he accepted me as a student and kept believing in me throughout the years. His depth of expertise and diligent editing have been a huge help to me. My willingness to publish my research work in its current shape was made possible by his unconditional support, invaluable inputs, patience, and cooperation. His long experience, guidance and editing enhanced this research work beyond my expectations.

Thank you to *Prof. Sujeet Chaudhary*, *Prof. Pankaj Srivastava*, and *Dr. Harish Kumar*, members of my SRC. Their supportive remarks and insightful, comprehensive feedback mean a lot to me. Furthermore, I am deeply grateful to my earlier mentors *Prof. Sanjeev Aggarwal*, *Prof. Fakir Chand*, *Prof. Manish K. Kashyap*, and *Prof. Anita Goyal* at Kurukshetra University for their ongoing encouragement that helped me get to where I am today.

Shantanu Banerjee, Sagar Dhanuskar, Sonu Kumar, Akshit Agarwal, Anuj Srivastava, Sahil Garg, and other friends deserve my gratitude for providing me with inspiration and excellent suggestions both directly and indirectly during the course of this study.

My labmates Dr. Dimple Tuteja, Dr. Ashu Jain, Dr. Rashmi Shrivastava, Dr. Reenu Gill, Dr. Jasvendra Tyagi, Dr. Aparna Sharma, Dr. Sheetal Punia, Dr. Lalita Devi, Munish, Manish Dwivedi, Sandeep, Tamanna Punia, Dhananjay Verma, Rakesh Kumar, Mohit Kumar, Subhajit Bhasker, Yetendra Prasad Jha, Gaurav Kumar, Deepak Kumar and Simranjeet Kaur, who were always willing to assist with any questions I had, deserve special recognition.

I will always be grateful to my family for everything they have done for me. My mother, *Smt. Poonam Dhawan* taught me how to write with clarity and purpose, my father, *Sh. Vijay Dhawan* taught me how to acknowledge history and storytelling, and my brother, *Mr. Pankaj Dhawan* taught me that an assertion of dominance is not necessarily a bad thing. I am grateful to my sister, *Ms. Sonali Mehta*, for always supporting me and for affirming my awesomeness even when I did not feel it. I devote everything, including this thesis, to my family.

At last, I acknowledge the financial support from Council of Scientific and Industrial Research (CSIR), Govt. of India [Grant Reference Number: 09/086(1289)/2017-EMR-1], and Indian Institute of Technology Delhi.



**Rajat Dhawan**



## Abstract

---

In microelectronics, semiconductors and automobiles industries, the surface properties of the adopted materials degrade continuously and also their applications are being constrained because of the issues of poor corrosion resistance, wear resistance, surface roughness, fatigue failure, and lower hardness. The performance of a material is determined by its surface properties. Therefore, in order to explore engineering industries in a greater detail, it is necessary to minimize hostile environments so that the material surfaces can be protected. One of the imperative ways to deal with such problems is the plasma-based material processing through the understanding of plasma-surface interactions. Plasma-based surface treatments are vitally used to modify the specific surface biological property while bulk properties remain unaltered. In order to understand the mechanism of plasma-surface interactions, it is necessary to understand the concept of sheath, which is a thin layer of charged species that is formed surrounding a metallic conducting surface when it comes into the contact of a plasma.

Electronegative plasma is composed of electrons, negative ions and positive ions. Such plasmas are being widely adopted for the last two decades because of their expanding applications in many fields such as spacecraft propulsion, microelectronics industries, thin-film deposition and sputtering, mass spectroscopy, plasma-based surface processing, and many more. Such plasmas are preferred for these applications because of relatively less impact of electrons on the surface of the material under investigation. In many applications, they serve as ion source because of the requirement of both positive and negative ion beams; these have also been used in low energy beam applications and also when energetic electrons can produce destructive effects on the surface. The best method to ward off irregular shapes is the addition of negative ions to counterbalance the positive ions, assemble on the wafer and also to enhance the working of materials using in the fabrication of integrated circuits. Electronegative plasmas are widely adopted for soft substrates to have a defect-free analysis, as they develop immensely small sheath voltage in comparison with electropositive one.

A large number of theoretical models have been developed to study sheath formation criterion and behaviour of plasma parameters. However, these models still have some limitations. For example, in most of the investigations, the researchers assumed the behaviour of negative ions through their Boltzmann distribution, which is far from the reality due to the neglect of their mass. Since the difference of mobilities of the positive and negative ions is not much and it is not appropriate to consider Boltzmann distribution for only negative ions, both

these ions should be treated at equal footings with inclusion of their masses. Moreover, the mass-ratio of the ions is also neglected, which plays a crucial role in the sheath formation process during plasma-based material processing. A very few mathematical models are available in the literature which investigate the influence of non-extensive distributed electrons on the sheath characteristics. Therefore, it is desirable to develop new models to study the realistic situation in a greater detail.

In the present thesis, keeping in mind all the above points, we have developed theoretical models where the finite mass of ions is considered and the behaviour of both the positive and negative ions is taken to be governed by the fluid equations. We have also considered the drift term in the momentum transfer equation of the negative ions to explore the practical case by taking into account the generalized situation of their different masses from the positive ions. In view of the realistic situation, the cases of presence and absence of the negative ions' drift term has been compared and it is shown that this drift term has a significant effect on the sheath formation criterion. The impact of negative-to-positive ion mass-ratio on the behaviour of plasma parameters and sheath characteristics has also been analyzed. We have established a relation which speaks about the sheath thickness. Our mathematical models have explained the exact sheath thickness determination and plasma parameters, like potential profile, the density of the charged species, ions velocity, etc. in the sheath region. The case of doubly charged ions is also considered herewith. A mathematical model has also been developed to investigate two-temperature non-extensive distributed electrons in the electropositive warm plasma having finite collisions and ionizations. Some singularities were encountered in the mathematical treatment, which have been discussed in detail and are removed while applying appropriate boundary conditions. One of the important results is the absence of oscillatory structure of the potential when the negative ions are described by their fluid equations (as that of the positive ions), instead of their Boltzmann distribution as assumed by the other workers. In magnetized collisional electronegative warm plasma if the magnetic field is strong, then the profile of positive-ion density near the sheath edge has shown a pulse-like structure for the case when we neglect the components of the positive ions' velocity parallel to the probe/wall at the sheath edge. This pulse-like structure disappeared when all the components of the positive ions velocity at the sheath edge have been included.

The outcome of this thesis would be advantageous in the experiments like plasma-based material processing where higher potential gradient is preferred to have a better thin films formation, since the positive ions are accumulated within a short region and results in preferred

thin film formed. These results would help experimentalists to select a particular plasma for a specific application. These results would help to understand those experiments where the negative ions are intentionally added to counterbalance the positive ions to ward off irregular shapes. Such results would enhance the working of materials used in the fabrication of integrated circuits. It is also expected to play a significant role in understanding astrophysical plasmas and plasma reactors at low-pressure conditions, where two types of the electrons are formed and the density distribution of these species is far from their usual Boltzmann distribution. The problem of communication blackout, which is occurred when a hypersonic speed is attained by space vehicles during their travelling through the atmosphere, can also be addressed.



## सार

माइक्रोइलेक्ट्रॉनिक, अर्धचालक और ऑटोमोबाइल उद्योगों में अपनाये गए पदार्थों की सतह के गुणों में लगातार गिरावट आती है और खराब संक्षारण प्रतिरोध, धातु श्रांतिकी प्रतिरोध, सतह खुरदरापन, श्रांतिज पात और कम कठोरता के मुद्दों के कारण उनके अनुप्रयोगों को भी बाधित किया जा रहा है। किसी पदार्थ का प्रदर्शन उसकी सतह के गुणों से निर्धारित होता है। इसलिए, इंजीनियरिंग उद्योगों का अधिक विस्तार से पता लगाने के लिए, प्रतिकूल वातावरण को कम करना आवश्यक है ताकि पदार्थों की सतहों को संरक्षित किया जा सके। ऐसी समस्याओं से निपटने के अनिवार्य तरीकों में से एक प्लाज्मा-सतह की अन्योन्यक्रिया की समझ के माध्यम से प्लाज्मा-आधारित सामग्री प्रसंस्करण है। प्लाज्मा आधारित सतह के उपचार का उपयोग विशिष्ट सतह जैविक गुण को संशोधित करने के लिए किया जाता है जबकि बल्क गुण अपरिवर्तित रहते हैं। प्लाज्मा-सतह के अंतःक्रियाओं के तंत्र को समझने के लिए, म्यान की अवधारणा को समझना आवश्यक है, जो कि आवेशित प्रजातियों की एक तनु परत होती है जो एक प्लाज्मा के संपर्क में आने पर धातु की संवाहक सतह के आसपास बनती है।

इलेक्ट्रॉनगेटिव प्लाज्मा इलेक्ट्रॉनों, नकारात्मक आयनों और सकारात्मक आयनों से बना होता है। इस तरह के प्लाज्मा को पिछले दो दशकों से अंतरिक्ष यान प्रणोदन, माइक्रोइलेक्ट्रॉनिक उद्योग, तनु-फिल्म जमाव और स्पटरिंग, मास स्पेक्ट्रोस्कोपी, प्लाज्मा-आधारित सतह प्रसंस्करण, और कई अन्य क्षेत्रों में उनके विस्तारित अनुप्रयोगों के कारण व्यापक रूप से अपनाया जा रहा है। जांच के तहत पदार्थ की सतह पर इलेक्ट्रॉनों के अपेक्षाकृत कम प्रभाव के कारण इन अनुप्रयोगों के लिए ऐसे प्लाज्मा को प्राथमिकता दी जाती है। कई अनुप्रयोगों में, वे सकारात्मक और नकारात्मक आयन बीम दोनों की आवश्यकता के कारण आयन स्रोत के रूप में कार्य करते हैं; इनका उपयोग कम ऊर्जा बीम अनुप्रयोगों में भी किया गया है और तब भी जब ऊर्जावान इलेक्ट्रॉन सतह पर विनाशकारी प्रभाव पैदा कर सकते हैं। अनियमित आकार को दूर करने का सबसे अच्छा तरीका वेफर पर इकट्ठा हुए सकारात्मक आयनों को संतुलित करने के लिए नकारात्मक आयनों को जोड़ना है, और एकीकृत सर्किट के निर्माण में उपयोग की जाने वाली सामग्रियों के काम को बढ़ाने के लिए भी है। इलेक्ट्रॉनगेटिव प्लाज्मा को व्यापक रूप से नरम सबस्ट्रेट के लिए एक दोष-मुक्त विश्लेषण के लिए अपनाया जाता है, क्योंकि वे इलेक्ट्रोपोसिटिव प्लाज्मा की तुलना में अत्यधिक छोटे म्यान वोल्टेज विकसित करते हैं।

म्यान निर्माण मानदंड और प्लाज्मा मापदंडों के व्यवहार का अध्ययन करने के लिए बड़ी संख्या में सैद्धांतिक मॉडल विकसित किए गए हैं। हालाँकि, इन मॉडलों की अभी भी कुछ परि सीमानताएँ हैं। उदाहरण के लिए, अधिकांश जांचों में, शोधकर्ताओं ने बोल्ट्जमान वितरण के माध्यम से नकारात्मक आयनों के व्यवहार को अपनाया है, जो कि उनके द्रव्यमान की उपेक्षा के कारण वास्तविकता से बहुत दूर है। चूँकि धनात्मक और ऋणात्मक आयनों की गतिशीलता का अंतर अधिक नहीं है और केवल ऋणात्मक आयनों के लिए बोल्ट्जमान वितरण को अपनाना उचित नहीं है, इन दोनों आयनों को उनके द्रव्यमानों को शामिल करते हुए समान स्तर पर व्यवहार किया जाना चाहिए। इसके अलावा, आयनों के द्रव्यमान-अनुपात की भी उपेक्षा की जाती है, जो प्लाज्मा-आधारित सामग्री प्रसंस्करण के दौरान म्यान निर्माण प्रक्रिया में महत्वपूर्ण भूमिका निभाता है। साहित्य में बहुत कम गणितीय मॉडल उपलब्ध हैं जो म्यान विशेषताओं पर गैर-व्यापक वितरित इलेक्ट्रॉनों के प्रभाव की जांच करते हैं। इसलिए, यथार्थवादी स्थिति का अधिक विस्तार से अध्ययन करने के लिए नए मॉडल विकसित करना वांछनीय है।

वर्तमान थीसिस में, उपरोक्त सभी बिंदुओं को ध्यान में रखते हुए, हमने सैद्धांतिक मॉडल विकसित किए हैं जहाँ आयनों के परिमित द्रव्यमान पर विचार किया गया है और सकारात्मक और नकारात्मक

दोनों आयनों के व्यवहार को द्रव समीकरणों द्वारा नियंत्रित किया गया है। हमने सकारात्मक आयनों से नकारात्मक आयनों के भिन्न द्रव्यमानों की सामान्यीकृत स्थिति को ध्यान में रखते हुए व्यावहारिक मामले का पता लगाने के लिए नकारात्मक आयनों के गति हस्तांतरण समीकरण में बहाव शब्द पर भी विचार किया है। वास्तविक स्थिति को देखते हुए ऋणात्मक आयनों की प्रवाह अवधि की उपस्थिति और अनुपस्थिति के मामलों की तुलना की गई है और यह दिखाया गया है कि इस प्रवाह शब्द का म्यान गठन मानदंड पर महत्वपूर्ण प्रभाव पड़ता है। प्लाज्मा मापदंडों और म्यान विशेषताओं के व्यवहार पर नकारात्मक-से-सकारात्मक आयन द्रव्यमान-अनुपात के प्रभाव का भी विश्लेषण किया गया है। हमने एक संबंध स्थापित किया है जो म्यान की मोटाई के बारे में बताता है। हमारे गणितीय मॉडल ने म्यान क्षेत्र में सटीक म्यान मोटाई निर्धारण और प्लाज्मा मापदंडों, जैसे संभाव्यता प्रोफाइल, आवेशित प्रजातियों का घनत्व, आयनों का वेग, आदि की व्याख्या की है। दोगुने आवेशित आयनों के मामले पर भी इसके साथ विचार किया गया है। परिमित टकराव और आयनीकरण वाले इलेक्ट्रोपोसिटिव गर्म प्लाज्मा में दो-तापमान गैर-व्यापक वितरित इलेक्ट्रॉनों की जांच के लिए एक गणितीय मॉडल भी विकसित किया गया है। गणितीय उपचार में कुछ विलक्षणताओं का सामना करना पड़ा, जिन पर विस्तार से चर्चा की गई है और उपयुक्त सीमा शर्तों को लागू करते हुए हटा दिए गए हैं। महत्वपूर्ण परिणामों में से एक संभाव्यता की दोलन संरचना की अनुपस्थिति है जब नकारात्मक आयनों को उनके बोल्ट्ज़मैन वितरण के बजाय जैसा कि अन्य श्रमिकों द्वारा माना गया है उनके तरल समीकरणों (सकारात्मक आयनों की तरह) द्वारा वर्णित किया जाता है। मैग्नेटाइज्ड कोलिजनल इलेक्ट्रॉनगेटिव वार्म प्लाज्मा में यदि चुंबकीय क्षेत्र मजबूत है, तो म्यान किनारे के पास सकारात्मक-आयन घनत्व के प्रोफाइल में एक पल्स जैसी संरचना दिखाई देती है जब हम म्यान किनारे पर जांच/दीवार के समानांतर धनात्मक आयनों के वेग के घटकों की उपेक्षा करते हैं। यह पल्स जैसी संरचना गायब हो जाती है जब म्यान के किनारे पर सकारात्मक आयनों के वेग के सभी घटकों को शामिल किया गया।

इस थीसिस का परिणाम प्लाज्मा-आधारित पदार्थ प्रसंस्करण जैसे प्रयोगों में लाभदायक होगा, जहां अपेक्षाकृत अच्छी तनु फिल्मों के निर्माण के लिए उच्च संभाव्यता ढाल को प्राथमिकता दी जाती है, क्योंकि सकारात्मक आयन एक छोटे क्षेत्र के भीतर जमा होते हैं और इसके परिणामस्वरूप वांछित तनु फिल्म बनती है। ये परिणाम प्रयोगवादियों को एक विशिष्ट अनुप्रयोग के लिए एक विशेष प्लाज्मा का चयन करने में मदद करेंगे। ये परिणाम उन प्रयोगों को समझने में मदद करेंगे जहां अनियमित आकार को दूर करने के लिए सकारात्मक आयनों को संतुलित करने के लिए जानबूझकर नकारात्मक आयनों को जोड़ा जाता है। इस तरह के परिणाम एकीकृत परिपथों के निर्माण में उपयोग की जाने वाले पदार्थों के कामकाज में वृद्धि करेंगे। इन परिणामों से एस्ट्रोफिजिकल प्लाज्मा और कम दबाव की स्थिति में प्लाज्मा रिएक्टरों को समझने में भी महत्वपूर्ण भूमिका निभाने की उम्मीद है, जहां दो प्रकार के इलेक्ट्रॉन बनते हैं और इन प्रजातियों का घनत्व वितरण उनके सामान्य बोल्ट्ज़मान वितरण से बहुत दूर है। संचार ब्लैकआउट की समस्या, जो तब होती है जब अंतरिक्ष वाहनों द्वारा वातावरण के माध्यम से यात्रा के दौरान एक अतिध्वनिक गति प्राप्त की जाती है, को भी संबोधित किया जा सकता है।

# Table of Contents

---

<b>Certificate.....</b>	<b>i</b>
<b>Acknowledgements.....</b>	<b>ii</b>
<b>Abstract.....</b>	<b>iii</b>
<b>Table of Contents.....</b>	<b>viii</b>
<b>List of Figures.....</b>	<b>xiv</b>
<b>List of Symbols.....</b>	<b>xxiii</b>
<b>List of Tables.....</b>	<b>xxvii</b>
<b>Chapter 1: Introduction and Literature Review.....</b>	<b>1</b>
1.1. Plasma and Sheath.....	1
1.2. Bohm Sheath Criterion.....	3
1.3. Child Langmuir’s Law.....	6
1.4. Pre-sheath Rgion.....	7
1.5. Electronegative Plasmas.....	9
1.6. Why Plasma-surface Interactions?.....	11
1.7. Literature Review.....	12
1.8. Motivation.....	15
1.9. Thesis Organisation.....	16
<b>Chapter 2: Sheath Structure in Electronegative Plasma having Cold Ions: An Impact of Negative Ions’ Mass.....</b>	<b>23</b>
2.1. Mathematical Model.....	23
2.2. Normalization Parameters.....	24
2.3. Equations in Normalized/dimensionless Form.....	25
2.4. Boundary Conditions.....	26
2.5. Results.....	26

2.5.1. Impact of mass ratio of ions and Electronegativity.....	26
2.5.2. Sheath thickness, potential and modified Bohm velocity.....	29
2.5.3. Behaviour of parameters for different probe radii.....	32
2.5.4. Limiting cases.....	36
2.5.4.1. Boltzmann distribution for negative ions.....	36
2.5.4.2. Electropositive plasma.....	39
2.6. Applications.....	40
<b>Chapter 3: Behaviour of Sheath in Electronegative Warm Plasma.....</b>	<b>41</b>
3.1. Basic Equations.....	41
3.2. Normalization Parameters.....	42
3.3. Equations in Normalized/dimensionless Form.....	42
3.4. Boundary Conditions.....	44
3.5. Results.....	45
3.5.1. Spherical geometry.....	45
3.5.1.1. Impact of temperature of positive and negative ions.....	45
3.5.1.2. Mass ratio of ions and electronegativity.....	46
3.5.2. Cylindrical geometry.....	47
3.5.2.1. Impact of temperature of positive and negative ions.....	47
3.5.3. Limiting cases.....	47
3.5.3.1. Boltzmann distributed negative ions.....	47
3.5.3.2. Electropositive plasma.....	49
3.5.3.3. Doubly charged ions.....	49
3.6. Applications.....	50
<b>Chapter 4(A): Sheath Criterion in Collisional Electronegative Warm Plasma.....</b>	<b>53</b>
4.1. Theoretical Formalism.....	53

4.2. Normalization Parameters.....	56
4.3. Equations in Normalized/dimensionless Form.....	56
4.4. Boundary Conditions and Removal of Singularities.....	56
4.5. Validation of Ions Velocity at Sheath Edge.....	59
4.6. Results.....	60
4.6.1. Normalized density and positive ion velocity.....	60
4.6.2. Positive ion velocity at probe/wall surface.....	64
4.6.3. Electric potential profile and comparative study of behaviour of negative ions with fluid approach and Boltzmann distribution.....	64
4.6.4. Sheath thickness.....	67
4.6.5. Limiting cases.....	70
4.6.5.1. Different and same collision cross sections at ion sound velocity.....	70
4.6.5.2. Same cross-sections for both the ions.....	71
4.6.5.3. Same collisional frequency for both the ions.....	71
4.6.5.4. Doubly charged ions.....	72
<b>Chapter 4(B): Effect of Negative Ions Mass and Low Frequency Ionization on Sheath Characteristics.....</b>	<b>73</b>
4.7. Mathematical Approach.....	73
4.8. Normalization Parameters.....	75
4.9. Equations in Normalized/dimensionless Form.....	75
4.10. Boundary Conditions and Removal of Singularities.....	75
4.11. Results.....	77
4.11.1. Impact of collisional parameter.....	77
4.11.2. Impact of negative ion concentration.....	79
4.11.3. Impact of negative ion temperature.....	81

4.11.4. Impact of the mass ratio of negative to positive ions.....	82
4.11.5. Impact of positive ion temperature.....	85
4.11.6. Impact of ionization rate.....	86
4.11.7. Relationship among ionization, attachment and detachment frequencies.....	87
<b>Chapter 5(A): Influence of Ionization on Sheath Structure in Electropositive Warm Plasma carrying Two-Temperature Electrons with Non-extensive Distribution.....</b>	<b>89</b>
5.1. Non-extensive Statistics.....	89
5.2. Formulation of the Problem.....	91
5.3. Normalization Parameters.....	92
5.4. Equations in Normalized/dimensionless Form.....	92
5.5. Boundary Conditions and Modified Bohm Criterion.....	93
5.6. Results.....	95
5.6.1. Lower allowed value of ion velocity at the sheath edge.....	95
5.6.2. Allowed band for ion velocity at the sheath edge.....	96
5.6.3. Validation of modified Bohm criterion.....	97
5.6.4. Electric potential profile.....	98
5.6.5. Sheath thickness.....	100
<b>Chapter 5(B): Modelling of Electronegative Collisional Warm Plasma for Plasma-Surface Interaction Process.....</b>	<b>103</b>
5.7. Basic equations for modelling.....	103
5.8. Normalization Parameters.....	104
5.9. Equations in Normalized/dimensionless Form.....	104
5.10. Boundary Conditions and Modified Bohm Criterion.....	105
5.11. Results.....	106
5.11.1. Minimum allowed values of positive ion velocity at the sheath edge.....	106

5.11.2. Charged species densities and net space charge density.....	108
5.11.3. Electric potential profile.....	109
5.11.4. Comparative study of electropositive and electronegative plasma.....	110
5.11.5. Validity of the range of electron-to-negative ion temperature ratio.....	111
5.11.6. Comparative study of sheath thickness with experimental data.....	111
<b>Chapter 6: Effect of an Oblique and Constant Magnetic Field on Sheath Characteristics.....</b>	<b>113</b>
6.1. Non-extensive Statistics in Three-dimensions.....	113
6.2. Basic Equations.....	114
6.3. Normalized Parameters.....	116
6.4. Equations in Normalized/dimensionless Form.....	116
6.5. Sheath Formation Criterion.....	117
6.5.1. Limiting cases.....	118
6.6. Results.....	119
6.6.1. Minimum allowed values of z-component of positive ion velocity at the sheath edge.....	119
6.6.2. Impact of boundary conditions.....	120
6.6.2.1. Positive ion density and negative species densities.....	120
6.6.2.2. x-, y- and z-components of positive ion velocity.....	121
6.6.3. Impact of different strength of magnetic field.....	122
6.6.4. Impact of incidence angle of magnetic field .....	124
6.6.5. Comparative study of isothermal and adiabatic approximation.....	125
<b>Chapter 7: Conclusions, Applications and Future Prospective.....</b>	<b>127</b>
7.1. Conclusions of Thesis Work.....	127
7.2. Applications of the Results.....	129

7.3. Future Scope.....131

**References.....133**

**Brief Bio-Data of Author.....143**

## List of Figures

---

**Figure. 1.1:** Sheath formation mechanism.

**Figure. 1.2:** The potential profile inside a planer sheath.

**Figure. 1.3:** Behaviour of electric potential in front of a negatively biased wall for (a) small but finite  $\epsilon = \lambda_D/L$ ; (b)  $\epsilon \rightarrow 0$ , presheath scale  $z = \frac{x}{L}$ ; (c)  $\epsilon \rightarrow 0$ , sheath scale  $\xi = \frac{x}{\lambda_D}$ .

**Figure. 2.1:** Normalized potential as a function of normalized distance from the surface of the probe with  $N_{N0} = 1$ ,  $r_P = 100$  and  $Z_P = Z_N = 1$ . Here,  $\frac{M_N}{M_P} = 0.275, 0.5$  and  $1$  correspond to  $CF_4$ , Oxygen and  $C_{60}$  plasmas, respectively.

**Figure. 2.2:** Normalized density distribution of charged species as a function of normalized distance from the surface of the probe for different mass ratio of negative to positive ions with  $N_{N0} = 1$ ,  $r_P = 100$  and  $Z_P = Z_N = 1$ .

**Figure. 2.3:** Normalized electric potential as a function of normalized distance from the surface of the probe with  $\frac{M_N}{M_P} = 0.275$ ,  $r_P = 100$  and  $Z_P = Z_N = 1$ .

**Figure. 2.4:** Sheath thickness as a function of electronegativity for different values of mass ratio with  $r_P = 100$  and  $Z_P = Z_N = 1$ . Here,  $z_S$  and  $z_P$  are designate to sheath edge and probe position, whereas,  $\eta_S$  and  $\eta_P$  are corresponding potential.

**Figure. 2.5:** Normalized potential at sheath edge as a function of electronegativity for different values of mass ratio with  $r_P = 100$  and  $Z_P = Z_N = 1$ .

**Figure. 2.6:** Normalized positive ion velocity at sheath edge as a function of electronegativity for different values of mass ratio.

**Figure. 2.7:** Sheath thickness as a function of electronegativity for different values of probe radius with  $\frac{M_N}{M_P} = 0.5$  for (a)  $r_P = 10$ , (b)  $r_P = 50$  and (c)  $r_P = 100$ .

**Figure. 2.8:** Normalized positive ion velocity at sheath edge as a function of electronegativity for different values of probe radius for  $\frac{M_N}{M_P} = 0.5$  for (a)  $r_P = 10$ , (b)  $r_P = 50$  and (c)  $r_P = 100$ .

**Figure. 2.9:** Normalized potential at sheath edge as a function of electronegativity for different values of probe radius for  $\frac{M_N}{M_P} = 0.5$  for (a)  $r_P = 10$ , (b)  $r_P = 50$  and (c)  $r_P = 100$ .

**Figure. 2.10:** Sheath thickness as a function of electronegativity for different probe potential with  $r_p = 100$ ,  $\frac{M_N}{M_P}$  and  $Z_P = Z_N = 1$ . Here,  $\eta_P$  corresponds to the probe potential.

**Figure. 2.11:** Comparative study of negative ions' density distribution based on their Boltzmann distribution (a), and fluid approach (b) as a function of distance from the probe for different temperature ratio of negative ions to electrons ( $\gamma_N$ ).

**Figure. 2.12:** Variation of normalized net space charge density with the normalized distance from the surface of the probe for different negative ion temperature, when  $\frac{M_N}{M_P} = 0.275$ ,  $N_{N0} = 4$ ,  $r_p = 100$  and  $Z_P = Z_N = 1$ .

**Figure. 2.13:** Variation of gradients in positive ion density and negative species' densities with the normalized distance from the surface of the probe for  $\gamma_N = 0.1$  and the other parameters the same as in Fig 2.12.

**Figure. 2.14:** Variation of first derivative of normalized net space charge density with the normalized distance from the surface of the probe for different negative ions temperature, when  $\frac{M_N}{M_P} = 0.275$ ,  $N_{N0} = 4$ ,  $r_p = 100$  and  $Z_P = Z_N = 1$ .

**Figure. 3.1:** Sheath thickness profile as a function of  $\gamma_P$  for different  $\gamma_N$  when  $K = 2$ ,  $Z_P = 1$ ,  $Z_N = 1$ ,  $M_P = 69$ ,  $M_N = 19$ ,  $N_{N0} = 2$ ,  $\psi_P = 100$  and  $\xi_P = 10$ .

**Figure. 3.2:** Sheath thickness profile as a function of  $N_{N0}$  for different  $\frac{M_N}{M_P}$  when  $K = 2$ ,  $Z_P = 1$ ,  $Z_N = 1$ ,  $\gamma_P = 0.1$ ,  $\gamma_N = 0.25$ ,  $\psi_P = 100$  and  $\xi_P = 10$ .

**Figure. 3.3:** Sheath thickness profile as a function of  $\gamma_P$  for different  $\gamma_N$  when  $K = 1$ ,  $Z_P = 1$ ,  $Z_N = 1$ ,  $M_P = 69$ ,  $M_N = 19$ ,  $N_{N0} = 2$ ,  $\psi_P = 100$  and  $\xi_P = 10$ .

**Figure. 3.4:** Comparative study of sheath thickness profile for fluid approach and Boltzmann distribution as a function of  $\gamma_P$  when  $K = 2$ ,  $Z_P = 1$ ,  $Z_N = 1$ ,  $M_P = 69$ ,  $M_N = 19$ ,  $N_{N0} = 2$ ,  $\psi_P = 100$  and  $\xi_P = 10$ .

**Figure. 3.5:** Comparative study of sheath thickness profile as a function of  $\gamma_P$  for electropositive and electronegative plasma when  $K = 2$ ,  $Z_P = 1$ ,  $\psi_P = 100$  and  $\xi_P = 10$  for electropositive plasma and  $K = 2$ ,  $Z_P = 1$ ,  $Z_N = 1$ ,  $M_P = 69$ ,  $M_N = 19$ ,  $N_{N0} = 2$ ,  $\gamma_N = 0.15$ ,  $\psi_P = 100$  and  $\xi_P = 10$  for electronegative plasma.

**Figure. 3.6:** Comparative study of sheath thickness profile as a function of  $N_{N0}$  for singly and doubly charged ions when  $K = 2$ ,  $M_P = 69$ ,  $M_N = 19$ ,  $\gamma_P = 0.1$ ,  $\gamma_N = 0.25$ ,  $\psi_P = 100$  and  $\xi_P = 10$ .

**Figure. 4.1:** Normalized positive (a) and negative (b) ions' velocity profiles as a function of normalized distance from the plasma sheath boundary to probe/wall surface for different initial values of negative ions' velocity at the sheath edge ( $U_{N0}$ ) when  $\frac{M_N}{M_P} = 0.275$ ,  $\gamma = -1$ ,  $\gamma_P = 0.1$ ,  $\gamma_N = 0.15$ ,  $\alpha = 0.25$ ,  $U_{P0} = 1$ ,  $Z_P = 1$  and  $Z_N = 1$ .

**Figure. 4.2:** Density profile of positive and negative ions' species in the different collisional environment with  $\frac{M_N}{M_P} = 0.275$ ,  $\gamma_P = 0.1$ ,  $\gamma_N = 0.1$ ,  $Z_P = 1$  and  $Z_N = 1$ . Here, solid, dashed and dash-dot lines correspond to  $\alpha = 0.03$ ,  $\alpha = 0.25$  and  $\alpha = 0.5$ , respectively.

**Figure. 4.3:** Normalized positive ions' velocity profile as a function of distance from the plasma sheath boundary to probe/wall surface for different collisions parameters ( $\alpha$ ) with  $\gamma = 0$ ,  $\frac{M_N}{M_P} = 0.275$ ,  $\gamma_P = 0.1$ ,  $\gamma_N = 0.1$ ,  $Z_P = 1$  and  $Z_N = 1$ .

**Figure. 4.4:** Normalized positive ions' velocity profile as a function of distance from the plasma sheath boundary to probe/wall surface for different mass ratio of negative to positive ions ( $\frac{M_N}{M_P}$ ) with  $\gamma = 0$ ,  $\alpha = 0.03$ ,  $\gamma_P = 0.1$ ,  $\gamma_N = 0.1$ ,  $Z_P = 1$  and  $Z_N = 1$ .

**Figure. 4.5:** Normalized positive ions' velocity profile as a function of distance from the plasma sheath boundary to probe/wall surface for different temperature of positive ions ( $\gamma_P$ ) with  $\gamma = 0$ ,  $\alpha = 0.5$ ,  $\frac{M_N}{M_P} = 0.5$ ,  $\gamma_N = 0.1$ ,  $Z_P = 1$  and  $Z_N = 1$ .

**Figure. 4.6:** Normalized positive ions' velocity at probe/wall surface as a function of the dimension-less parameter ( $\gamma$ ) for the different collisional parameter ( $\alpha$ ) with  $\frac{M_N}{M_P} = 0.5$ ,  $\gamma_P = 0.1$ ,  $\gamma_N = 0.1$ ,  $Z_P = 1$  and  $Z_N = 1$ .

**Figure. 4.7:** The behaviour of normalized electric potential as a function of distance from the plasma sheath boundary or sheath edge to probe/wall surface for the different mass ratio of negative to positive ions ( $\frac{M_N}{M_P}$ ) with  $\gamma = 0$ ,  $\alpha = 0.03$ ,  $\gamma_P = 0.1$ ,  $\gamma_N = 0.1$ ,  $Z_P = 1$  and  $Z_N = 1$ .

**Figure. 4.8:** A comparative study of normalized electric potential as a function of distance from the plasma sheath boundary or sheath edge to probe/wall surface for the behaviour of negative ions by fluid approach and Boltzmann distribution for the different collisional parameter ( $\alpha$ ) with  $\frac{M_N}{M_P} = 0.275$ ,  $\gamma = 0$ ,  $\gamma_P = 0.1$ ,  $\gamma_N = 0.1$ ,  $Z_P = 1$  and  $Z_N = 1$ . Here, light and bold lines correspond to Boltzmann distribution and fluid approach, respectively.

**Figure. 4.9:** A comparative study of normalized electric potential as a function of distance from the plasma sheath boundary or sheath edge for the behaviour of negative ions by fluid approach and Boltzmann distribution for the different temperature of positive ions ( $\gamma_P$ ) with  $\gamma = 0$ ,  $\alpha = 0.03$ ,  $\frac{M_N}{M_P} = 0.5$ ,  $\gamma_N = 0.1$ ,  $Z_P = 1$  and  $Z_N = 1$ . Here, solid, dotted and dash-dot lines correspond to  $\gamma_P = 0, 0.25$  and  $0.5$ , respectively.

**Figure. 4.10:** A comparative study of normalized density as a function of normalized distance from the plasma sheath boundary to probe/wall surface for the behaviour of negative ions by fluid approach and Boltzmann distribution with  $\frac{M_N}{M_P} = 0.275$ ,  $\gamma_P = 0.1$ ,  $\gamma_N = 0.1$ ,  $\alpha = 0.25$ ,  $Z_P = 1$  and  $Z_N = 1$ . Here, light and bold lines correspond to Boltzmann distribution and fluid approach, respectively. Solid and dash-dot lines correspond to positive and total negative species' densities, respectively.

**Figure. 4.11:** A comparative study of sheath thickness as a function of the dimensionless parameter ( $\gamma$ ) for the behaviour of negative ions by fluid approach and Boltzmann distribution for the different collisional parameter ( $\alpha$ ) with  $\frac{M_N}{M_P} = 0.275$ ,  $\gamma_P = 0.1$ ,  $\gamma_N = 0.1$ ,  $Z_P = 1$  and  $Z_N = 1$ . Here, light and bold lines correspond to Boltzmann distribution and fluid approach, respectively. Solid, dashed, dash-dot and dotted lines correspond to  $\alpha = 0.005, 0.03, 0.25$  and  $0.5$ , respectively.

**Figure. 4.12:** The behaviour of sheath thickness as a function of negative ions' temperature for different negative ions' concentration with  $\gamma = 0$ ,  $\frac{M_N}{M_P} = 0.275$ ,  $\alpha = 0.5$ ,  $\gamma_P = 0.1$ ,  $Z_P = 1$  and  $Z_N = 1$ .

**Figure. 4.13:** Normalized electric potential profile as a function of normalized distance from the plasma sheath boundary to probe/wall surface for different cases of collision cross section at the ion sound velocity for both the ions when  $\frac{M_N}{M_P} = 0.275$ ,  $\gamma = 0$ ,  $\gamma_P = 0.1$ ,  $\gamma_N = 0.15$ ,  $\alpha = 0.25$ ,  $Z_P = 1$  and  $Z_N = 1$ .

**Figure. 4.14:** A comparative study of normalized sheath thickness as a function of the dimensionless parameter ( $\gamma$ ) for the cases of different ( $\sigma_P \neq \sigma_N$ ) and same ( $\sigma_P = \sigma_N$ ) cross-sections of the ions and different ( $v_P \neq v_N$ ) and same ( $v_P = v_N$ ) collisional frequencies of the ions when  $\frac{M_N}{M_P} = 0.275$ ,  $\gamma_P = 0.1$ ,  $\gamma_N = 0.15$ ,  $\alpha = 0.5$ ,  $Z_P = 1$  and  $Z_N = 1$ .

**Figure. 4.15:** A comparative study of normalized sheath thickness as a function of the dimensionless parameter ( $\gamma$ ) for the singly charged ions ( $Z_P = 1$  &  $Z_N = 1$ ) and doubly charged ions ( $Z_P = 2$  &  $Z_N = 2$ ) with  $\frac{M_N}{M_P} = 0.275$ ,  $\gamma_P = 0.1$ ,  $\gamma_N = 0.1$  and  $\alpha = 0.5$ .

**Figure. 4.16:** Variation of normalized positive ion velocity (a), electrostatic potential (b), charged species densities (c) and net space charge density (d) with normalized distance from the sheath edge ( $\xi_s$ ) for different collisional parameters ( $\alpha$ ) when  $\delta = 0.005$ ,  $Z_P = Z_N = 1$ ,  $\gamma_P = \gamma_N = 10$ ,  $\frac{M_N}{M_P} = 0.5$ ,  $N_{N0} = 2$ ,  $\gamma = 0$ ,  $A = 0.0005$ ,  $D = 0.0015$  and  $\psi_P(\xi_{PP}) = 25$ . Comparative study of the sheath thickness for  $\gamma = 0$  and  $-1$  as a function of the collisional parameter is depicted in (e). In Fig. 4.16(c), solid, dash-dot and dotted lines correspond to  $\alpha = 0.01$ ,  $0.1$  and  $1$ , respectively. Here, dark and light lines are represented for positive and negative species density profile, respectively.

**Figure. 4.17:** Variation of normalized charged species densities (a), electrostatic potential (b), positive ion velocity (c) and net space charge density (d) with normalized distance from the sheath edge ( $\xi_s$ ) for different electronegativity ( $N_{N0}$ ) when  $\delta = 0.005$ ,  $Z_P = Z_N = 1$ ,  $\gamma_P = \gamma_N = 10$ ,  $\frac{M_N}{M_P} = 0.5$ ,  $\alpha = 0.01$ ,  $\gamma = 0$ ,  $A = 0.0005$ ,  $D = 0.0015$  and  $\psi_P(\xi_{PP}) = 25$ . Comparative study of the sheath thickness for  $\gamma = 0$  and  $-1$  as a function of electronegativity is depicted in (e). In Fig. 4.17(a), solid, dash-dot and dotted lines correspond to  $N_{N0} = 1$ ,  $5$  and  $10$ , respectively. Here, dark and light lines are represented for positive and negative species density profile, respectively.

**Figure. 4.18:** Variation of normalized electrostatic potential (a), positive ion velocity (b) and charged species densities (c) with normalized distance from the sheath edge ( $\xi_s$ ) for different temperature ratio of electrons to negative ions ( $\gamma_N$ ) when  $\delta = 0.005$ ,  $Z_P = Z_N = 1$ ,  $\gamma_P = 10$ ,  $\frac{M_N}{M_P} = 0.5$ ,  $\alpha = 0.01$ ,  $N_{N0} = 2$ ,  $\gamma = 0$ ,  $A = 0.0005$ ,  $D = 0.0015$  and  $\psi_P(\xi_{PP}) = 25$ . Comparative study of the sheath thickness for  $\gamma = 0$  and  $-1$  as a function of temperature ratio of electrons to negative ions is depicted in (d). In Fig. 4.18(c), solid, dash-dot and dotted lines correspond to  $\gamma_N = 2$ ,  $4$  and  $10$ , respectively. Here, dark and light lines are represented for positive and negative species density profile, respectively.

**Figure. 4.19:** The behaviour of normalized positive ion velocity (a), electrostatic potential (b), charged species densities (c) and net space charge density (d) with normalized distance from the sheath edge ( $\xi_s$ ) for different mass ratio of negative to positive ions ( $\frac{M_N}{M_P}$ ) when  $\delta = 0.005$ ,  $Z_P = Z_N = 1$ ,  $\gamma_P = \gamma_N = 10$ ,  $\alpha = 0.01$ ,  $N_{N0} = 2$ ,  $\gamma = 0$ ,  $A = 0.0005$ ,  $D = 0.0015$  and  $\psi_P(\xi_{PP}) =$

25. Comparative study of the sheath thickness for  $\gamma = 0$  and  $-1$  as a function of mass ratio of negative to positive ions is depicted in (e). In Fig. 4.19(c), solid, dash-dot and dotted lines correspond to  $\frac{M_N}{M_P} = 0.275, 0.5$  and  $1$ , respectively. Here, dark and light lines are represented for positive and negative species density profile, respectively.

**Figure. 4.20:** The behaviour of normalized positive ion velocity (a) and electrostatic potential (b) as a function of normalized distance from the sheath edge ( $\xi_s$ ) for different temperature ratio of electrons to positive ions ( $\gamma_P$ ) when  $\delta = 0.005, Z_P = Z_N = 1, \gamma_N = 10, \frac{M_N}{M_P} = 0.5; \alpha = 0.01, N_{N0} = 2, \gamma = 0, A = 0.0005, D = 0.0015$  and  $\psi_P(\xi_{PP}) = 25$ . Comparative study of the sheath thickness for  $\gamma = 0$  and  $-1$  as a function of temperature ratio of electrons to positive ions is depicted in (c).

**Figure. 4.21:** Behaviour of normalized electrostatic potential (a), positive ion velocity (b) and net space charge density (c) as a function of normalized distance from the sheath edge ( $\xi_s$ ) for different non-neutrality parameter ( $\delta$ ) when  $Z_P = Z_N = 1, \gamma_P = \gamma_N = 10, \alpha = 0.01, \frac{M_N}{M_P} = 0.5, N_{N0} = 2, \gamma = 0, A = 0.0005, D = 0.0015$  and  $\psi_P(\xi_{PP}) = 25$ . Comparative study of the sheath thickness for  $\gamma = 0$  and  $-1$  as a function of non-neutrality parameter is depicted in (d).

**Figure. 4.22:** Comparative study of normalized electric potential as a function of normalized distance for  $v_{ion} > v_{det} > v_{att}$  and  $v_{det} > v_{att} > v_{ion}$  when  $\delta = 0.005, Z_P = Z_N = 1, \gamma = -1, \frac{M_N}{M_P} = 0.5, \gamma_P = \gamma_N = 10, \alpha = 0.01, N_{N0} = 2$  and  $\psi_P(\xi_{PP}) = 25$ .

**Figure. 5.1:** Normalized values of the lower allowed ion velocity at the sheath edge, i.e.  $U_{P0Min}$ , as a function of the non-extensive parameter ( $q$ ) for (a) different values of the collisional parameter ( $\alpha$ ) and non-neutrality parameter ( $\delta$ ) with  $\alpha = 0.1$  and  $\delta = 0.025$  (curve-1),  $\alpha = 0.1$  and  $\delta = 0.05$  (curve-2) and  $\alpha = 1$  and  $\delta = 0.05$  (curve-3) when  $\alpha_c = 0.6, \psi'_0 = 0.1, T_P = 0.2$  eV,  $T_h = 6$  eV,  $T_c = 2$  eV and  $Z_P = 1$ ; (b) for different values of the cold electron density ( $\alpha_c$ ) and ion temperature ( $T_P$ ) with  $\alpha_c = 0.3$  and  $T_P = 0.2$  eV (curve-1),  $\alpha_c = 0.6$  and  $T_P = 0.5$  eV (curve-2) and  $\alpha_c = 0.6$  and  $T_P = 0.2$  eV (curve-3) when  $\delta = 0.05, \alpha = 1, \psi'_0 = 0.1, T_h = 6$  eV,  $T_c = 2$  eV and  $Z_P = 1$ ; and (c) for different values of the hot electron temperature ( $T_h$ ) when  $\alpha_c = 0.6, \delta = 0.05, \alpha = 1, \psi'_0 = 0.1, T_P = 0.2$  eV,  $T_c = 2$  eV and  $Z_P = 1$ .

**Figure. 5.2:** Normalized values of the allowed band for the ion velocity at the sheath edge as a function of the initial electric field at the sheath edge ( $\psi'_0$ ) when  $\alpha_c = 0.6, \delta = 0.05, \alpha = 1, T_P = 0.2$  eV,  $T_h = 6$  eV,  $T_c = 2$  eV,  $q = 0.1$  and  $Z_P = 1$ . Here, curve-1 and curve-2, respectively, correspond to  $U_{P0Max}$  and  $U_{P0Min}$ .

**Figure. 5.3:** Normalized densities of electrons (curve-1) and ions (curve-2) as a function of the normalized distance from the sheath edge ( $\xi_s$ ) for (a)  $U_{P0} < U_{P0Min}$ , i.e. 0.55; (b)  $U_{P0} > U_{P0Max}$ , i.e. 1.35; and (c)  $U_{P0Min} < U_{P0} < U_{P0Max}$ , i.e. 0.7 when  $\alpha_c = 0.6$ ,  $\delta = 0.05$ ,  $\alpha = 1$ ,  $\psi'_0 = 0.1$ ,  $T_p = 0.2$  eV,  $T_h = 6$  eV,  $T_c = 2$  eV,  $q = 0.25$  and  $Z_p = 1$ .

**Figure. 5.4:** Variation of electric potential with the normalized distance from the sheath edge ( $\xi_s$ ) for (a) different values of the cold electron density ( $\alpha_c$ ), collisional parameter ( $\alpha$ ) and non-neutrality parameter ( $\delta$ ) with  $\alpha_c = 0.7$ ,  $\alpha = 0.1$  and  $\delta = 0.05$  (curve-1),  $\alpha_c = 0.3$ ,  $\alpha = 0.1$  and  $\delta = 0.2$  (curve-2),  $\alpha_c = 0.3$ ,  $\alpha = 0.1$  and  $\delta = 0.05$  (curve-3) and  $\alpha_c = 0.3$ ,  $\alpha = 1$  and  $\delta = 0.05$  (curve-4) when  $\psi'_0 = 0.1$ ,  $T_p = 0.2$  eV,  $T_h = 6$  eV,  $T_c = 2$  eV,  $q = 0.1$  and  $Z_p = 1$ ; and (b) for different values of the ion temperature ( $T_p$ ), hot electron temperature ( $T_h$ ) and non-extensive parameters ( $q$ ) with  $T_h = 6$  eV,  $T_p = 0.2$  eV and  $q = 0.99$  (curve-1),  $T_h = 2$  eV,  $T_p = 0.2$  eV and  $q = 0.25$  (curve-2),  $T_h = 6$  eV,  $T_p = 0.8$  eV and  $q = 0.25$  (curve-3) and  $T_h = 6$  eV,  $T_p = 0.2$  eV and  $q = 0.25$  (curve-4) when  $\alpha_c = 0.6$ ,  $\delta = 0.05$ ,  $\alpha = 1$ ,  $\psi'_0 = 0.1$ ,  $T_c = 2$  eV and  $Z_p = 1$ .

**Figure. 5.5:** Normalized sheath thickness as a function of the (a) cold electron density ( $\alpha_c$ ) for different values of the collisional parameter ( $\alpha$ ) and non-neutrality parameter ( $\delta$ ) with  $\alpha = 1$  and  $\delta = 0.05$  (curve-1),  $\alpha = 0.1$  and  $\delta = 0.05$  (curve-2) and  $\alpha = 0.1$  and  $\delta = 0.2$  (curve-3) when  $\psi'_0 = 0.1$ ,  $T_p = 0.2$  eV,  $T_h = 6$  eV,  $T_c = 2$  eV,  $q = 0.1$  and  $Z_p = 1$ ; and as a function of the (b) non-extensive parameter ( $q$ ) for different values of the ion temperature ( $T_p$ ) and hot electron temperature ( $T_h$ ) with  $T_h = 10$  eV and  $T_p = 0.2$  eV (curve-1),  $T_h = 10$  eV and  $T_p = 0.8$  eV (curve-2) and  $T_h = 6$  eV and  $T_p = 0.2$  eV (curve-3) when  $\alpha_c = 0.6$ ,  $\delta = 0.05$ ,  $\alpha = 1$ ,  $\psi'_0 = 0.1$ ,  $T_c = 2$  eV and  $Z_p = 1$ .

**Figure. 5.6:** Behaviour of  $U_{P0}$  as a function of the non-extensive parameter ( $q$ ) for (a) different values of the collisional parameter ( $\alpha$ ) when  $\psi'_0 = 0.1$ ,  $N_{N0} = 5$ ,  $\gamma_p = 10$  and  $\gamma_N = 10$ ; (b) for different values of electronegativity ( $N_{N0}$ ) when  $\psi'_0 = 0.1$ ,  $\alpha = 0.1$ ,  $\gamma_p = 10$  and  $\gamma_N = 10$ ; (c) for different values of negative ion temperature ( $\gamma_N$ ) when  $\psi'_0 = 0.1$ ,  $\alpha = 0.1$ ,  $\gamma_p = 10$  and  $N_{N0} = 5$ ; and (d) for different values of positive ion temperature ( $\gamma_p$ ) when  $\psi'_0 = 0.1$ ,  $\alpha = 0.1$ ,  $\gamma_N = 10$  and  $N_{N0} = 5$ .

**Figure. 5.7:** Behaviour of charged species densities, i.e.  $N_p$ ,  $N_N$  and  $N_e$  as a function of distance from the sheath edge to probe/wall position for different values of (a)  $\gamma_p = 5$  and (b)  $\gamma_p = 25$  when  $\psi'_0 = 0.1$ ,  $\alpha = 0.1$ ,  $\gamma_N = 10$ ,  $q = 0.5$  and  $N_{N0} = 2$ . Behaviour of net space charge

density,  $N_{Net}$  (c) as a function of distance from the sheath edge to probe/wall position for different values of  $\gamma_P$  with the similar aforesaid parameters.

**Figure. 5.8:** Behaviour of (a) electric potential ( $\psi$ ) and (b) positive ion velocity ( $U_P$ ) as a function of distance from the sheath edge to probe/wall position for different values of collisional parameter ( $\alpha$ ) when  $\psi'_0 = 0.1$ ,  $\gamma_N = 10$ ,  $\gamma_P = 15$ ,  $q = 0.5$  and  $N_{N0} = 5$ .

**Figure. 5.9:** Comparative study of charged species densities as a function of distance from the sheath edge to probe/wall position for electropositive (thin lines) and electronegative plasma (thick lines) when  $\psi'_0 = 0.1$ ,  $\gamma_N = 10$ ,  $\gamma_P = 5$ ,  $q = 0.5$  and  $\alpha = 0.1$ . Here,  $N_{N0} = 0$  corresponds to electropositive plasma.

**Figure. 6.1:** Geometry of the system.

**Figure. 6.2:** Minimum allowed values of z-component of positive ion velocity at the sheath edge, i.e.  $U_{P0zMin}$ , for (a) distinctive non-neutrality parameter ( $\delta$ ) with  $\alpha = 1$  and  $q = 0.4$ ,  $\alpha = 1$  and  $q = 0.75$  and  $\alpha = 2.5$  and  $q = 0.4$  when  $Z_P = 1$ ,  $Z_N = 1$ ,  $\psi'_0 = 0.1$ ,  $\gamma_N = 0.2$ ,  $\gamma_P = 0.1$ ,  $\theta = 30$ ,  $C = 1$ ,  $N_{N0} = 2$  and  $\alpha_B = 1.2869$ ; (b) distinctive initial electric field at the sheath edge ( $\psi'_0$ ) with  $\gamma_P = 0.01$  and  $\gamma_N = 0.05$ ,  $\gamma_P = 0.01$  and  $\gamma_N = 0.2$  and  $\gamma_P = 0.1$  and  $\gamma_N = 0.05$  when  $\delta = 0.05$ ,  $\alpha = 1$ ,  $Z_P = 1$ ,  $Z_N = 1$ ,  $N_{N0} = 2$ ,  $q = 0.4$ ,  $\theta = 30$ ,  $C = 1$  and  $\alpha_B = 1.2869$ ; (c) distinctive incidence angle of magnetic field ( $\theta$ ) with  $C = 1$ ,  $C = 5/3$  and  $C = 3$  when  $\delta = 0.05$ ,  $\alpha = 1$ ,  $Z_P = 1$ ,  $Z_N = 1$ ,  $\psi'_0 = 0.1$ ,  $\gamma_N = 0.2$ ,  $\gamma_P = 0.1$ ,  $q = 0.4$ ,  $N_{N0} = 2$  and  $\alpha_B = 1.2869$ ; and (d) distinctive negative ion background density ( $N_{N0}$ ) with  $U_{P0y} = \frac{\psi'_0 \sin \theta}{\alpha_B}$  and  $U_{P0y} = 0$  when  $\delta = 0.05$ ,  $\alpha = 1$ ,  $Z_P = 1$ ,  $Z_N = 1$ ,  $\psi'_0 = 0.1$ ,  $\gamma_N = 0.2$ ,  $\gamma_P = 0.1$ ,  $q = 0.4$ ,  $\theta = 30$  and  $\alpha_B = 1.2869$ .

**Figure. 6.3:** Impact of boundary conditions (the components of positive ions velocity parallel to the probe/wall at the sheath edge) on the positive ion density (a) and negative species densities (b) as a function of distance from the sheath edge with  $U_{P0x} = U_{P0z} \tan \theta$  and  $U_{P0y} = \frac{\psi'_0 \sin \theta}{\alpha_B}$  (solid line),  $U_{P0x} = 0$  and  $U_{P0y} = \frac{\psi'_0 \sin \theta}{\alpha_B}$  (dotted-dashed line),  $U_{P0x} = U_{P0z} \tan \theta$  and  $U_{P0y} = 0$  (dashed line) and  $U_{P0x} = 0$  and  $U_{P0y} = 0$  (dotted line) when  $\delta = 0.05$ ,  $\alpha = 1$ ,  $Z_P = 1$ ,  $Z_N = 1$ ,  $\psi'_0 = 0.1$ ,  $N_{N0} = 2$ ,  $\gamma_N = 0.2$ ,  $\gamma_P = 0.1$ ,  $q = 0.7$ ,  $\theta = 30$ ,  $C = 1$  and  $\alpha_B = 1.2869$ .

**Figure. 6.4:** Impact of boundary conditions (the components of positive ions velocity parallel to the probe/wall at the sheath edge) on x-, y- and z-components of positive ion velocity with  $U_{P0x} = U_{P0z} \tan \theta$  and  $U_{P0y} = \frac{\psi'_0 \sin \theta}{\alpha_B}$  (a),  $U_{P0x} = 0$  and  $U_{P0y} = 0$  (b),  $U_{P0x} = U_{P0z} \tan \theta$  and

$U_{P0y} = 0$  and  $U_{P0x} = 0$  and  $U_{P0y} = 0$  when  $\delta = 0.05$ ,  $\alpha = 1$ ,  $Z_P = 1$ ,  $Z_N = 1$ ,  $\psi'_0 = 0.1$ ,  $N_{N0} = 2$ ,  $\gamma_N = 0.2$ ,  $\gamma_P = 0.1$ ,  $q = 0.7$ ,  $\theta = 30$ ,  $C = 1$  and  $\alpha_B = 1.2869$ .

**Figure. 6.5:** Profiles of electric potential (a) and positive ion density (b) as a function of distance from the sheath edge with distinctive strength of the magnetic field ( $\alpha_B$ ) and initial x-component of positive ion velocity ( $U_{P0x}$ ) when  $\delta = 0.05$ ,  $\alpha = 1$ ,  $Z_P = 1$ ,  $Z_N = 1$ ,  $\psi'_0 = 0.1$ ,  $N_{N0} = 2$ ,  $\gamma_N = 0.2$ ,  $\gamma_P = 0.1$ ,  $q = 0.7$ ,  $\theta = 30$  and  $C = 1$ .

**Figure. 6.6:** Profiles of x-, y- and z-components of positive ion velocity with distinctive magnetic field values when  $\delta = 0.05$ ,  $\alpha = 1$ ,  $Z_P = 1$ ,  $Z_N = 1$ ,  $\psi'_0 = 0.1$ ,  $N_{N0} = 2$ ,  $\gamma_N = 0.2$ ,  $\gamma_P = 0.1$ ,  $q = 0.7$ ,  $\theta = 30$ ,  $C = 1$ ,  $U_{P0x} = 0$  and  $U_{P0y} = \frac{\psi'_0 \sin \theta}{\alpha_B}$ .

**Figure. 6.7:** Profiles of electric potential (a) and z-component of positive ion velocity (b) as a function of distance from the sheath edge with distinctive incidence angle of magnetic field ( $\theta$ ) when  $\delta = 0.05$ ,  $\alpha = 1$ ,  $Z_P = 1$ ,  $Z_N = 1$ ,  $\psi'_0 = 0.1$ ,  $N_{N0} = 2$ ,  $\gamma_N = 0.2$ ,  $\gamma_P = 0.1$ ,  $q = 0.7$ ,  $\alpha_B = 1.2869$ ,  $C = 1$ ,  $U_{P0x} = U_{P0z} \tan \theta$  and  $U_{P0y} = \frac{\psi'_0 \sin \theta}{\alpha_B}$ .

**Figure. 6.8:** Profiles of electric potential (a) and z-component of positive ion velocity (b) as a function of distance from the sheath edge with  $C = 1$ ,  $C = 5/3$  and  $C = 3$  when  $\delta = 0.05$ ,  $\alpha = 1$ ,  $Z_P = 1$ ,  $Z_N = 1$ ,  $\psi'_0 = 0.1$ ,  $N_{N0} = 2$ ,  $\gamma_N = 0.2$ ,  $\gamma_P = 0.1$ ,  $q = 0.7$ ,  $\theta = 30$ ,  $\alpha_B = 1.2869$ ,  $U_{P0x} = U_{P0z} \tan \theta$  and  $U_{P0y} = \frac{\psi'_0 \sin \theta}{\alpha_B}$ .



## List of Symbols

---

$\alpha$  = Normalized collisional parameter

$\alpha_c$  = Background concentration ratio of cold electrons to total electrons

$\alpha_h$  = Background concentration ratio of hot electrons to total electrons

$\epsilon_0$  = Permittivity of the free space

$C$  = Polytropic constant

$c_s$  = Sound/acoustic speed

$\delta$  = Ionization parameter/non-neutrality parameter

$\vec{\nabla}P_N$  = Pressure gradient term for negative ions

$\vec{\nabla}P_P$  = Pressure gradient term for positive ions

$e$  = Electronic charge

$\vec{F}_c$  = Collisional drag force

$\gamma$  = Power factor or dimensionless factor ranging from  $-1$  to  $0$

$\gamma_c$  = Normalized cold electrons temperature

$\gamma_h$  = Normalized hot electrons temperature

$\gamma_N$  = Normalized negative ions temperature

$\gamma_P$  = Normalized positive ions temperature

$i_N$  = Negative ion current collected by probe

$i_P$  = Positive ion current collected by probe

$j_N$  = Negative ion current density

$j_P$  = Positive ion current density

$K_B$  = Boltzmann constant

$K$  = Geometric constant

$L$  = Finite plasma size/characteristics length of plasma

$\lambda_D$  = Debye length

$\Lambda$  = Ionization length

$M_e$  = Mass of electrons

$M_N$  = Mass of negative ions

$M_P$  = Mass of positive ions

$\mu$  = Mass ratio of electrons to positive ions

$n_c$  = Cold electrons density

$n_e$  = Electron density

$n_{e0}$  = Electron density in plasma/background density of electrons

$n_g$  = Neutral gas density

$n_h$  = Hot electrons density

$n_N$  = Negative ions density

$n_{N0}$  = Negative ion density in plasma/background density of negative ions

$n_P$  = Positive ions density

$n_{P0}$  = Positive ion density in plasma/background density of positive ions

$N_c$  = Normalized cold electrons density

$N_e$  = Normalized electron density

$N_h$  = Normalized hot electrons density

$N_N$  = Normalized negative ion density

$N_{Net}$  = Net space charge density

$N_{N0}$  = Electronegativity

$N_P$  = Normalized positive ion density

$N_{P0}$  = Electropositivity

$\nu$  = Collisional frequency

$v_{att}$  = Attachment frequency

$v_{det}$  = Detachment frequency

$v_{iz}$  = Ionization frequency

$v_N$  = Speed/velocity of negative ions

$v_{N0}$  = Negative ion velocity at sheath edge

$v_P$  = Speed/velocity of positive ions

$\phi$  = Electric potential

$\phi_{wall}$  or  $\phi_P$  = Electric potential at wall/probe

$\psi$  = Normalized electric potential

$\psi'$  = Normalized electric field

$\psi_{wall}$  or  $\psi_P$  = Normalized potential at the wall/probe

$\psi_0$  or  $\psi_s$  = Normalized potential at sheath edge

$\psi'_0$  or  $\psi'_s$  = Normalized electric field at sheath edge

$q$  = Non-extensivity of the system

$r$  = Distance from the surface of spherical/cylindrical probe

$\sigma(v)$  = Momentum-transfer collisional cross-section between the ions and the neutrals

$T_c$  = Temperature of cold electrons

$T_e$  = Temperature of electrons

$T_{eff}$  = Effective temperature

$T_h$  = Temperature of hot electrons

$T_N$  = Temperature of negative ions

$T_P$  = Temperature of positive ions

$U_N$  = Normalized negative ion velocity

$U_{N0}$  = Normalized negative ion velocity at sheath edge

$U_P$  = Normalized positive ion velocity

$U_{P0}$  = Normalized positive ion velocity at sheath edge

$U_{P_{Probe}}$  = Positive ion velocity at probe/wall surface

$v_{P0}$  = Positive ion velocity at sheath edge/positive ion drift velocity at  $x = 0$

$x$  = Distance

$z$  = Space coordinate in pre-sheath scale

$\xi$  = Normalized distance

$\xi_{PP}$  = Normalized position of probe/wall

$\xi_S$  = Normalized distance corresponding to sheath edge

$Z_N$  = Charge on negative ions

$Z_P$  = Charge on positive ions

## List of Tables

---

Table 4.1: Minimum allowed values of negative ions' velocity at the sheath edge  $(U_{N0})_{Min}$  for different combinations of positive to negative ions mass ratio  $\frac{M_P}{M_N}$  and temperature ratio  $\gamma_N$  of negative ions to electron.