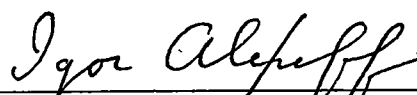


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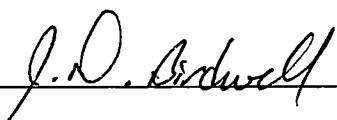
I am submitting herewith a dissertation written by Weng Lock Kang entitled "An Exploratory Study of A Novel Enhanced Corona Discharge for Sterilization." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Electrical Engineering.


Igor Alexeff, Major Professor

We have read this dissertation
And recommend its acceptance:









Accepted for the Council:


Associate Vice Chancellor and
Dean of The Graduate School

**AN EXPLORATORY STUDY
OF
A NOVEL ENHANCED CORONA DISCHARGE
FOR
STERILIZATION**

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Weng Lock Kang
May 2000

DEDICATION

This Dissertation Is Dedicated To

My

Brothers And Sisters

And

My

Girlfriend

ACKNOWLEDGEMENTS

I wish to thank my advisor, Professor Igor Alexeff, for the help and support he has given me. I am particularly grateful to my Dissertation Committee, Professors Marshall Pace, J. Douglas Birdwell, Thomas Meek and Mark Rader for their advice and encouragement.

There are a number of other people whose assistance should be acknowledged here. Thus, I would like to thank Doctor Eusebio Garate of the Applied Pulsed Power Technologies for the sterilization results. Doctor Mounir Laroussi had shared his expertise in the field of plasma science and offered invaluable suggestions on conducting the research.

Last but not least, I would like to thank AFOSR (Air Force Office of Scientific Research) for the financial support. Without the STTR project, I would never have embarked upon this research.

ABSTRACT

Conventional methods of sterilization have their shortcomings and limitations. The methods used have recently raised public controversies concerning their environmental effects and other health issues. In an attempt to eliminate these drawbacks, new approaches based on different technologies are being investigated by researchers the world over. Among the approaches, plasma-aided processing is perhaps the most promising. This dissertation describes a novel enhanced corona discharge for sterilization. Reducing or avoiding the attachment of electrons to the oxygen molecules will enhance corona discharge at atmospheric pressure and ambient room temperature. Such enhancement has been achieved by replacing the air around the limited corona points with non-electronegative gases such as argon, helium, and nitrogen. Three configurations of electrode are constructed or designed for the purpose and an enhanced corona discharge sterilization apparatus is developed. By biasing a parallel pair of electrodes positively and negatively, two species of ions are created. The two streams of ions migrate into the bulk plasma, overcoming density limitation that usually occurs in a single-species corona discharge. Plasma characteristics such as the I-V relationship, local ion density, the spatial ion density profiles and ozone productions are analyzed. Plasma ion densities of the enhanced corona discharge have reached the order of 10^{11} ion/cm³. In the sterilization tests, preliminary results indicate that the atmospheric pressure enhanced corona discharge is effective in sterilizing surfaces contaminated with microorganisms such as *Escherichia coli* and *Bacillus subtilis* cells. The bi-phasic killing curves reveal two different D values, a faster 29 seconds followed by a slower 104 seconds for *E. coli*.

For *B. subtilis*, the values are 30 seconds and 485 seconds respectively. A 4.8 and 1.5 minutes of exposure times have resulted in a 6-log and 3-log reduction of *E. coli* and *B. subtilis* populations respectively. The antimicrobial mechanism of the enhanced corona discharge is not investigated but it is believed that charged particles, active free radicals, and radiation produced by the discharge have played a major role in the sterilization process. Though the sterilization tests on *E. coli* and *B. subtilis* are preliminary, the results are encouraging to merit a more thorough investigation in the future.

TABLE OF CONTENTS

CHAPTER	PAGE
1. INTRODUCTION.....	1
1.1 The need for new methods of sterilization	1
1.2 Why plasma-aided processing for sterilization	3
1.3 Inspired objectives of the dissertation	7
1.4 Scopes and organization of the dissertation	7
 2. LITERATURE REVIEW.....	 10
2.1 Sterilization basics.....	10
2.1.1 Microorganisms.....	10
2.1.2 Sterilization and disinfection	12
2.1.3 Testing criteria for sterilization method.....	13
2.2 Conventional methods of sterilization	18
2.2.1 Sterilization by dry heat	18
2.2.2 Sterilization by saturated steam	20
2.2.3 Sterilization by gaseous chemicals	22
2.2.4 Sterilization by ionizing radiation.....	25
2.2.5 Sterilization by ultraviolet radiation.....	27
2.2.6 Filtration of liquids and air.....	29
2.2.7 Chemical disinfection.....	29
2.2.8 Summary of conventional methods of sterilization.....	30
2.3 Plasma-aided sterilization.....	34
2.3.1 Ozone for the treatment of water.....	35
2.3.2 Plasma-aided sterilization attempts before the advent of STERRAD®....	36
2.3.3 The STERRAD® 100 sterilization system.....	37
2.3.4 Atmospheric plasma for sterilization.....	40
2.3.5 Comparison between plasma-aided sterilization.....	42
2.4 Comparison between conventional and plasma-aided sterilization.....	44
2.5 Taking the step further.....	47
 3. PHYSICS OF ENHANCED CORONA DISCHARGE.....	 49
3.1 Physics of electrical breakdown of gases.....	49
3.2 Single-species corona discharge.....	52
3.3 Space charge limitation in a single-species corona discharge.....	56

3.4 Two-species corona discharge for enhancement.....	59
3.5 Enhanced corona discharge with a gas feed.....	59
4. THE ENHANCED CORONA DISCHARGE APPARATUS.....	62
4.1 The design of the electrodes.....	62
4.2 The construction of the apparatus.....	70
4.3 The testing of the apparatus for enhanced corona discharge.....	73
5. PLASMA CHARACTERIZATION OF THE APPARATUS.....	81
5.1 The I-V characteristics of the enhanced corona discharge.....	81
5.1.1 Effect of airflow on the I-V characteristics.....	83
5.1.2 Effect of electrode spacing on the I-V characteristics.....	89
5.1.3 Effect of gas flow on the I-V characteristics.....	95
5.1.4 Comparison and analysis.....	105
5.1.5 The arcing of argon-fed discharge at a high flow rate of 120 cc/s.....	108
5.2 The probe for plasma density measurement.....	114
5.3 Local density measurement at the center of the discharge	117
5.3.1 Effect of airflow on the local ion density.....	118
5.3.2 Effect of electrode spacing on the local ion density.....	125
5.3.3 Effect of gas flow on the local ion density.....	131
5.4 Spatial ion density profile across the apparatus	137
5.5 The ozone production rate.....	147
6. STERILIZATION TEST.....	152
6.1 Why <i>Escherichia coli</i> and <i>Bacillus subtilis</i>	152
6.2 Preparation of the sample microorganism.....	153
6.3 Subjecting the microorganisms to the sterilizer for treatment	154
6.4 Sterilization results	158
6.5 Comparing with results from other atmospheric plasma sterilization methods.....	162
7. CONCLUSION.....	166
7.1 Nature of enhanced corona discharge.....	167
7.2 Sterilization results from enhanced corona discharge.....	167
7.3 Some important results from other atmospheric plasma treatment.....	169
7.4 Plasma-aided sterilization versus conventional method of sterilization.....	169
7.5 Antimicrobial mechanism and other unsolved issues.....	170

7.6 Interdisciplinary nature of the plasma-aided sterilization research.....	171
7.7 Suggested future work.....	172
REFERENCES.....	174
VITA.....	185

LIST OF TABLES

Table	Page
1.1. Common failures of the conventional methods of sterilization.....	2
1.2. Sizes of shrinking semiconductor structures	5
1.3. Sizes of microorganisms	6
2.1. Types of microorganisms and their distinguishing characteristics	11
2.2. Summary of conventional methods of sterilization	31
2.3. Why conventional methods of sterilization are inadequate	33
2.4. Comparison between selected plasma-aided sterilizations	43
2.5. Comparison between conventional and plasma-aided sterilization	45
5.1. Summary of analysis for Figure 5.4.....	101
5.2. Density probe measurements (i_p , v_p , n) at the respective data points (I, V) of Figure 5.2 where effect of airflow was investigated.....	120
5.3. Density probe measurements (i_p , v_p , n) at the respective data points (I, V) for Figure 5.3 where the effect of electrode spacing was investigated	126
5.4. Density probe measurements (i_p , v_p , n) at the respective data points (I, V) of Figure 5.4 where the effect of gas flow rates was investigated	132
5.5. The spatial ion density measurements across the discharge chamber with no gas feed (center of probe lying on the plane formed by the sharp-points).....	138
5.6. The spatial ion density measurements across the discharge chamber with no gas feed (center of probe lying at 0.5 cm below the plane formed by the sharp- points).....	141
5.7. The spatial ion density measurements across the discharge chamber with no gas feed (center of probe lying at 0.5 cm above the plane formed by the sharp- points).....	144
5.8 Production of ozone inside the enhanced corona discharge apparatus with different gas feeds.....	151

LIST OF FIGURES

Figure	Page
2.1. Steps for laboratory testing of a sterilization method.....	14
2.2. Typical death rate curves.....	17
3.1. A typical current-voltage curve of the DC low-pressure discharge tube.....	51
3.2. Breakdown voltage of dry air at 20°C as a function of the product pd.....	53
3.3. Two common electrode configurations for generating DC corona discharge	55
3.4. Positive point and a grounded plane.....	57
3.5. Negative point and a grounded plane.....	58
3.6. Enhanced corona discharge with non-electronegative gas feed.....	61
4.1. A design of the sharp-point electrode.....	63
4.2. A photo of the sharp-point electrode.....	65
4.3. A design of the slit electrode.....	66
4.4. A photo of the slit electrode.....	67
4.5. A design of the blade electrode.....	68
4.6. Axial views of (a) sharp-point electrode and (b) slit electrode.....	69
4.7. The enhanced corona discharge apparatus.....	71
4.8. Assembly of the enhanced corona discharge apparatus.....	72
4.9. Starting of the enhanced corona discharge with sharp-point electrodes separated by a distance of 7.62 cm from each other.....	74
4.10. Uniform enhanced corona discharge with sharp-point electrodes separated by a distance of 7.62 cm from each other.....	75
4.11. Streaking of a more luminous enhanced corona discharge with sharp-point electrodes separated by a distance of 7.62 cm from each other	76

4.12. Enhanced corona discharge with sharp-point electrodes separated by a distance of 15.24 cm from each other.....	77
4.13. Enhanced corona discharge with slit electrodes separated by a distance of 7.62 cm from each other.....	78
4.14. Enhanced corona discharge with slit electrodes separated by a distance of 15.24 cm from each other.....	79
5.1. Experimental setup for measuring the current I and voltage V applied on the electrodes of the enhanced corona discharge (ECD) apparatus.....	82
5.2. Effect of airflow on the I-V characteristics of ECD with sharp-points electrode separated by a spacing of 3 inches (7.62 cm) between them.....	85
5.3. Effect of electrode spacing on the I-V characteristics of ECD with sharp-point electrodes.....	91
5.4. Effect of gas flow rate on the I-V characteristics of ECD with sharp-point electrodes separated by a spacing of 3 inches (7.62 cm) between them.....	97
5.5. I-V characteristics of (a) low-pressure DC glow discharge at 1 torr, (b) plasma torch at 1 atmospheric pressure, and (c) positive point-to-plane corona discharge at a gap of 13 mm in atmospheric air	106
5.6. Selected I-V characteristics of ECD with sharp-point electrodes separated by a spacing of 7.62 cm and operated under different discharge conditions.....	107
5.7. I-V characteristics of argon-fed discharge at 120 cc/s, showing signs of approaching arcing.....	109
5.8. Physics of gas-fed discharge at a high flow rate.....	111
5.9. Mathematical presentation of $N_g(t)$ and $N_{air}(t)$ for Figure 5.8.....	113
5.10. Plasma density probe sitting in the discharge chamber.....	115
5.11. A simple parallel-plate probe for measuring ion density.....	116
5.12. Ion density located at the center of the discharge showing the influence of three different discharge chamber operating conditions.....	124
5.13. Ion density located at the center of the discharge showing the influence of different electrode spacing	130

5.14. Ion density located at the center of the discharge showing the influence of the types of gas feed at different flow rates	136
5.15. Spatial ion density profile (no gas feed) with the center of the probe lying on the plane formed by the sharp-points.....	139
5.16. Spatial ion density profile (no gas feed) with the center of the probe located at 0.5 cm below the sharp-point plane.....	142
5.17. Spatial ion density profile (no gas feed) with the center of the probe located at 0.5 cm above the sharp-point plane.....	145
5.18. Monitoring the ozone production inside the ECD apparatus	148
6.1. Electrode with multiple lines of pins.....	155
6.2. Apparatus used to conduct sterilization tests.....	156
6.3. DC power dissipated at different gap distance between the electrodes of the apparatus shown in Figure 6.2.....	157
6.4. Survivability of <i>Escherichia coli</i> under enhanced corona discharge treatment in air.....	159
6.5. Survivability of <i>Bacillus subtilis</i> under enhanced corona discharge treatment in air	160
6.6. Survivability of <i>Escherichia coli</i> under OAUGDP treatment.....	163
6.7. Survivability of <i>Bacillus subtilis</i> under OAUGDP treatment.....	165

CHAPTER 1

INTRODUCTION

1.1 The need for new methods of sterilization

The principles and practice of methods used for killing, disinfecting, or sterilizing microorganisms to assist in the prevention of infectious disease are one of the main concerns of the medical/health science community as well as the food science industry. The primary methods of sterilization currently in use include dry heat, saturated steam, gaseous chemicals, ionizing irradiation, and ultraviolet radiation, whereas the methods of disinfection include filtration and chemical disinfectants [1.1, 1.2]. The available methods must deal with various problems or failures as shown in Table 1.1.

Though effective in the killing of the microorganisms, each of the conventional methods has its limited usage, as it cannot kill a wide range of microorganisms. The method used may have some inadvertent effects on the materials treated [1.3]. Dry heat sterilization, for example, causes destruction to materials that are thermally sensitive [1.4]. Saturated steam sterilization, commonly known as autoclaving ¹, can damage the materials due to the moisture content in the steam [1.5]. Long processing cycles have tended to make some of the methods obsolete, as they can no longer meet today's needs and demands. As for regulation compliance, it is becoming harder for conventional methods to comply with the increasingly stringent federal, state, or even the local level of

¹ An autoclave is a vessel fitted with a self-closing door, not descriptive of modern steam sterilizers but continued usage is still in practice.

Table 1.1. Common failures of the conventional methods of sterilization.

<u>Failure</u>	<u>Explanation</u>
1. Limitation	Each method has its limited usage.
2. Inadvertent Consequence	May be detrimental to the materials treated.
3. Obsolete	Inadequate in meeting today's health care/sterilization needs or demands.
4. Regulation Compliance	Becoming harder and harder to comply with the increasingly stringent federal, state or local level of regulations or standards.
5. Public Relation	Environmental unfriendliness.
6. Costs	Not cost effective in the eyes of the health care management teams.

regulations or standards. And as if this is not enough, public relations are another concern: the methods have recently raised public controversies concerning their environmental effects and other health issues [1.6]. Thus, the formation of toxic by-products has made gaseous chemicals sterilization (chiefly ethylene oxide) undesirable [1.7, 1.8], whereas stringent safety regulation and the expensive capital equipment cost are the problems encountered by sterilization via ionizing radiation [1.9]. Under tightening budgets, health care management teams feel that the present methods of sterilization are not cost effective enough [1.10]. There is therefore a trend of looking for new methods of sterilization.

1.2 Why plasma-aided processing for sterilization

One may perhaps look no further than the plasma-aided processing as a potentially promising new method of sterilization. A plasma is a partially or fully ionized gas containing electrons, ions, and neutral gas atoms or molecules. Plasma science is the study of the collective interactions of these electrically charged particles with each other or neutral gas atoms and molecules in electric and magnetic fields [1.11].

For the last two decades, the applications of the just-mentioned plasma science for industrial processing and manufacturing had been quite successful and diverse [1.12, 1.13]. Today, the applications continue to grow at an encouraging pace. As a matter of fact, plasma processing of material is of vital importance to several of the largest manufacturing industries in the world [1.12]. Foremost among these industries is the electronics industry, in which plasma-based processes are indispensable for the manufacturing of very large-scale integrated (VLSI) and ultra large-scale integrated

(ULSI) microelectronic circuits (or chips). Plasma processing of materials is also a critical technology in the aerospace, automobiles, steel, biomedicine, paper, textile, and toxic-waste management industry [1.13]. Today, the success of the application of the plasma-aided manufacturing to semiconductor fabrication continues to marvel a lot of researchers as the sizes of semiconductor structures continue to shrink [1.14]. In the situation such as the etching of fine structure of semiconductor devices as shown in Table 1.2 [1.15], it was, and is expected to be, the only way to achieve the needed result [1.14]. If one considers the sizes of microorganisms shown in Table 1.3 [1.16], one cannot help but notices that they are quite comparable to that of the semiconductor structures shown in Table 1.2. Despite the fact that a microorganism is a biological entity while a semiconductor is a physical structure, one may wonder if plasma-aided processing can also be applied effectively to the sterilization of microorganisms in the microscopic world. As a matter of fact, Chau et al suggested that the dry plasma sterilization process is similar to plasma etching [1.17]. One may thus ponder the wonders of this nonequilibrium, low temperature plasma-aided processing. The processing produces abundant combination of electrons, ions, excited atoms or molecules, free radicals, ultra-violet radiation, and ozone. The active species produced are more chemically reactive and more energetic than the species associated with any conventional chemical processing. Could any of these species play the antimicrobial role in the sterilization or decontamination of microorganisms?

Table 1.2. Sizes of shrinking semiconductor structures.

<u>Year</u>	<u>Minimum scale size</u>
1997	250 nm
1999	180 nm
2001	150 nm
2003	130 nm
2006	100 nm
2009	70 nm
2012	50 nm

Table 1.3. Sizes of microorganisms.

<u>Microorganisms</u>	<u>Sizes</u>
Bacteria: 1. spherical cocci 2. rod-shaped bacilli	1 μm in diameter 0.2-2.0 μm in width 2-10 μm in length
Virus	10-200 nm
Fungi	5 μm in diameter

1.3 Inspired objectives of the dissertation

Plasma-aided sterilization has been attempted in the past, but efforts are few and far in between. It was not until early 1997 that the Air Force Office of Scientific Research (AFOSR) and the Defense Advanced Research Project Agency (DARPA) started their respective first ever proposal solicitations in the use of plasma discharges for biological sterilization and chemical warfare agent decontamination [1.18]. Since then the application of plasma for biological sterilization and surface decontamination has received a lot of its long-deserved attention [1.19]. One can perhaps envision the day when plasma-aided sterilization becomes one of the main methods, if not the most dominant method, of sterilization and decontamination.

Encouraged in part by this probable exciting development, the author decided to devote his dissertation to the investigation of sterilization with plasma-aided processes. The main objective is to explore the feasibility of designing and constructing a novel, practical and inexpensive sterilization apparatus, using DC enhanced corona discharge operating at standard atmospheric pressure and room temperature. The sterilization ability of the apparatus will be assessed by exposing samples of a common harmful bacteria *Escherichia coli* and a highly resistive bacteria spore *Bacillus subtilis* to the discharge for treatment.

1.4 Scopes and organization of the dissertation

The investigation begins with chapter 2 as a brief literature review of the conventional methods of sterilization as well as the sterilization with plasma-aided processes. It begins with the sterilization basics, followed by a critical review of the

conventional methods. A survey of the basic research on plasma-aided sterilization is then given. The two methods are compared. Needless to say, the shortcomings of either method inspire a lot of researchers to look for novel methods of sterilization.

Chapter 3 explores the physical principles of enhanced corona discharge, which is employed as the novel method of sterilization in this study. The physics of the electrical breakdown of gases and corona discharge is given here; followed by the principle of a single-species corona discharge and its space charge limitation, and how an enhanced two-species corona discharge can be achieved.

Based on the densely synthesized plasma described in chapter 3, an enhanced corona activated sterilization and decontamination apparatus can be constructed. This is depicted in Chapter 4 where the design and construction of the various configurations of the discharge electrodes, as well as the apparatus, are described in detail.

The characterization of the plasma parameters is presented in chapter 5. A simple probe is designed and constructed to measure the plasma density profile in such a way that it does not perturb the plasma itself. The production of the ozone level is also monitored. The current-voltage (I-V) characteristic of the enhanced corona discharge is investigated and analyzed. The characteristic resembles that of a low pressure DC gaseous discharge tube. Argon, nitrogen, and helium gases are used in the study.

Chapter 6 presents the sterilization testing results on the microorganisms *Escherichia coli* and *Bacillus subtilis*. The electrodes used in the enhanced corona discharge are an array of multiple lines of pins and a ground plane. An apparatus with a slightly different design from that described in Chapter 4 is being used for the sterilization test. This sterilization result is compared to those presented by other

researchers who have used other forms of atmospheric pressure plasma discharge to treat the same samples of bacteria.

Chapter 7 concludes the findings by looking into the feasibility of the atmospheric plasma-aided sterilization in general, the still ill-elucidated antimicrobial mechanisms by the method of plasma-aided sterilization, the advantages and disadvantages associated with the method, and any other issues that may inherited with the nature of the process. At the end, a further study is being suggested to gather a broader database and thereby to promote a better understanding of the antimicrobial mechanisms by plasma-aided processes. A truly operable atmospheric pressure plasma sterilizer can be realized only when the antimicrobial mechanism is fully understood.

CHAPTER 2

LITERATURE REVIEW

This chapter begins with the sterilization basics, followed by a brief literature review on the conventional methods of sterilization, as well as the methods of plasma-aided sterilization. Except for one particular apparatus that has already been successfully introduced to the market, plasma-aided sterilization remains essentially at the research and development stage. The two methods are compared. The shortcomings of both inspire the author to engage in the search for a novel method of sterilization.

2.1. Sterilization basics

Essential to a better understanding of the dissertation, the relevant sterilization basics such as (a) what is a microorganism, (b) what is the distinction between sterilization and disinfection, and (c) the criteria for laboratory testing of sterilization are given below.

2.1.1 Microorganisms

Microorganisms are primitive life forms that have little in common except for the need of a microscope to observe them. The major groups of microorganisms are bacteria, viruses, fungi (molds and yeast), protozoa, and algae. Table 2.1 lists the microorganism groups and some of their distinguishing characteristics, together with their relationship to higher form of life [2.1].

Table 2.1. Types of microorganisms and their distinguishing characteristics [2.1].

Group	Sizes	Affiliates	Growth habits	Sources
Bacteria: 1. spherical cocci ----- 2. rod-shaped bacilli ---- 3. spiral spirilla	-- 1 μm in diameter -- width: 0.2-2.0 μm length: 2-10 μm	Neither plants nor animals	Free-living, saprophytic, or pathogenic	Soil, water, organic materials, man, animals, plants
Viruses	10-200 nm	Subcellular particles	Obligate intracellular parasites	Human, animal, plant or bacterial hosts
Fungi (moulds and yeasts)	5 μm in diameter	Some resemblance to plants, but not photosynthetic	Free-living or parasitic	Decaying organic matter, soil, fruit juices, plants, animals, man
Protozoa	varied	Animals	Free-living or parasitic	Soil, water
Algae	varied	Green plants	Free-living	Sea, fresh water, soil

As implicated in the table, microorganisms exist practically everywhere. They are widely distributed in outdoor and indoor environments, on the human skin and in the mouth, upper respiratory tract, large intestine and parts of the urogenital tract. They are rarely harmful in these situations but are likely to cause disease if they gain access to organs or tissues that are normally free of these agents. Thus, despite their small sizes and primitive nature, microorganisms present a formidable challenge to the practices and methods for preventing the spread of infection.

2.1.2 Sterilization and disinfection

The term “sterile” means “incapable of reproduction or free of microorganisms” [2.2]. Sterility of microorganisms is thus synonymous with death since their activities are usually undetectable in the absence of multiplication. In a very strict sense then, material that is free of living organisms is termed “sterile” while the presence of a single microorganism renders it “unsterile”. However, it is impossible to guarantee that every microorganism exposed to a particular sterilization treatment has been killed. Hence, for all practical purpose, sterilization is defined by researchers in the field as “the process by which living organisms are removed or killed to the extent that they are no longer detectable in standard culture media in which they previously have been found to proliferate” [2.3].

Terms that are quite often associated with sterilization are disinfection and decontamination, though both are not the synonyms of sterilization. Disinfection is “a process that is intended to kill or remove pathogenic microorganisms, with the exception of bacteria spores” [2.4]. Only the sterilization process can kill spores. Terminal

disinfection of used equipment that may be contaminated with harmful microorganisms is commonly referred to as decontamination [2.4].

2.1.3 Testing criteria for sterilization method

As shown in Figure 2.1, laboratory testing of sterilization methods usually involves three steps: a) growing the samples of the particular microorganism in a culture medium [2.5], b) subjecting the microorganisms to the sterilizer for treatment [2.6], and c) analyzing the effectiveness of the sterilization [2.7].

(a) Growing the microorganism samples

Most bacteria are isolated as a pure culture and grown on a suitable artificial culture medium (such as basal or liquid media) in the laboratory. Basal media are prepared from meat extracts but added blood or serum may be required to isolate some pathogenic bacteria. Liquid media can be solidified to a gel by the addition of agar for the isolation of microorganisms in pure culture [2.5].

When the culture medium has been inoculated with material containing bacteria, it is incubated at the optimum temperature for the likely species (usually 37°C in medical bacteriology) and in the presence or absence of oxygen as appropriate. Incubation times for the development of bacteria colonies on an agar medium or of turbidity in a liquid medium range from less than 24 hours to several days.

When a small number of cells of a fast-growing species of bacterium are inoculated in a suitable medium and incubated in suitable conditions, cell division may occur at 20 minutes intervals doubling the population each time. The number of bacteria

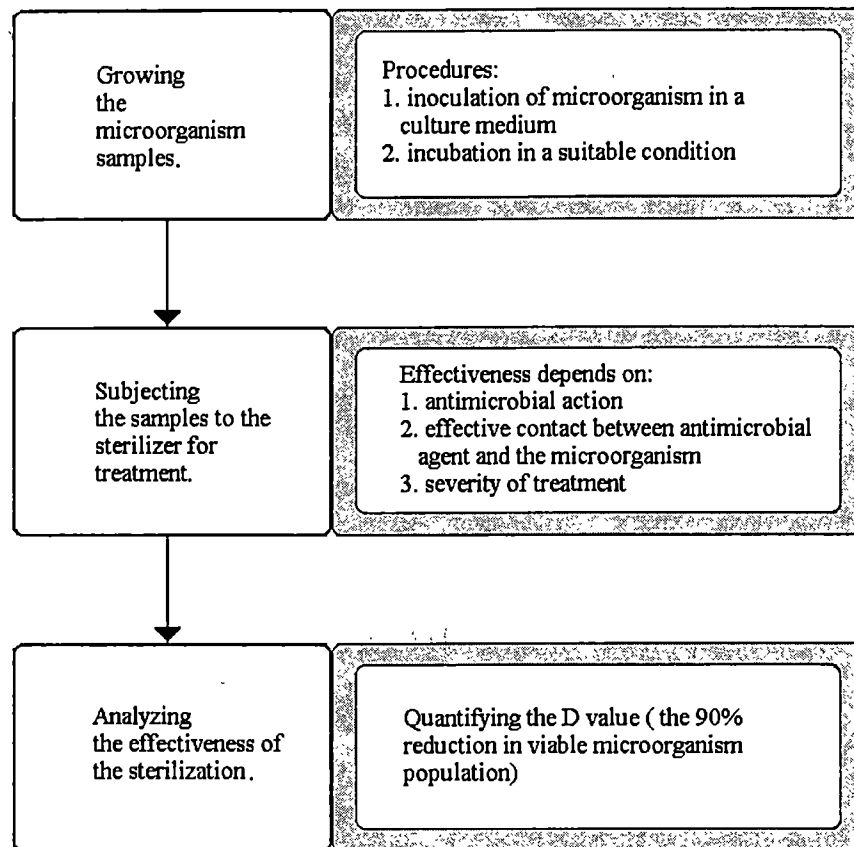


Figure 2.1. Steps for laboratory testing of a sterilization method.

reaches a maximum at 10^8 – 10^{10} per milliliters of a broth culture. Exhaustion of oxygen or an essential nutrient, or the accumulation of metabolic waste products slows and eventually terminates multiplication.

(b) Subjecting the microorganisms to the sterilizer

A sterilizer is an apparatus that utilizes a particular antimicrobial agent to sterilize or disinfect the microorganisms. Conventional antimicrobial agents for sterilization include dry heat, saturated steam, gaseous chemicals, ionizing radiation, and UV radiation. Biocidal agents for disinfection include hot water, low-temperature steam, and chemical disinfectants.

The efficiency of sterilization and disinfection depends on the following factors: 1) antimicrobial action, 2) effective contact between antimicrobial agent and the microorganisms, and 3) severity of treatment [2.6]. Antimicrobial action implies death of microorganisms, as indicated by their failure to multiply in any situation. Effective contact between an antimicrobial agent and its target requires penetration of the physical or chemical agent to all sites at which the microorganisms may be located. Severity of treatment is the minimum holding time for which the whole of the material treated must be held at the sterilizing environment to kill the microbial contaminants.

A sterilization apparatus must be designed to meet the challenges of the above mentioned factors optimally.

(c) Analyzing the effectiveness of the sterilization

After the microorganisms have been subjected to the sterilization treatment, the determination of death rate is needed to evaluate the effectiveness of the killing of the microorganisms. The rate at which an antimicrobial agent reduces the number of viable cells in a microbial population is determined by counting the survivors in samples obtained after treatment. If the initial count and the sample counts are plotted on a logarithm scale against the exposure time and a line is drawn through the separate points, a death rate curve is obtained. A straight line represents a constant (logarithmic or exponential) death rate. Non-logarithmic death rate is represented by curves which shown initial or final lags in the killing rate. Figure 2.2 [2.7] shows the typical logarithmic as well as the non-logarithmic death rate curves.

The death rate is usually quantified as D value [2.7]. The D value, or Decimal Reduction Time, is the time required achieving a tenfold reduction in the number of viable microorganisms, which is equivalent to 90 % kill. When the D value refers to sterilizing radiation, it is expressed in radiation dosage.

The D value is a constant for logarithmic killing rate (Figure 2.2a). It is difficult to estimate a useful D value for a non-logarithmic death rate curve unless the observed deviation can be explained and accounted for as, for example, when an initial shoulder or hump is followed by a logarithmic killing rate (Figure 2.2: b and c). When the curve does not include a linear section of significant length (Figure 2.2d), an average D value may be calculated from the equation [2.8]

$$D = \frac{t}{\log N_o - \log N_t} \quad (2.1)$$

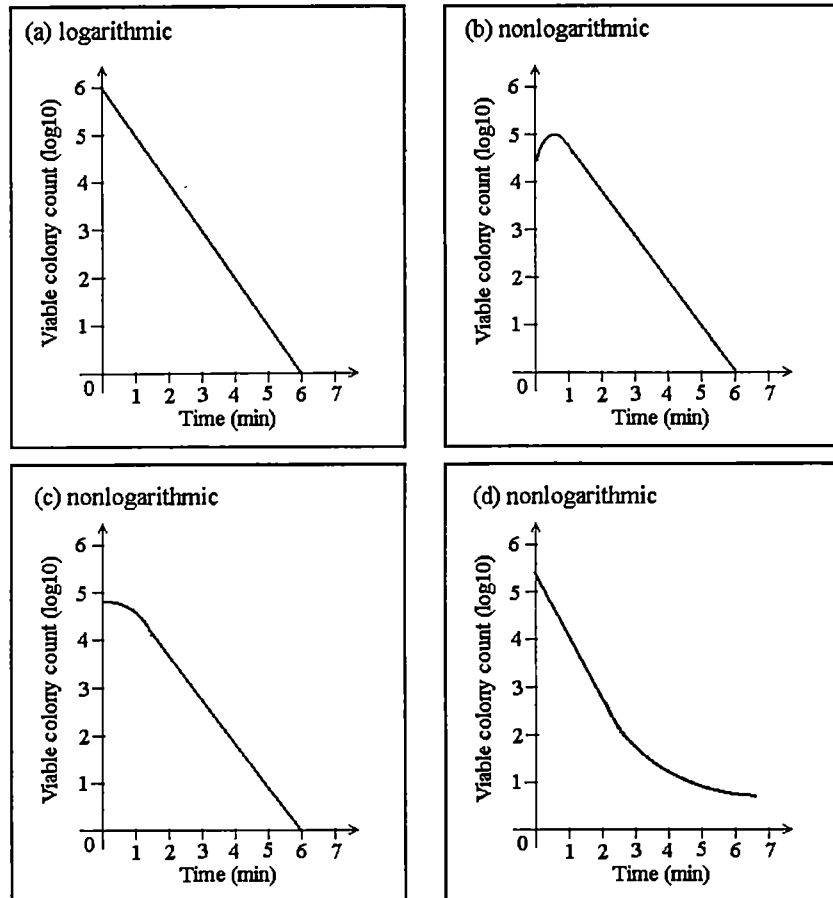


Figure 2.2. Typical death rate curves.

where t is the relevant time, N_0 the initial viable count and N_t the viable count at time t .

2.2 Conventional methods of sterilization

Conventional methods include sterilization by dry heat, saturated steam, gaseous chemicals, ionizing radiation, and ultraviolet radiation, and disinfection by filtration and chemical means [2.9, 2.10]. Each method is reviewed briefly in below, with emphasis on its characteristics, the antimicrobial mechanism, its application and limitation, and any environmental issues associated with the method.

2.2.1 Sterilization by dry heat

(a) Characteristics of dry heat sterilization

Dry heat sterilization is the oldest and most recognized agent of destruction [2.11]. It refers to a variety of methods, in which the only common factor is the absence of liquid water from the heating environment [2.12]. The dry condition actually embraces a wide range of moisture levels, from just above complete dryness to just below full saturation.

Dry heat sterilization is an oxidation process and is used only for those materials that cannot be sterilized by steam, when the moisture would either damage the material or they would be impermeable to it. Sources of dry heat sterilization include hot air, radiant heat, conducted heat, direct flaming, and incineration [2.12]. Hot air sterilization is carried out in electrical ovens with mechanical air convection. Radiant heat sterilization includes infrared and microwave radiation, which are characterized by long wavelengths and low levels of radiant energy. Both hot air and radiant heat sterilization have limited

usage. Amongst the sources, only incineration has been used widely in the hospital and microbiological laboratory environments primarily for waste management.

Factors that influence the efficiency of dry heat sterilization are temperature and moisture levels [2.12]. The time required for sterilization varies inversely with temperature. Dry heat sterilization is conducted in a high temperature range of 160-180°C as the rate at which spores are killed accelerates markedly in this range. For moisture levels, the efficiency depends on the initial moisture level of microbial cells and the direction and extent of changes that may occur during the heat treatment by exchange of water between the microorganisms and the heating environment.

(b) Antimicrobial mechanism in dry heat sterilization

The mechanism for destruction by dry heat is primarily an oxidation process [2.12]. Reported D values vary widely because, although the importance of specifying the moisture is now appreciated, it was not always known or controlled during the test [2.12]. D values of 0.35 minutes for *Bacillus stearothermophilus* and 1.8 minutes for *Bacillus subtilis* var. niger at 160°C have been reported [2.13].

(c) Application and limitation of dry heat sterilization

The principle advantage of dry heat sterilization is its ability to penetrate solids, non-aqueous liquids and closed cavities. Lack of corrosion is also important in the sterilization of non-stainless metals and instruments with fine cutting edge. The disadvantages of dry heat sterilization are as follows: 1) heating is slow, 2) long

sterilization periods are required, 3) high temperatures are required, which may be deleterious to materials, and 4) materials may deteriorate because of oxidation [2.11].

(d) Environmental issue in dry heat sterilization

There is practically no serious environmental issue associated with the method except for incinerators. Medical waste incinerators are the top contributors of dioxin, a class of pollutants to the environment [2.14, 2.15]. Dioxin is a group of persistent, very toxic chemicals. The technology designed to protect the public against a potential biological threat is now the source of significant chemical pollution.

2.2.2 Sterilization by saturated steam

(a) Characteristics of saturated steam sterilization

Saturated steam sterilization [2.11, 2.16] is one of the moist heat sterilization methods that include boiling water. Although boiling water at ambient pressure is not a good sterilizing agent because of its relatively low temperature, its principal advantage is its availability. Sterilization by saturated steam depends on the use of steam above 100°C, usually at a temperature in the range of 121-134°C [2.16]. Wet steam can be heated to temperature above 100°C by increasing the pressure above that of a normal atmosphere at sea level.

Sterilization by steam under pressure is nearly universally applied except where penetration or heat and moisture damage is a problem. Steam sterilization equipment, commonly known as the autoclave, is found in a wide variety of shapes and sizes in hospitals, clinics, microbiologic laboratories, and industrial production facilities. Despite

their differences, sterilizers are designed to operate on an automatic sterilization cycle which may typically include the following sequence of stages: 1) removal of air and heating of the chamber, 2) sterilization of the load, 3) removal of steam, followed by cooling of the liquid, and 4) restoration the chamber at atmospheric pressure [2.17].

(b) Antimicrobial mechanism in saturated steam sterilization

The antimicrobial mechanism of saturated steam sterilization is due to its moisture deposition and latent heat delivered to the load [2.16]. Saturated steam has a relative humidity of 100 per cent. This is the condition in which bacteria spores are least resistant to heat. When steam condenses on the article to be sterilized it deposits a film of water on all accessible surfaces, ensuring that the microbial contaminants will be killed rapidly. Steam has a greater heat content than does water at the same temperature. For 100°C, water has a sensible heat of 419 kJ/kg whereas vapor has an additional latent heat of 2257 kJ/kg [2.16]. The sensible heat is the quantity of heat required to raise the water to the boiling point (from 0°C to 100°C). The latent heat is the additional heat that is absorbed when boiling water is converted to steam at the same temperature. When steam condenses on cooler objects in the sterilizing chamber, the latent heat is released but the sensible heat is retained, and the condensate remains at the same temperature. The large amount of latent heat that is released is communicated directly to the surfaces of the load in the sterilizer, heating them rapidly to the temperature selected for sterilization. The sensible heat and latent heat are 509 and 2199 kJ/kg respectively for a steam at 121°C, and 567 and 2160 kJ/kg for a steam at 135°C [2.16].

(c) Application and limitation of saturated steam sterilization

Steam sterilization works better than the other forms of conventional sterilization because steam destroys most resistant bacteria spores in a brief exposure and heats rapidly because of mass heat transfer as it condenses. Well-designed steam sterilization equipment delivers steam to the bacteria sites throughout the load. The major problems during this process are air removal, superheat, load wetness, and material damage [2.16]. Chamber air is the factor most detrimental to efficient steam sterilization. If temperature varies in the chamber environment and cold spots occur in a load, air has not been adequately removed from the sterilization environment. During steam sterilization, some degree of superheat can be tolerated, but higher degrees result in a loss of sterilization efficiency. In a wet state, sterilized materials are more susceptible to recontamination [2.18].

(d) Environmental issue in saturated steam sterilization

In contrast to other forms of conventional sterilization, no adverse environmental issue has been raised on saturated steam sterilization.

2.2.3 Sterilization by gaseous chemicals

(a) Characteristics of gaseous chemical sterilization

Sterilization using gaseous chemicals has been practiced for many years [2.19, 2.20, and 2.21]. The most widely used gaseous sterilization is C_2H_4O (ethylene oxide or EtO). This gas is used in hospitals in the United States almost exclusively to sterilize items that cannot be sterilized by saturated steam or dry heat. Hospital items that may be

sterilized by ethylene oxide include endoscopic instruments, cardiac equipment, devices for implantation, medical and dental equipment. In addition, those industries supplying the hospitals with medical devices are using EtO sterilization for products that are heat sensitive or contain materials not compatible with sterilization by radiation. The sterilization of medical products by other gaseous agents such as propylene oxide, formaldehyde, and methyl bromide has not been as extensive [2.21].

An ethylene oxide sterilizer is usually nothing more than a pressure vessel with the capacity to evacuate air, warm and moistureize the product uniformly, add gas at a specific temperature, and remove gas after a specific time interval [2.22]. A typical sterilization cycle includes the following stages [2.23]:

1. Evacuating of air to 90 kPa below atmospheric pressure followed by humidification and heating of the load. The duration of this pre-conditioning stage is about 30-60 minutes.
2. Sterilization of the load at an effective combination of parameters which include EtO concentrations of 700-1000 mg/l, temperatures of 45-60°C, relative humidity of 70%, and sterilization times of 2-4 hrs. The concentration of EtO in the chamber is regulated by pressure of the gas mixture.
3. Removing of gases from the chamber and exhausting it to a suitable vent. The chamber is then restored to atmosphere pressure before the door of the sterilizer could be opened to complete the sterilization cycle. This stage takes at least 30 minutes to complete.

(b) Antimicrobial mechanism in gaseous chemical sterilization

Ethylene oxide is an alkylating agent. Alkylation involves the addition of certain saturated hydrocarbon groups to reactive amino (NH_2), sulphhydryl (SH), hydroxyl (OH) or carboxyl (COOH) groups on protein molecules and to amino (NH) groups which are part of the ring structure of nuclei acid bases. Alkylation of nuclei acids by EtO is believed to be the principal mechanism of antimicrobial action [2.22] because these vital cell components control protein synthesis.

The major factors that affect the inactivation of microorganisms by ethylene oxide and other gases are gas concentration, temperature, relative humidity, and exposure time. Almost all types of microorganisms are susceptible to ethylene oxide if they are exposed to suitable combinations of concentration, temperature, and relative humidity for an adequate time. Taking *Bacillus subtilis* var. niger for example, the D value is 3 minutes at 600 mg/l and 1.7 minutes at 1200 mg/l at a temperature of 55°C and relative humidity of 50% [2.24]. For *Escharichia coli*, the D value is 2.9 minutes with 700 mg/l ethylene oxide concentration at 109°F testing temperature [2.25].

(c) Application and limitation of gaseous chemical sterilization

Sterilization by ethylene oxide has one main drawback. In addition to the lengthily sterilization cycle described previously, the sterilized load needs to be aerated [2.26] to remove the ethylene oxide residues. The long and uncertain aeration time required for desorption of ethylene oxide at ambient temperature are unsatisfactory in hospitals where complex equipment is often required for use as quickly as possible.

(d) Environmental issue in gaseous chemical sterilization

Besides the drawbacks just described, ethylene oxide sterilization has adverse environment effects. Ethylene oxide is flammable and highly explosive [2.27] at all concentrations above 3.6% by volume in air. Introduction of ethylene oxide presents occupational hazards to operators of the sterilization process [2.28, 2.29]. Ethylene oxide concentration below 700 ppm in air cannot be detected by smell, whereas level down to 1 ppm may be toxic [2.30] and carcinogenic [2.31]. Because of these detrimental and adverse effects, both OSHA (Occupational Safety and Health Administration) and EPA (Environmental Protection Agency) have enforced stringent regulations and standards on the usage of EtO [2.32, 2.33, 2.34].

2.2.4 Sterilization by ionizing radiation

(a) Characteristics of sterilization by ionizing radiation

The use of ionizing radiation [2.35, 2.36] to sterilize medical products is widespread, and its applicability is increasing greatly because it has proven to be an economic and reliable sterilizing agent [2.37]. In general, radiation may be classified into two groups: the electromagnetic and particle radiation.

Electromagnetic radiation includes gamma ray, X-ray, ultraviolet, visible, infrared, and microwave. Amongst them, only gamma and x-rays are ionizing radiation. Both have considerable penetrating power. Cobalt-60 (Co^{60}) is used as the source for gamma radiation in sterilization facilities. Cesium-137 (Cs^{137}) emitting gamma rays at 0.662 Mev can also be used for sterilization. Ultraviolet light may damage bacterial nuclei acids but generally has very little effect on microorganisms. Infrared radiation is sometimes used

as a rapid method of heat transfer in dry heat sterilization process but its action is limited to heating the exposed surfaces of solid objects. Microwave energy generates heat in moist food but it has no essential role in sterilization.

In particulate radiation, the only particle that is currently being used in sterilization is the beta particle or electron. The energy at which the electrons are produced is restricted, at practice, to levels that do not exceed 10 Mev as higher energy ions may induce radioactivity in the treated materials.

(b) Antimicrobial mechanism in the sterilization by ionizing radiation

The various types of ionizing radiation in the electromagnetic spectrum produce bactericidal effects by transferring the energy of a photon into characteristic ionizations in or near a biologic target. In addition to creating pairs of positive and negative electrons, ions can also produce free radicals and activated molecules. These effects, which are produced without any appreciable rise in temperature, have been termed "cold sterilization" when applied to the destruction of microorganisms.

Ionizing radiation can cause a wide variety of physical and chemical effects in microorganisms. Although many factors influence the radiation resistivity of various microorganisms, they can generally be classified as to inherent resistivity.

(c) Application and limitation of sterilization by ionizing radiation

The main application of the sterilization by ionizing radiation is in the health and medical industries. The use of gamma rays to sterilize hospital supplies such as plastic hypodermic syringes, sutures, and containers is the main commercial application of

ionizing radiation [2.35, 2.36]. Other uses of radiation include sterilization and pasteurization of food where in December of 1997, the FDA (Food and Drug Administration) approved the use of irradiation as a measure to reduce or eliminate pathogens in red meat [2.38]. Radiation has also been used to treat sewage and industrial sludge in order to reduce the microflora.

(d) Environmental issue in sterilization by ionizing radiation

This method of sterilization has a potential environmental effect if proper shielding of radioactive materials is not maintained. Co^{60} and Cs^{137} have a half-life of 5.3 and 33 years respectively and require appropriate safeguards and disposal procedures.

2.2.5 Sterilization by ultraviolet radiation

(a) Characteristics of sterilization by ultraviolet radiation

Ultraviolet (UV) radiation for sterilization [2.39] is different from the ionization irradiation sterilization described previously. UV radiation is called non-ionizing since most organic molecules require wavelengths below 180 nm to effect ionization. Because of this, for all practical purposes, ionization may be excluded as one of the immediate consequences of UV irradiation in biological materials.

(b) Antimicrobial mechanism in the sterilization by ultraviolet radiation

A number of reviews and books have been written about the mechanisms of UV action on microbial agents [2.40, 2.41]. The germicidal effect of UV may result from

absorbed radiation and from an indirect effect of toxic compounds produced in the surrounding media.

Factors that can influence the bacterial sensitivity to UV are relative humidity, sensitivity at different stages of bacteria growth cycles, and presence of spores. If the amount of damage exceeds the cell's ability to repair itself, the cell will die. The reduction of the injurious effect of UV by subsequent visible light, i.e. photo-reactivation has been recognized as general phenomenon and may be a setback for the method [2.42].

(c) Application and limitation of sterilization by ultraviolet radiation

The most important applications of UV are directed at: 1) destruction of air-borne organisms, 2) inactivation of microorganisms located on surfaces or suspended in liquid but accessible to UV, and 3) protection and disinfection of many products of unstable composition that cannot be treated by other conventional methods. UV may destroy viruses, mycoplasma, bacteria, and fungi, whether they are suspended in air or in liquids or deposited on surfaces. Because UV will not penetrate most substances, food and fabrics cannot be sterilized by this radiation.

UV is an effective and practical alternative to chlorine as a means of disinfecting municipal effluent. Air is the important vehicle of microorganisms that may become responsible for deterioration and spoilage of many consumable products, and others. Judicious application of UV light can neutralize this possibility.

(d) Environmental issue in sterilization by ultraviolet radiation

The most practical method of generating UV radiation is by passage of electrical discharge through low-pressure mercury vapor enclosed in spherical glass tubes, known commercially as germicidal lamps. Prolonged exposure to germicidal intensities of UV may lead to undesirable physiological effects. These are manifested primarily by reddened skin and irritated eyes.

2.2.6 Filtration of liquids and air

Filtration [2.43] differs from other methods of sterilization, as it does not involve killing microorganisms or inhibiting their growth. Living and non-living particles are removed from liquids and gases by passage through fibrous, granular or synthetic membrane filters of appropriate retention efficiency. Since the subject of filtration is irrelevant to this dissertation, no further review will be made here.

2.2.7 Chemical disinfection

Disinfection is a process that is intended to kill or remove pathogenic microorganisms, with the exception of bacterial spores. Chemical disinfection [2.44] is the applications of chemical antimicrobial agents as solutions in water or alcohol for disinfection of equipment, surfaces, and intact skin in mucous membranes. Disinfection chemical agents include alcohol, aldehydes, chlorhexidine, chlorine compounds, hexachlorophene, iodophors, strong oxidizing agents (chlorine dioxide, paracetic acid, hydrogen peroxide), phenols, and quaternary ammonium compounds [2.44]. Disinfection by chemical means is also an irrelevant subject here and will not be discussed further.

2.2.8 Summary of conventional methods of sterilization

Conventional methods include the using of dry heat, saturated steam, gaseous chemicals, ionizing radiation, UV radiation, filtration, and chemical disinfection. Table 2.2 depicts the summary on these methods with an emphasis on their characteristics, mechanisms of killing, typical killing rates (D values), applications/limitations, and the environmental issues. All the topics have been covered previously in sections 2.2.1-2.2.7.

When sterilization or decontamination is needed, the particular method chosen for the purpose depends in large part on the materials involved and factors such as costs, safety, handling, and disposal requirements. Time requirements also impose an important limitation on the choice of sterilization method in a particular application.

In putting the conventional methods in a critical perspective, one may argue that the methods are inadequate and undesirable. Table 2.3 makes a list of the arguments. The list includes obsolescence, biocompatibility inadequacy, long cycle of operation, environmental unfriendliness, failure of regulation compliance, and costs.

On obsolescence, the methods used are simply incapable of keeping up with the modern day health care's needs and demands. On the biocompatibility inadequacy, the advertent effects due to the nature of a particular technique on the treated materials are well-documented [2.45]. On the cycle of running the sterilization, the holding times for ensuring safety and other precaution measures are just too time-consuming. Long cycle is counterproductive and can be very costly. On the environmental issues, the excessive production of dioxin (as in incineration), the toxic/carcinogenic residue (as in ethylene oxide sterilization), and induced radioactive residue (as in ionizing radiation) are some of

Table 2.2. Summary of conventional methods of sterilization.

Method	Characteristics	Mechanism of killing	Killing Rate (D values)	Applications	Limitations	Environmental Issues
1. Dry Heat (hot air, radiant heat, conducted heat, direct flaming, incineration)	1. absence of liquid media from heating environment 2. 160-180 °C	Oxidation process	1.8 minutes for <i>B. subtilis</i>	1. heat resistant materials 2. hospitals for reusable supplies and instruments 3. microbiological lab	1. long sterilization periods 2. high temperature deleterious to materials 3. material deterioration due to oxidation	Incinerator is the chief contributor to the toxic dioxin pollutant.
2. Saturated Steam (boiling water, autoclave)	1. steam above 100 °C at increased pressure 2. 121-134 °C	Moisture deposition and latent heat	Few minutes for <i>E. coli</i>	1. steam resistant materials 2. liquids 3. use in hospitals, clinics, microbiologic lab, industrial product facilities	1. penetration problems 2. moisture damage problems 3. heat sensitive materials 4. length of time required	None is raised
3. Gaseous Chemicals (EtO)	1. EtO concentration of 700-1000 mg/l @ 45-60 °C.	Alkylation	1. 3 minutes for <i>B. subtilis</i> @ 600 mg/l EtO 2. 2.9 minutes for <i>E. coli</i> @ 700 mg/l EtO	1. exclusively for items that cannot be sterilized by dry air or saturated steam. 2. hospital items and sealed packages	1. lengthy sterilization cycle (24-48 hrs) 2. stringent handling and safety requirements	1. EtO is flammable, explosive, 2. Occupational hazards/toxic

Table 2.2. continued.

Method	Characteristics	Mechanism of killing	Killing Rate (D values)	Applications	Limitations	Environmental Issues
4. Ionizing Radiation (Gamma rays, High energy Electron beams)	1. gamma ray considerably penetrative 2. Co^{60} and Cs^{137} as γ sources 3. e-beam < 10 Mev	1. energy transfer within the target molecules 2. diffusion of radicals to target	0.06 Mrad on <i>B. subtilis</i> 0.009 Mrad on <i>E. coli</i>	1. medical and laboratory implements, and supplies, and equipment 2. sterilization and pasteurization of foods	1. capital equipment cost 2. some materials easily damaged by radiation 3. stringent handling and safety requirements	1. Co^{60} and Cs^{137} half-lives (5.3 and 33 years respectively) 2. radiation hazards
5. Ultraviolet Radiation	1. nonionizing 2. applicable wavelength 220-300 nm	1. absorbed radiation 2. indirect effects of toxic compounds	Has very limited effect on microorganisms	1. destruction of air borne organisms 2. production of unstable composition that cannot be treated by other methods	1. photo-reactivation is common 2. will not penetrate most materials 3. cannot be used for food and fabrics	1. prolonged exposure lead to undesirable physiological effects

Table 2.3. Why conventional methods of sterilization are inadequate.

1. **Obsolescence:**
Most methods cannot keep up with the modern day's health care needs or demands.
2. **Biocompatibility Inadequacy:**
Most methods have detrimental effects on the materials treated.
3. **Long Cycle of Operation:**
Long cycle is counterproductive and costly.
4. **Environmental Unfriendliness:**
Dioxin pollutant due to incineration.
Toxic/carcinogenic nature of ethylene oxide.
Induced radioactive residue due to ionizing radiation.
5. **Regulation Compliance:**
Stringent EPA or OSHA regulations are hard to comply.
Compliance failure is not that uncommon.
6. **Costs (Overall):**
Initial equipment capital cost is only tiny part of it.
Direct and indirect costs are rising exponentially.

the main concerns. On the regulation compliance, it is becoming harder and harder to comply with the ever increasingly stringent EPA and/or OSHA regulations and standards. Failure of compliance can be costly due to legal activities. As for the overall cost, high equipment capital cost is not the only part of it. Long cycle of operation and equipment replacement due to advertent consequence of a particular method can contribute directly or indirectly, to the overall costs of running the sterilization [2.46].

The just mentioned adversity does not mean, however, that the end is near for the conventional methods of sterilization. Dry heat (incineration), saturated steam (autoclave), ionizing radiation (γ rays), and gaseous chemicals (ethylene oxide) are still widely used. Incineration is still viable in taking care of industrial or hospital waste, despite the dioxin dilemma. The autoclave retains its status as the most desirable method because there is no main environmental issue involved and that it costs less to autoclave. For ionizing radiation, though high capital equipment costs and stringent regulation can be a setback, it has nonetheless gained a lot of momentum since the approval by EPA in December 1997 for its usage in the treatment of red meat [2.38]. EtO sterilization, on the other hand, faces the most adversity. Due to its difficulties in the environmental and regulation aspects as described in section 2.2.3, it is on its way out as once a mighty conventional method! It is now being replaced and is facing the prospects of a total phase out in the near future [2.47, 2.48].

2.3 Plasma-aided Sterilization

Since conventional methods of sterilization have limitations and undesirable properties, new methods have been explored. Amongst the emerging alternatives, those

using electromagnetic fields (such as high power microsecond electrical pulses) and ionized gases (plasma) are most promising [2.49]. Only plasma-aided sterilization process will be covered here.

The use of plasma as purification, decontamination or sterilization agent has actually been known for quite some times. For example, ozone generated by plasma has been used for large-scale purification of water for years. There is a commercial plasma-aided sterilizer, namely the STERRAD®¹, available as a hospital sterilization facility now. Discussion on the use of ozone for the treatment of water, the plasma-aided sterilization attempts before the advent of STERRAD, the commercial STERRAD sterilization system, and the potential role of atmospheric pressure plasma for sterilization will be given below.

2.3.1 Ozone for the treatment of water

Historically, dating back to 1857, Siemens used silent discharge to show that ozone could be produced in an oxygen flow passing through an annular discharge space between two coaxial glass cylinders [2.50]. Shortly after 1900 the first large industrial ozone-generating systems for the treatment of drinking water were installed in Nice, France (1907) and St. Petersburg, Russia (1910). Today, more than 1500 drinking water plants throughout the world use ozone generators by silent discharge for purification of waters. Strictly speaking, ozone treatment of water is a disinfecting process, and not a sterilization process. No further discussion will be presented here.

2.3.2 Plasma-aided sterilization attempts before the advent of STERRAD®

Practically, various forms of plasma such as glow discharge, corona discharge, silent or dielectric barrier discharge, and RF discharge have been attempted for decontamination or sterilization.

More recent plasma-aided sterilization work includes the following. In 1968, Menashi used corona discharge at atmospheric pressure to sterilize the surfaces of materials [2. 51]. In 1974, Fraser et al used radio frequency generated plasma to sterilize packages [2.52]. Gases such as argon, nitrogen, oxygen, helium, and xenon were used. In 1978, Boucher et al [2.53] used glutaraldehyde gas plasma. The plasma was generated by radio frequency in the 1-10 MHz range at sub-atmosphere pressure. In 1980, a cyclically pulsed pressure plasma system was suggested by Bithell to sterilize objects of irregular shape [2.54]. Though each of the researchers was awarded a patent for their respective works, none seemed to have a significant impact. In 1987 and 1988, however, Jacobs and Lin were issued two patents on low temperature hydrogen peroxide plasma sterilization [2.55, 2.56] that have proved to be milestones for plasma-aided sterilization processes.

Jacobs and Lin's patents are significant in the sense that Johnson & Johnson Medical Inc. later utilized the patents to launch a highly successful sterilizer, namely the STERRAD® 100 system, into the market. These two patents are also significant in the sense that since then more than 50 other plasma related sterilization patents issued to other researchers have referenced the two in their respective works.

Details and comments on how this low-temperature hydrogen peroxide plasma sterilization works will be given in the following section.

¹ STERRAD® is the trademark of Advanced Sterilization Products, a division of Johnson & Johnson

2.3.3 The STERRAD® 100 sterilization system

The first breakthrough in sterilization technology in nearly half a century happened to be a plasma-aided process. It occurred commercially in 1992 when Johnson and Johnson introduced the STERRAD® 100 sterilization system into the international hospital market. The system was subsequently introduced into the U. S. market in 1993. Currently, more than 2000 hospitals worldwide are using the system to sterilize various medical materials and devices.

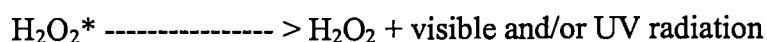
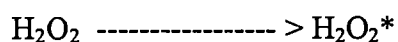
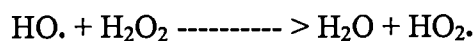
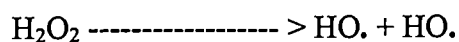
(a) Characteristics of STERRAD® sterilizer

The STERRAD 100 sterilizer has a 100-liter (about 4 cubic feet) capacity and other sizes are under consideration. The system is based on the patented process [2.55, 2.56] involving the generation of a low-temperature hydrogen-peroxide gas plasma through radio waves. Low-temperature, glow discharge plasma can be produced by a strong electric field. In the unique STERRAD technology, aqueous hydrogen peroxide is allowed to diffuse throughout the materials and come in close proximity to the devices to be sterilized prior to generation of the low temperature plasma. When the field is created electrons are stripped from some of the atoms, and the resulting charged particles are accelerated. As the stripped electrons recombine with atoms or the electrons return from higher to lower energy states in activated atoms, a visible glow is produced. Molecular collisions also occur in the cloud, and the hydrogen peroxide is converted into a variety of other species, including, for example, hydroproxyl and hydroxyl free radicals, water and oxygen. The reactive species in the plasma recombine to form primary oxygen and

water as by-products, eliminating the need for aeration. The combined use of hydrogen peroxide and plasma safely and rapidly sterilize medical instruments and material without toxic residue [2.57].

(b) Antimicrobial mechanism of STERRAD® sterilizer

Hydrogen peroxide (H_2O_2) is a known antimicrobial agent. In a plasma where H_2O_2 serves as a precursor, the following series of reaction can take place:



where $HO.$ and $HO_2.$ are hydroxyl and hydroproxyl free radicals respectively, and $H_2O_2^*$ is the excited hydrogen peroxide molecule.

The STERRAD sterilizer thus produces a biocidal environment where the above reactive species are capable of inactivating microorganisms by chemical interactions at multiple biologically important sites as suggested by Jacobs [2.58].

(c) Application and limitation of STERRAD® sterilizer

Johnson & Johnson claims that "Laboratory tests have demonstrated that the STERRAD System destroys a broad spectrum of microorganisms, including Gram negative and Gram positive vegetative bacteria, mycobacteria, yeasts, fungi, lipophilic viruses and hydrophilic viruses, as well as highly resistant aerobic and anaerobic bacteria spores [2.59]." This establishes the unique ability of plasma-aided sterilization, as

conventional methods are limited to their abilities to kill a certain spectrum of microorganisms.

Besides the above-mentioned unique ability, it is claimed that the STERRAD sterilizer has other uniqueness that include ease of installment, excellent material compatibility, and short total cycle time [2.59]. As for ease of installment, it requires no special installation, ventilation, aeration, drain or piping. Only an electric outlet (208 V) is required. As material compatibility, the STERRAD sterilization process is gentle. It can be used in a wide range of treatment, including heat and moist-sensitive surgical instrument. As for short total cycle time, it takes 75 minutes to sterilize a wide variety of instruments. No special D-value is mentioned by Johnson & Johnson.

These unique abilities make the STERRAD an apparatus of unlimited usage compared to conventional methods.

(d) Environmental issues related to STERRAD® sterilizer

For the STERRAD, the reactive species in the plasma recombine to form primary oxygen and water as by-products at the end of the process. There are no toxic residues left [2.57]. Thus, it does not damage the environment nor does it pose a health risk to patients or to workers using the equipment. During its long history of widespread use in a variety of industries, no epidemiological association has been found between hydrogen peroxide and human illness [2.59].

2.3.4 Atmospheric plasma for sterilization

Except for the corona discharge, the above-mentioned plasma-aided sterilization methods need vacuum systems. From an economic point of view, they are not necessarily more attractive than the conventional methods of sterilization. There may be an economic advantage to plasma-aided sterilization using a discharge operated at atmosphere pressure and room temperature.

At the University of Tennessee, researchers have attempted to use atmospheric plasma for sterilization. In 1988-89, Alexeff et al used corona discharge to sterilize sealed packages [2.60]. In 1995-96, Ku et al [2.61, 2.62] and Laroussi [2.63, 2.64, 2.65] reported their separate findings on sterilization using a propriety one-atmosphere uniform glow discharge plasma (OAUGDP) [2.66]. This section is limited to the discussion of sterilization by OAUGDP.

(a) Characteristics of OAUGDP sterilizer

In OAUGDP sterilization, the medium to be sterilized is immersed in the discharge generated at atmosphere pressure and room temperature between two insulated metal plate electrodes powered by a low-frequency RF supply. Typical operating conditions for the discharge are voltages in the range of 3-5 kV, frequencies in the range of 5-7 kHz, a gap distance of approximately 5mm, and a plasma density in the order of $10^{16} / \text{m}^3$.

(b) Antimicrobial mechanism of OAUGDP sterilizer

The antimicrobial mechanism of the OAUGDP sterilization has not been elucidated yet. It is speculated that combinations of several physical and chemical effects on the

microorganisms are responsible for the antimicrobial action. The medium is constantly bombarded by a combination of charge particles, active free radicals and radiation (including UV radiation), a rather unique happening unfounded in any of the conventional methods of sterilization.

(C) Application and limitation of OAUGDP sterilizer

With air as the feed gas, Ku et al [2.62] reported that the OAUGDP technology was employed to kill *Staphylococcus aureus* and *Escherichia coli*. It was reported that a treatment time of 30 and 15 seconds was sufficient to cause a complete sterilization on Whatman filter paper seeded with *S. aureus* and *E. coli* respectively under plasma operating conditions of 5 kV and 5.5 kHz. When the filter paper seeded with *S. aureus* was placed in a sealed bag, a similar 30 seconds of treatment time was needed for complete sterilization. Further more, when *S. aureus* were embedded in a solid growth media such as Tryptic Soy Agar, a complete kill was obtained with a 60-second exposure. Interestingly, the solid culture media sterilized by plasma exposure was subsequently able to support normal cell growth, suggesting the growth medium was not altered or damaged by exposure to the plasma. Note that a complete sterilization mentioned by Ku et al indicates a zero colony forming units (CFU) as compared to a control 200 CFU before plasma treatment. No specific D values were mentioned in the study. Using the same apparatus but with helium as the feed gas, Laroussi [2.65] reported that an exposure time of 10 minutes was enough to kill completely the $4 \times 10^6/\text{ml}$ *Pseudomonas fluorescents* bacteria seeded in the yeast extract polypeptone glucose solution (YEPT). In 1997, Carr

reported the killing of microorganisms in a sealed sterilization bag by using the same atmospheric glow discharge [2.67].

Preliminary tests on OAUGDP sterilization indicated that the discharge could kill a limited range of microorganisms. Killing efficiency depended largely on the plasma operating conditions, types of microorganisms, and the culture medium used. The small gap distance between the electrodes seriously limited the availability of sterilizing space.

(d) Environmental issue in OAUGDP sterilization

No environmental issue has been raised or is expected.

2.3.5 Comparison between plasma-aided sterilization

The comparison between the STERRAD and OAUGDP as a successful sterilizer and a sterilizer still in the research and development stage respectively is shown in Table 2.4.

The two are extremely different in respect to their device characteristics. STERRAD is operated at low pressure (0.1-10 torr) and low temperature (<50°C) whereas OAUGDP is a dielectric barrier discharge apparatus operated at standard atmospheric pressure and room temperature. STERRAD uses hydrogen peroxide vapor as precursor gas whereas OAUGDP operates in air or with other gas feed.

The two devices have some similarities. As mechanism of killing goes, both probably achieve the antimicrobial action by some common reactive species created by their respective discharge environments. Both have killing rates that range within tens of seconds. As for environmental issue, both probably will face no serious difficulty.

Table 2.4. Comparison between selected plasma-aided sterilizations.

Method	Characteristics	Mechanism of killing	Killing Rate (D values)	Applications	Limitations	Environmental Issues
STERRAD® 100 Sterilization System	1. low pressure (0.1-10 torr) 2. low temperature (<50 °C) 3. RF powered 4. H₂O₂ as precursor of active species 5. 100 litre in volume 6. 75 minutes cycle time	Reactive active species damage the cell walls	Tens of seconds to kill a wide range of microorganisms	Over 2000 hospitals worldwide are using the STERRAD® sterilization system for a wide range of usage	Not known	None has been raised
OAUGDP	1. Atmospheric pressure 2. room temp. 3. RF powered 4. frequency 5-7 kHz 5. voltage 3-5 kV 6. air or other gases used 7. electrode gap distance 5 mm 8. dielectric barrier discharge	Reactive active species damage the cell walls (further elucidation needed)	Tens of seconds to kill a limited range of microorganisms	Still in the research and development stage	Volume limited due to small gap between the electrodes	None expected

One important aspect must be stressed here. The STERRAD system has a large discharge volume for sterilization operation. The OAUGDP, on the other hand, has a limited operable sterilization treatment space. This is due to its extremely small gap (about 5 mm) between the electrodes. The limited space can impose a big difficulty for OAUGDP in its attempt of breaking into the real world market for sterilization.

2.4 Comparison between conventional and plasma-aided sterilization

A comparison between the conventional method and the plasma-aided sterilization can be inferred from Table 2.2 and Table 2.4. The comparison is summarized in Table 2.5.

Though effective in the killing of the microorganisms, the conventional methods must deal with various problems associated with each particular method. The limitations on each method have been discussed in section 2.2. and are re-captured below. Dry heat sterilization may cause destruction to the materials that are thermally sensitive. Saturated steam sterilization can damage the materials due to moisture content in the steam. The formation of toxic by-products makes gaseous chemicals sterilization somewhat undesirable, whereas the cost and inefficiency in performance are the problems encountered by sterilization via ionizing radiation. Thus, in the conventional methods, application dictates sterilizer options [2.68]. Several factors need to be considered when selecting a particular method. These factors include the compatibility of the method with the material to be sterilized, the space requirements of the work area, the regulatory guidelines, the effects of sterilization time on materials, and the ability of the chamber to accommodate the materials.

Table 2.5. Comparison between conventional and plasma-aided sterilization.

Method	Heat/ Temperature	Pressure	Killing mechanism known?	Killing rate (D value)	Detrimental to treated material?	Environmental Friendly?
<u>Conventional</u>						
1. Dry heat	high temp. (160-180 °C)	atmospheric	yes	few minutes	yes	no
2. Saturated steam (autoclave)	high temp. (121-134 °C)	> atmospheric (vacuum needed)	yes	few minutes	yes	yes
3. Gaseous Chemical (Ethylene oxide)	45-60 °C	< atmospheric (vacuum needed)	yes	few minutes	yes	no
4. Ionizing radiation (γ ray, e-beams)	radiant heat	vacuum needed	yes	tens of 10 ³ rad.	yes	no
5. UV radiation	radiant heat	atmospheric	yes	ineffective	no	no for prolonged exposure
<u>Plasma-aided</u>						
1. STERRAD®	low temp.	low pressure (vacuum needed)	need to be elucidated	tens of a few seconds	no	yes
2. OAUGDP	room temp.	atmospheric (no vacuum system needed)	need to be elucidated	tens of a few seconds	probably no	probably yes

In contrast to the conventional methods that have far-reaching effects on the biocompatibility of the material being sterilized, the STERRAD is gentle and has good material compatibility including its ability to sterilize heat and moisture sensitive surgical instruments. The process is dry and leaves no toxic residue [2.57]. Thus as compared to EtO, the process presents virtually no safety issues for users and the environments. As for equipment capital costs, the STERRAD system is superior to the sterilization by ionizing radiation for it does not require special installation, ventilation aeration, drain or piping [2.59]. It is amazing that a single plasma-aided sterilizer can eliminate the wide range of problems facing almost all the conventional methods of sterilization.

As the STERRAD system represents the major breakthrough, the advent of the atmospheric-pressure plasma for sterilization such as OAUGDP [2.69] has the potential to take the breakthrough a step further. The atmospheric-pressure process has the same advantage as the low-pressure STERRAD system over the conventional methods, but is performed at the atmospheric pressure and room temperature. It may also lower capital and laboratory costs as no vacuum system is needed, as compared to STERRAD where a vacuum system is in use.

The OAUGDP technology may be especially important for sterilization processes in hospital, where costly equipment and personnel can ill afford to stand idle for lengthy period of time. Of special note is the technology's ability to sterilize implements and materials inside sealed packages, thus providing an economical alternative to EtO sterilization. The active ionic species generated by OAUGDP apparently penetrates medical packaging in the same manner as EtO and kill all viable organisms inside.

However, the OAUGDP sterilization process can be performed in a fraction of time (<10%) required for EtO [2.69].

2.5 Taking the step further

The OAUGDP plasma is generated by capacitive RF discharge. While this method may be cost-effective compared to the conventional methods of sterilization and the STERRAD, it is by no means the only method that can generate an inexpensive atmospheric-pressure plasma. As a matter of fact, RF generated plasma could be expensive because a RF amplifier, a cooling system, and matching networks are needed. It is believed that DC-fed plasma could perform the same effective sterilization treatment but with lesser costs.

In early 1997, the Air Force Office of Scientific Research (AFOSR) initiated a Small-Business Technology Transfer (STTR) program in plasma-aided sterilization. In early 1998, the Defense Advanced Research Product Agency (DARPA) joined force to initiate a similar program on sterilization.

Encouraged by the exciting results obtained by various researchers using atmospheric pressure for sterilization and by the initiatives of AFOSR and DARPA, the author was motivated to push the steps further. The mission was to investigate the feasibility of constructing a novel, efficient, and potentially cost effective sterilization apparatus using a DC-fed enhanced corona discharge at atmospheric pressure and ambient room temperature. In the course of the research, the main objectives were: 1) to investigate the physical principles behind the enhanced corona discharge; 2) to design the discharge electrodes and construct the sterilization apparatus; 3) to characterize the

properties of the plasma discharge itself; and 4) to subject the sterilizer for antimicrobial test on microorganisms *Escherichia coli* and *Bacillus subtilis*. By doing so, the author wished to pave the road toward a better atmospheric plasma sterilizer beyond the present low-pressure STERRAD operating system.

CHAPTER 3

PHYSICS OF ENHANCED CORONA DISCHARGE

Corona or unipolar discharge is a phenomenon characteristic of Townsend dark discharge that occurs in regions of high electric field near sharp points, edges, or wires in electrically stressed gases prior to the point of electrical breakdown. The discharge is an integral part of electrical discharge for industrial uses. The phenomenon has been studied widely [3.1, 3.2, 3.3]. However, the enhanced corona discharge to be described below has only been studied recently [3.4, 3.5, 3.6]. This chapter describes the physics of electrical breakdown of gases, the principle of single-species corona discharge, the space charge limitation, and the principle and sustaintment of two-species enhanced corona discharge.

3.1 Physics of electrical breakdown of gases

The electrical breakdown of gases or ionization process occurs as the result of the collisions between electrons or photons and gas molecules. The process is one of the most chaotic phenomena known but can be accurately described [3.7, 3.8] and simulated. It begins with a single charged seed particle in the surrounding gas. Either natural radiation, electrical stress on the surrounding gas, or photo ionization creates the seed particle. Under normal conditions, these seed particles decay or loose their charge in a short period of time. This loss occurs either through collision with another particle or through collision with a surface. However, under the influence of a high enough applied voltage, the seed particle can initiate ionization.

For a parallel plate configuration, for example, this seed particle experiences an electric field E and an electric force F given by

$$E = \frac{V}{d} \quad (3.1)$$

and

$$F = qE \quad (3.2)$$

respectively, where V is the applied voltage, d the plate separation, and q the signed charge of the particle. With the increase of electrode voltage, charged particles are accelerated to gain kinetic energy. These particles may transfer energy to gas atoms or molecules by collisions. Sufficient kinetic energy will cause molecule splitting. In this situation, excitation, ionization or charge exchange occurs, and the electric current jumps exponentially from the order of magnitude of 10^{-7} up to 10^{-5} amps. In this regime, corona discharge may be visible to the eyes, although it is a phenomenon characteristic of the Townsend dark discharge as shown in Figure 3.1 [3.9], the typical characteristic curve of a dc low pressure discharge tube.

Corona discharge is a continuous phenomenon with very low current. It is quite different from electric breakdown, which is usually a transient and localized discharge with relatively high current. At high pressure above 100 torr, corona may be formed before actual gas breakdown occurs. In fact, many factors affect the breakdown voltage, such as gas type, temperature, pressure, electrode separation, humidity and so on. According to Paschen's Law, the breakdown voltage V_b for a given dry working gas is a

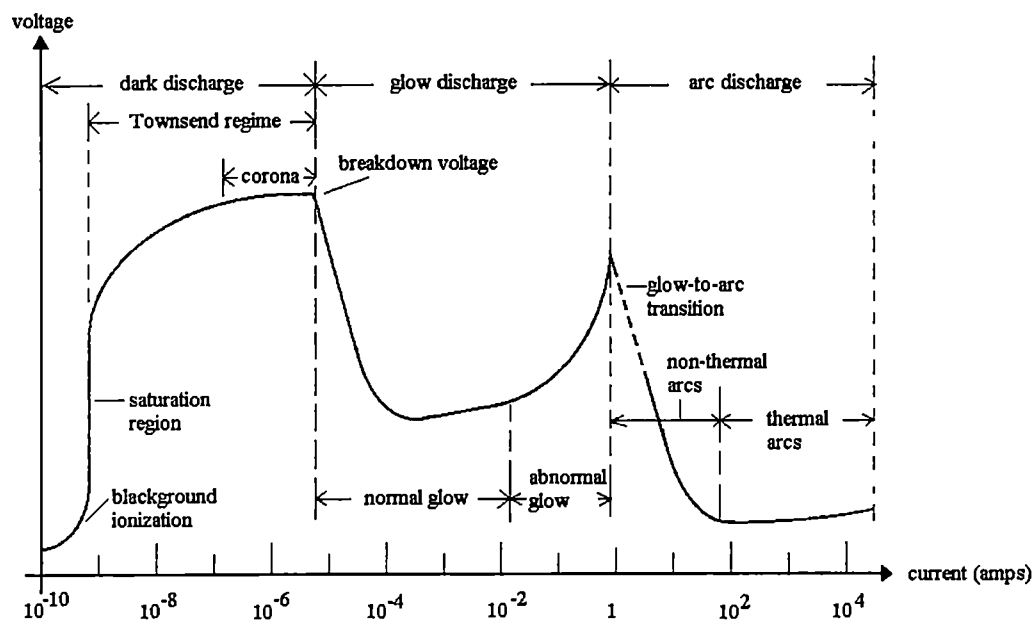


Figure 3.1. A typical current-voltage curve of the DC low-pressure discharge tube [3.9].

function of pd , where p is the pressure and d the electrode spacing. The Paschen's Law is given by the equation [3.10]:

$$V_b = \frac{C}{\ln[A/\ln(1+1/\gamma)]}$$

$$= f(pd) \quad (3.3)$$

where A and C are constants which relate to the electron kinetic temperature, the type of gases and effective ionization potential, whereas γ is the secondary electron emission coefficient. This equation indicated that the breakdown voltage for a particular dry gas depends only on the product pd . Figure 3.2 is a plot of the breakdown voltage V_b versus the product of pressure and gap distance pd [3.11]. The data presented is that for a dry air at 20°C. This breakdown voltage is a function of the humidity and becomes lower at higher humidity. From the figure, V_b has a value of 30 kV at atmospheric pressure (1.01 bar) when d is 10 mm.

3.2 Single-species corona discharge

In atmospheric air, corona can be initiated when high voltage is applied to sharp points, fine wires, sharp edges, or scratches and when the localized electric field is greater than the breakdown electric field of the medium surrounding it. The breakdown electric field at standard temperature and pressure for dry air is given by the equation [3.12]

$$E_b = 3000 + 1.35/d \quad (kV/m) \quad (3.4)$$

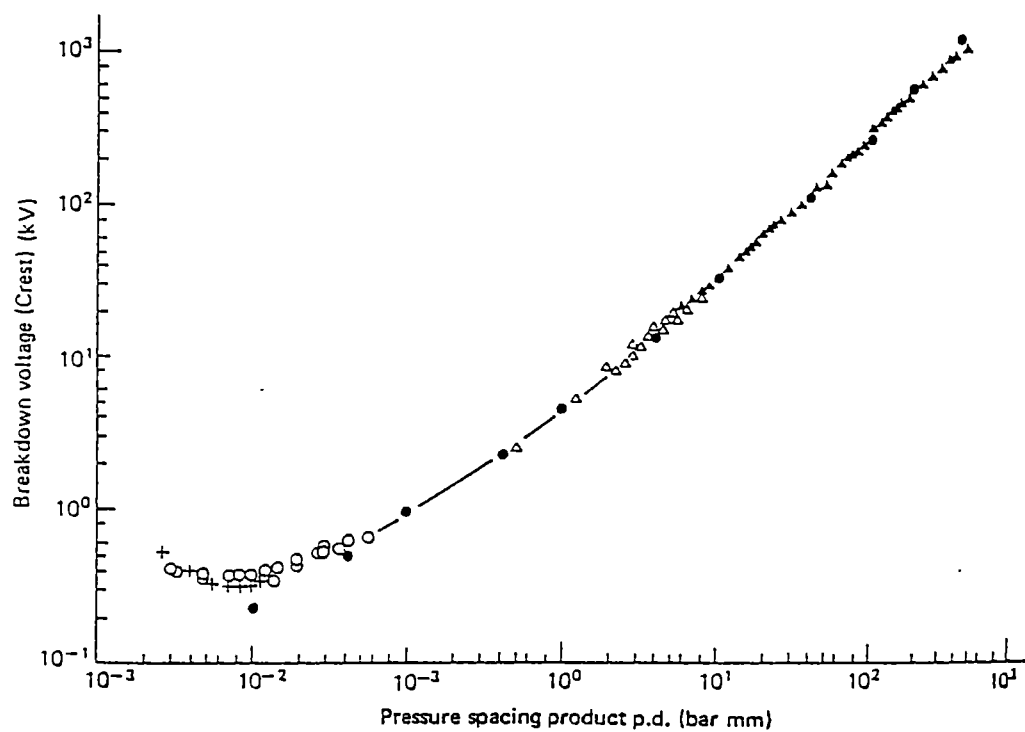


Figure 3.2. Breakdown voltage of dry air at 20°C as a function of the product pd [3.11].

The breakdown electric field for dry air at standard atmospheric condition is about 30 kV/cm. It is not hard to create a local electric field greater than this value to initiate the corona discharge. Figure 3.3 shows the two simplest configurations for generating the corona discharge in industrial application.

For the sharp point above the ground plate configuration, the localized surface electric field E_{s1} on the sharp point can be approximated as [3.13]

$$E_{s1} = \frac{V_o}{a[1 - a/d]} \quad (3.5)$$

where V_o is the applied voltage, a the radius of the sharp point, and d the distance between the sharp point and the grounded plates. Corona discharge can be initiated with a voltage as low as 5 kV with this type of configuration.

For the parallel wire or conductor configuration, the localized surface electric field E_{s2} along the biased wire can be expressed as [3.13]

$$E_{s2} = \frac{V_o}{a \left[\sqrt{\frac{s-2a}{s+2a}} + \ln \left[\frac{s}{2a} + \sqrt{\left(\frac{s}{2a}\right)^2 - 1} \right] \right]} \quad (3.6)$$

where a is the radius of the conductor, and s the distance between the electrodes. If $s > a$, the surface electric field is reduced to

$$E_{s2} = \frac{V_o}{a \left[\ln \left(\frac{s}{a} \right) \right]} \quad (3.7)$$

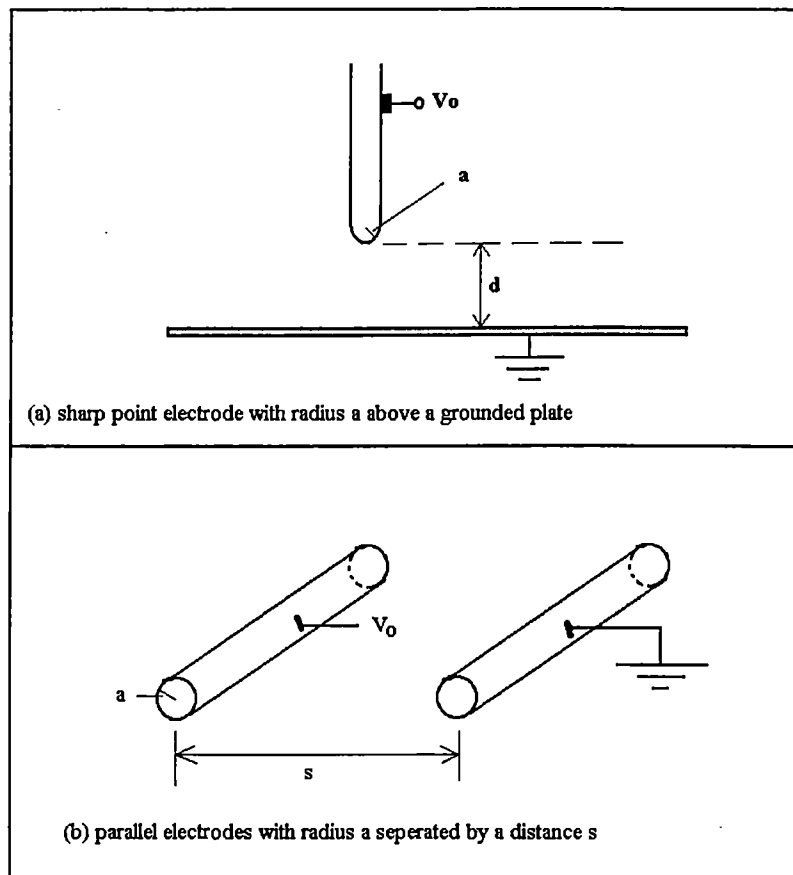


Figure 3.3. Two common electrode configurations for generating DC corona discharge.

When the localized electric field as expressed in equation (3.5) or (3.6) is greater than the breakdown electric field of equation (3.4), corona discharge can be initiated. The local high electric field causes local breakdown, which however, does not propagate into the bulk medium. What is produced is a steady stream of ions, positive corona from positive electrode and negative corona from negative electrodes.

3.3 Space charge limitation in a single-species corona discharge

The breakdown voltage that initiates the corona discharge and the distorted electric field resulting from space charge build-up are quite different for corona of different polarities [3.14, 3.15]. Figures 3.4 and 3.5 show the space charge build-up and the associated field distortion of a positive point and a negative point with a ground plane respectively [3.16].

For the case of a positive point-plane gap shown in Figure 3.4(a), ionization by electron collision takes place in the high field region near the point. Because of their higher mobility, electrons will be readily drawn into the anode, leaving the positive space charge behind. This space charge will cause a reduction in the field strength close to the anode and at the same time will increase the field further away from it. The dotted curve in Figure 3.4(b) represents the original undisturbed field distribution across the gap while the solid line shows the distorted field.

For the case of a negative point-plane gap shown in Figure 3.5(a), the electrons are repelled into the low field region. And in the case of attaching gases, they become attached to the gas molecules and tend to hold back the positive space charge that remains in the space between the negative charge and the point. The field is grossly

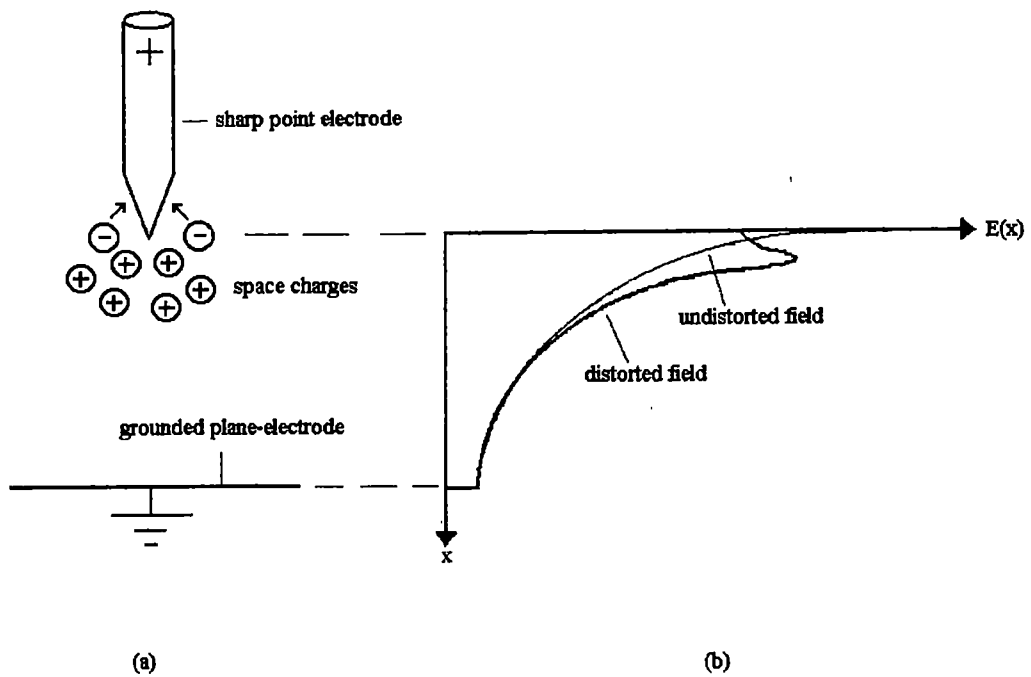


Figure 3.4. Positive point and a grounded plane: (a) space charge build-up, (b) distorted field due to space charge [3.16].

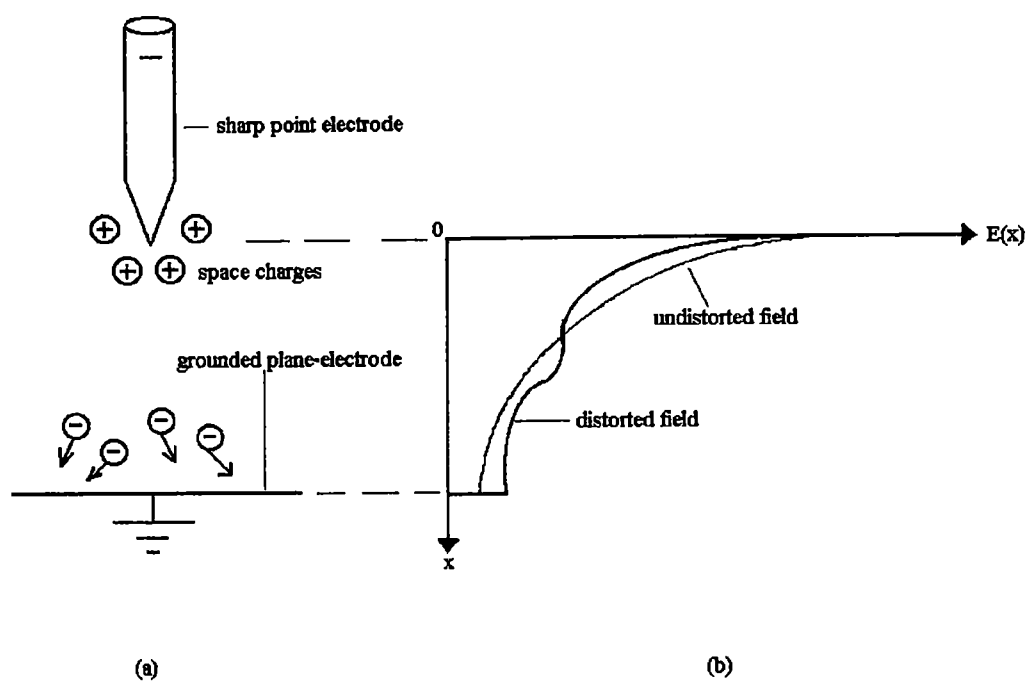


Figure 3.5. Negative point and a grounded plane: (a) space charge build-up, (b) distorted field due to space charge [3.16].

enhanced but the ionization region is drastically reduced in the vicinity of the point. The effect is to terminate ionization. Once ionization stops, the applied field sweeps away the negative and positive space charge from the vicinity of the point and the cycle starts again after the clearing time for the space charge. A high voltage is required to overcome this retarding action of the ions. Thus, the negative breakdown voltage is higher than the positive breakdown voltage in gaps with marked asymmetrical fields.

3.4 Two-species corona discharge for enhancement

In a single-species corona discharge described in the previous section, what is produced is a steady stream of ions, positive from positive electrode and negative from negative electrode. These two streams can be combined to produce dense synthesized plasma in the atmospheric air.

The combining of both positive and negative ions into plasma overcomes the previously density limitation that occurred because of space charge in a single-species corona discharge.

3.5 Enhanced corona discharge with a gas feed

While two-species corona discharge overcomes the density limitation occurring in a single species discharge, a further enhanced discharge can be achieved by replacing the air by a gas feed [3.4, 3.5, 3.6]. The following describes how such enhancement is achieved and sustained.

In atmospheric air corona discharge, electrons can be depleted by attachment to the molecules of the air. The processes of electron attachment occur in electronegative gases

where there is finite probability that when an electron comes into the vicinity of an atom, it will be captured to form a negative ion. Attachment takes electrons out of the air by the process such as



The attachment process leads to the reduction of current flowing to the electrodes, and thus the reduction of plasma density.

Attachment can be reduced or avoided by replacing the air surrounding the limited region around the corona points by a non-electronegative gas. Figure 3.6 shows a sharp point configuration consisting of pins fastened to a brass pipe at one end and protrude from the other end through tiny holes. The sharp points of the pins serve as corona points. The brass tube can be fed a non-electronegative (non-electron absorbing) gas such as argon, nitrogen, or helium through the feed line. The feed gas escapes through the holes and provides a local atmosphere around the corona points. It thus replaces the air in this region and attachment process can be reduced or avoided. Thus enhanced corona discharge is achieved.

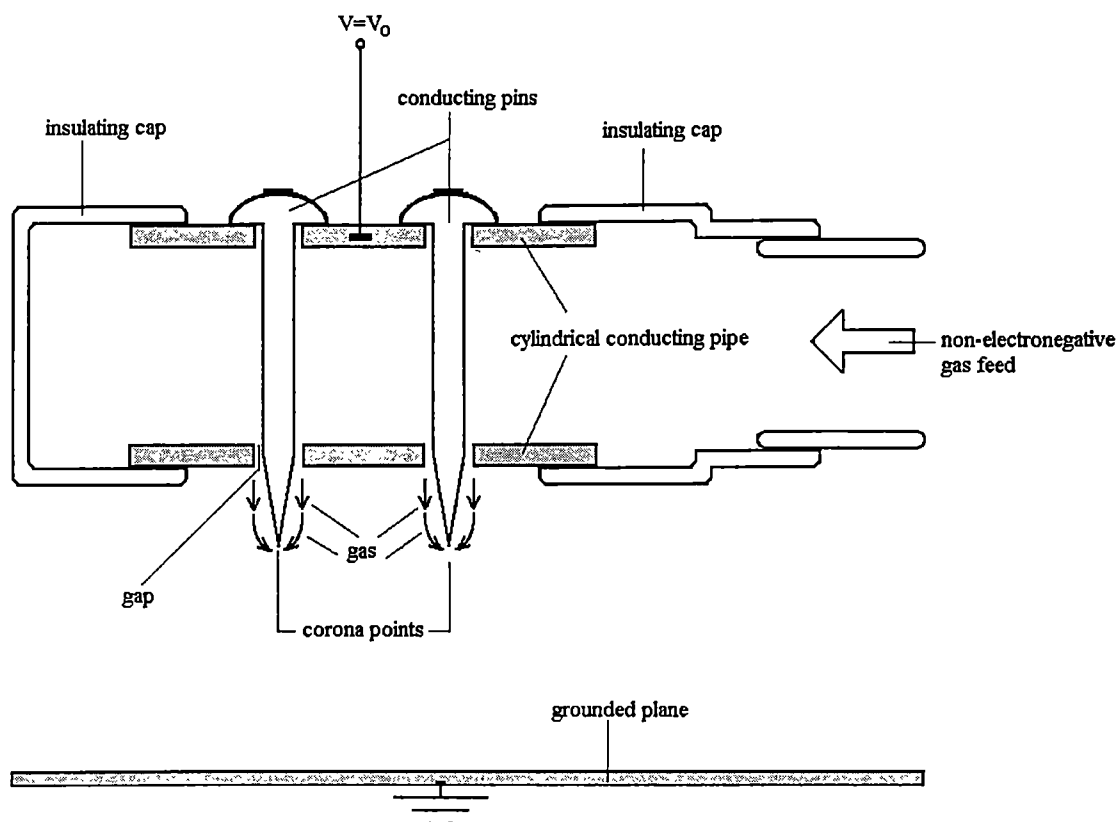


Figure 3.6. Enhanced corona discharge with non-electronegative gas feed.

CHAPTER 4

THE ENHANCED CORONA DISCHARGE APPARATUS

Based on the densely synthesized plasma described in the previous chapter, an enhanced corona discharge activated sterilization and decontamination apparatus can be constructed. The following sections describe the design of the electrodes, the construction of the apparatus, and the testing of the apparatus for enhanced corona discharge.

4.1 The design of the electrodes

The design of the electrodes comes in three different forms. They are the sharp-point electrode, the slit electrode, and the blade electrode.

Figure 4.1 shows the design of the sharp-point electrode. The design is based on a United State Patent assigned to the University of Tennessee Research Corporation and co-invented by Rader, Alexeff, Tsai, and Wadsworth [4.1]. Similar to the design shown in Figure 3.6, the electrode is constructed with an array of $\frac{1}{2}$ -inch pins attached to a conducting brass pipe. The brass pipe is $\frac{3}{8}$ inch in diameter, 8 inches in length, and has 1-inch insulation at both ends. One end of the tube is sealed while the other end is connected to a gas feed. The pins are separated by $\frac{1}{4}$ inch from each other. The pinheads are soldered to the brass pipe at one side, with the sharp points protrude diagonally from the other side through tiny pinholes.

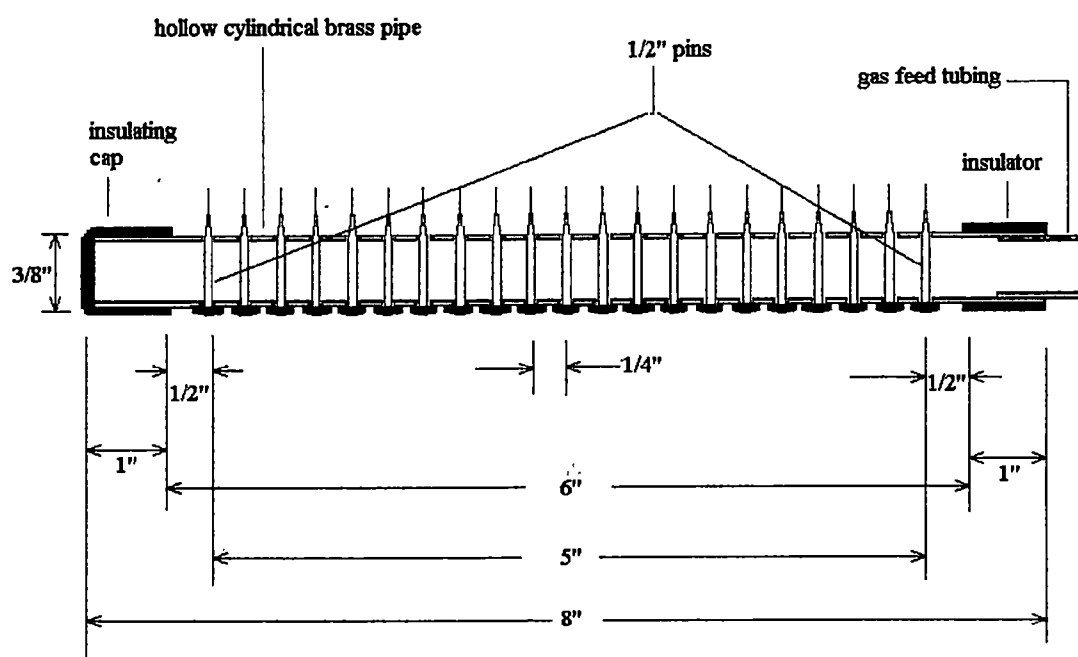


Figure 4.1. A design of the sharp-point electrode.

The sharp points of the pins serve as corona points. The brass pipe can be fed a non-electronegative (non-electron absorbing) gas such as argon, nitrogen, or helium through the feed line. The feed gas escapes through the pinholes and provides a local atmosphere around the corona points of the pins. The gas thus replaces the air in this region and, by reducing or eliminating electron attachment, enhanced corona discharge is achieved. The tube is enclosed at the other end and corona production can be obtained without large gas throughput.

A photograph of the sharp-point electrode is shown in Figure 4.2. It is by no means the only electrode that can be used for the apparatus. Figures 4.3 and 4.4 show respectively the design and a photo of the slit electrode that has been constructed as an excellent alternative to the sharp-point electrode. Figure 4.5, the blade electrode, shows yet another idea for electrode designs.

The slit electrode is made of an oval-shaped brass tube of 6 inches long. A 4-inch long slit is cut along the tube. The two sharp edges that "sandwich" the slit served as if they are two continuous lines of sharp points. The tube has a $\frac{3}{4}$ -inch insulation wrap at both ends. One of the ends is sealed and the other opened for gas feed. Compared to the sharp-point electrode, the slit electrode has the advantages of being simpler in structure design, easier to construct, and less hazardous to handle. Figure 4.6 shows the axial view of both the sharp-point electrode and the slit electrode. The simplicity of the slit electrode is obvious.

The blade electrode (Figure 4.5) can also be seen as a version of the sharp-point electrode, with the blade represents a continuous line of sharp points. It is in contrast to Figure 4.1 where the sharp points are separated from each other. Being a continuous line

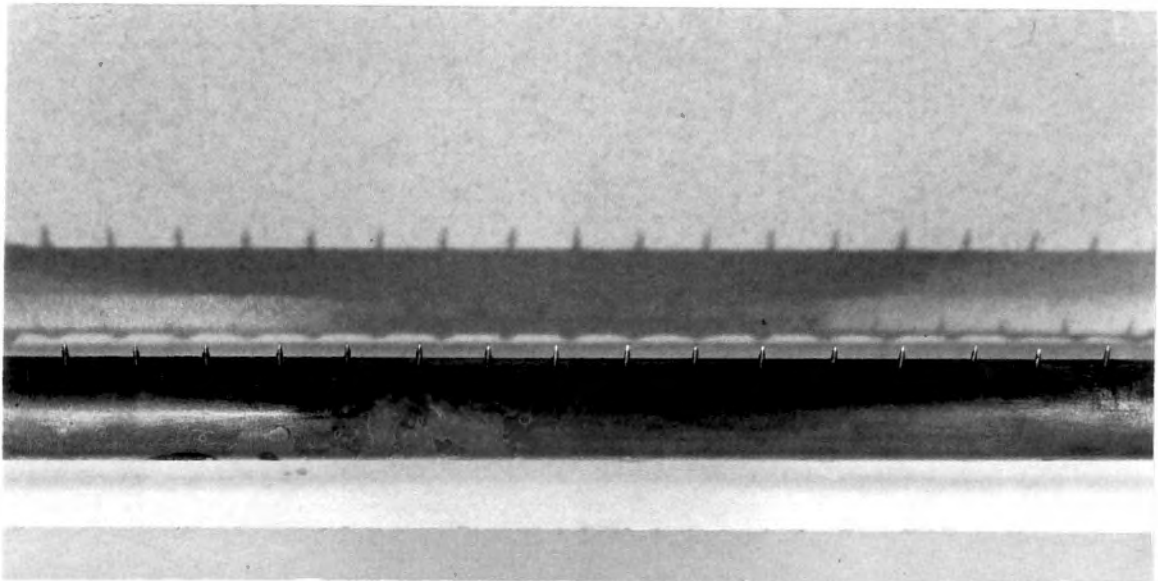


Figure 4.2. A photo of the sharp-point electrode.

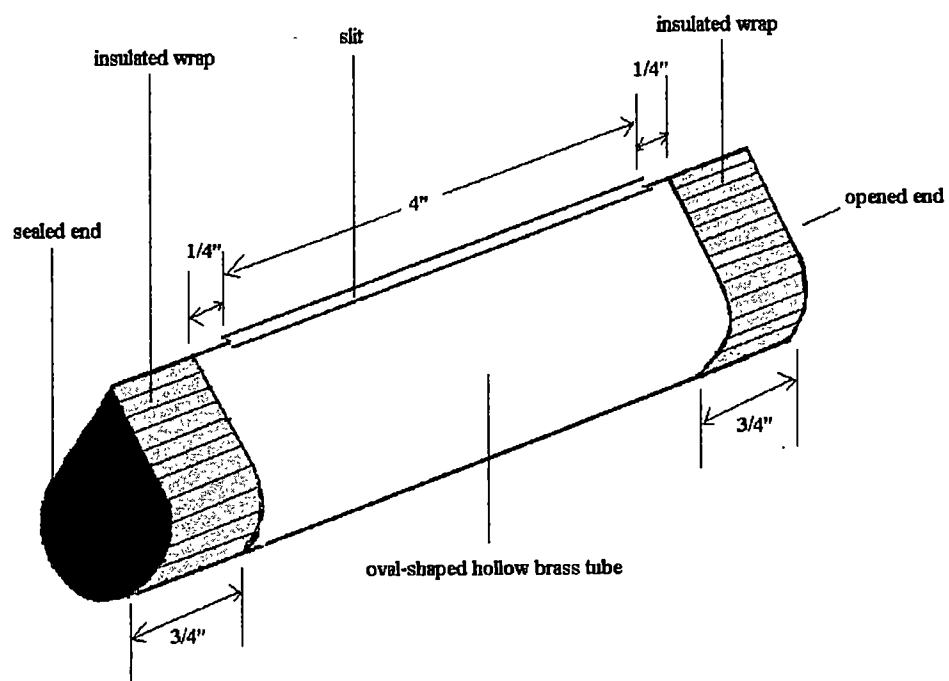


Figure 4.3. A design of the slit electrode.

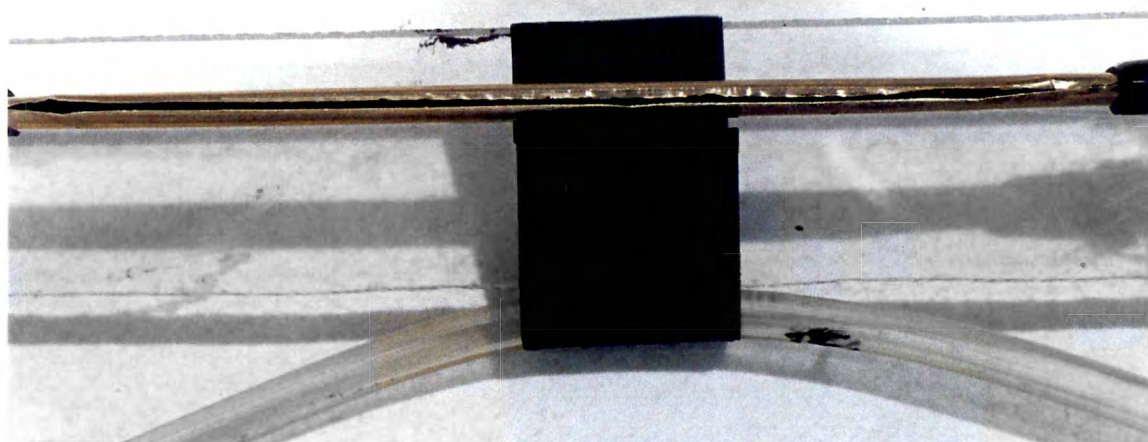


Figure 4.4. A photo of the slit electrode.

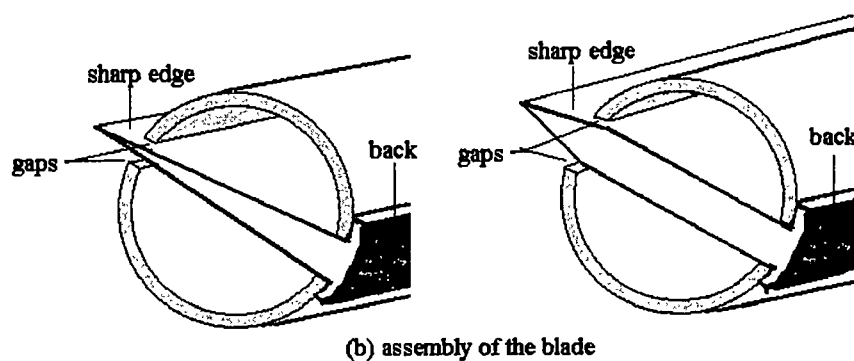
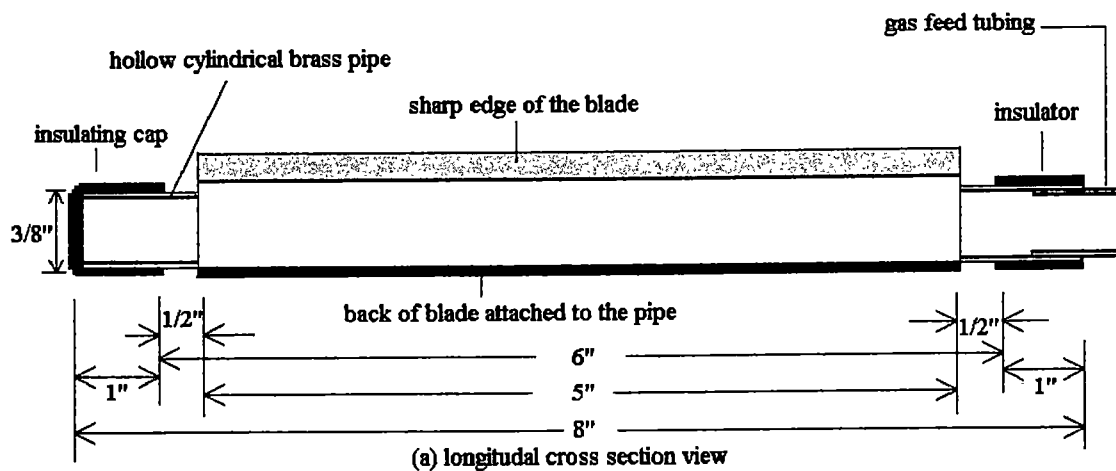


Figure 4.5. A design of the blade electrode.

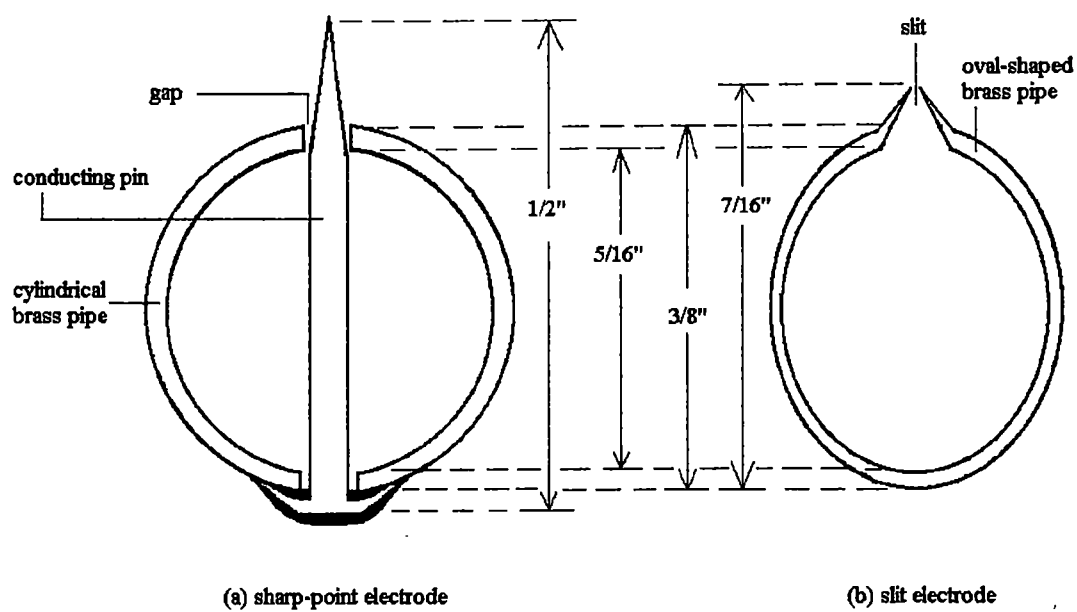


Figure 4.6. Axial views of (a) sharp-point electrode and (b) slit electrode.

of sharp points, it is believed that the blade electrode can produce a much more uniform discharge than the sharp-point electrode. Actual construction of the blade electrode has not been made.

4.2 The construction of the apparatus

Figure 4.7 shows the construction of the apparatus. The rectangular box is made of Plexiglas and has an outside dimension of 18 inches in length, 12 inches in width, and 6 inches in height. Inside dimension is $\frac{1}{2}$ inch less in each of the length, width, and height. The box consists of three rooms: the power/gas feed room, the discharge room, and the handling room. The power/gas feed room has a dimension of 10"x1.75"x6" and is simply a room containing connectors for power supply and gas feed. The discharge room has the dimension of 10"x10.25"x6" and is where the enhanced corona discharge occurred. It contains a pair of electrodes that can be tilted at a chosen angle. One of the electrodes is fixed at a position while the other is movable such that the distance between the pair of the electrodes, now designed to vary from 3 to 6 inches, can be adjusted. The handling room has the dimension of 8"x12"x6". Between the discharge and handling rooms is a 5"x6" movable door such that test sample can be moved in and out.

The apparatus, when properly connected to a DC power supply and gas feed, completes the assembly for sterilization. This is shown in Figure 4.8.

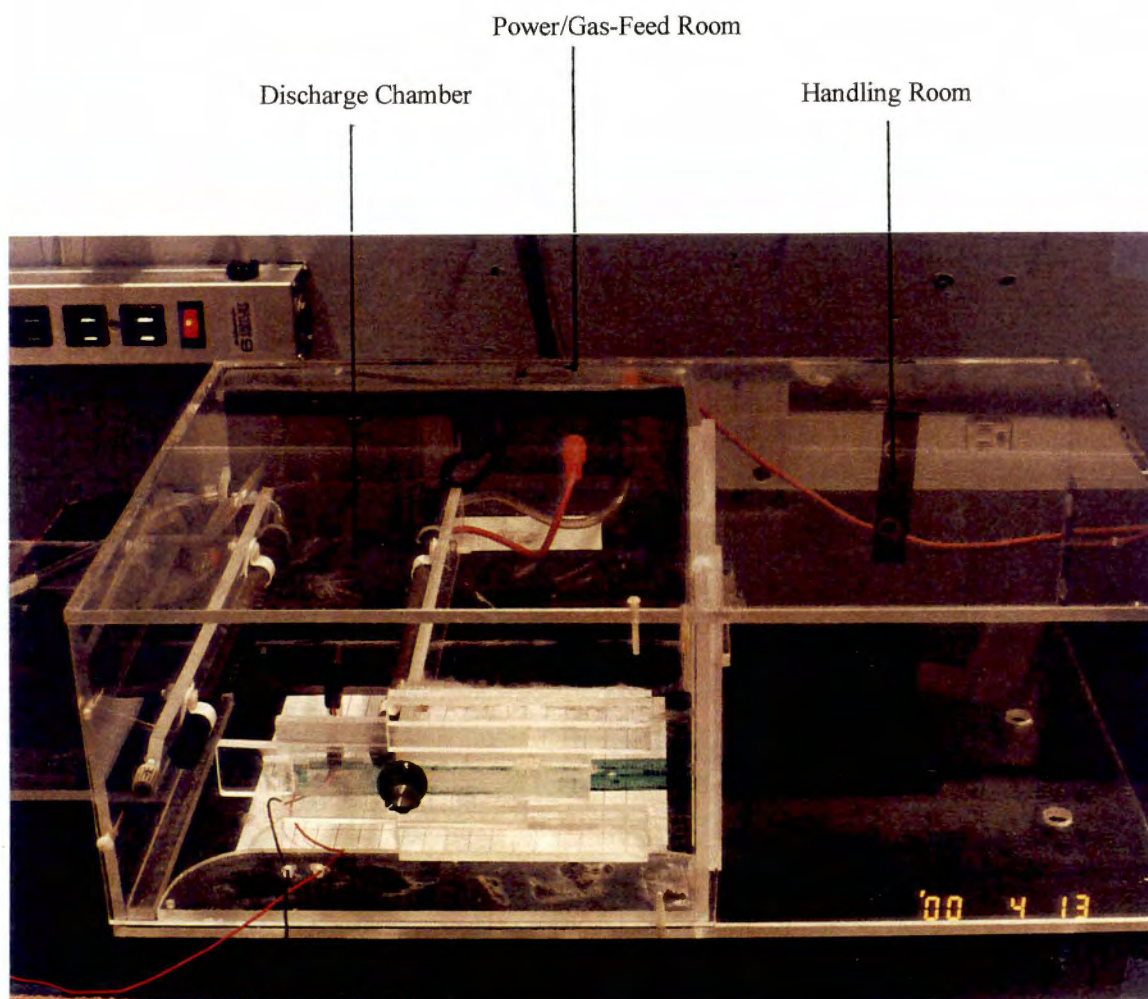


Figure 4.7. The enhanced corona discharge apparatus.

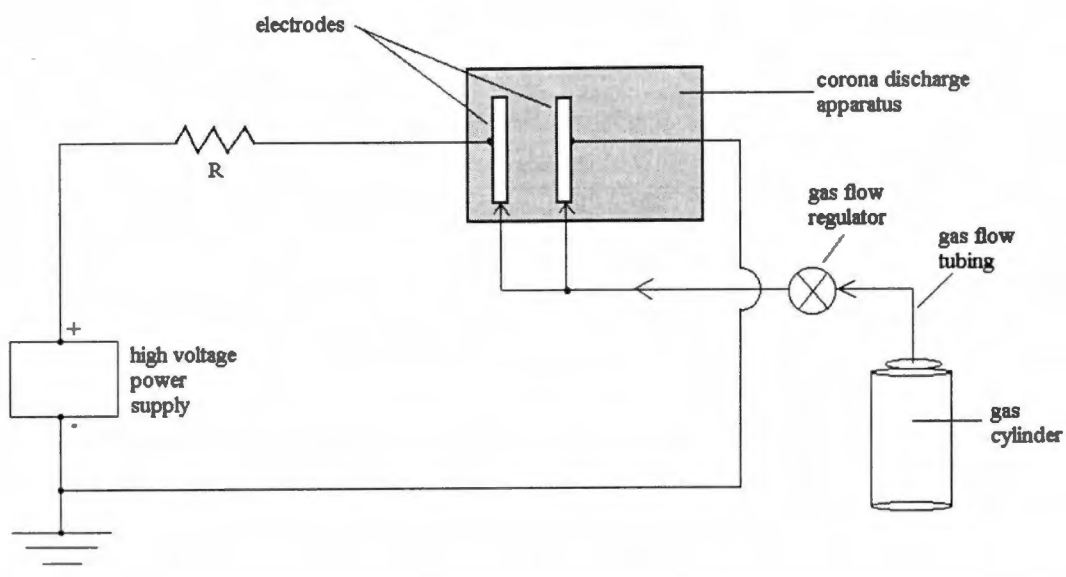


Figure 4.8. Assembly of the enhanced corona discharge apparatus.

4.3 The testing of the apparatus for enhanced corona discharge

The testing of the apparatus for enhanced corona discharge is documented as follows. Figure 4.9, 4.10, 4.11, and 4.12 show the discharge of that of the sharp-point electrodes, while Figure 4.13 and 4.14 depict that of the slit electrode. Note that all the discharges shown were generated using argon as feed gas.

Figure 4.9 reveals that the discharge was just starting to appear around the corona points. The flow rate of the argon gas feed was 80 cc/s and the electrodes were separated by 3 inches from each other. The source voltage was set at 7.5 kV. The applied voltage and current on the electrodes were that of the onset of the Townsend discharge at 7.5 kV and 0.024 μ A respectively (see Table 5.4c in chapter 5).

A further increase of electrode voltage would push the discharge in Figure 4.9 into a more uniform glow discharge as shown in Figure 4.10. Figure 4.10 had the same gas flow rate and electrode spacing as Figure 4.9. But the source voltage had been increased to 20 kV. The corresponding applied voltage and current on the electrodes were 14.53 kV and 365 μ A respectively.

If the discharge in Figure 4.10 were allowed to accumulate without proper ventilation or the electrode voltage and gas flow were further increased, the discharge might become more intense. The resulting effect would be a streaking of more luminous enhanced corona discharge as shown in Figure 4.11. The gas flow rate in the figure was set at about 120 cc/s while the source voltage was set at 25 kV. The electrode voltage and current were not measured because the discharge was starting to arc over. Note that

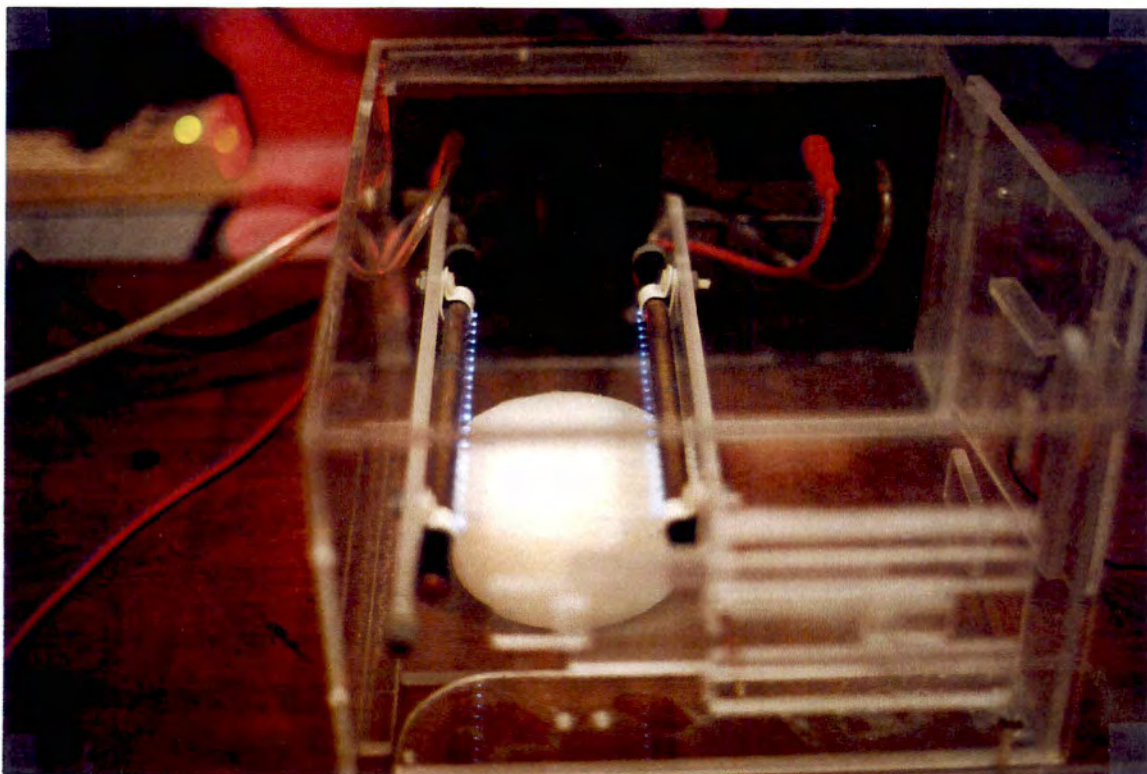


Figure 4.9. Starting of the enhanced corona discharge with sharp-point electrodes separated by a distance of 7.62 cm from each other.

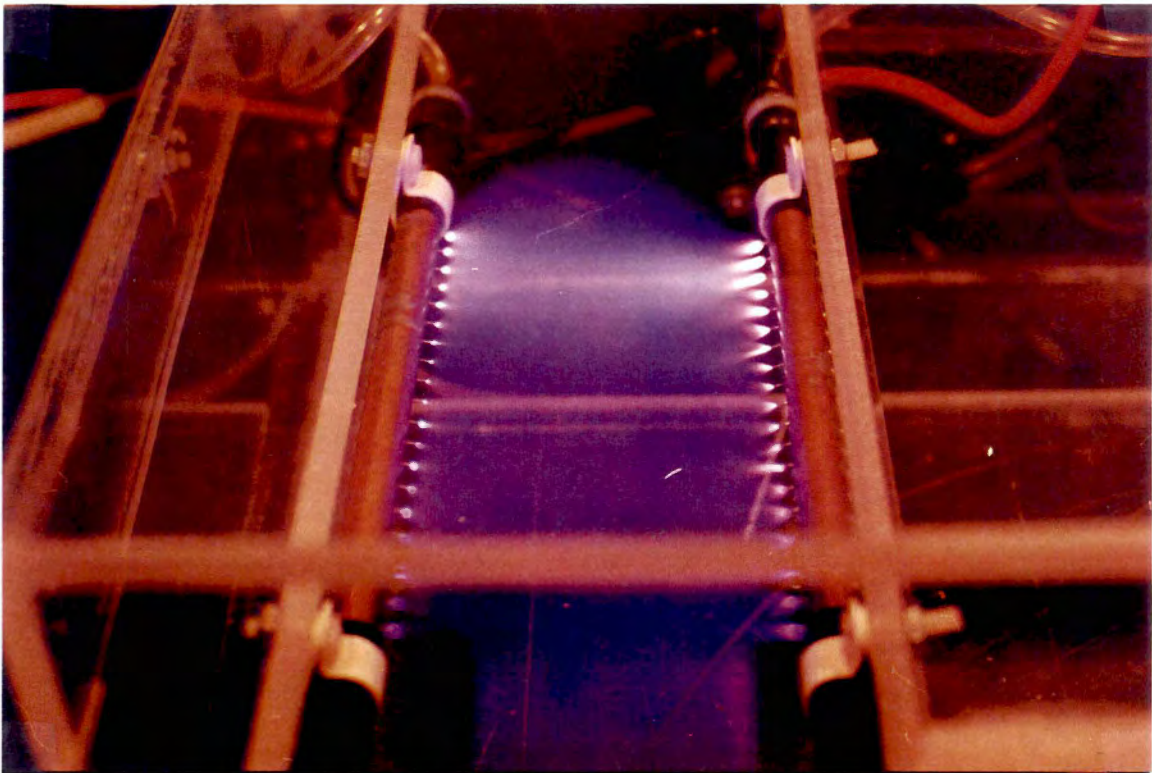


Figure 4.10. Uniform enhanced corona discharge with sharp-point electrodes separated by a distance of 7.62 cm from each other.

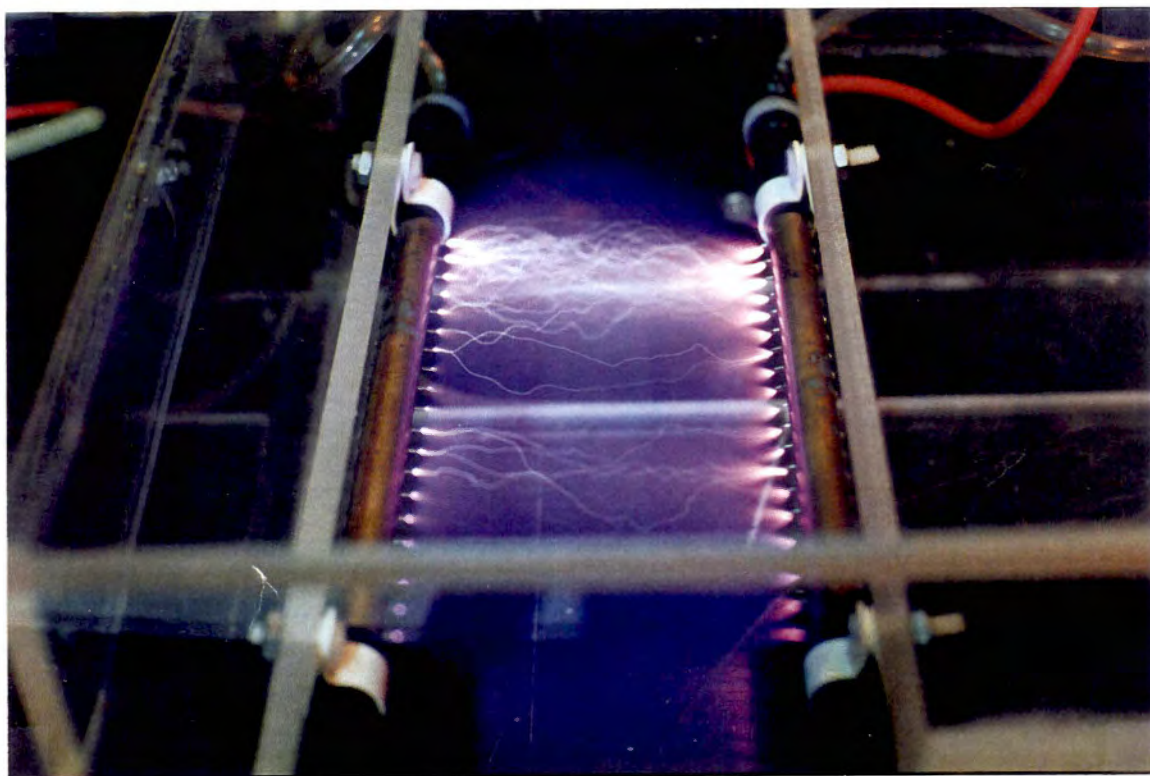


Figure 4.11. Streaking of a more luminous enhanced corona discharge with sharp-point electrodes separated by a distance of 7.62 cm from each other.

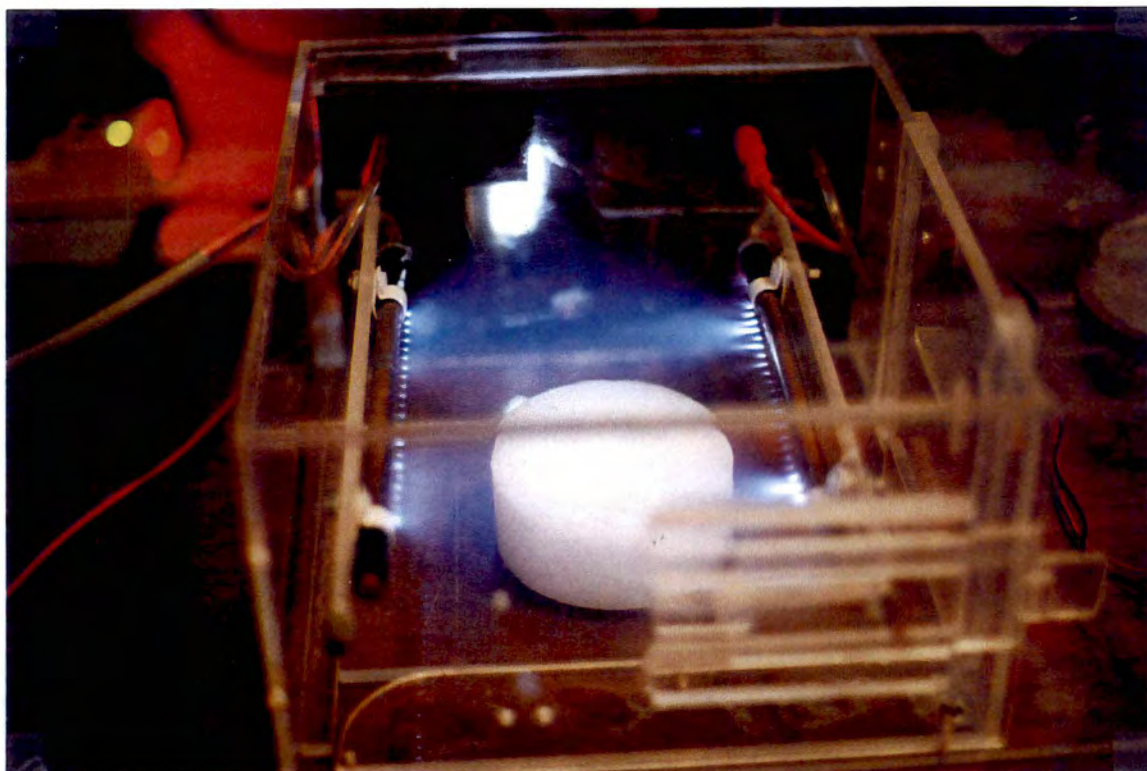


Figure 4.12. Enhanced corona discharge with sharp-point electrodes separated by a distance of 15.24 cm from each other.

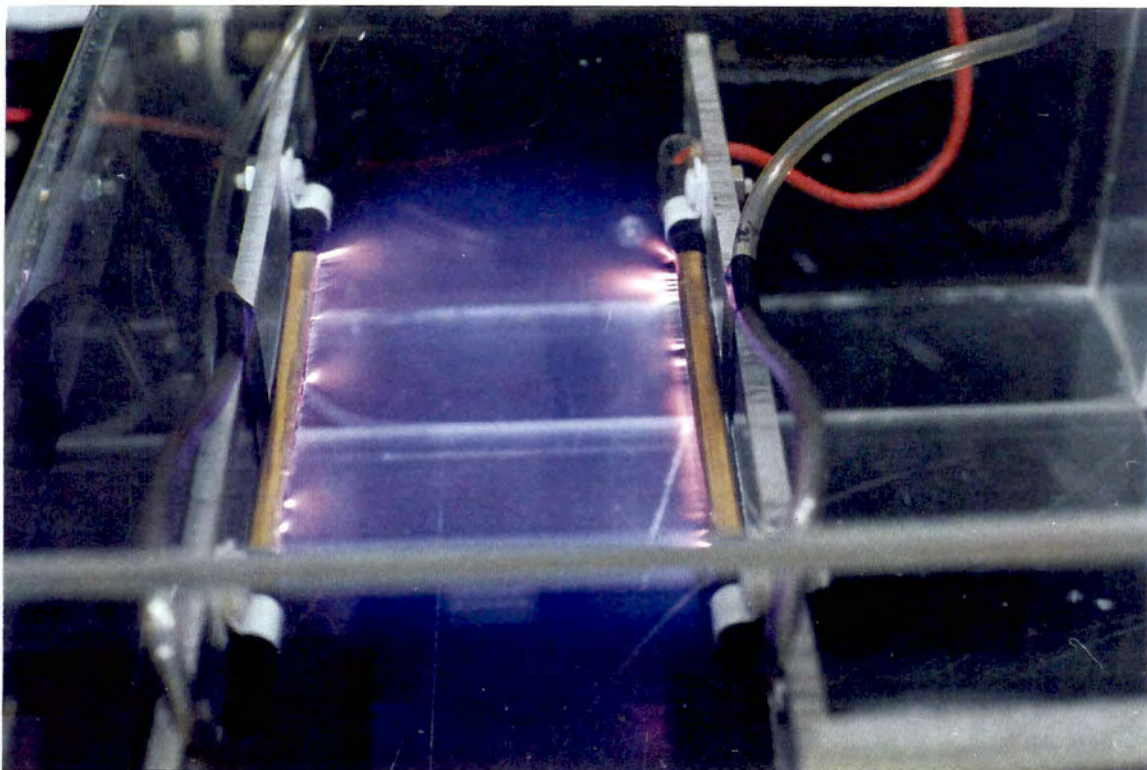


Figure 4.13. Enhanced corona discharge with slit electrodes separated by a distance of 7.62 cm from each other.

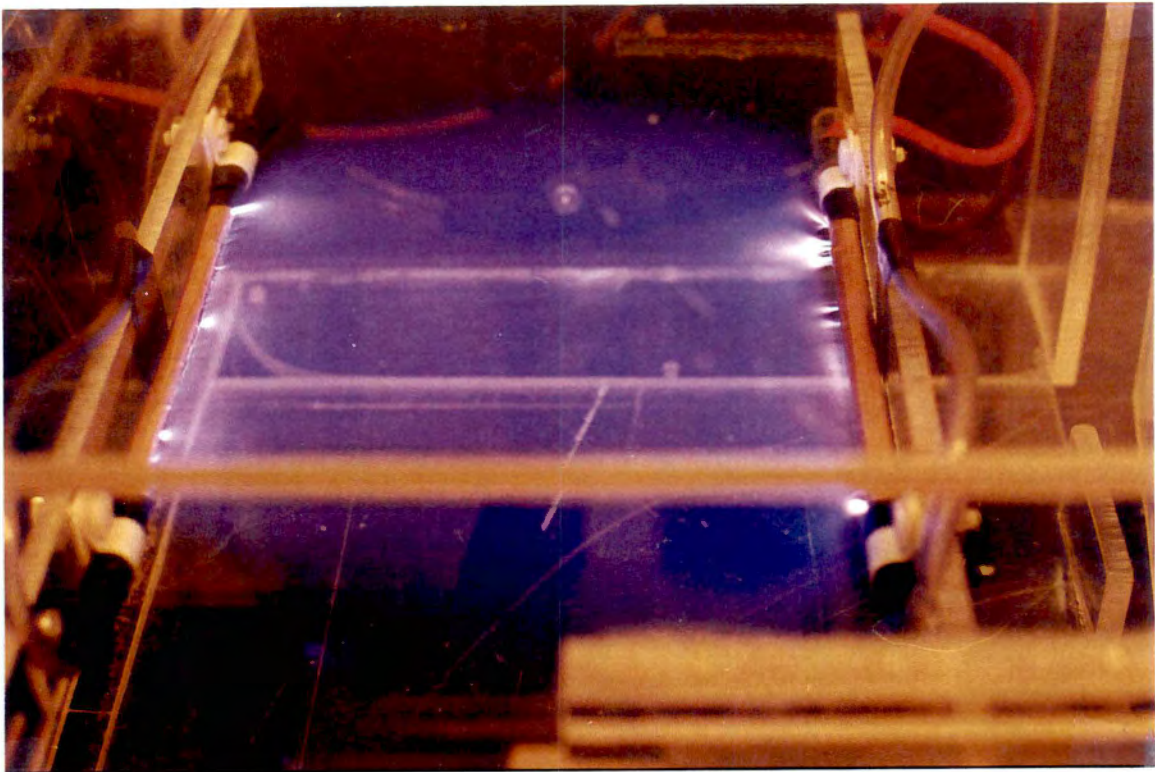


Figure 4.14. Enhanced corona discharge with slit electrodes separated by a distance of 15.24 cm from each other.

discharge like Figure 4.11 is not necessarily bad except precaution must be taken to prevent the discharge from developing into arcing mode.

While Figures 4.9-4.11 show the discharges of that of the sharp-point electrodes separated by a distance of 3 inches from each other, Figure 4.12 shows the discharge of the same configuration but with electrodes separated by a distance of 6 inches. The gas flow was set at 80 cc/s and the source voltage at 20 kV. The electrode voltage and current were not documented.

No quantitative analysis was made here regarding the sharp-point electrode discharges. The task is left for chapter 5. For the slit-electrode discharges, Figures 4.13 and 4.14 reveal the discharges with electrode-separation of 3 and 6 inches respectively. The discharge was set at 80 cc/s for the gas flow and 20 kV for the source voltage. The slit-electrodes discharge appeared to be more uniform than that of their sharp-point electrode counterparts.

CHAPTER 5

PLASMA CHARACTERIZATION OF THE APPARATUS

This chapter describes the characterization of the enhanced corona discharge (ECD) apparatus. The current-voltage (I-V) relationship, the ion density located at the geometrical center of the discharge, the spatial profile of the ion density across the cross section of the discharge chamber, and the detection of ozone are presented.

5.1 The I-V characteristics of the enhanced corona discharge

By studying the characteristic relationship between the voltage and current applied on the electrodes, one can gain an insight into the operation of the discharge involved. Figure 5.1 shows the simple circuit used in the investigation of the I-V characteristics of the enhanced corona discharge. The electrodes are connected in series with a DC power supply V_s and a resistor R . The power supply has a typical voltage in the range of 0-30 kV and a current in the range of 0-1 mA. The resistor has a value of 15 M Ω .

The behavior of the applied current I and voltage V on the electrodes were monitored under several operating conditions while the effects of airflow, electrode spacing, and gas flow on the characteristics were investigated. The results are presented in sections 5.1.1, 5.1.2, and 5.1.3.

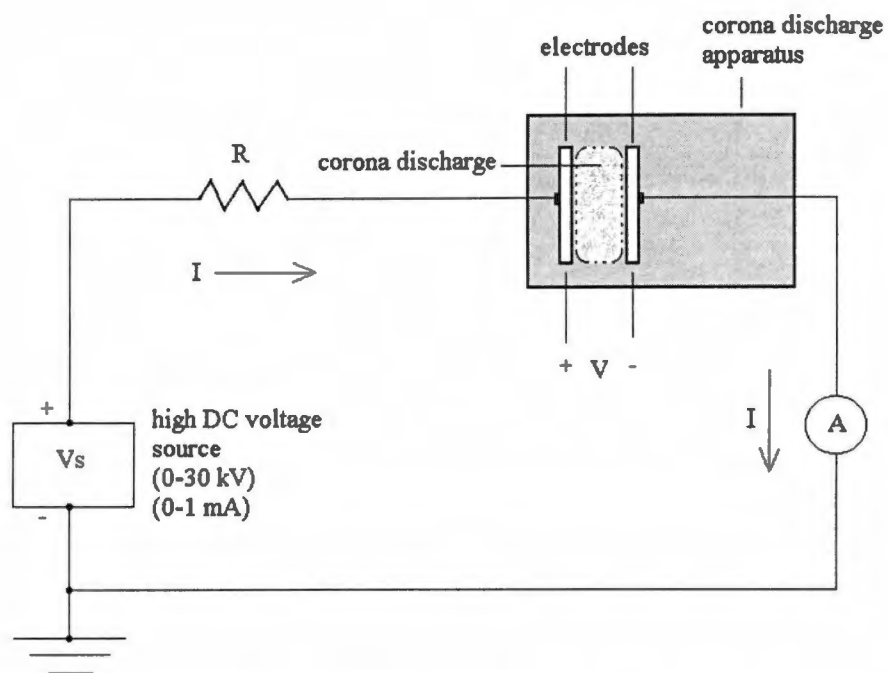


Figure 5.1. Experimental setup for measuring the current I and voltage V applied on the electrodes of the enhanced corona discharge (ECD) apparatus.

5.1.1 Effect of airflow on the I-V characteristics

The effect of airflow on the I-V characteristics was investigated under three different conditions. The discharge was first restricted only in the enclosed discharge chamber. Then the discharge chamber was left ajar (with the door between the discharge room and the adjacent handling room lifted) with no airflow acting. Finally, the discharge chamber was confronted with airflow (provided by a 5.3 cfm microfan) blowing into it. Note that under the last two operating conditions, the apparatus itself was enclosed and isolated from its immediate environments.

The results obtained are presented below. Figures 5.2a, 5.2b, 5.2c, and 5.2d depict the characteristics of the discharge with no gas feed in the atmospheric air, argon-fed discharge at a low flow rate of 40 cc/s, nitrogen-fed discharge at a moderate flow rate of 80 cc/s, and helium-fed discharge at a high flow rate of 120 cc/s respectively. In each of the figures, both linear and semi-logarithmic plots are presented. The latter reveals a more detailed behavior over the wide applied current range.

In Figure 5.2a where no gas was fed, the characteristic curves are closely identical to each other whether the discharge was restricted to an enclosed region or accessible to an opened space with or without airflow. The typical I-V curve shows a "saturation" region with a voltage below 15 kV and a current below 1 μ A. The "Townsend" region where corona discharge occurred begins at a voltage above 15 kV and a current above 1 μ A. The "saturation" and "Townsend" regions will be discussed in more detail later in section 5.1.4.

In Figure 5.2b where argon was fed into the discharge electrodes at a low flow rate of 40 cc/s, there was significant difference between the different operating conditions.

With the discharge chamber enclosed, the Townsend region began at a lower voltage of 10 kV and a higher current of 0.2 μ A. With the discharge chamber left ajar (both with and without airflow), the Townsend regions started at a higher voltage of 12.5 kV and a lower current of a few nA. Obviously then, restricting the discharge in an enclosed region is preferable.

In Figure 5.2c where nitrogen with a moderate flow rate (80 cc/s) was fed into the discharge electrodes, evidence again indicated that there were differences whether the discharge chamber was enclosed or not. With the discharge restricted to an enclosed region, the Townsend region began at a lower voltage (12.5 kV) and higher current (2×10^{-8} A). When the discharge was not restricted, the Townsend regions began at a higher voltage (15 kV) and approximately the same current range (a few 10^{-8} A). Enclosed discharge was again preferable.

In Figure 5.2d where a high flow rate (120 cc/s) of helium was applied, the I-V characteristics differed again as it was in Figures 5.2b and 5.2c. When the discharge was restricted, the Townsend region began at 7.5 kV and 4×10^{-8} A. When the discharge was not restricted, the Townsend regions began at a higher voltage of 10 kV. Here again, enclosed discharge was preferable.

In view that enclosed discharge was preferable since less applied voltage was needed to produce the same amount of current, all experiments presented hereafter were conducted with the discharges restricted to the enclosed space.

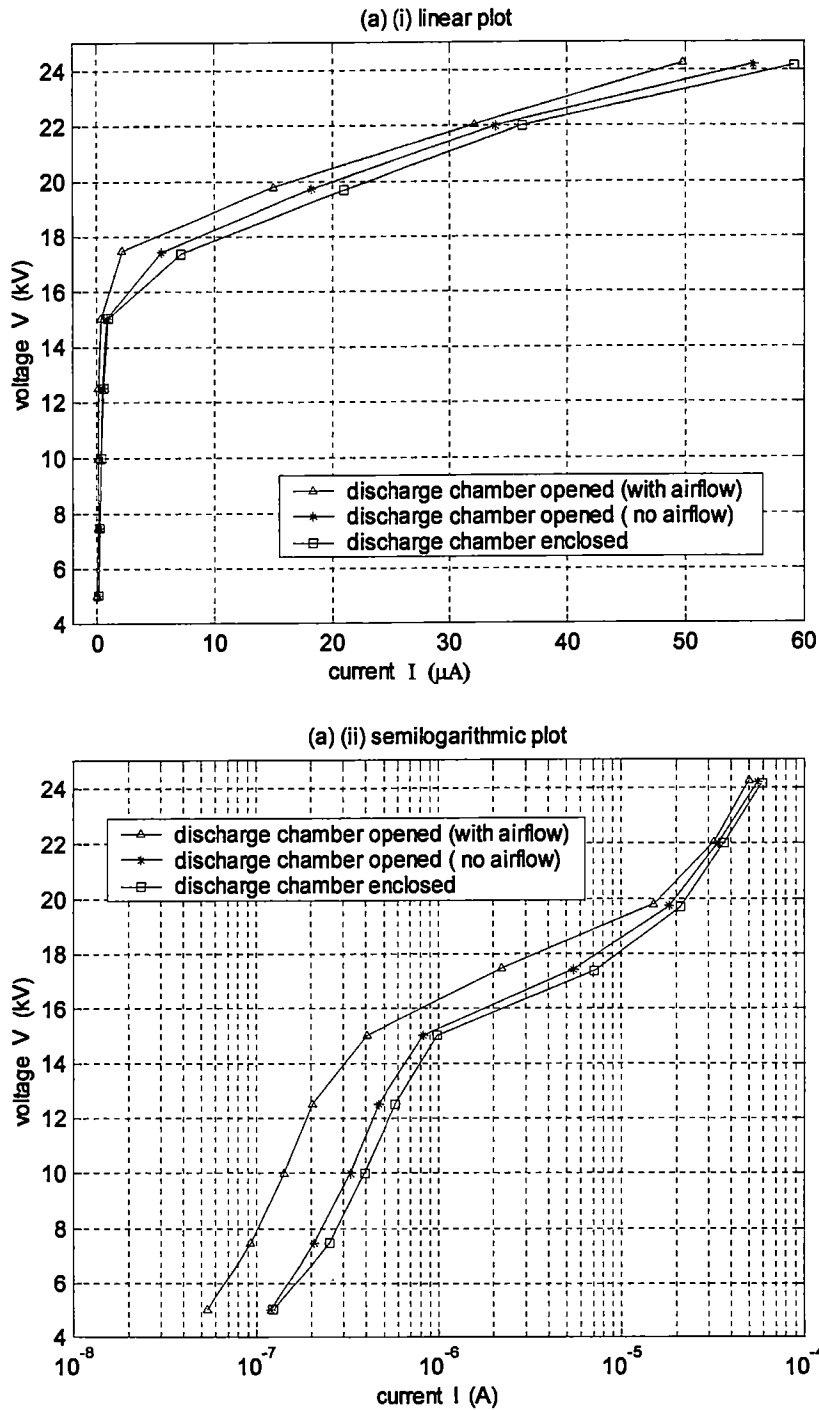


Figure 5.2. Effect of airflow on the I-V characteristics of ECD with sharp-point electrodes separated by a spacing of 3 inches (7.62 cm) between them: (a) discharge with no gas feed in the atmospheric air.

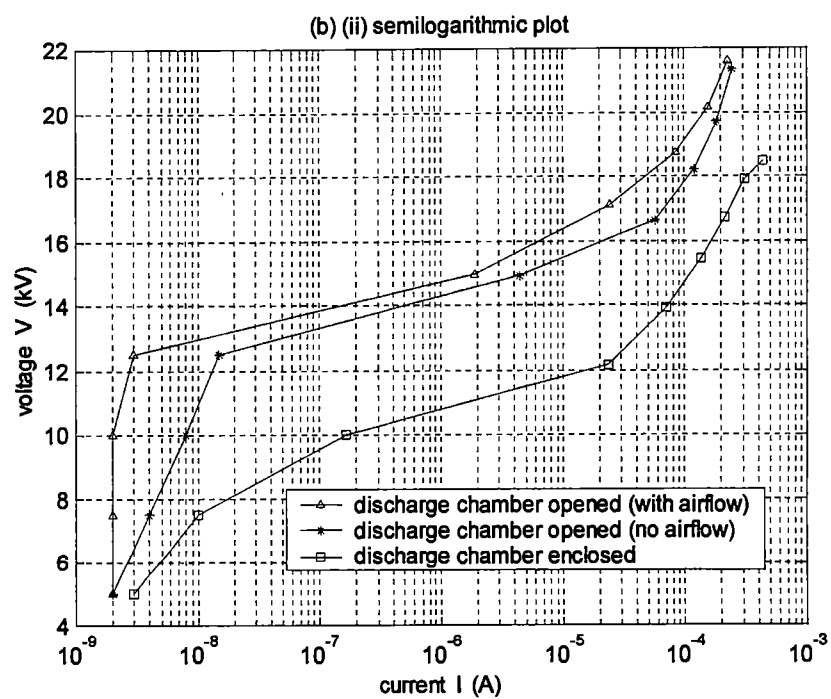
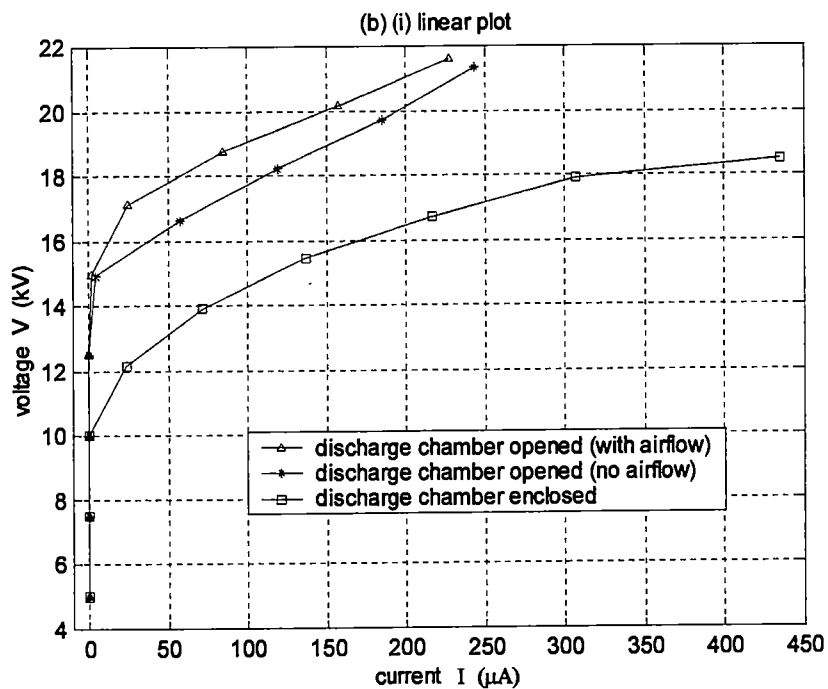


Figure 5.2. continued: (b) argon-fed discharge at a gas flow rate of 40 cc/s.

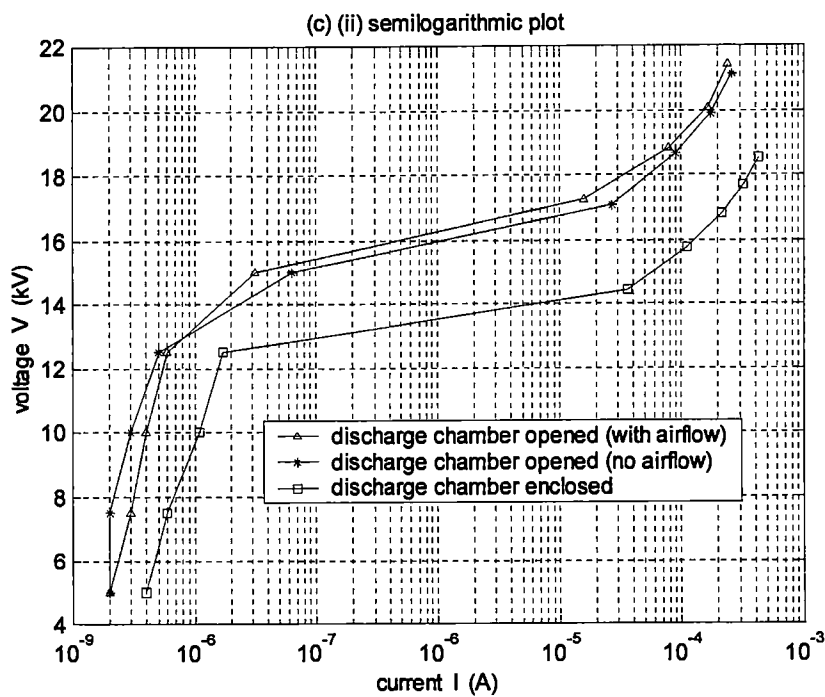
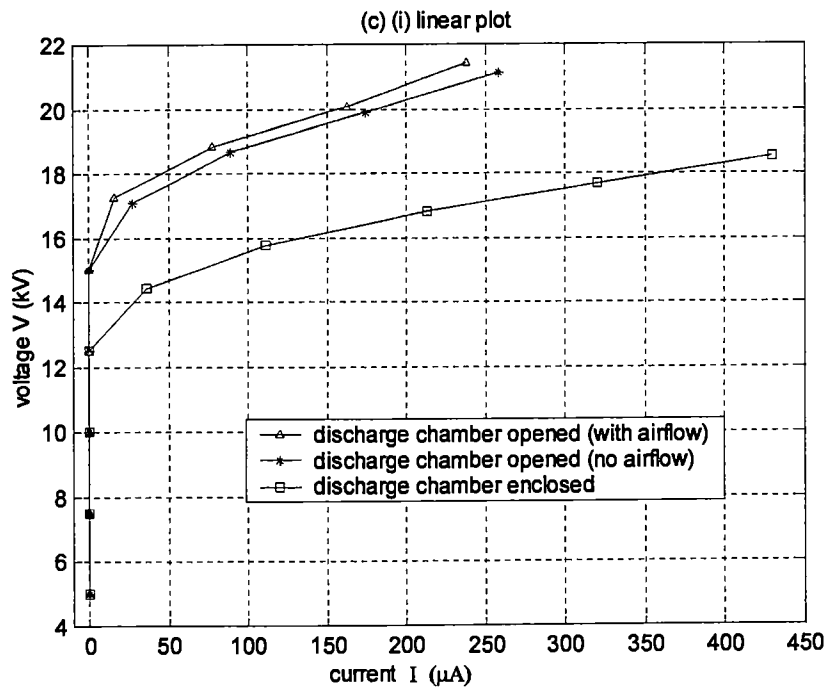


Figure 5.2. continued: (c) nitrogen-fed discharge at a gas flow rate of 80 cc/s.

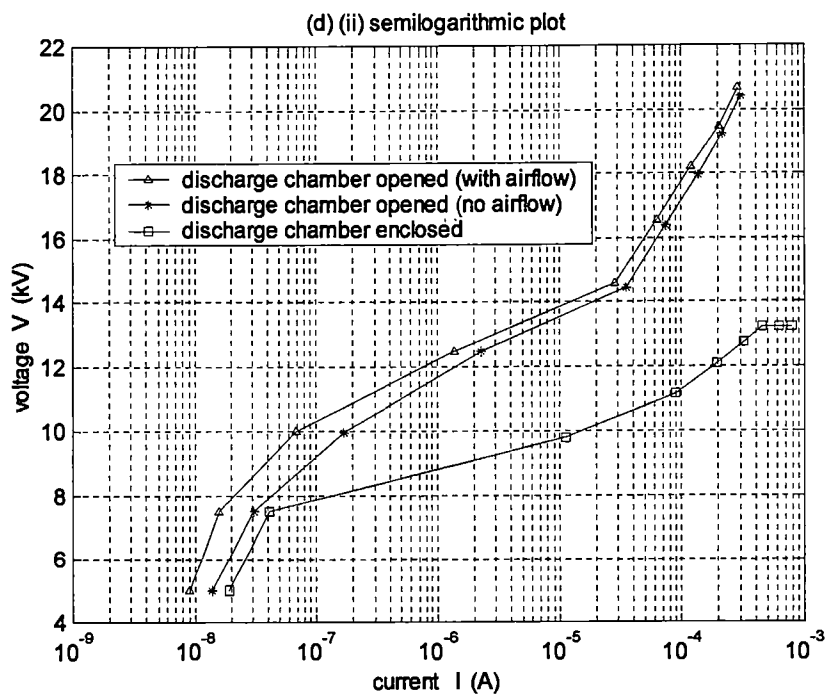
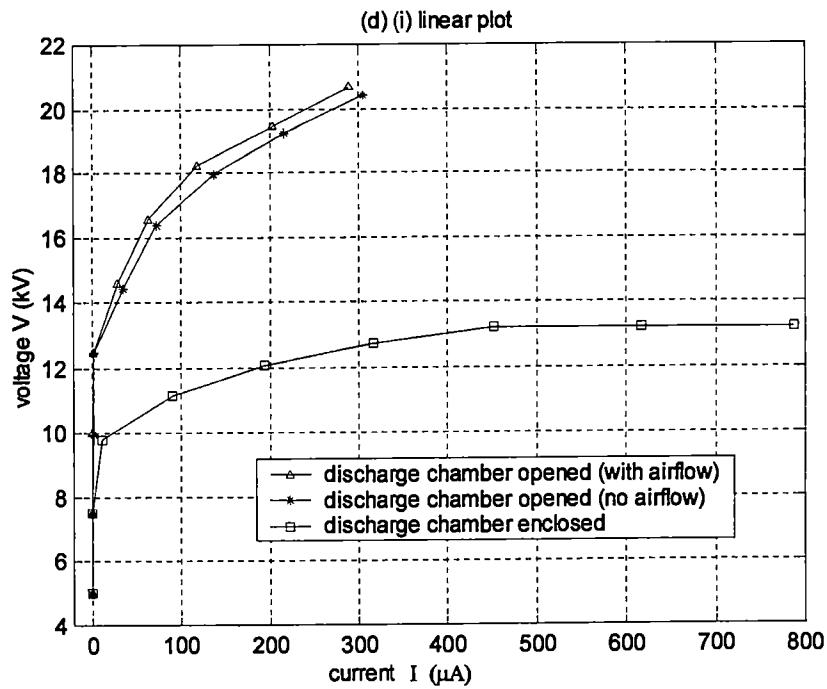


Figure 5.2. continued: (d) helium-fed discharge at a gas flow rate of 120 cc/s.

5.1.2 Effect of electrode spacing on the I-V characteristics

With the discharge restricted in the enclosed discharge chamber, the effect of electrode spacing on the I-V characteristics was investigated. The spacing between the sharp-point electrodes was set at 7.62 cm (3 inches), 10.16 cm (4 inches), 12.70 cm (5 inches) and 15.24 cm (6 inches) for the investigation. Figure 5.3 shows the results obtained.

In Figure 5.3a, no gas was fed to the discharge electrodes. It is evident that with the same voltage applied on the electrodes, the current flowing through the electrodes increased inversely with the electrode spacing. Taking for example at applied voltage of 20 kV, the currents flowing between the electrodes were 21, 9, 5, and 3 μA for 7.62, 10.16, 12.70 and 15.24-cm spacing respectively. At lower applied voltages, the respective current differences were lower. At 15 kV, the currents were 1, 0.76, 0.62, and 0.49 μA for the respective four electrode spacings mentioned above. Note that 15 kV was the onset of the Townsend regions for all the spacings.

In Figure 5.3b, a low flow rate (40 cc/s) of argon was fed to the discharge electrodes. It is again evident that the current increased inversely with the spacing at the same applied voltage. For the 10.16, 12.70, and 15.24-cm spacings, though they all had the onset of Townsend discharge at 12.5 kV, the currents were 0.5, 0.2, and 0.007 μA respectively. The onset of the Townsend discharge for the 7.62-cm spacing was at a lower voltage of 10 kV and a current of 0.17 μA . Compared to that when no gas was fed (Figure 5.3a), the low flow rate of argon-fed discharge described herewith is more favorable because of the lower onset of Townsend discharge.

In Figure 5.3c, a moderate flow rate (80 cc/s) of nitrogen was fed to the discharge electrodes. It is again evident that a smaller spacing was preferable. For the 7.62-cm spacing, the Townsend discharge began at 12.5 kV with a current of 0.017 μA . For the 10.16-cm spacing, it started at 15 kV and 0.03 μA . The I-V characteristics for both the 12.7 and 15.24-cm spacing were quite similar: both started the Townsend regions at 17.5 kV with currents of 0.15 and 0.12 μA respectively.

In Figure 5.3d where a high flow rate (120 cc/s) of helium was applied, the lowest electrode spacing was again preferable. The Townsend region for the 7.62-cm spacing began at 7.5 kV with a corresponding current of 0.04 μA . For higher electrode spacings, they all had approximately the same Townsend onset voltages of 10 kV but with different currents of 0.9, 0.06, and 0.03 μA respectively.

The effects of electrode spacing on the I-V characteristics described above thus preclude the usage of bigger spacing between the electrodes. In conjunction with the preferable restricted discharge in an enclosed chamber as described in the section before this, the investigation on the effect of gas flow in the next section will be limited to the enclosed discharges with the electrodes separated by 3 inches (7.62 cm) from each other.

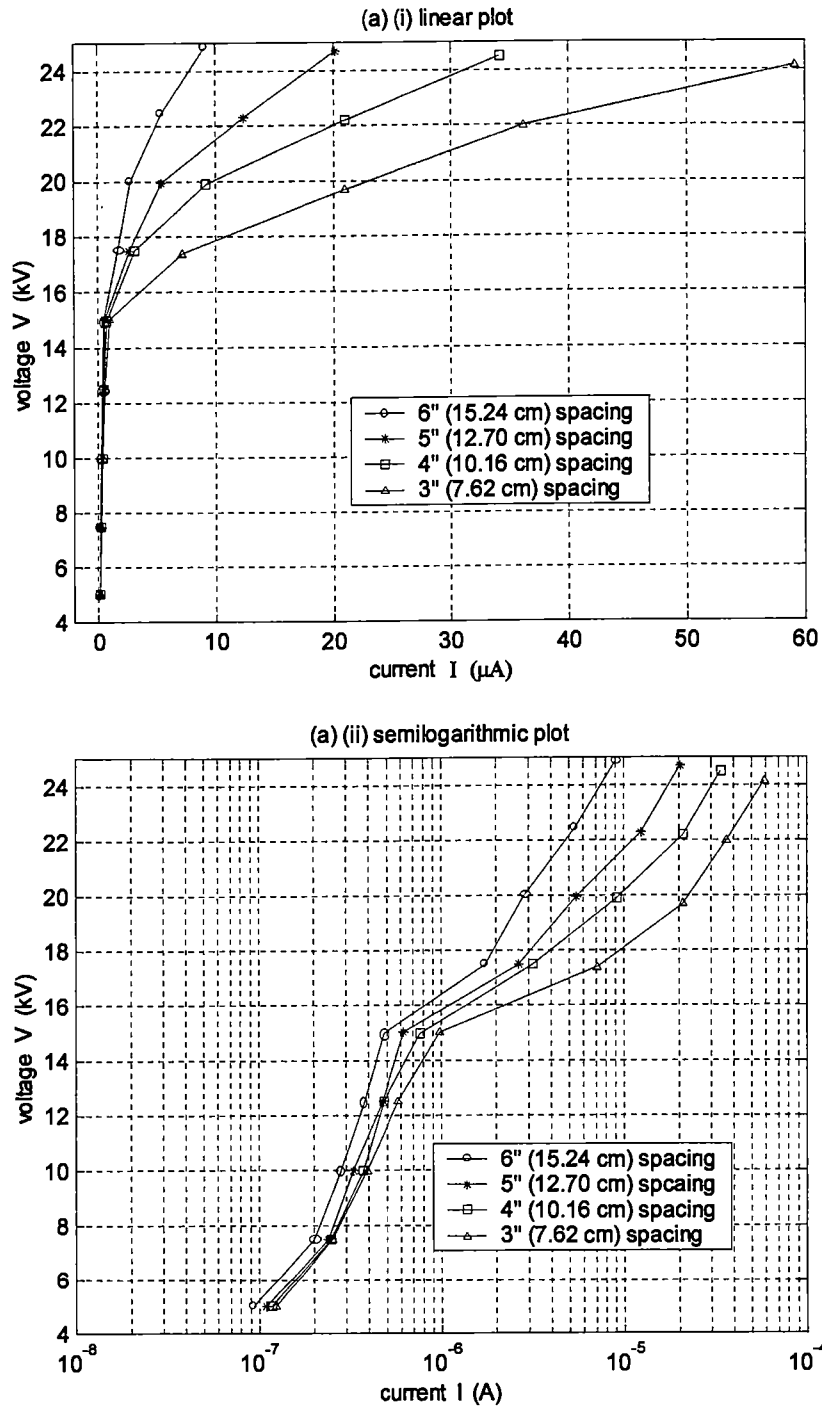


Figure 5.3. Effect of electrode spacing on the I-V characteristics of ECD with sharp-point electrodes: (a) discharge with no gas feed in the atmospheric air.

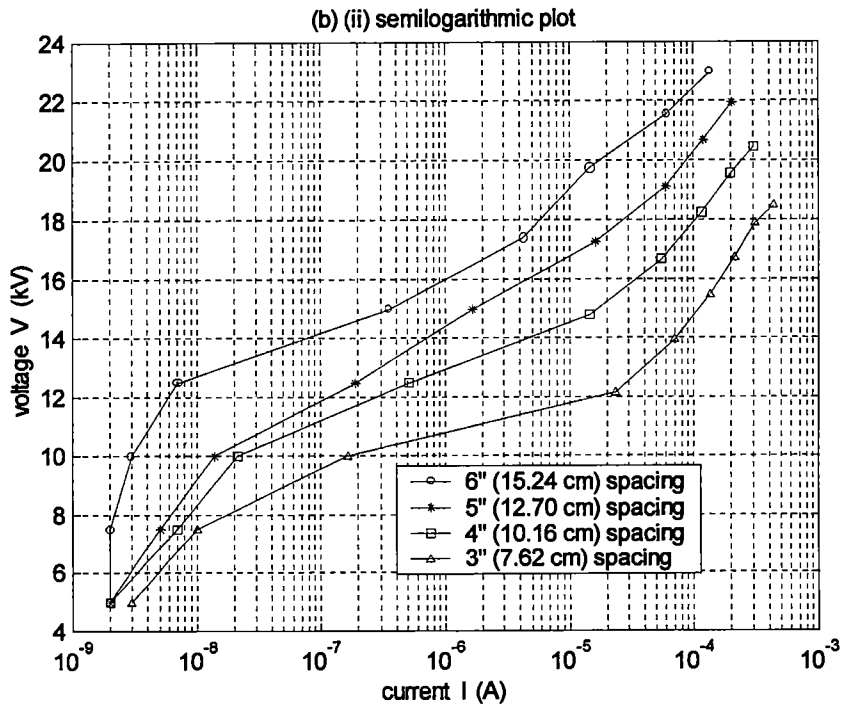
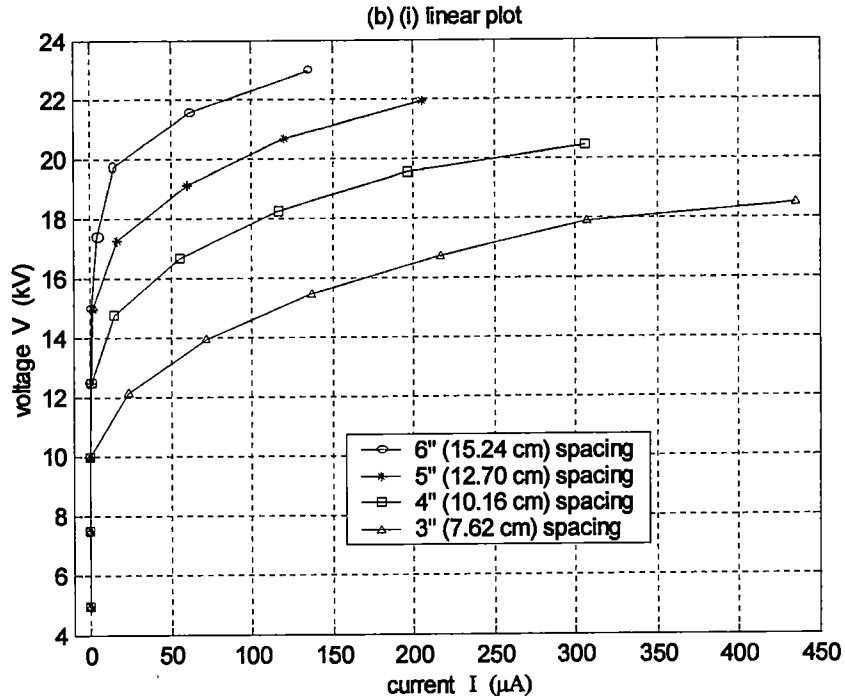


Figure 5.3. continued: (b) argon-fed discharge at a gas flow rate of 40 cc/s.

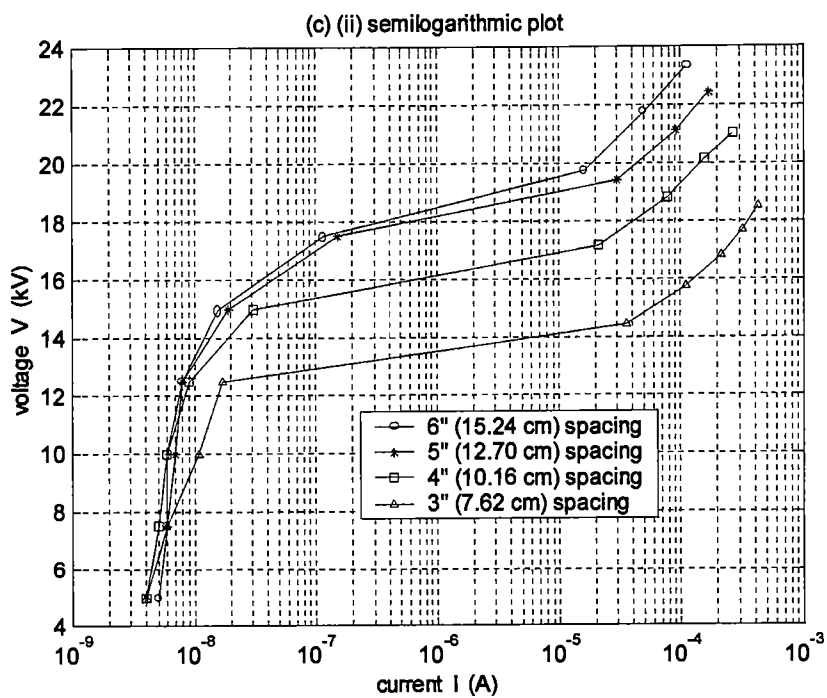
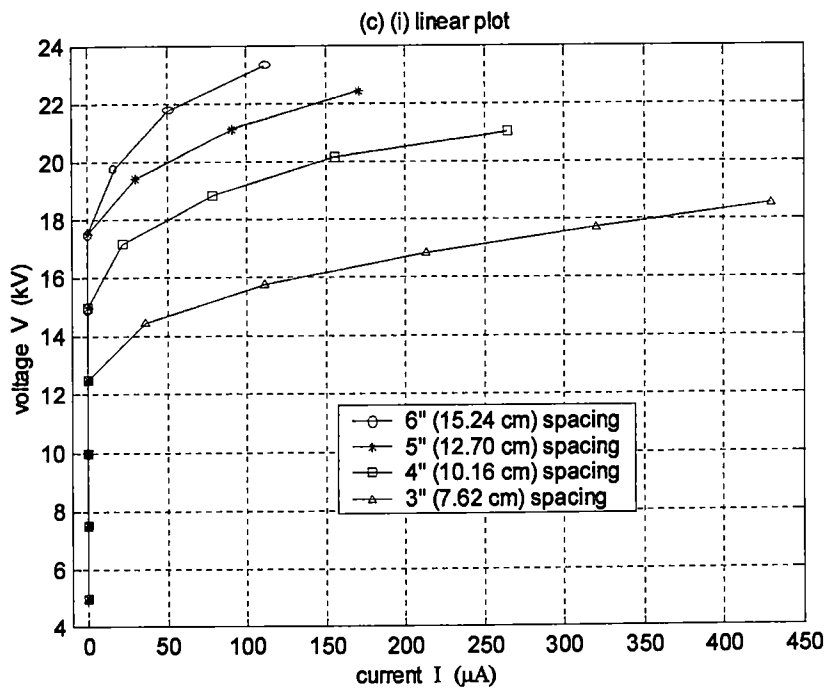


Figure 5.3. continued: (c) nitrogen-fed discharge at a gas flow rate of 80 cc/s.

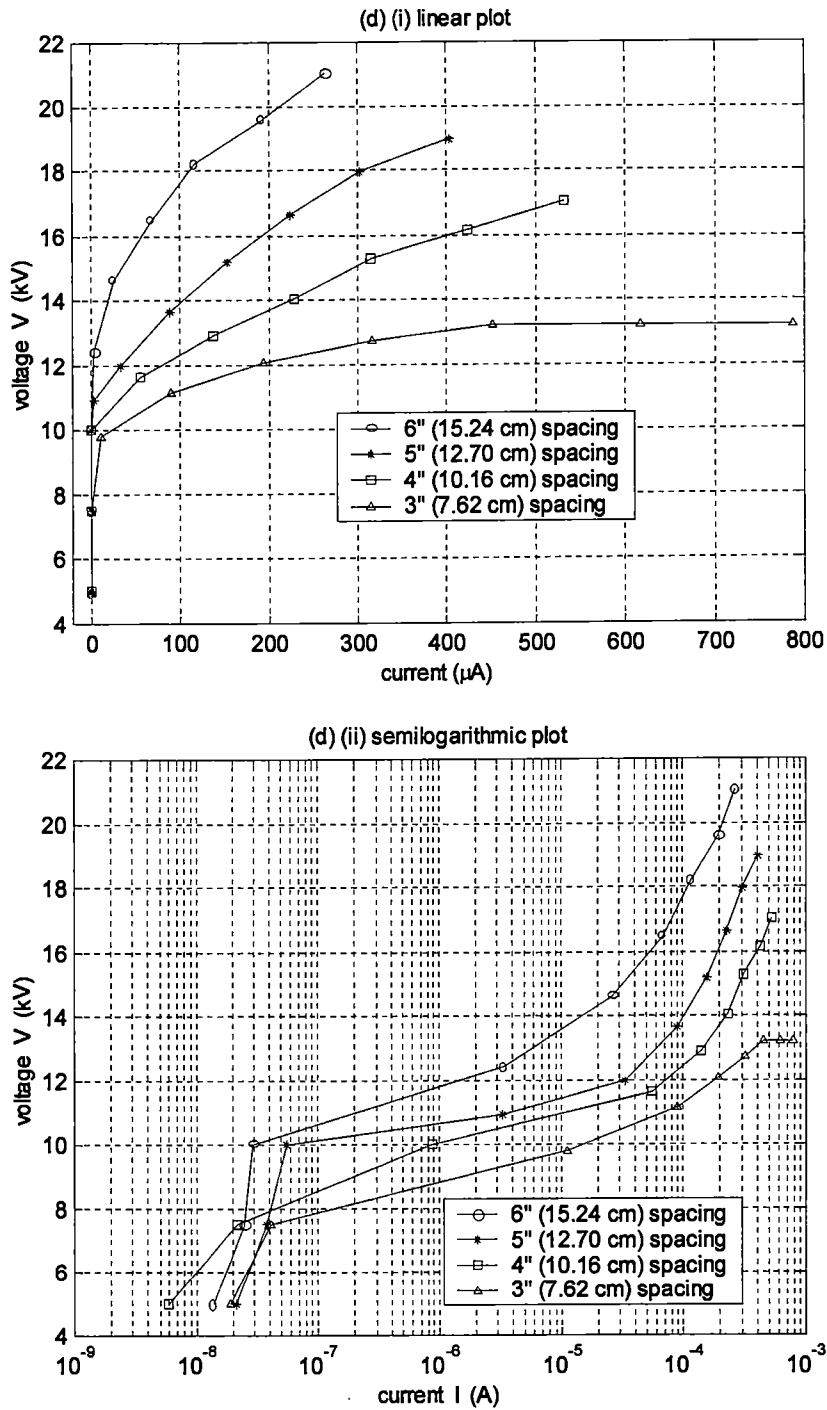


Figure 5.3. continued: (d) helium-fed discharge at a gas flow rate of 120 cc/s.

5.1.3 Effect of gas flow on the I-V characteristics

With the discharge restricted in the enclosed discharge chamber and the electrode spacing set at 7.62 cm, the effect of gas flow on the I-V characteristics was investigated. Figure 5.4 shows the result obtained.

In Figure 5.4a, a comparison between the no-gas-feed discharge and the low flow rate (10 cc/s) of nitrogen-, helium-, and argon-fed discharge was made. Even at this low flow rate, the effect was profound. When no gas was fed, the onset of Townsend discharge was at 15 kV and 1 μA , and the transition from saturation to Townsend regions was rather gradual. For nitrogen-fed discharge, the Townsend region appeared at 15 kV (0.05 μA) and was not favored over that of no-gas-feed discharge before 20 kV was reached. For helium-fed discharge, the Townsend region also began at 15 kV (0.25 μA), but with a rather sudden transition. The discharge was favored after 16 kV was reached. For argon-fed discharge, the Townsend region began at 12.5 kV (0.614 μA) and the current increased by an order of magnitude compared to the no-gas-feed discharge after 15 kV was reached.

In Figure 5.4b, another low gas flow was applied at 40 cc/s. For nitrogen-fed discharge, the Townsend region began at 15 kV with a current of 0.44 μA . But the favorable operating voltage had been lowered to 16 kV as compared to 20 kV for the 10 cc/s flow rate. For helium-fed discharge, the Townsend region now began at 12.5 kV. The favorable operating voltage now began at 12.5 kV as compared to 16 kV for the 10 cc/s flow rate. The current increased by a little more than an order of magnitude compared to that of no-gas-feed discharge after 14 kV was reached. For argon-fed discharge, the Townsend region as well as the favorable operating voltage began now at

10 kV as compared to 12.5 kV for the 10 cc/s flow rate. The current increased to almost two orders of magnitude compared to the no-gas-feed discharge.

In Figure 5.4c, a moderate gas flow rate at 80 cc/s was applied. The effect was more astounding than the cases with lower gas flows. The Townsend regions for nitrogen-, helium-, and argon-fed discharges now began at 12.5, 10, and 7.5 kV respectively. At the onset of the Townsend discharge, the current increased by three orders of magnitude (from 0.017 μA at 12.5 kV to 36.07 μA at 14.46 kV) for nitrogen-fed discharge. The current increased by two orders of magnitude (from 0.044 μA at 10 kV to 23.84 μA at 12.14 kV) for helium-fed discharge, and three orders of magnitude (from 0.024 μA at 7.5 kV to 27.81 μA at 9.38 kV) for argon-fed discharge. The favorable operating voltage began at about 1 kV beyond the onset of the Townsend discharge for each of the three feeding gases. Note that at 80 cc/s flow rate, argon-fed discharge showed signs of transiting to glow/arc discharge at 14.5 kV.

In Figure 5.4d, a high flow rate (120 cc/s) of nitrogen and helium was applied. Argon was not attempted because of its arcing at this rate. The onset of the Townsend region for nitrogen- and helium-fed discharges was at 10 and 7.5 kV respectively. Note that helium also showed signs of transiting to a glow discharge at 13.5 kV.

The details discussed in the preceding four paragraphs are summarized in Table 5.1. Data used in Figures 5.4a to 5.4d are also re-utilized to plot Figures 5.4e to 5.4g where individual gas-fed discharge with different flow rates are presented in the same graph.

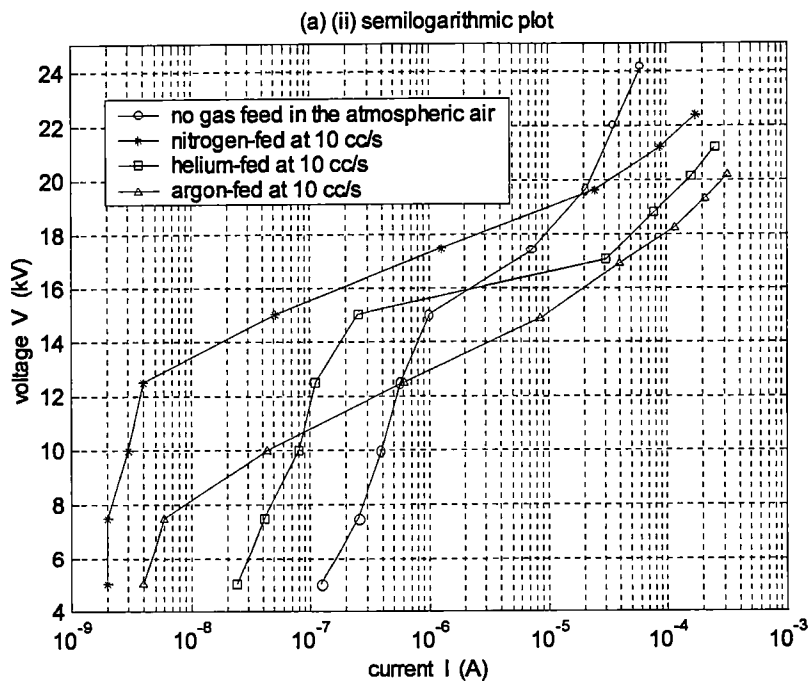
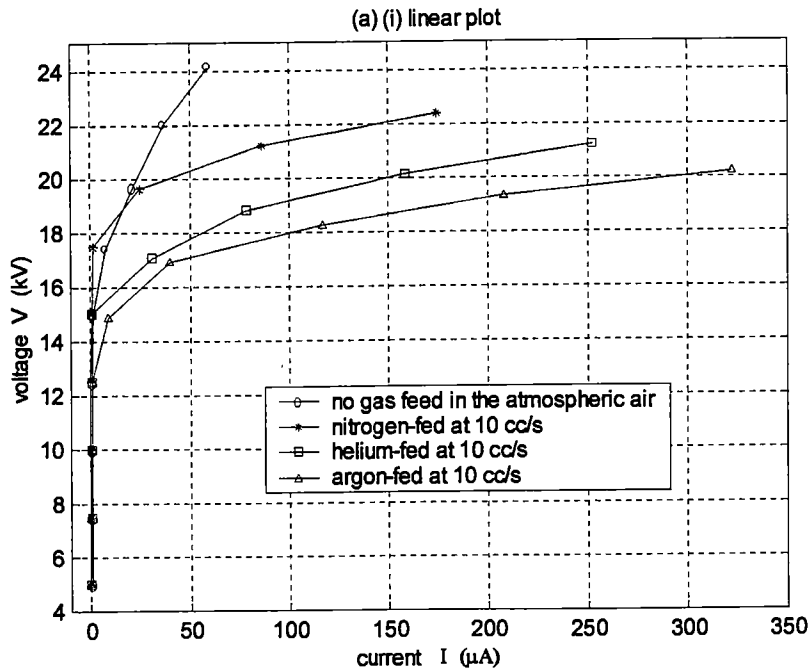


Figure 5.4. Effect of gas flow rate on the I-V characteristics of ECD with sharp-point electrodes separated by a spacing of 3 inches (7.62 cm) between them: (a) atmospheric air versus low gas flow rate of 10 c/s for nitrogen, helium, and argon.

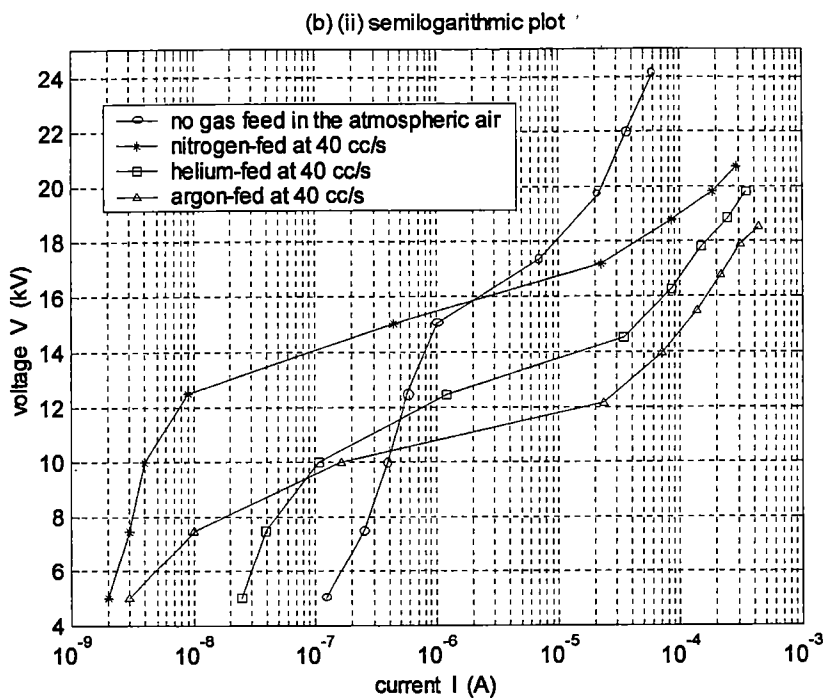
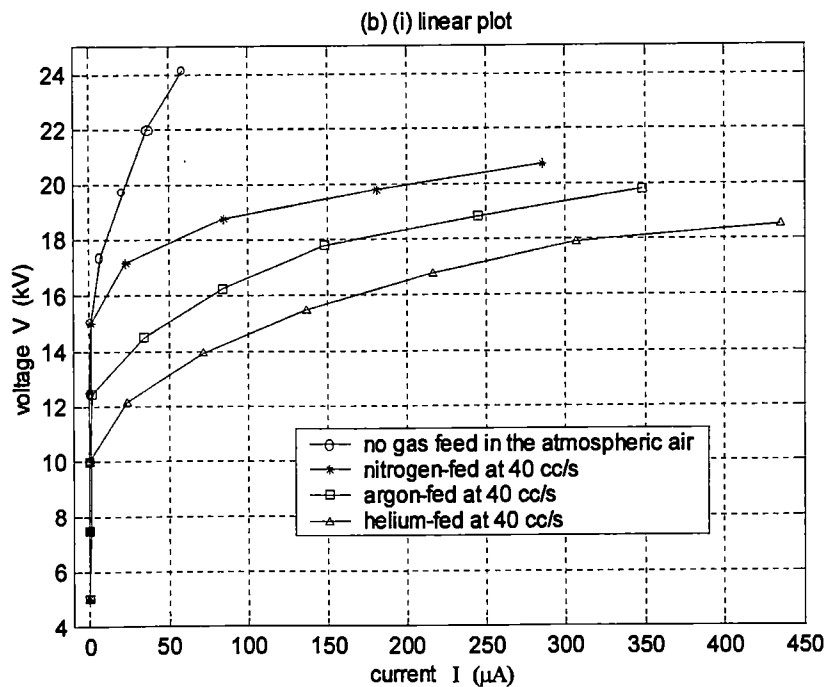


Figure 5.4. continued: (b) atmospheric air versus low gas flow rate of 40 cc/s for nitrogen, helium, and argon.

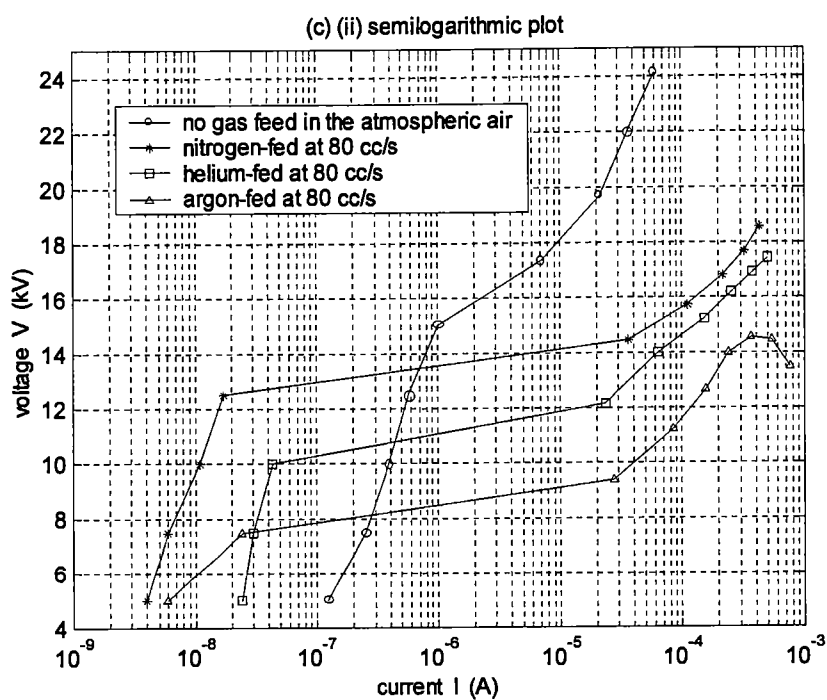
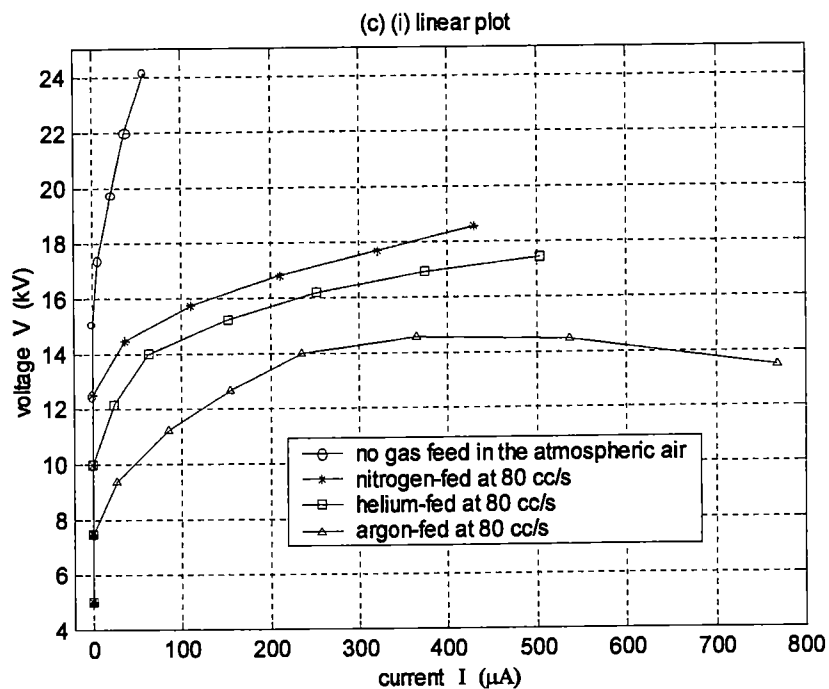


Figure 5.4. continued: (c) atmospheric air versus moderate gas flow rate of 80 cc/s for nitrogen, helium, and argon.

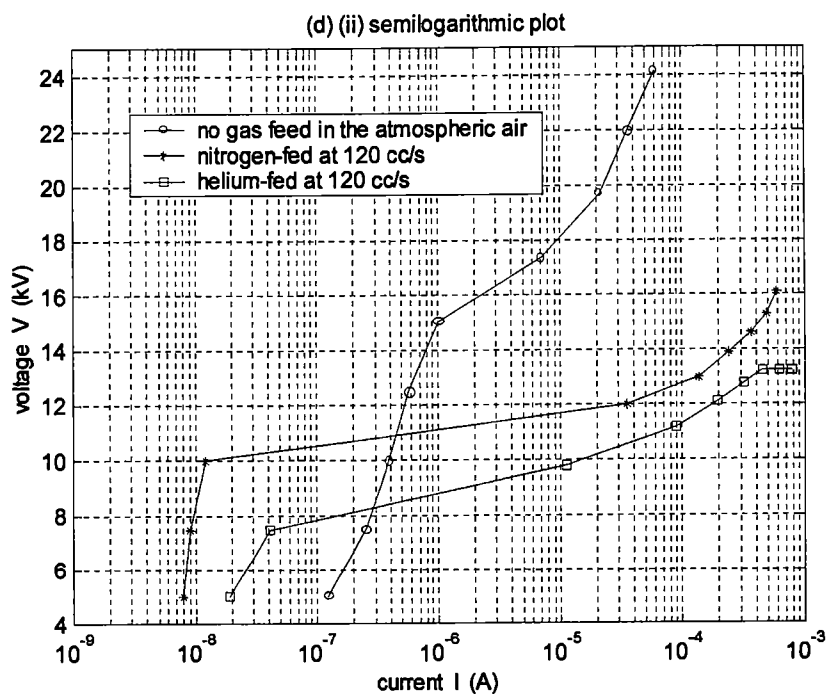
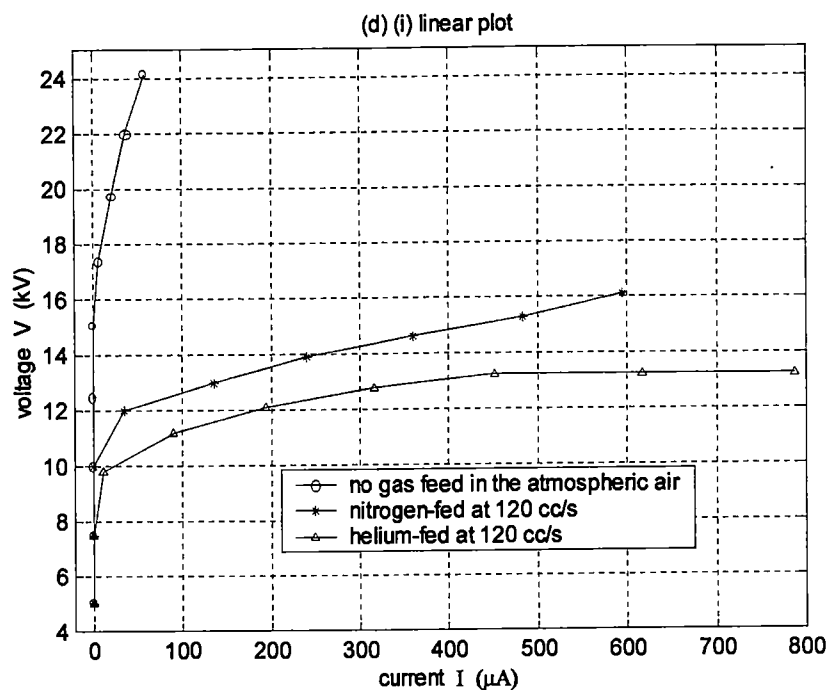


Figure 5.4. continued: (d) atmospheric air versus high gas flow rate of 120 cc/s for nitrogen and helium.

Table 5.1. Summary of analysis for Figure 5.4.

No-gas-feed discharge	Nitrogen-fed discharge	Helium-fed discharge	Argon-fed discharge
a) 15 kV, 0.991 μ A b) 24.1 kV, 59.2 μ A c) factor of 7.2 at (17.4 kV, 7.2 μ A)	<u>10 cc/s</u> a) 15 kV, 0.051 μ A b) 22.4 kV, 174 μ A c) factor of 25 at (17.5 kV, 1.27 μ A) d) 19 kV	<u>10 cc/s</u> a) 15 kV, 0.25 μ A b) 21.2 kV, 252 μ A c) factor of 123 at (17 kV, 30.67 μ A) d) 16 kV	<u>10 cc/s</u> a) 12.5 kV, 0.61 μ A b) 20.2 kV, 322 μ A c) factor of 14 at (14.9 kV, 8.6 μ A) d) 12.5 kV
	<u>40 cc/s</u> a) 15 kV, 0.44 μ A b) 20.7 kV, 285 μ A c) factor of 51 at (17.2 kV, 22.5 μ A) d) 16 kV	<u>40 cc/s</u> a) 12.5 kV, 1.21 μ A b) 19.8 kV, 348 μ A c) factor of 28.6 at (14.5 kV, 34.6 μ A) d) 12.5 kV	<u>40 cc/s</u> a) 10 kV, 0.17 μ A b) 18.5 kV, 435 μ A c) factor of 142 at (12.2 kV, 23.4 μ A) d) 10.3 kV
	<u>80 cc/s</u> a) 12.5 kV, 0.017 μ A b) 18.5 kV, 429.8 μ A c) factor of 2122 at (14.5 kV, 36.1 μ A) d) 13.5 kV	<u>80 cc/s</u> a) 10 kV, 0.044 μ A b) 17.44 kV, 504 μ A c) factor of 542 at (12.1 kV, 23.8 μ A) d) 11.5 kV	<u>80 cc/s</u> a) 7.5 kV, 0.024 μ A b) 13.5 kV, 768 μ A c) factor of 1158 at (9.4 kV, 27.8 μ A) d) 8 kV
	<u>120 cc/s</u> a) 10 kV, 0.012 μ A b) 16.1 kV, 595 μ A c) factor of 2917 at (12 kV, 35 μ A) d) 11 kV	<u>120 cc/s</u> a) 7.5 kV, 0.041 μ A b) 13.2 kV, 786.8 μ A c) factor of 273 at (9.8 kV, 11.2 μ A) d) 8.2 kV	<u>120 cc/s</u> arcing problem over times
a) onset of Townsend discharge b) last data point when 25 kV source voltage was applied to the circuit (indicating the range of Townsend discharge from the onset point) c) factor by which the current increases at next data point after the onset of Townsend discharge d) voltage at which the respective curve intersects with that of non-gas-fed discharge			

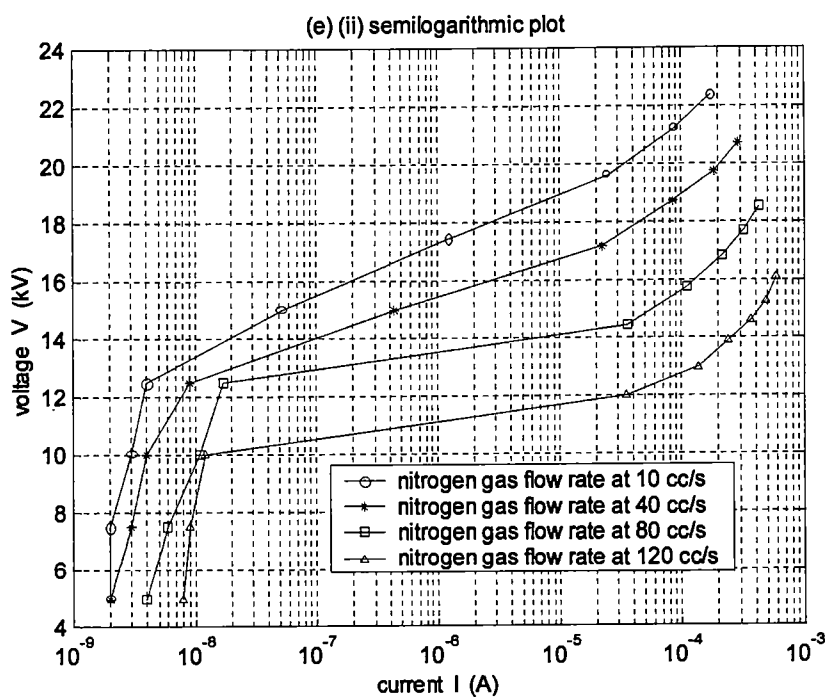
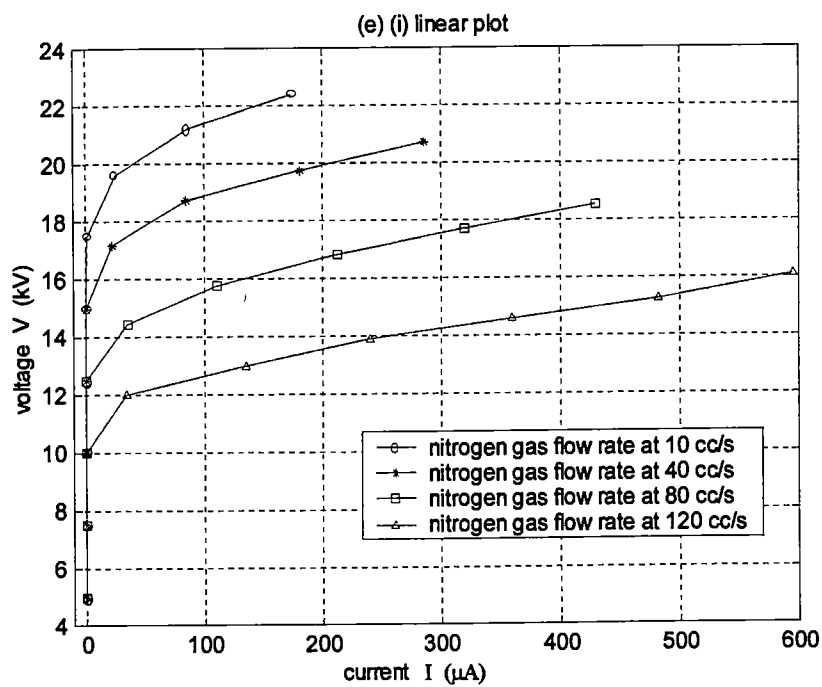


Figure 5.4. continued: (e) nitrogen-fed discharge at gas flow rates of 10, 40, 80, and 120 cc/s.

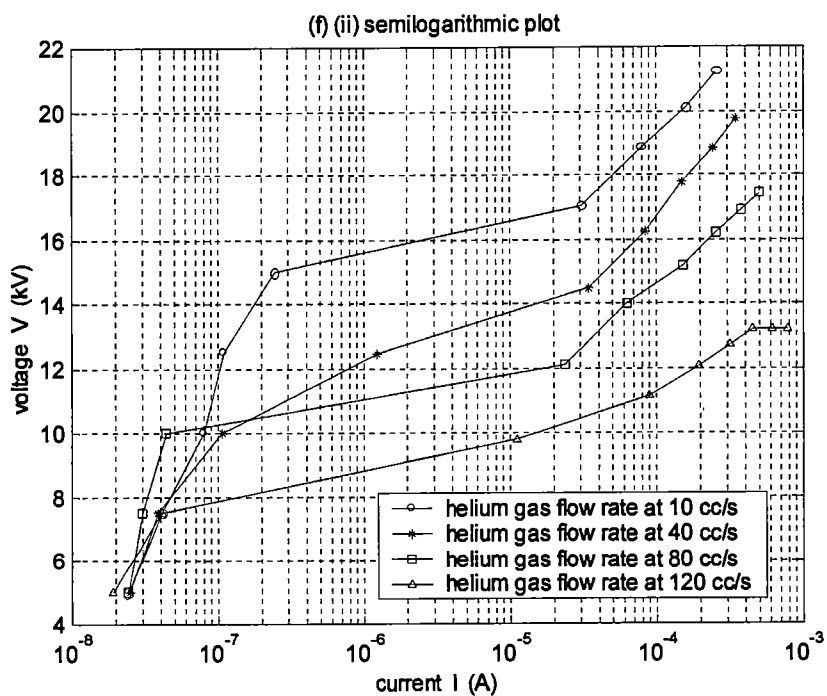
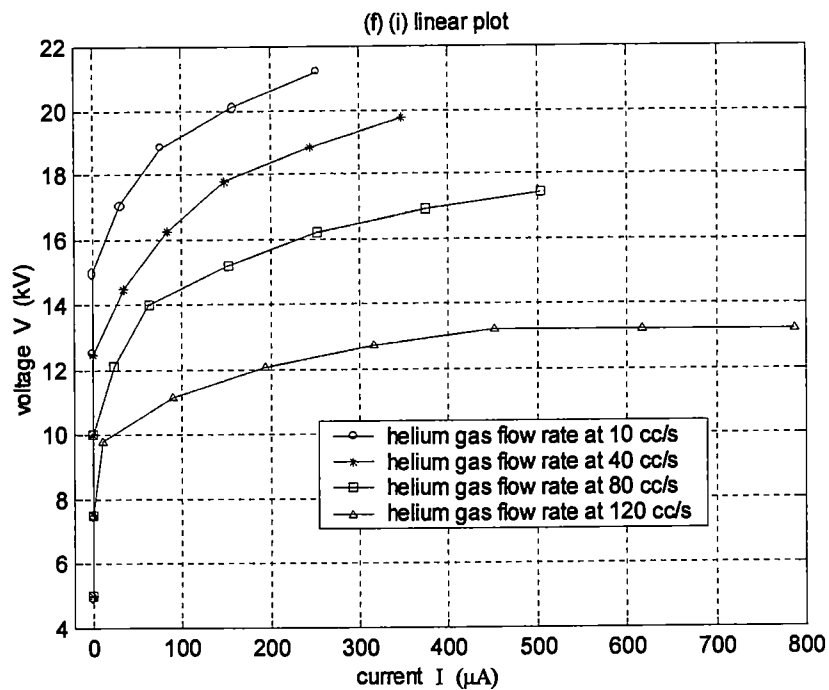


Figure 5.4. continued: (f) helium-fed discharge at gas flow rates of 10, 40, 80, and 120 cc/s.

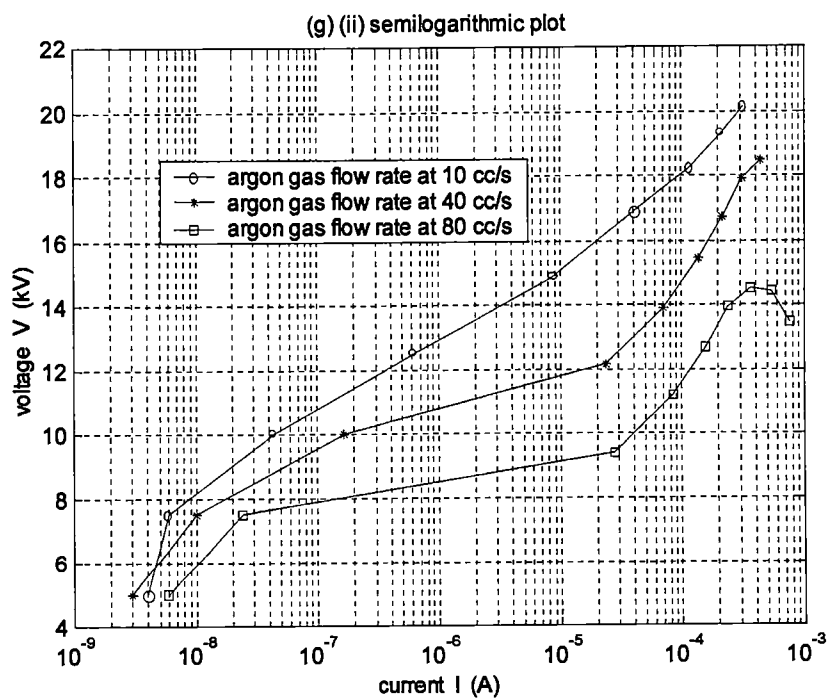
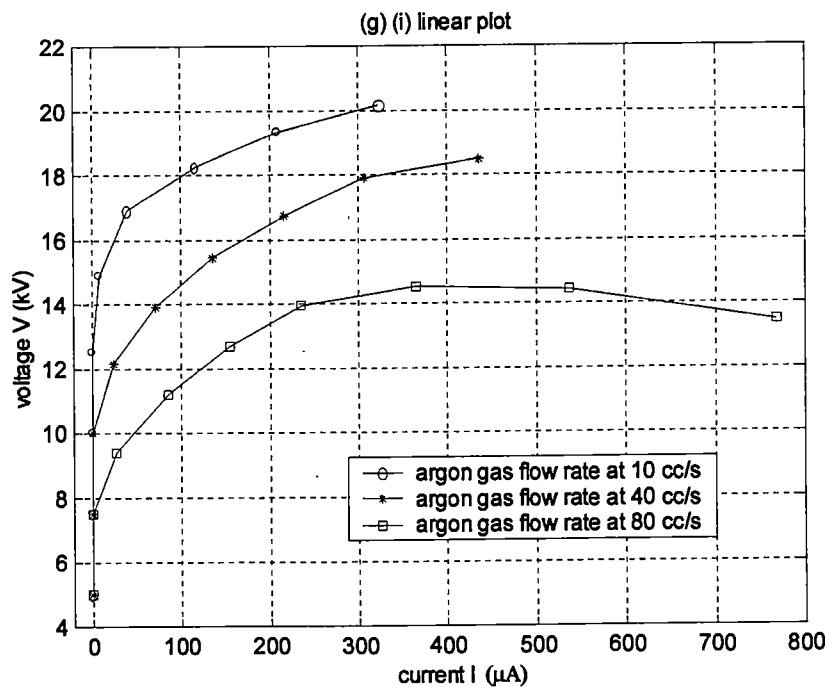


Figure 5.4. continued: (g) argon-fed discharge at gas flow rate of 10, 40, and 80 cc/s.

5.1.4 Comparison and analysis

The I-V characteristic for a classical low-pressure DC glow discharge was shown previously in Figure 3.1. The discharge can be divided into four regions: 1) the “dark” or “Townsend discharge” prior to the voltage breakdown; 2) the “normal glow” where the voltage is constant or slightly decreasing with current; 3) “abnormal glow” where the voltage increases with current; and 4) “arc discharge” where the plasma becomes highly conductive.

Figure 5.5a shows yet another I-V characteristics of a low-pressure DC glow discharge, now at 1 torr [5.1]. The normal and abnormal glow regions (regions 2 and 3 in the figure) tend to shrink with higher pressure. For many gases, the breakdown even proceeds directly to arcing at atmospheric pressure (760 torr) as shown in Figure 5.5b for a plasma torch [5.2]. For corona discharge, the I-V characteristics resemble neither of the curves just shown. Figure 5.5c shows the typical characteristics for a positive point-to-plane corona operating at a gap of 13 mm in atmospheric air [5.3].

The plasma shown in Figure 5.5c ignites at a voltage of 2-5 kV and produces extremely small current of $10^{-10} - 10^{-5}$ A. Above 10^{-5} A, the voltage rapidly increases with current. This coincides with the generation of micro-arcs, or “streamers” that extend between the electrodes. A maximum voltage of 12.5 kV is recorded at about 5×10^{-4} A, where the device begins to arc. Corona operates at currents below the onset of arcing.

The semi-logarithmic plots of the I-V characteristics of ECD shown in the previous sections resemble that of Figure 5.5c. A selected few are re-plotted in Figure 5.6 for comparison with the figure.

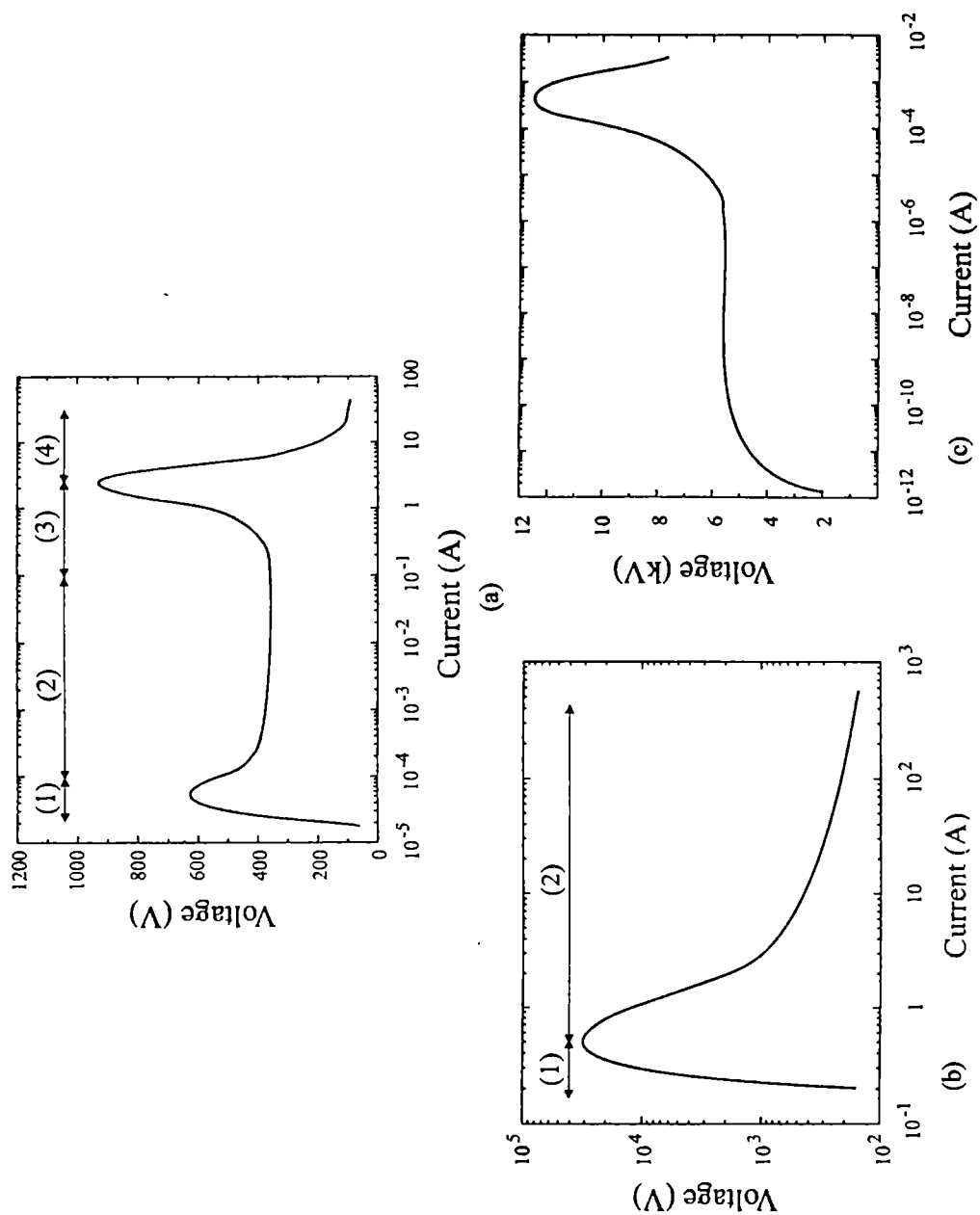


Figure 5.5. I-V characteristics of (a) low-pressure DC glow discharge at 1 torr [5.1], (b) plasma torch at 1 atmospheric pressure [5.2], and (c) positive point-to-plane corona discharge at a gap of 13 mm in atmospheric air [5.3].

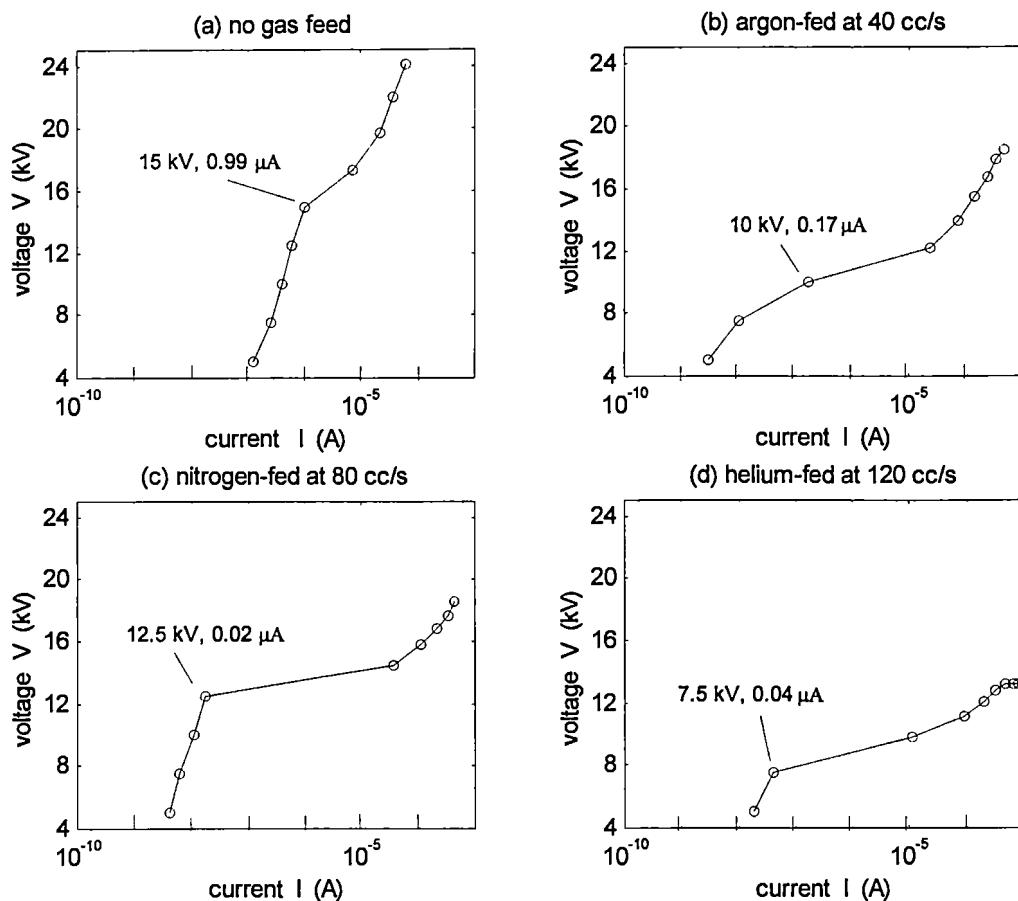


Figure 5.6. Selected I-V characteristics of ECD with sharp-point electrodes separated by a spacing of 7.62 cm and operated under different discharge conditions.

For the no-gas-feed discharge shown in Figure 5.6a, the onset of Townsend discharge occurs at a higher voltage (15 kV) as compared to a lower voltage (5.5 kV) for the single point-to-plane corona discharge in Figure 5.5c. The difference is due to gap distance (7.62 cm versus 1.3 cm) and different electrode configurations. While arcing occurs at 12.5 kV and 500 μ A for Figure 5.5c, it is absent in the enhanced corona discharge shown in Figure 5.6 or other I-V characteristics figures shown in previous sections. One must be cautioned, however, this is not necessarily the case if higher flow rates of gas feed were to be applied. More will be said about the arcing of argon-fed discharge at a high flow rate (120 cc/s) in the next section.

In the analysis of the I-V characteristics shown in the previous sections, the term "Townsend discharge" has been used quite often. Corona discharge is considered as a Townsend discharge [5.4], which is the exponential increasing portion of the dark discharge in the I-V characteristic curve.

The onset of Townsend discharge is also indicated in Figures 5.6. Identifying the onset of Townsend discharge is not a difficult task. It could be readily identified in the linear or semi-logarithmic plots of the I-V characteristic curves. Consulting the data collected would also help. The data used to plot Figures 5.2 to 5.4 are presented later in Tables 5.2 to 5.4 (see sections 5.3.1 to 5.3.3).

5.1.5 The arcing of argon-fed discharge at a high flow rate of 120 cc/s

Argon-fed discharge at a high flow rate is different from that at a low or moderate flow rate discussed previously. Discharge at a high flow rate may cause arcing. Figure 5.7 shows the I-V characteristics of argon-fed discharge at 120 cc/s. It indicates that the

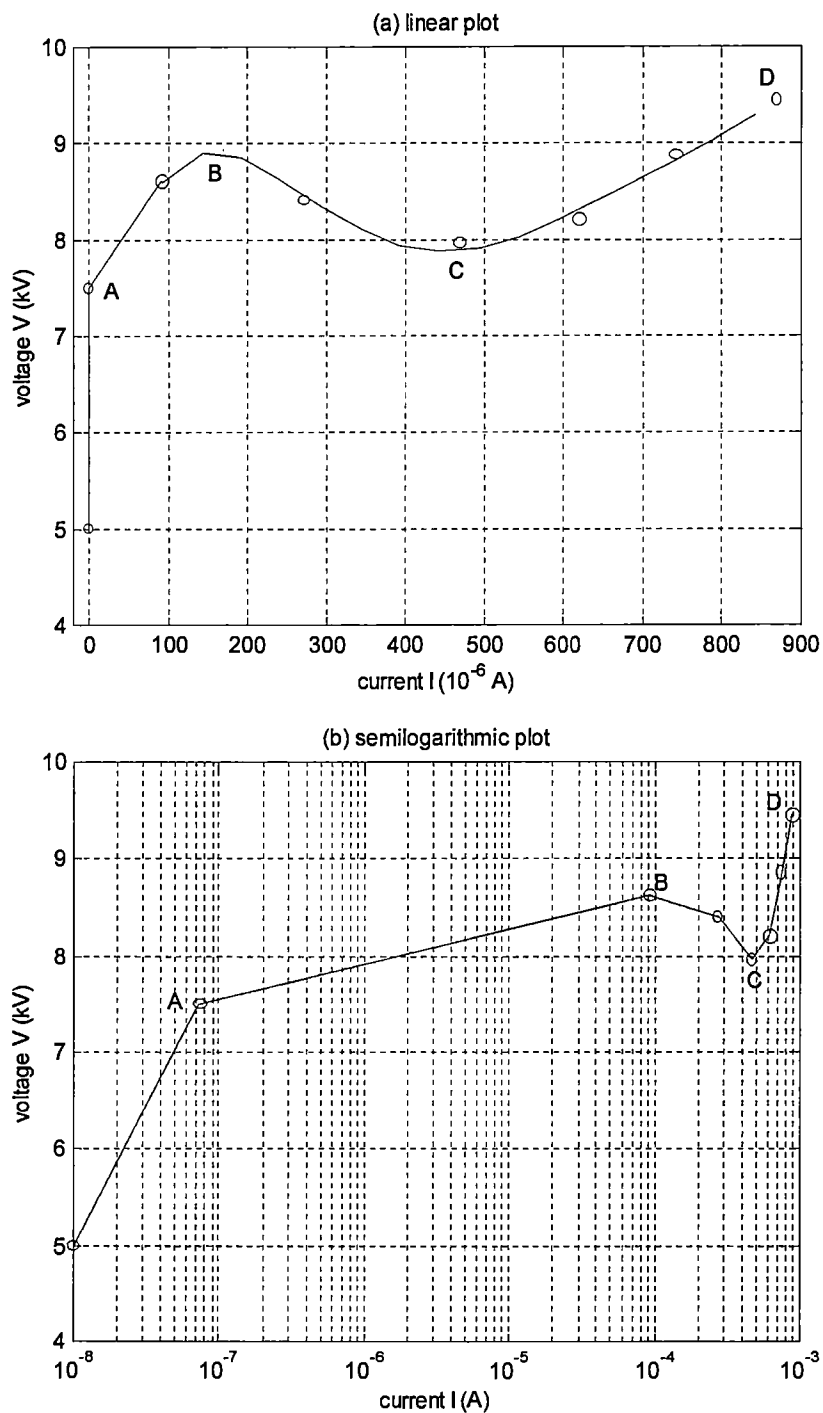


Figure 5.7. I-V characteristics of argon-fed discharge at 120 cc/s, showing signs of approaching arcing.

discharge has gone through three different stages: the Townsend, normal glow, and abnormal glow.

The Townsend region starts at point A (7.5 kV, 7×10^{-8} A) and ends at point B (8.8 kV, 1.4×10^{-4} A). The normal glow discharge, signified by decreasing voltages with increasing currents, begins at point B and stops at point C (8 kV, 4.7×10^{-4} A). The abnormal glow discharge is between points C and D (9.5 kV, 8.7×10^{-4} A).

The rapidly increasing voltages with increasing currents between points C and D indicate that the discharge is fast approaching arcing. Arcing is a situation one needs to avoid. It was recorded that arcing started to occur at point D, 650 seconds after the gas was fed.

The physics of gas-fed discharge at high flow rate can be interpreted with the help of Figure 5.8. Assuming that before the gas is fed at time $t=0$, the discharge chamber with volume V_{ol} is occupied fully by air with density N_o as shown in Figure 5.8a. As the gas at a constant flow rate of G_{rate} is introduced into the chamber as shown in Figure 5.8b, the air density remains in the chamber is reducing to $N_{air}(t)$. The gas occupied the chamber is $N_g(t)$, which replaces the deducted air density $N_o - N_{air}(t)$.

Ignoring the plasma chemical reaction that may take place, it can be assumed that the air density is decreasing at a rate $dN_{air}(t)/dt$ which is proportional to the density $N_{air}(t)$ itself with a constant k . Mathematically then,

$$\frac{dN_{air}(t)}{dt} = -kN_{air}(t) \quad (5.1)$$

where k is defined as

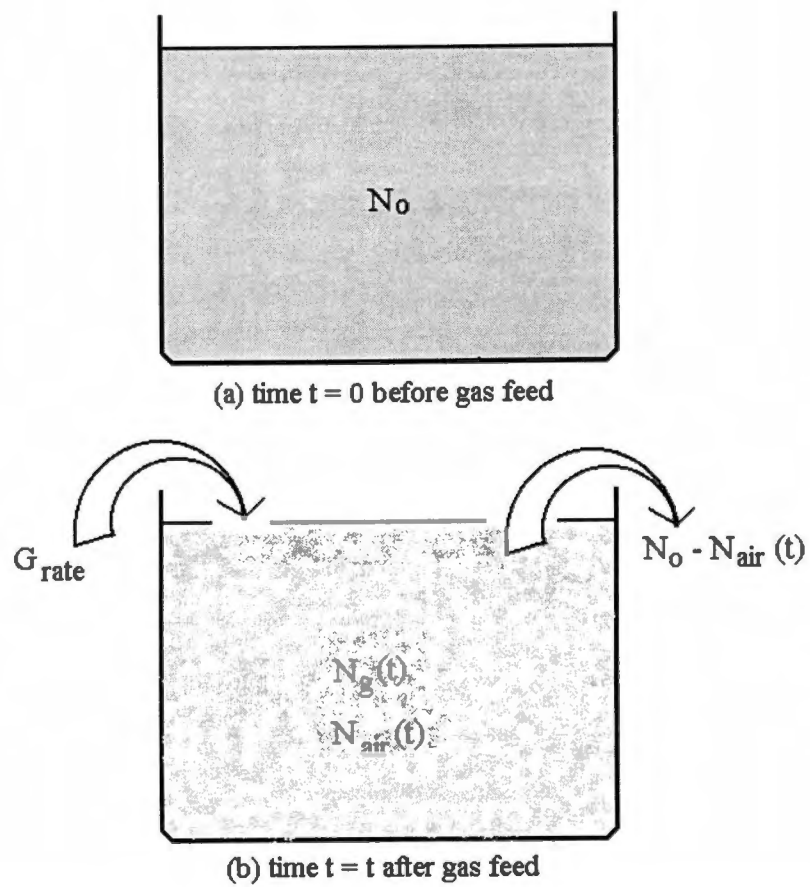


Figure 5.8. Physics of gas-fed discharge at a high flow rate.

$$k \equiv \frac{1}{t_c} \equiv \frac{G_{rate}}{V_{ol}}. \quad (5.2)$$

Since the chamber is originally occupied with density N_o at time $t=0$, the solution for equation (5.1) is

$$N_{air}(t) = N_o e^{-t/t_c}. \quad (5.3)$$

At time t , the gas density $N_g(t)$ occupying the discharge chamber is equal to the amount of air density that has been displaced, Thus

$$\begin{aligned} N_g(t) &= N_o - N_{air}(t) \\ &= N_o(1 - e^{-t/t_c}) \end{aligned} \quad (5.4)$$

Equation (5.3) and (5.4) are plotted in Figure 5.9. For argon-fed discharge at G_{rate} of 120 cc/s and discharge chamber with volume V_{ol} of $1.0098 \times 10^4 \text{ cm}^3$, the time constant t_c is 84.15 seconds. The discharge started to arc 650 seconds after the gas was fed. Thus equation (5.4) becomes

$$N_g(650) = 0.9996 N_o. \quad (5.5)$$

This means that the discharge starts to arc if air density is reduced to $4 \times 10^{-4} N_o$ when argon is fed to the system at 120 cc/s. Note that the analysis does not necessarily apply to lower flow rates of argon. Assumption (5.1) is over-simplified and does not necessarily hold true at lower rates.

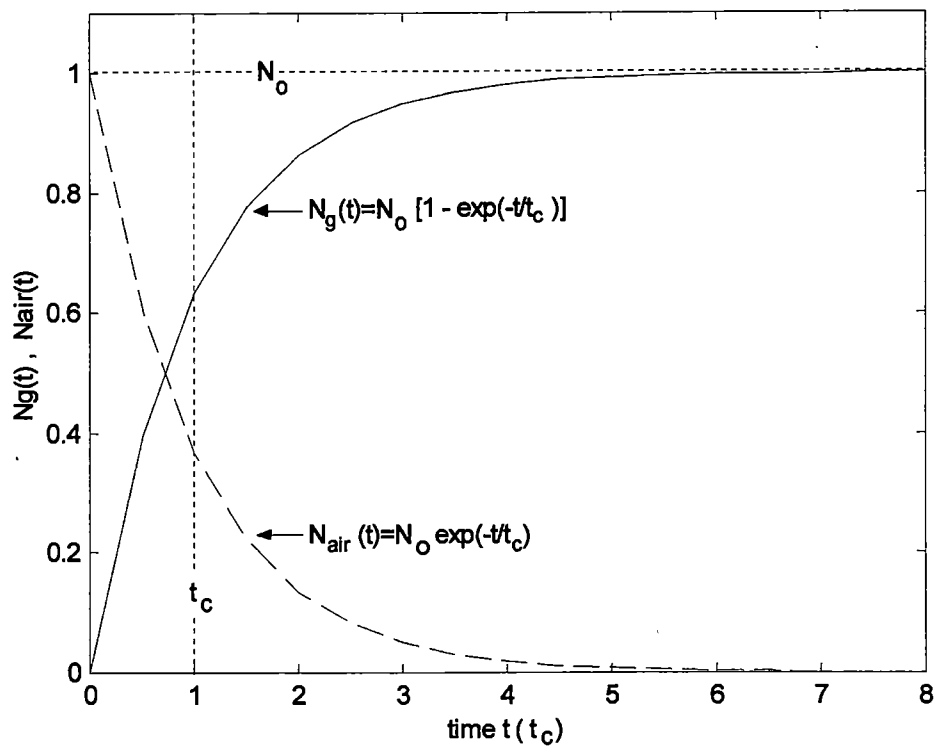


Figure 5.9. Mathematical presentation of $N_g(t)$ and $N_{air}(t)$ for Figure 5.8.

5.2. The probe for plasma density measurement

Plasma density is an essential parameter in a gaseous discharge. In this section, the construction of a double probe for density measurement is discussed. The density located at the center of the bulk of the discharge is given in section 5.3. while the spatial density profile across the discharge volume is given in section 5.4.

The plasma density can be measured by inserting a small double probe in the path of the discharge to intercept the ion flow as shown in Figure 5.10. The probe must be of small size such that it does not perturb the discharge itself. The construction of such probe is shown in Figure 5.11. It is constructed with a pair of metal plates of area A separated by a distance d . For the parallel plate configuration, the ion current density j can be expressed as [5.5]

$$\begin{aligned} j &= \frac{i_p}{A} \\ &= nev_d \end{aligned} \tag{5.6}$$

where i_p is the current flowing through the plates, n the ion density, e the ion charge (generally singly charged), and v_d the ion drift velocity.

For the case where the motion of the charge carrier is dominated by collision, the drift velocity is proportional to the electric field E as expressed in the equation below [5.6]

$$v_d = \mu E. \tag{5.7}$$

where μ is the mobility of the charge carrier.

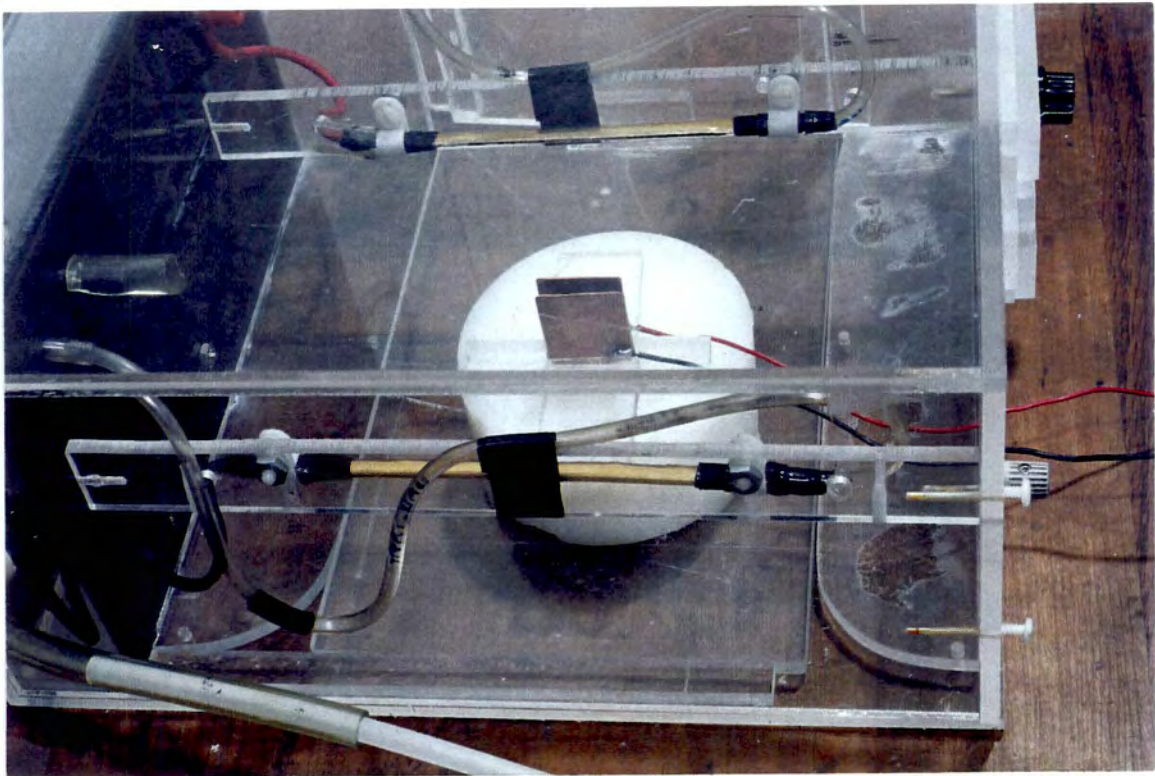


Figure 5.10. Plasma density probe sitting in the discharge chamber.

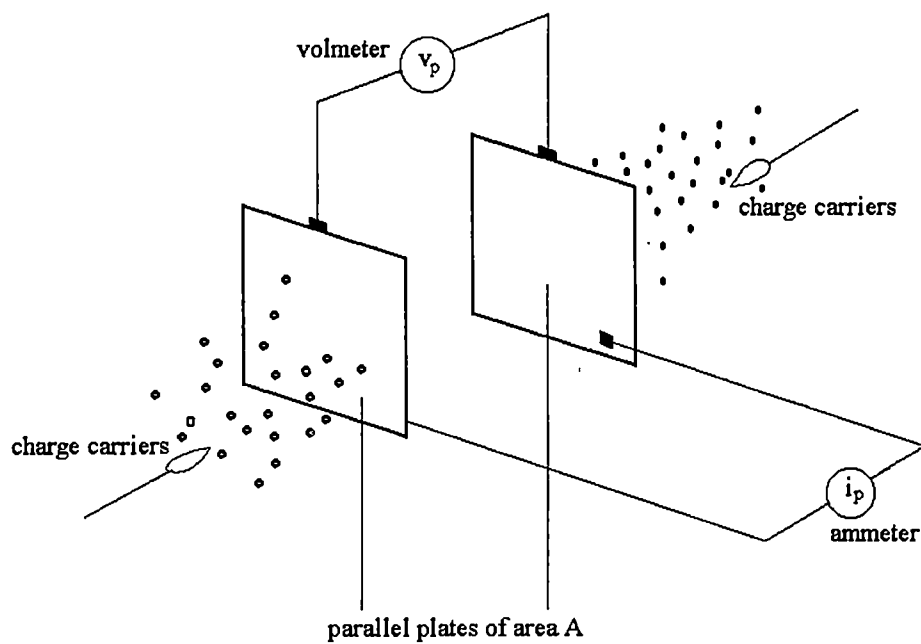


Figure 5.11. A simple parallel-plate probe for measuring ion density.

From equation (5.6) and (5.7), we get

$$\begin{aligned}
 n &= \frac{i_p}{Ae v_d} \\
 &= \frac{i_p}{Ae \mu E} \\
 &= \frac{i_p d}{Ae \mu v_p} \tag{5.8}
 \end{aligned}$$

Thus with a probe of proper dimensions, the current i_p and voltage v_p can be measured to obtain the ion density.

5.3 Local density measurement at the center of the discharge

The mobility of air, argon, helium, and nitrogen are 1.36, 1.37, 5.09, and 1.27 $\text{cm}^2/\text{volt-sec}$ respectively [5.7]. Using a probe with an area of 1 square inch (6.4516 cm^2) and a spacing of $\frac{1}{4}$ inch (0.635 cm), equation (5.8) becomes

$$n = 9.0464 \times 10^{17} i_p / v_p \quad \text{cm}^{-3} \quad (\text{for air}) \tag{5.9a}$$

$$n = 8.9804 \times 10^{17} i_p / v_p \quad \text{cm}^{-3} \quad (\text{for argon}) \tag{5.9b}$$

$$n = 2.4171 \times 10^{17} i_p / v_p \quad \text{cm}^{-3} \quad (\text{for helium}) \tag{5.9c}$$

$$n = 9.6875 \times 10^{17} i_p / v_p \quad \text{cm}^{-3} \quad (\text{for nitrogen}) \tag{5.9d}$$

Note that a factor of two has been included in the equation for calculation since both positive and negative ions are present and the plasma is charge neutral. Using equation (5.9), the density measurement located at the center of the discharge was

conducted at each data point of Figures 5.2, 5.3, and 5.4. where the effects of airflow, electrode spacing, and gas flow rate were monitored. The ammeter and voltmeter used for the density measurement had a resolution of 1 nA and 1 mV respectively.

5.3.1 Effect of airflow on the local ion density

Effect on airflow on the I-V characteristics were discussed in section 5.1.1. While collecting the data for the I-V characteristics, the density measurements located at the center of the discharge were also performed at each of the respective data points. The data are presented in Table 5.2.

Under each discharge condition shown in the table, there are two columns of data. The three numbers in each cell of the first column represent the source voltage V_s , the current I , and voltage V applied to the electrodes respectively. These (I , V) data were used to plot Figure 5.2. The numbers in each cell of the second column represent the probe current i_p , the probe voltage v_p , and the ion density n respectively. Note that i_p and v_p were taken when the particular I and V in the same row were applied to the electrodes. The density n was evaluated by using equation (5.9). Note that a dash (-) indicates no measured value was registered.

In Table 5.2a, the discharge was operated with no gas feed. With enclosed discharge, the density (in units of 10^{10} cm^{-3}) varies from 8.19 just before the onset of Townsend discharge to 9.24 well into the Townsend discharge. When the discharge chamber was left ajar, the density varies from 8.22 to 9.15. When it was left ajar but with airflow, the density varies from 8.14 to 9.17. Well into the Townsend discharge regions

(the last four rows of data in the table), the average density is 9.15, 8.99, and 8.98 respectively for the operating conditions just described.

In Table 5.2b, the discharge was fed with argon at 40 cc/s. For enclosed discharge, the density increases steadily from 8.82 to 9.43. The density increases from 8.36 to 9.14, and from 8.34 to 9.07 respectively when the chamber was ajar and ajar with airflow. The average density is 9.22, 8.98, 8.94 respectively for the enclosed, ajar, and ajar with airflow operating conditions.

In Table 5.2c, the discharge was fed with nitrogen at 80 cc/s. With enclosed discharge, the density varies slightly from 9.66 to 9.98. The density increases from 9.51 to 9.77, and from 7.60 to 9.65 respectively when the chamber was ajar and ajar with airflow. The average density is 9.85, 9.60, and 9.12 respectively for the three operating conditions just mentioned.

In Table 5.2d, the discharge was fed with helium at 120 cc/s. The density varies from 1.61 to 2.69, from 0.32 to 2.59, and from 0.89 to 2.53 respectively for the three cases of enclosed, ajar, and ajar with airflow operating conditions. Well into the Townsend discharge regions, the average density is 2.58, 2.53, and 2.53 respectively.

Figure 5.12 gives the graphical presentation for Table 5.2.

Table 5.2. Density probe measurements (i_p , v_p , n) at the respective data points (I , V) of Figure 5.2 where effect of airflow was investigated: (a) discharge with no gas feed in the atmospheric air.

Discharge chamber enclosed		Discharge chamber opened (no airflow)		Discharge chamber opened (with air flow)	
V_s (kV) I (μA) V (kV)	i_p (μA) v_p (V) n ($10^{10}/cm^3$)	V_s (kV) I (μA) V (kV)	i_p (μA) v_p (V) n ($10^{10}/cm^3$)	V_s (kV) I (μA) V (kV)	i_p (μA) v_p (V) n ($10^{10}/cm^3$)
5	-	5	-	5	-
0.124	-	0.119	-	0.054	-
5	-	5	-	5	-
7.5	-	7.5	-	7.5	-
0.250	-	0.206	-	.093	-
7.5	-	7.5	-	7.5	-
10	-	10	-	10	-
0.394	-	0.325	-	0.143	-
9.99	-	10	-	10	-
12.5	0.026	12.5	0.015	12.5	0.018
0.578	0.287	0.463	0.165	0.203	0.20
12.49	8.19	12.49	8.22	12.5	8.14
15	0.072	15	0.077	15	0.059
0.991 ^a	0.78	0.822 ^a	0.83	0.405 ^a	0.62
14.99 ^a	8.35	14.98 ^a	8.39	15 ^a	8.61
17.5	0.89	17.5	0.69	17.5	0.87
7.15	9.01	5.52	7.3	2.23	8.98
17.39	8.93	17.42	8.55	17.47	8.77
20	1.92	20	1.73	20	1.51
20.98	18.8	18.27	17.1	15.09	14.89
19.69	9.24	19.73	9.15	19.77	9.17
22.5	3.79	22.5	3.51	22.5	3.176
36.15	37.2	33.9	34.8	32.17	31.8
21.96	9.22	21.99	9.12	22.02	9.03
25	5.7	25	5.08	25	4.50
59.21	56.1	55.7	49.9	49.80	45.6
24.11	9.19	24.16	9.15	24.25	8.93
	9.15 ^b		8.99 ^b		8.98 ^b
^a : onset of Townsend discharge regions ^b : average density n for the last four cells in the same column					

Table 5.2. continued: (b) argon-fed discharge at a gas flow rate of 40 cc/s.

Discharge chamber enclosed		Discharge chamber opened (no airflow)		Discharge chamber opened (with air flow)	
V _s (kV) I (μA) V (kV)	i _p (μA) v _p (V) n (10 ¹⁰ /cm ³)	V _s (kV) I (μA) V (kV)	i _p (μA) v _p (V) n (10 ¹⁰ /cm ³)	V _s (kV) I (μA) V (kV)	i _p (μA) v _p (V) n (10 ¹⁰ /cm ³)
5 0.003 5	- - -	5 0.002 5	- - -	5 0.002 5	- - -
7.5 0.010 7.5	- - -	7.5 0.004 7.5	- - -	7.5 0.002 7.5	- - -
10 0.165 ^a 10 ^a	- - -	10 0.008 10	- - -	10 0.002 10	- - -
12.5 23.44 12.15	0.478 4.869 8.82	12.5 0.015 ^a 12.5 ^a	- - -	12.5 0.003 ^a 12.5 ^a	- - -
15 71 13.94	1.420 14.33 8.89	15 4.39 14.93	0.254 2.73 8.36	15 1.893 14.97	0.209 2.250 8.34
17.5 136.45 15.45	2.729 27.10 9.04	17.5 57.45 16.64	1.293 13.32 8.72	17.5 24.26 17.14	1.162 12.08 8.64
20 216.6 16.75	3.671 36.14 9.12	20 119.33 18.21	2.676 26.56 9.05	20 84.5 18.73	1.758 17.61 8.97
22.5 307 17.90	4.723 45.63 9.29	22.5 184.97 19.73	4.404 43.28 9.14	22.5 156.95 20.15	3.62 35.88 9.06
25 435 18.48	6.214 59.18 9.43	25 243.2 21.35	5.41 53.9 9.01	25 227.45 21.59	4.52 44.75 9.07
	9.22 ^b		8.98 ^b		8.94 ^b
^a : onset of Townsend discharge regions ^b : average density n for the last four cells in the same column					

Table 5.2. continued: (c) nitrogen-fed discharge at a gas flow rate of 80 cc/s.

Discharge chamber enclosed		Discharge chamber opened (no airflow)		Discharge chamber opened (with air flow)	
Vs (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n ($10^{10}/\text{cm}^3$)	Vs (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n ($10^{10}/\text{cm}^3$)	Vs (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n ($10^{10}/\text{cm}^3$)
5 0.004 5	- - -	5 0.002 5	- - -	5 0.002 5	- - -
7.5 0.006 7.5	- - -	7.5 0.002 7.5	- - -	7.5 0.003 7.5	- - -
10 0.011 10	- - -	10 0.003 10	- - -	10 0.004 10	- - -
12.5 0.017 ^a 12.5 ^a	- - -	12.5 0.005 12.5	- - -	12.5 0.006 12.5	- - -
15 36.07 14.46	0.065 0.63 9.98	15 0.063 ^a 15 ^a	0.026 0.265 9.51	15 0.032 ^a 15 ^a	0.004 0.051 7.60
17.5 110.8 15.84	0.135 1.33 9.83	17.5 27.1 17.09	2.274 22.54 9.77	17.5 15.89 17.26	0.301 3.114 9.36
20 212.5 16.81	0.23 2.25 9.88	20 89.25 18.66	2.872 29.05 9.58	20 77.8 18.83	2.92 30.13 9.39
22.5 319.9 17.70	2.334 23.4 9.66	22.5 174.4 19.88	4.28 43.6 9.51	22.5 162.3 20.06	4.05 40.9 9.59
25 429.8 18.54	2.53 24.7 9.92	25 258 21.13	5.37 54.08 9.62	25 237.5 21.44	5.06 50.8 9.65
	9.85 ^b		9.60 ^b		9.12 ^b
^a : onset of the Townsend discharge regions ^b : average density n for four cells in the same column					

Table 5.2. continued: (d) helium-fed discharge at a gas flow rate of 120 cc/s.

Discharge chamber enclosed		Discharge chamber opened (no airflow)		Discharge chamber opened (with air flow)	
Vs (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n ($10^{10}/\text{cm}^3$)	Vs (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n ($10^{10}/\text{cm}^3$)	Vs (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n ($10^{10}/\text{cm}^3$)
5 0.019 5	- - -	5 0.014 5	- - -	5 0.009 5	- - -
7.5 0.041 ^a 7.5 ^a	- - -	7.5 0.031 ^a 7.5 ^a	- - -	7.5 0.016 7.5	- - -
10 11.2 9.83	0.032 0.46 1.68	10 1.69 9.97	0.004 0.304 0.32	10 0.069 ^a 10 ^a	0.004 0.045 0.89
12.5 89.6 11.16	1.26 18.9 1.61	12.5 2.25 12.47	0.006 0.36 0.40	12.5 1.38 12.48	0.016 0.169 2.29
15 194.6 12.08	5.19 60.5 2.07	15 35.58 14.47	2.07 19.4 2.50	15 28.74 14.57	2.43 23.6 2.49
17.5 316.4 12.75	7.33 75 2.36	17.5 73.63 16.40	4.18 39 2.59	17.5 63.19 16.55	4.11 38.05 2.61
20 452.2 13.22	10.6 96.3 2.66	20 137.18 17.94	7.37 69.6 2.56	20 119.12 18.21	7.17 68.2 2.53
22.5 617.4 13.24	12.44 109 2.69	22.5 216.47 19.25	9.5 92.9 2.47	22.5 203.6 19.45	9.7 93.4 2.51
25 786.8 13.20	14.24 134 2.59	25 304.1 20.44	12.14 119.2 2.50	25 288.5 20.67	12.6 122.6 2.48
	2.58 ^b		2.53 ^b		2.53 ^b
^a : onset of Townsend discharge regions ^b : average density n for the last four cells in the same column					

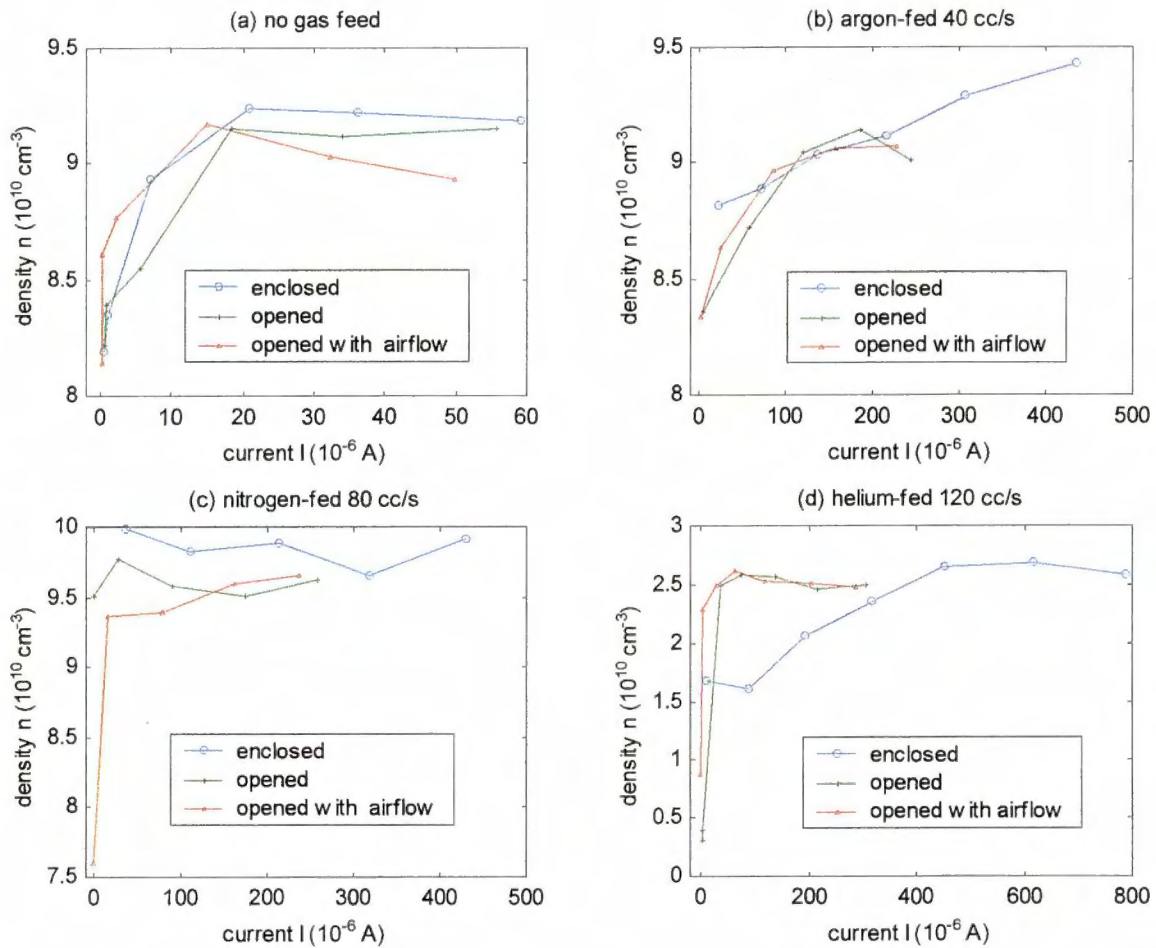


Figure 5.12. Ion density located at the center of the discharge showing the influence of three different discharge chamber operating conditions (note that the current shown is that applied to the discharge electrodes).

5.3.2 Effect of electrode spacing on the local ion density

Effect of electrode spacing on the I-V characteristics was discussed in section 5.1.2. The effect on the local ion density is presented in Table 5.3. The data are presented in the same way as described in second paragraph in section 5.3.1.

In Table 5.3a, the discharge was operated with no gas feed. The density (in units of 10^{10} cm^{-3}) varies from 8.19 to 9.24, 8.18 to 9.03, 8.17 to 8.97, and 7.92 to 8.80 for the 7.6, 10.2, 12.7, and 15.2 cm-spacing respectively. Well into the Townsend region, the average density is 9.15, 8.77, 8.79, and 8.68 respectively.

In Table 5.3b, the discharge was argon-fed at 40 cc/s. The density varies from 8.82 to 9.43, 5.98 to 9.21, 5.61 to 8.96, and 5.56 to 8.72 respectively for 7.6, 10.2, 12.7, and 15.2 cm-spacings. The average density is 9.22, 9.04, 8.67, and 8.36 respectively well into the Townsend regions.

In Table 5.3c, the discharge was nitrogen-fed at 80 cc/s. The density varies from 9.66 to 9.98, 8.33 to 9.76, 1.66 to 9.83, and 3.42 to 9.09 respectively for the 7.6, 10.2, 12.7, and 15.2 cm-spacings. Well into the Townsend regions, the average density is respectively 9.86, 9.55, 9.43, and 8.66.

In Table 5.3d, the discharge was helium-fed at 120 cc/s. The density varies from 2.12 to 2.69, 2.23 to 2.56, 2.28 to 2.53, and 1.9 to 2.45 respectively for the 7.6, 10.2, 12.7, and 15.2 cm-spacings. The average density is 2.57, 2.46, 2.46, and 2.35 respectively well into the Townsend region.

Figure 5.13 gives the graphical presentation for Table 5.3.

Table 5.3. Density probe measurements (i_p , v_p , n) at the respective data points (I , V) for Figure 5.3 where the effect of electrode spacing was investigated: (a) discharge with no gas feed in the atmospheric air.

3 inch (7.62 cm) spacing		4 inch (10.16 cm) spacing		5 inch (12.70 cm) spacing		6 inch (15.24 cm) spacing	
V_s (kV) I (μA) V (kV)	i_p (μA) v_p (V) n^*	V_s (kV) I (μA) V (kV)	i_p (μA) v_p (V) n^*	V_s (kV) I (μA) V (kV)	i_p (μA) v_p (V) n^*	V_s (kV) I (μA) V (kV)	i_p (μA) v_p (V) n^*
5 0.124 5	- - -	5 0.117 5	- - -	5 0.109 5	- - -	5 0.093 5	- - -
7.5 0.250 7.5	- - -	7.5 0.245 7.5	- - -	7.5 0.238 7.5	- - -	7.5 0.201 7.5	- - -
10 0.394 9.99	- - -	10 0.368 10	- - -	10 0.328 10	- - -	10 0.279 10	- - -
12.5 0.578 12.49	0.026 0.287 8.19	12.5 0.488 12.49	0.018 0.210 8.18	12.5 0.475 12.49	0.029 0.321 8.17	12.5 0.380 12.5	0.007 0.08 7.92
15 0.991 ^a 14.99 ^a	0.072 0.78 8.35	15 0.761 ^a 14.98 ^a	0.023 0.252 8.26	15 0.616 ^a 14.99 ^a	0.057 0.619 8.33	15 0.487 ^a 14.99 ^a	0.014 0.156 8.12
17.5 7.15 17.39	0.89 9.01 8.93	17.5 3.177 17.45	0.330 3.5 8.53	17.5 2.648 17.46	0.149 1.56 8.64	17.5 1.738 17.47	0.045 0.486 8.38
20 20.98 19.69	1.92 18.8 9.24	20 9.22 19.86	0.603 6.31 8.64	20 5.437 19.92	0.272 2.810 8.76	20 2.821 19.96	0.155 1.59 8.80
22.5 36.15 21.96	3.79 37.2 9.22	22.5 21.03 22.18	1.34 13.68 8.86	22.5 12.4 22.31	0.923 9.31 8.97	22.5 5.4 22.42	0.366 3.79 8.74
25 59.21 24.11	5.7 56.1 9.19	25 34.07 24.49	1.723 17.27 9.03	25 20.15 24.67	1.130 11.59 8.82	25 9.06 24.86	0.505 5.19 8.8
	9.15 ^b		8.77 ^b		8.79 ^b		8.68 ^b
* : density n in units of 10^{10} ions/cm³ ^a : onset of Townsend regions ^b : average density n for the last four cells in the same column							

Table 5.3. continued: (b) argon-fed discharge at a gas flow rate of 40 cc/s.

3 inch (7.62 cm) spacing		4 inch (10.16 cm) spacing		5 inch (12.70 cm) spacing		6 inch (15.24 cm) spacing	
Vs (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n *	Vs (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n *	Vs (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n *	Vs (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n *
5 0.003 5	- - -	5 0.002 5	- - -	5 0.002 5	- - -	5 0.002 5	- - -
7.5 0.010 7.5	- - -	7.5 0.007 7.5	- - -	7.5 0.005 7.5	- - -	7.5 0.002 7.5	- - -
10 0.165 ^a 10 ^a	- - -	10 0.021 10	- - -	10 0.014 10	- - -	10 0.003 10	- - -
12.5 23.44 12.15	0.478 4.869 8.82	12.5 0.517 ^a 12.49 ^a	0.010 0.150 5.98	12.5 0.189 ^a 12.5 ^a	0.003 0.048 5.61	12.5 0.007 ^a 12.5 ^a	- - -
15 71 13.94	1.420 14.33 8.89	15 14.72 14.78	0.282 2.905 8.72	15 1.663 14.98	0.027 0.426 5.69	15 0.353 15	0.006 0.097 5.56
17.5 136.45 15.45	2.729 27.10 9.04	17.5 55.24 16.67	1.053 10.70 8.84	17.5 16.16 17.26	0.297 3.149 8.47	17.5 4.36 17.43	0.069 0.768 8.07
20 216.6 16.75	3.671 36.14 9.12	20 116.65 18.26	2.126 21.35 8.94	20 59.71 19.1	1.072 11.22 8.58	20 14.52 19.78	0.259 2.830 8.22
22.5 307 17.9	4.723 45.63 9.29	22.5 196.15 19.56	3.155 30.85 9.18	22.5 120.35 20.69	2.015 20.85 8.68	22.5 61.4 21.58	1.077 11.50 8.41
25 435 18.48	6.214 59.18 9.43	25 305.6 20.42	4.425 43.15 9.21	25 205 21.93	3.154 31.62 8.96	25 134.7 22.98	2.322 23.91 8.72
	9.22 ^b		9.04 ^b		8.67 ^b		8.36 ^b
* : density n in units of 10^{10} ions/cm ³ ^a : onset of Townsend discharge regions ^b : average density n for the last four cells in the same column							

Table 5.3. continued: (c) nitrogen-fed discharge at a gas flow rate of 80 cc/s.

3 inch (7.62 cm) spacing		4 inch (10.16 cm) spacing		5 inch (12.70 cm) spacing		6 inch (15.24 cm) spacing	
V _s (kV) I (μA) V (kV)	i _p (μA) v _p (V) n *	V _s (kV) I (μA) V (kV)	i _p (μA) v _p (V) n *	V _s (kV) I (μA) V (kV)	i _p (μA) v _p (V) n *	V _s (kV) I (μA) V (kV)	i _p (μA) v _p (V) n *
5 0.004 5	- - -	5 0.004 5	- - -	5 0.004 5	- - -	5 0.005 5	- - -
7.5 0.006 7.5	- - -	7.5 0.005 7.5	- - -	7.5 0.006 7.5	- - -	7.5 0.006 7.5	- - -
10 0.011 10	- - -	10 0.006 10	- - -	10 0.007 10	- - -	10 0.006 10	- - -
12.5 0.017 ^a 12.5 ^a	- - -	12.5 0.009 12.5	- - -	12.5 0.008 12.5	- - -	12.5 0.008 12.5	- - -
15 36.07 14.46	0.065 0.63 9.98	15 0.031 ^a 15 ^a	0.019 0.221 8.33	15 0.019 15	0.004 0.234 1.66	15 0.016 15	0.003 0.085 3.42
17.5 110.8 15.84	0.135 1.33 9.97	17.5 21.51 17.18	0.037 0.383 9.34	17.5 0.153 ^a 17.5 ^a	0.115 1.240 8.98	17.5 0.115 ^a 17.5 ^a	0.009 0.108 8.07
20 212.5 16.81	0.23 2.25 9.88	20 78.1 18.83	0.046 0.465 9.56	20 30.15 19.55	2.304 23.69 9.42	20 16.29 19.76	0.049 0.548 8.66
22.5 319.9 17.70	2.334 23.4 9.66	22.5 155.6 20.17	0.142 1.438 9.55	22.5 91 21.14	3.416 34.87 9.49	22.5 50.3 21.75	0.867 9.51 8.83
25 429.8 18.55	2.54 24.7 9.92	25 264.2 21.04	0.556 5.51 9.76	25 170.65 22.44	3.895 38.40 9.83	25 111.58 23.33	1.129 12.03 9.09
	9.86 ^b		9.55 ^b		9.43 ^b		8.66 ^b
* : density n in units of 10 ¹⁰ ions/cm ³ ^a : onset of Townsend discharge regions ^b : average density n for the last four cells in the same column							

Table 5.3. continued: (d) helium-fed discharge at a gas flow rate of 120 cc/s.

3 inch (7.62 cm) spacing		4 inch (10.16 cm) spacing		5 inch (12.70 cm) spacing		6 inch (15.24 cm) spacing	
Vs (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*	Vs (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*	Vs (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*	Vs (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*
5 0.019 5	- - -	5 0.006 5	- - -	5 0.021 5	- - -	5 0.014 5	- - -
7.5 0.041 ^a 7.5 ^a	- - -	7.5 0.022 7.5	- - -	7.5 0.038 7.5	- - -	7.5 0.025 7.5	- - -
10 11.2 9.83	0.32 3.6 2.14	10 0.871 ^a 10 ^a	0.058 0.63 2.23	10 0.055 ^a 10 ^a	- - -	10 0.029 ^a 10 ^a	- - -
12.5 89.6 11.16	1.76 18.9 2.25	12.5 55.72 11.66	2.52 25.8 2.36	12.5 33.6 12.0	0.7 7.4 2.28	12.5 3.40 12.45	0.11 1.4 1.9
15 194.6 12.08	5.29 60.5 2.12	15 138.4 12.92	3.57 36.1 2.39	15 88.2 13.68	1.9 19.4 2.37	15 26.04 14.61	0.65 6.91 2.27
17.5 316.4 12.75	7.33 75 2.36	17.5 229.6 14.06	4.36 44.3 2.38	17.5 154 15.19	2.5 26 2.32	17.5 68.6 16.47	0.92 9.9 2.25
20 452.2 13.22	10.6 96.3 2.64	20 313.6 15.30	5.54 54.9 2.44	20 224 16.64	3.46 33.5 2.49	20 117.6 18.24	1.4 14.5 2.33
22.5 617.4 13.24	12.14 109 2.69	22.5 423.4 16.15	6.20 61.3 2.44	22.5 302.4 17.96	4.39 42 2.53	22.5 193.2 19.60	1.89 19.2 2.38
25 786.8 13.20	14.24 134 2.59	25 532 17.02	8.07 76.2 2.56	25 403.2 18.95	5.0 48.5 2.49	25 264.6 21.03	3.29 32.5 2.45
	2.57 ^b		2.46 ^b		2.46 ^b		2.35 ^b
* : density n in units of 10^{10} ions/cm³ ^a : onset of Toensend discharge regions ^b : average density n for the last four cells in the same column							

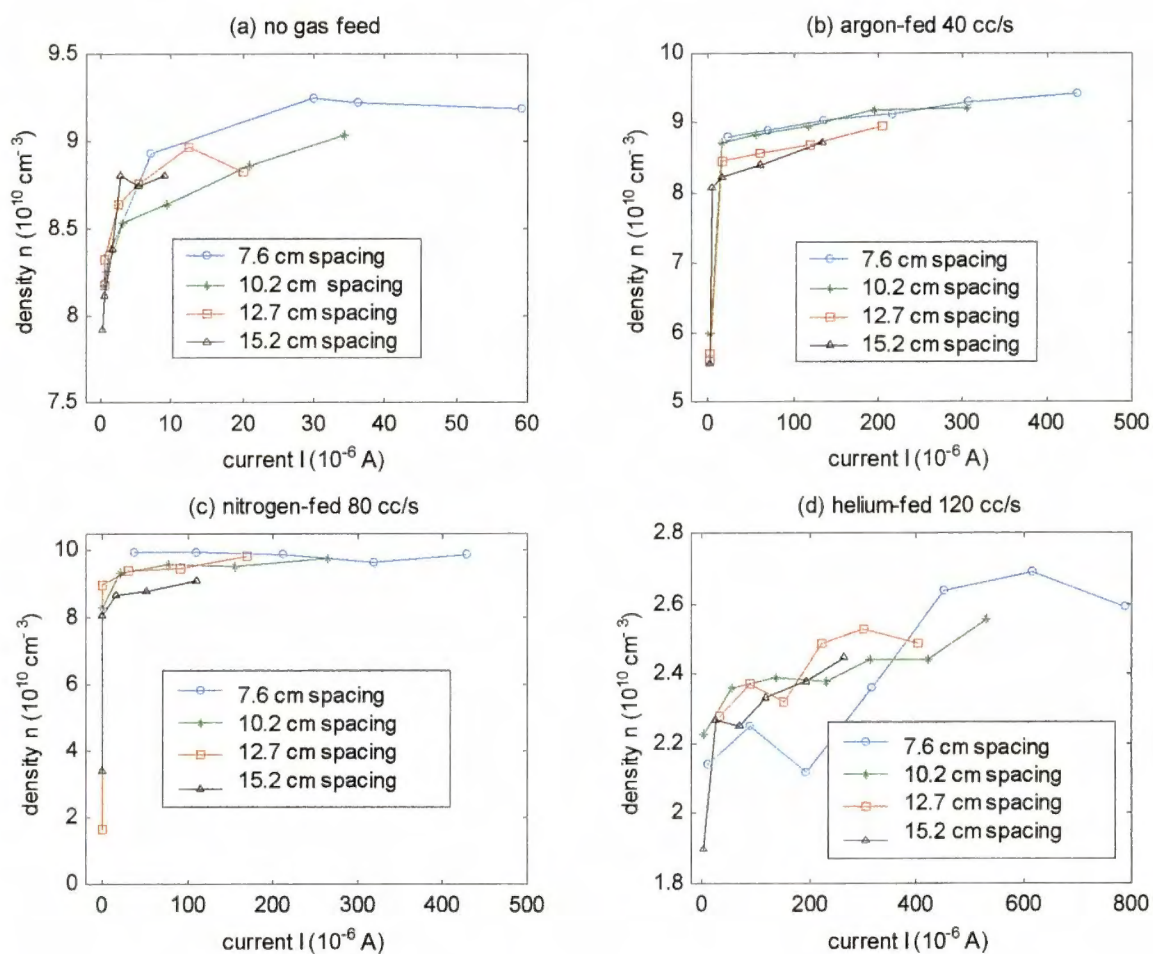


Figure 5.13. Ion density located at the center of the discharge showing the influence of different electrode spacing (note that the current shown is that applied to the discharge electrodes).

5.3.3 Effect of gas flow on the local ion density

The effect of gas flow on the density located at the center of the discharge is presented in Table 5.4 in the same way as described in the previous two sections.

In Table 5.4a, the discharge with no gas feed was compared to that of gas-fed discharges at 10 cc/s. With no gas feed, the density (in units of 10^{10} cm^{-3}) varies from 8.19 to 9.24. With 10 cc/s flow rate, the density varies from 6.46 to 9.52, 0.24 to 2.52, and 6.62 to 9.06 for nitrogen, helium, and argon-fed discharges respectively. Well into the Townsend regions, the average density is 9.15, 9.37, 2.40, and 8.82 respectively.

In Table 5.4b, the discharge was fed at 40 cc/s. The data for no-gas-feed discharge is the same as in Table 5.4a. With 40 cc/s flow rate, the density varies from 7.57 to 9.88, 1.88 to 2.56, and 8.82 to 9.43 respectively for nitrogen, helium, and argon-fed discharges. The average density well into the Townsend regions is 9.84, 2.50, and 9.22 respectively for nitrogen, helium, and argon-fed discharge.

In Table 5.4c, the discharge was fed at 80 cc/s. The data for no-gas-feed discharge are the same as before. With 80 cc/s flow rate, the density varies from 9.66 to 9.98, 0.26 to 2.48, and 8.93 to 9.78 for nitrogen, helium, and argon-fed discharges respectively. The average density well into the Townsend regions is 9.88, 2.43, and 9.48 respectively.

In Table 5.4d, the discharge was fed at 120 cc/s. The data for no gas feed are the same as before. With 120 cc/s flow rate, the density varies from 9.03 to 9.89, and 1.68 to 2.69 respectively for nitrogen and helium-fed discharge. The average density is 9.75 and 2.47 respectively.

Figure 5.14 gives the graphical presentation for Table 5.4.

Table 5.4. Density probe measurements (i_p , v_p , n) at the respective data points (I , V) of Figure 5.4 where the effect of gas flow rates was investigated: (a) no gas feed versus 10 cc/s flow rate for nitrogen, helium, and argon.

No gas feed in the atmospheric air		Nitrogen-fed at 10 cc/s		Helium-fed at 10 cc/s		Argon-fed at 10 cc/s	
V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*	V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*	V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*	V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*
5 0.124 5	- - -	5 0.002 5	- - -	5 0.024 5	- - -	5 0.004 5	- - -
7.5 0.250 7.5	- - -	7.5 0.002 7.5	- - -	7.5 0.041 7.5	- - -	7.5 0.006 7.5	- - -
10 0.394 10	- - -	10 0.003 10	- - -	10 0.081 10	0.003 0.300 0.24	10 0.043 10	- - -
12.5 0.578 12.49	0.026 0.287 8.19	12.5 0.004 12.5	- - -	12.5 0.109 12.5	0.008 0.350 0.55	12.5 0.614 ^a 12.5 ^a	0.007 0.095 6.62
15 0.991 ^a 14.99 ^a	0.072 0.78 8.35	15 0.051 ^a 15 ^a	0.003 0.045 6.46	15 0.249 ^a 15 ^a	0.007 0.300 0.56	15 8.6 14.87	0.156 1.638 8.55
17.5 7.15 17.39	0.89 9.01 8.93	17.5 1.27 17.48	0.063 0.664 9.19	17.5 30.69 17.04	0.75 8.5 2.13	17.5 39.91 16.9	0.739 7.65 8.59
20 20.98 19.69	1.92 18.8 9.24	20 24.72 19.63	0.894 9.28 9.33	20 78.43 18.82	1.42 13.7 2.51	20 117 18.25	2.217 21.78 8.77
22.5 36.15 21.96	3.79 37.2 9.22	22.5 85.95 21.21	2.923 30.06 9.42	22.5 158.2 20.13	2.48 23.8 2.52	22.5 208 19.34	3.410 34.61 8.85
25 59.21 24.11	5.7 56.1 9.19	25 174 22.39	4.97 50.6 9.52	25 252.3 21.21	3.6 35.5 2.45	25 322.1 20.17	4.806 47.64 9.06
	9.15 ^b		9.37 ^b		2.40 ^b		8.82 ^b
* : density n in units of 10^{10} ions/cm³ ^a : onset of Townsend discharge regions ^b : average density n for the last four cells in the same column							

Table 5.4. continued: (b) no gas feed versus 40 cc/s flow rate for nitrogen, helium, and argon.

No gas feed in the atmospheric air		Nitrogen-fed at 40 cc/s		Helium-fed at 40 cc/s		Argon-fed at 40 cc/s	
V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*	V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*	V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*	V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*
5 0.124 5	- - -	5 0.002 5	- - -	5 0.025 5	- - -	5 0.003 5	- - -
7.5 0.250 7.5	- - -	7.5 0.003 7.5	- - -	7.5 0.039 7.5	- - -	7.5 0.010 7.5	- - -
10 0.394 10	- - -	10 0.004 10	- - -	10 0.107 10	0.015 0.193 1.88	10 0.165 ^a 10 ^a	- - -
12.5 0.578 12.49	0.026 0.287 8.19	12.5 0.009 12.5	- - -	12.5 1.21 ^a 12.47 ^a	0.07 0.78 2.17	12.5 23.44 12.15	0.478 4.869 8.82
15 0.991 ^a 14.99 ^a	0.072 0.78 8.35	15 0.44 ^a 15 ^a	0.005 0.064 7.57	15 34.6 14.48	2.72 28.0 2.35	15 71 13.94	1.420 14.33 8.89
17.5 7.15 17.39	0.89 9.01 8.93	17.5 22.5 17.16	1.487 14.63 9.85	17.5 83.64 16.25	4.51 42.6 2.56	17.5 136.45 15.45	2.729 27.10 9.04
20 20.98 19.69	1.92 18.8 9.24	20 84.45 18.73	2.751 27.07 9.85	20 148.32 17.78	6.87 65.4 2.54	20 216.6 16.75	3.671 36.14 9.12
22.5 36.15 21.96	3.79 37.2 9.22	22.5 181.5 19.78	3.01 29.51 9.88	22.5 245.14 18.82	9.2 87.9 2.53	22.5 307 17.90	4.723 45.63 9.29
25 59.21 24.11	5.7 56.1 9.19	25 285.17 20.72	4.88 48.29 9.79	25 348.1 19.78	11.61 110.9 2.53	25 435 18.48	6.214 59.18 9.43
	9.15 ^b		9.84 ^b		2.50 ^b		9.22 ^b
* : density n in units of 10^{10} ions/cm³ ^a : onset of Townsend discharge regions ^b : average density n for the last four cells in the same column							

Table 5.4. continued: (c) no gas feed versus 80 cc/s flow rate for nitrogen, helium, and argon.

No gas feed in the atmospheric air		Nitrogen-fed at 80 cc/s		Helium-fed at 80 cc/s		Argon-fed at 80 cc/s	
V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*	V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*	V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*	V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*
5 0.124 5	- - -	5 0.004 5	- - -	5 0.024 5	- - -	5 0.006 5	- - -
7.5 0.250 7.5	- - -	7 0.006 7	- - -	7 0.03 7	- - -	7.5 0.024 ^a 7.5 ^a	- - -
10 0.394 10	- - -	10 0.011 10	- - -	10 0.044 ^a 10 ^a	0.004 0.270 0.26	10 27.81 9.38	0.598 6.014 8.93
12.5 0.578 12.49	0.026 0.287 8.19	12.5 0.017 ^a 12.5 ^a	- - -	12.5 23.84 12.14	0.05 0.57 2.12	12.5 85.25 11.22	1.795 17.98 8.97
15 0.991 ^a 14.99 ^a	0.072 0.78 8.35	15 36.07 14.46	0.065 0.63 9.98	15 63 14.0	1.22 12.4 2.39	15 154.5 12.68	3.287 32.02 9.22
17.5 7.15 17.39	0.89 9.01 8.93	17.5 110.8 15.84	0.135 0.133 9.97	17.5 153 15.21	2.12 20.7 2.48	17.5 235.5 13.97	4.282 41.30 9.31
20 20.98 19.69	1.92 18.8 9.24	20 212.5 16.81	0.23 2.25 9.88	20 253.3 16.21	3.4 33.65 2.42	20 365 14.53	5.984 56.81 9.46
22.5 36.15 21.96	3.79 37.2 9.22	22.5 319.9 17.7	2.334 23.4 9.66	22.5 373.5 16.9	4.4 44 2.42	22.5 536.5 14.45	8.508 79.42 9.62
25 59.21 24.11	5.7 56.1 9.19	25 429.8 18.54	2.53 24.7 9.92	25 504 17.44	5.7 56.5 2.44	25 768 13.48	11.82 108.5 9.78
	9.15 ^b		9.88 ^b		2.43 ^b		9.48 ^b
* : density n in units of 10^{10} ions/cm³ ^a : onset of Townsend regions ^b : average density n for the last four cells in the same column							

Table 5.4. continued: (d) no gas feed versus 120 cc/s flow rate for nitrogen, and helium.

No gas feed in the atmospheric air		Nitrogen-fed at 120 cc/s		Helium-fed at 120 cc/s	
V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*	V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*	V_s (kV) I (μ A) V (kV)	i_p (μ A) v_p (V) n^*
5 0.124 5	- - -	5 0.008 5	- - -	5 0.019 5	- - -
7.5 0.250 7.5	- - -	7.5 0.009 7.5	- - -	7.5 0.041 ^a 7.5 ^a	- - -
10 0.394 10	- - -	10 0.012 ^a 10 ^a	- - -	10 11.2 9.83	0.032 0.46 1.68
12.5 0.578 12.49	0.026 0.287 8.19	12.5 35 11.98	0.055 0.59 9.03	12.5 89.6 11.16	1.26 18.9 1.61
15 0.991 ^a 14.99 ^a	0.072 0.78 8.35	15 136 12.96	0.85 8.35 9.86	15 194.6 14.46	5.19 60.5 2.07
17.5 7.15 17.39	0.89 9.01 8.93	17.5 240 13.9	0.97 10.03 9.37	17.5 316.4 12.75	7.33 75 2.36
20 20.98 19.69	1.92 18.8 9.24	20 360 14.6	1.306 12.85 9.85	20 452.2 13.22	10.6 96.3 2.66
22.5 36.15 21.96	3.79 37.2 9.22	22.5 483 15.27	1.525 15.07 9.80	22.5 617.4 13.24	12.44 109 2.69
25 59.21 24.11	5.7 56.1 9.19	25 595 16.08	2.08 20.37 9.89	25 786.8 13.20	14.24 134 2.59
	9.15 ^b		9.75 ^b		2.47 ^b
* : density in units of 10^{10} ions/cm³ ^a : onset of Townsend discharge regions ^b : average density n for the last four cells in the same column					

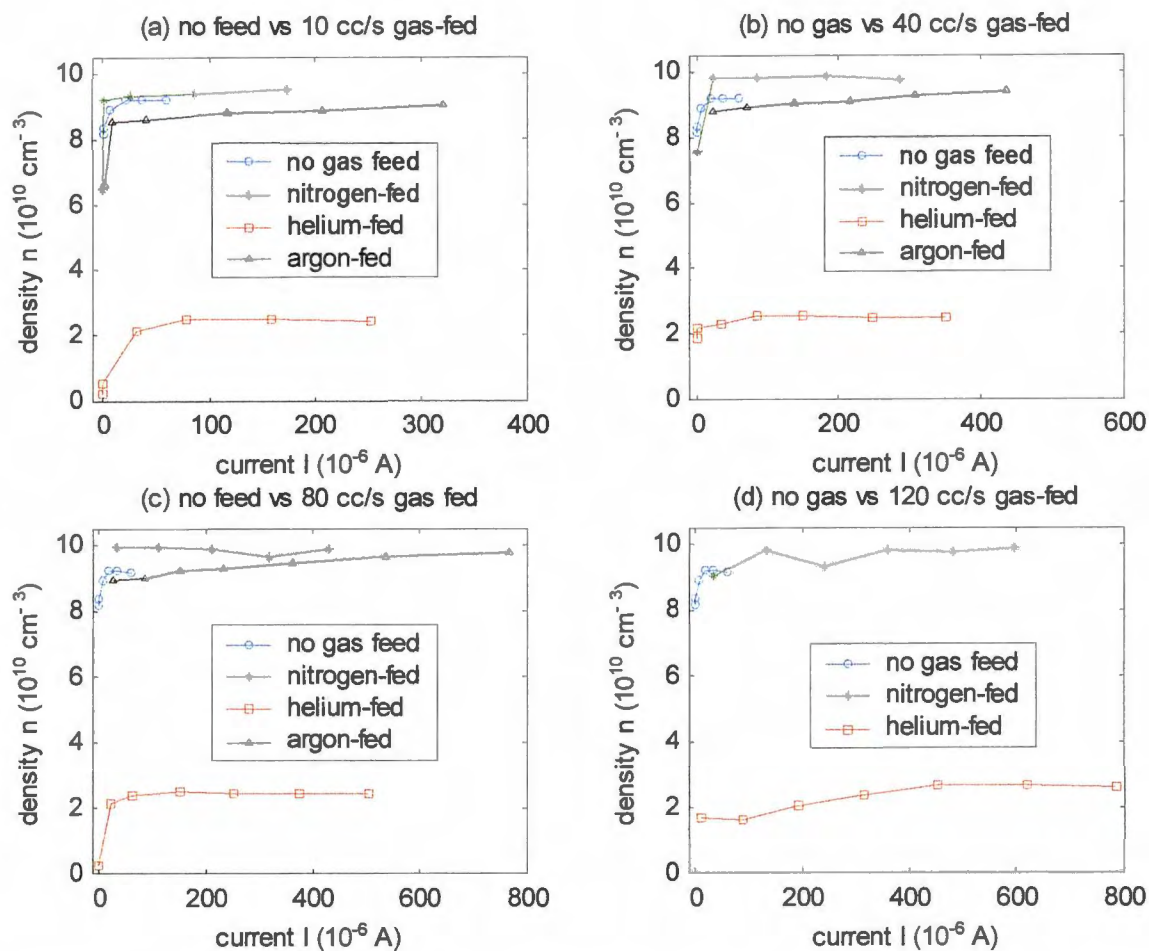


Figure 5.14. Ion density located at the center of the discharge showing the influence of the types of gas feed at different flow rates (note that the current shown is that applied to the discharge electrodes).

5.4 Spatial ion density profile across the apparatus

The density measurements described in the preceding section are those located at the geometrical center of the discharge. One might be interested in investigating the spatial distribution of the density over the entire discharge volume.

The spatial ion density profile across the apparatus can be conducted by properly placing a small-size probe at carefully chosen locations. Table 5.5 shows the result obtained when a small probe (1 cm^2 in area and 0.5 cm in plate spacing) was used to scan the discharge profile with its center lying on the plane defined by the sharp-points. The location of the probe is determined by the n th sharp-point and the probe's distance from the positive electrode. As shown in the table, the probe was placed to face the 1st, 4th, ... and 19th sharp-points at distances of 0.5 , 1.5 , ... and 6.5 cm from the positive electrodes. The spacing between the electrodes is 7 cm and the 19th sharp-point is closest to the gas feed tubing. There are 49 cells in the table. In each of the cells, are the listed measurements of the probe current i_p , probe voltage v_p , and ion density n .

The data in Table 5.5 is further used to plot the spatial ion density profile. This is shown in Figure 5.15 with the n th sharp-point, distance, and density axes corresponding to the x , y , and z axes of the Cartesian Coordinates respectively. As shown in the figure, the density appears to be higher at the center compared to the edges of the discharge.

The density profiles with the center of the probe lying at 0.5 cm below, as well as 0.5 cm above, the sharp-point plane were also conducted to compare with the profile just described. The results are shown in Table 5.6 and the corresponding Figure 5.16, as well as Table 5.7 and the corresponding Figure 5.17.

Table 5.5. The spatial ion density measurements across the discharge chamber with no gas feed (center of probe lying on the plane formed by the sharp-points).

	Sharp point directly facing the probe						
	1 st	4th	7th	10th	13th	16th	19th
0.5 cm	0.052 0.478 4.99	0.403 4.16 4.45	0.048 0.524 4.18	0.717 8.181 4.03	0.076 0.694 5.03	0.073 0.744 4.51	0.072 0.675 4.90
1.5 cm	0.026 0.268 4.46	0.034 0.351 4.46	0.008 0.070 5.25	0.154 1.414 5.00	0.031 0.306 4.66	0.109 1.107 4.52	0.032 0.284 5.17
2.5 cm	0.016 0.128 5.70	0.013 0.116 5.20	0.007 0.063 5.11	0.064 0.629 4.68	0.009 0.085 4.87	0.006 0.055 5.01	0.003 0.023 5.99
3.5 cm	0.013 0.105 5.69	0.008 0.065 5.66	0.012 0.103 5.35	0.015 0.123 5.60	0.004 0.032 5.74	0.057 0.518 5.11	0.022 0.176 5.74
4.5 cm	0.008 0.069 5.33	0.004 0.032 5.74	0.008 0.075 4.90	0.010 0.086 5.34	0.005 0.048 4.79	0.003 0.031 4.45	0.002 0.019 4.75
5.5 cm	0.094 0.936 4.62	0.005 0.048 4.68	0.006 0.053 5.21	0.133 1.412 4.33	0.037 0.325 5.23	0.003 0.034 4.06	0.004 0.041 4.48
6.5 cm	0.139 1.35 4.74	0.157 1.53 4.72	0.089 0.970 4.22	0.409 3.95 4.76	0.062 0.594 4.79	0.031 0.297 4.64	0.020 0.194 4.74
Notes: 1. The density probe is placed at a location defined by the columns (the nth pin) and rows (distance from positive electrode) of the table. 2. In each of the cells, the first number is the measurement of i_p (μA), the second number is the measurement of v_p (V), and the third number is that of n (10^{11} ions/cm ³).							

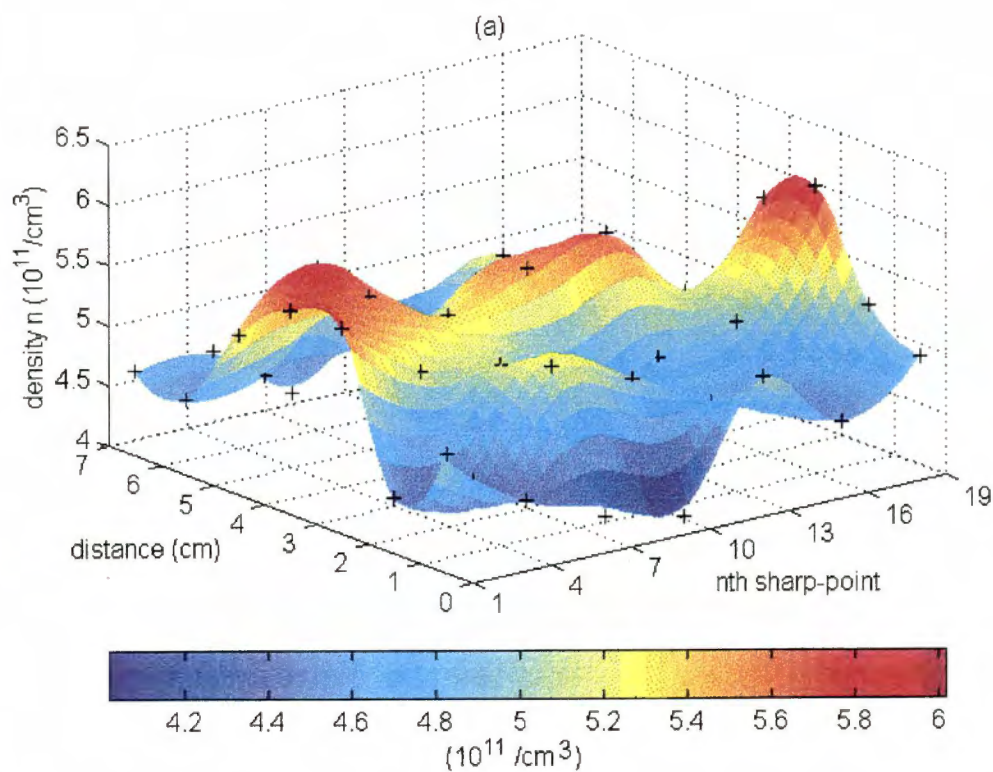


Figure 5.15. Spatial ion density profile (no gas feed) with the center of the probe lying on the plane formed by the sharp-points: (a) default view (-37° from the negative distance-axis, 30° above the sharp point-distance plane).

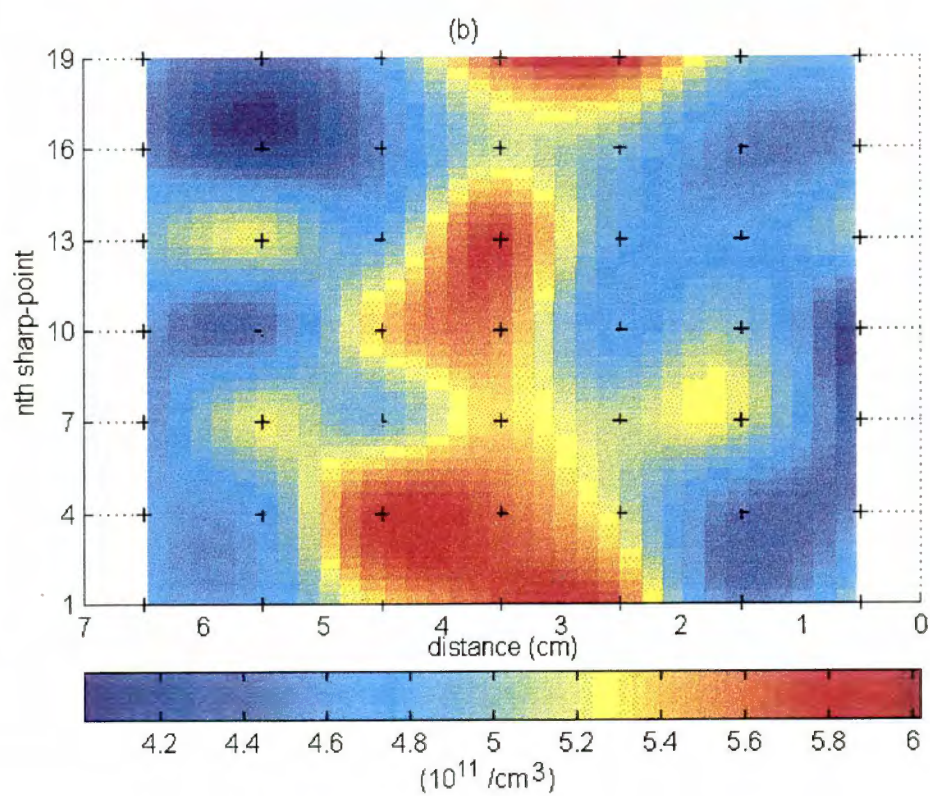


Figure 5.15. continued: (b) bird's-eye view over the plane of discharge.

Table 5.6. The spatial ion density measurements across the discharge chamber with no gas feed (center of probe lying at 0.5cm below the plane formed by the sharp-points).

	Sharp point directly facing the probe						
	1 st	4th	7th	10th	13th	16th	19th
0.5 cm	0.041 0.52 3.62	0.046 0.480 4.30	0.039 0.473 3.78	0.037 0.452 3.75	0.045 0.528 3.91	0.045 0.479 4.31	0.051 0.532 4.40
1.5 cm	0.023 0.253 4.17	0.045 0.469 4.40	0.053 0.513 4.74	0.026 0.279 4.28	0.027 0.284 4.36	0.030 0.327 4.22	0.023 0.250 4.23
2.5 cm	0.013 0.121 4.93	0.014 0.125 5.14	0.012 0.115 4.79	0.026 0.275 4.34	0.021 0.198 4.86	0.057 0.603 4.34	0.012 0.134 4.11
3.5 cm	0.013 0.108 5.53	0.019 0.168 5.19	0.021 0.183 5.27	0.019 0.179 4.87	0.009 0.085 4.86	0.013 0.126 4.74	0.029 0.302 4.41
4.5 cm	0.012 0.109 5.05	0.006 0.055 5.00	0.004 0.037 4.97	0.012 0.108 5.10	0.005 0.052 4.38	0.006 0.051 5.41	0.003 0.029 4.75
5.5 cm	0.005 0.047 4.86	0.004 0.043 4.27	0.013 0.136 4.39	0.212 2.240 4.35	0.005 0.044 4.78	0.005 0.044 5.22	0.014 0.146 4.40
6.5 cm	0.110 1.041 4.86	0.030 0.330 4.17	0.076 0.720 4.85	0.334 3.24 4.74	0.020 0.188 4.88	0.137 1.44 4.37	0.102 1.081 4.33
Notes: 1. The density probe is placed at a location defined by the columns (the nth pin) and rows (distance from positive electrode) of the table. 2. In each of the cells, the first number is the measurement of i_p (μA), the second number is the measurement of v_p (V), and the third number is that of n (10^{11} ions/cm³).							

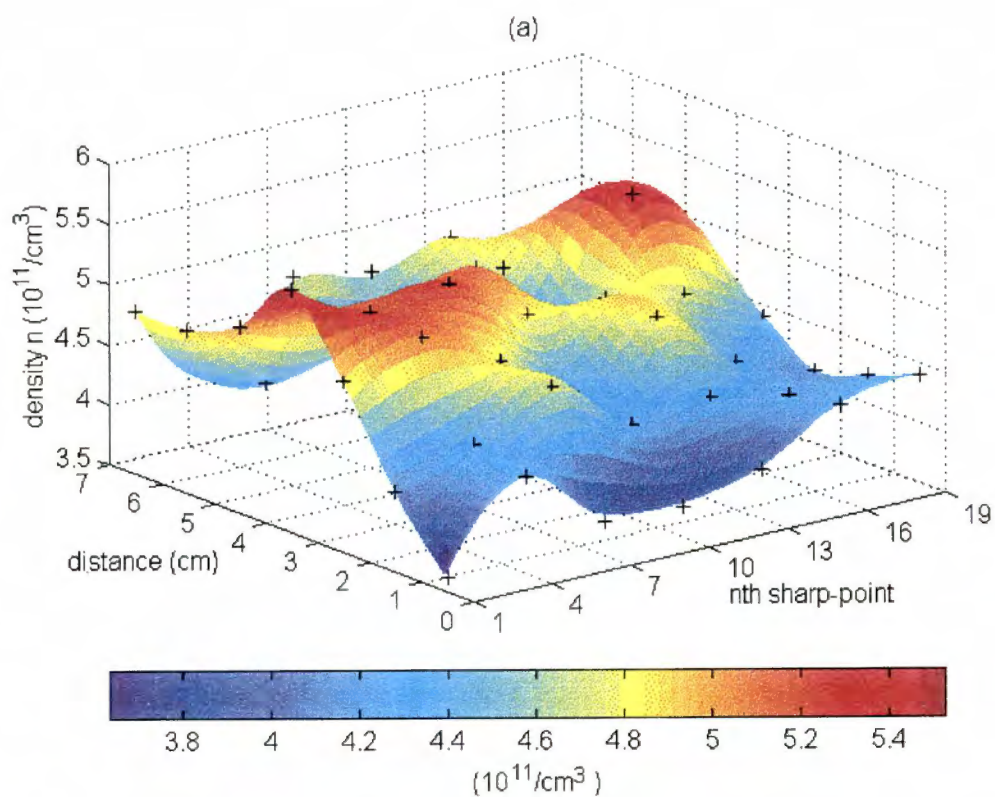


Figure 5.16. Spatial ion density profile (no gas feed) with the center of the probe located at 0.5 cm below the sharp-point plane: (a) default view (-37° from the negative distance-axis, 30° above the sharp point-distance plane).

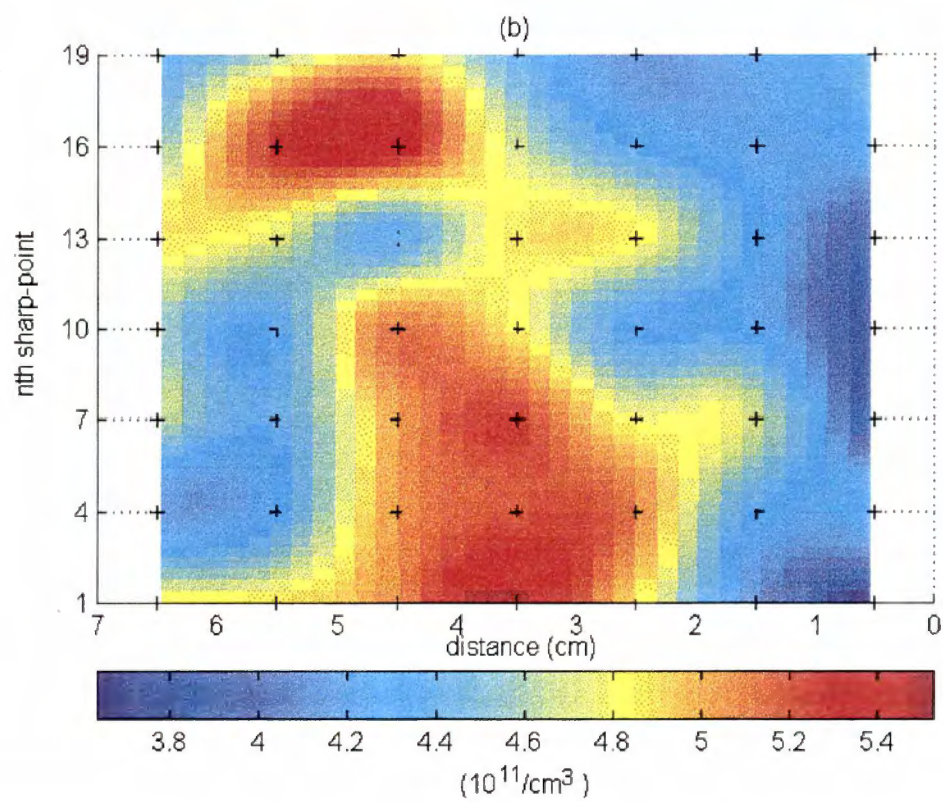


Figure 5.16. continued: (b) bird's-eye view over the plane of discharge.

Table 5.7. The spatial ion density measurements across the discharge chamber with no gas feed (center of probe lying at 0.5 cm above the plane formed by the sharp-points).

	Sharp point directly facing the probe						
	1 st	4th	7th	10th	13th	16th	19th
0.5 cm	0.328 4.036 3.77	0.055 0.698 3.62	0.038 0.564 3.09	0.444 5.04 4.04	0.351 4.90 3.28	0.206 2.286 4.13	0.110 1.180 4.31
1.5 cm	0.226 2.817 3.68	0.044 0.491 4.11	0.054 0.675 3.67	0.527 5.31 4.55	0.062 0.674 4.23	0.045 0.502 4.10	0.056 0.635 4.02
2.5 cm	0.234 2.572 4.18	0.029 0.293 4.52	0.032 0.336 4.37	0.462 4.82 4.40	0.009 0.095 4.35	0.049 0.515 4.37	0.027 0.298 4.16
3.5 cm	0.028 0.249 5.16	0.045 0.487 4.97	0.037 0.385 4.41	0.204 2.218 4.22	0.049 0.509 4.41	0.035 0.447 3.59	0.026 0.264 4.52
4.5 cm	0.012 0.112 4.92	0.011 0.099 5.09	0.029 0.273 4.87	0.223 2.09 4.89	0.102 0.987 4.74	0.032 0.323 4.55	0.029 2.67 4.99
5.5 cm	0.018 0.176 4.69	0.008 0.076 4.83	0.037 0.379 4.48	0.335 3.39 4.56	0.029 0.301 4.42	0.049 0.514 4.35	0.601 6.09 4.53
6.5 cm	0.258 2.830 4.18	0.071 0.744 4.38	0.325 3.596 4.15	0.766 8.02 4.38	0.106 1.024 4.75	0.276 2.904 4.36	0.428 4.22 4.65
Notes: 1. The density probe is placed at a location defined by the columns (the nth pin) and rows (distance from positive electrode) of the table. 2. In each of the cells, the first number is the measurement of i_p (μA), the second number is the measurement of v_p (V), and the third number is that of n (10^{11} ions/cm³).							

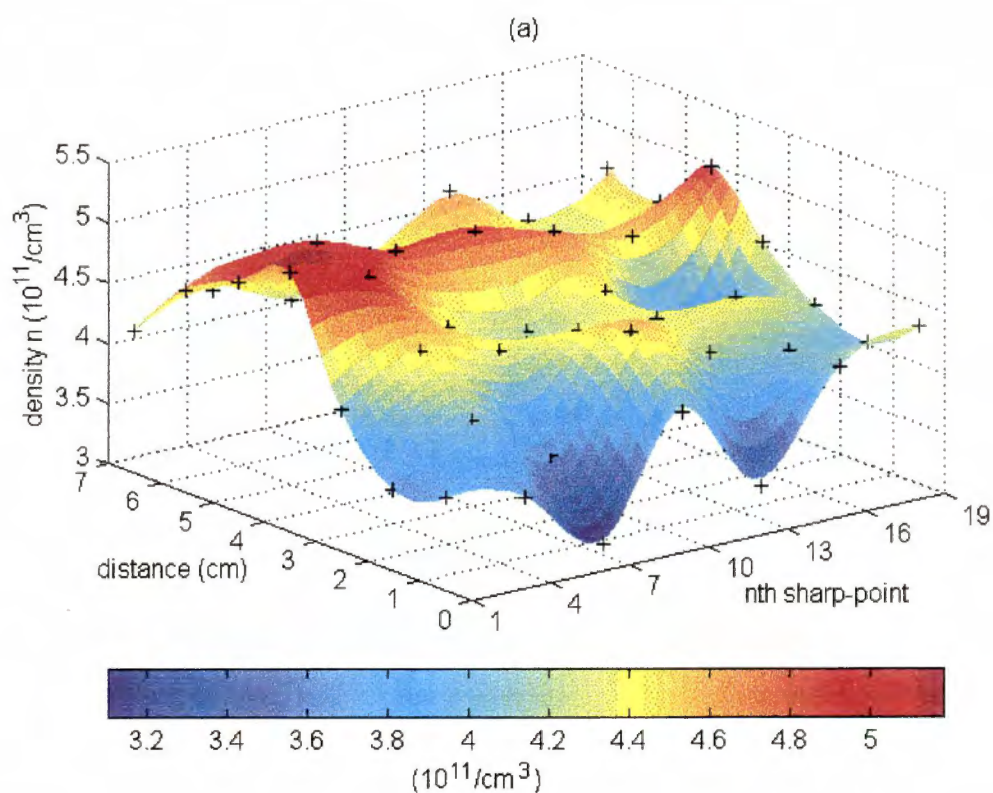


Figure 5.17. Spatial ion density profile (no gas feed) with the center of the probe located at 0.5 cm above the sharp-point plane: (a) default view (-37° from the negative distance-axis, 30° above the sharp point-distance plane).

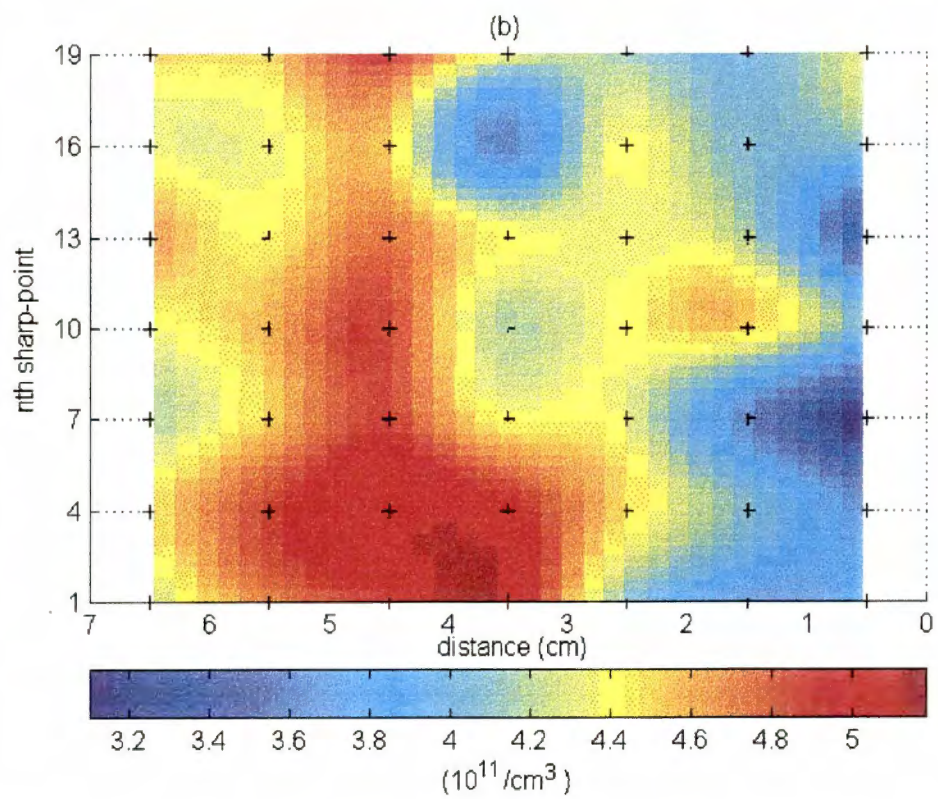


Figure 5.17. continued: (b) bird's-eye view over the plane of discharge.

The densities in both Figures 5.16 and 5.17 are slightly lesser than those shown in Figure 5.15 located at the same respective locations. This is especially true near the edges of the discharges. Similar to Figure 5.15, Figures 5.16 and 5.17 also show a higher concentration near the vicinity of the center of discharges.

Note that the data just presented are those operated with no gas feed with an applied source voltage of 20 kV. It is expected that a similar uniformity of discharge would occur if gas feeds were to be applied.

5.5 The ozone production rate

To monitor the production of ozone (O_3), a simple experiment setup was arranged as shown in Figure 5.18. The enclosed box was that of the apparatus described in chapter 4. The fan served as an airflow, driving the air to the vicinity of the sharp-point electrodes that were separated by 3 inches from each other. With proper DC power applied at the electrodes, corona discharge as well as ozone were created. A Spectrum Ozone detector by Enmet Corporation was placed inside the box to detect the ozone dissipated in the enclosed volume of $1.8318 \times 10^4 \text{ cm}^3$ over a known period of time. The production rate of O_3 could thus be evaluated.

Taking for example, with voltage V and current I of 25kV and 0.05mA respectively applied on the electrodes and without any gas feed, a detection d_t of 0.50 ppm (part per millions) of O_3 was recorded over a time t of 243 seconds. The following calculations were made:

$$\begin{aligned} n_o &\equiv \text{density of molecules at standard pressure and temperature} \\ &= 2.69 \times 10^{19} \text{ (molecules/cm}^3\text{)} \quad [5.8] \end{aligned}$$

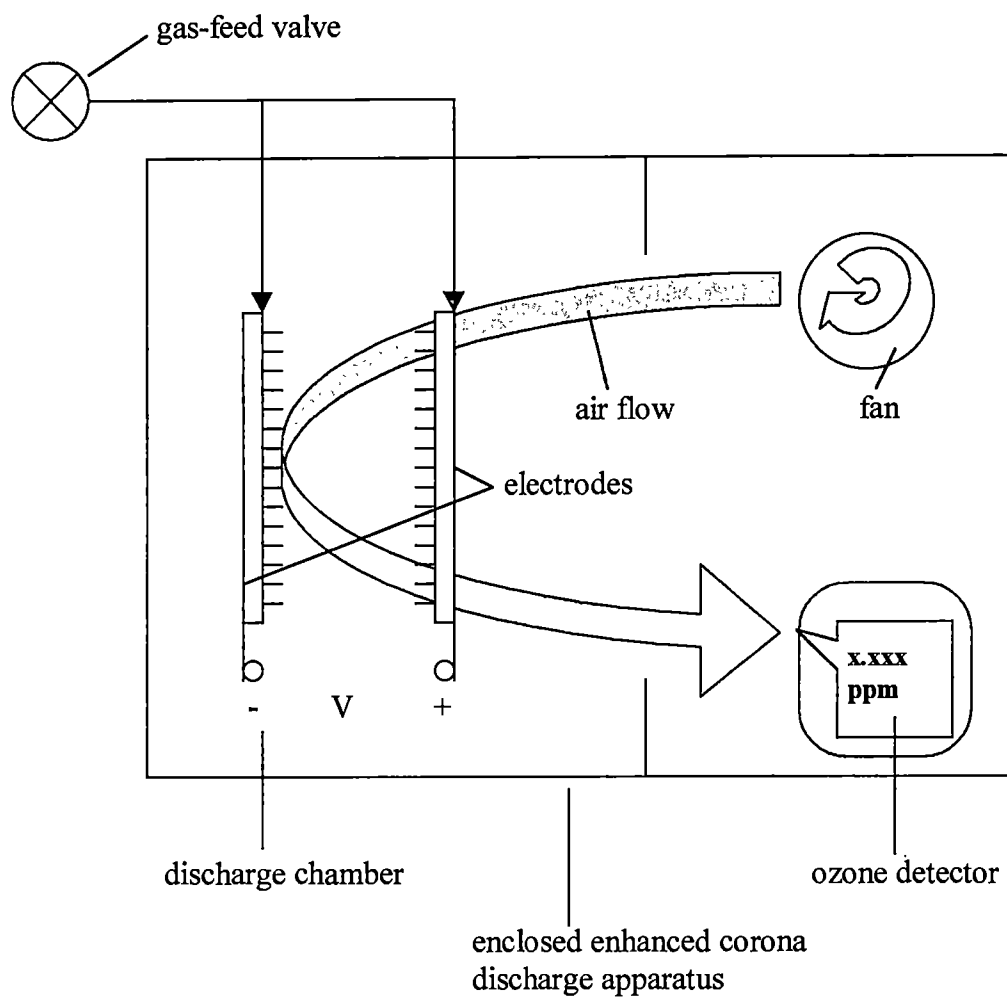


Figure 5.18. Monitoring the ozone production inside the ECD apparatus.

N_{air} $\equiv$ number of air molecules in the enclosed box

$$\begin{aligned} &= (2.69 \times 10^{19}) \times (1.8138 \times 10^4) \\ &= 4.88 \times 10^{23} \quad (\text{molecules of air}) \end{aligned}$$

$R_{ozone}(\text{air})$ $\equiv$ ozone production rate with air as gas feed

$$\begin{aligned} &= (N_{air} \times d_t) / t \\ &= (4.88 \times 10^{23} \times 0.50 \times 10^{-6}) / 243 \\ &= 1.004 \times 10^{15} \quad (\text{O}_3 \text{ molecules / sec}) \end{aligned}$$

$R_{electron}$ $\equiv$ electron production rate by the applied current I

$$\begin{aligned} &= I / e \\ &= 0.05 \times 10^{-3} / 1.602 \times 10^{-19} \\ &= 3.125 \times 10^{14} \quad (\text{electrons/sec}) \end{aligned}$$

R_{oe} $\equiv$ ratio of ($R_{ozone} / R_{electron}$)

$$= 3.213 \quad (\text{ozone/electron})$$

P $\equiv$ power applied to the electrode

$$\begin{aligned} &= VI \\ &= 1.25 \text{ watts} \\ &= 7.81 \times 10^{18} \quad (\text{eV/sec}) \end{aligned}$$

W $\equiv$ energy used to produce one molecule of O_3

$$\begin{aligned} &= P / R_{ozone} \\ &= 7.78 \times 10^3 \quad (\text{eV / O}_3) \end{aligned}$$

$$\begin{aligned}
 W_{eff} &\equiv \text{energy efficiency in producing one molecule of O}_3 \\
 &= (10/W) \text{ (note: it takes 10 eV to produce one O}_3\text{)} \\
 &= 0.12 \%
 \end{aligned}$$

Thus, without gas feed and with an applied voltage of 25kV and current of 0.05mA, the ozone production rate is 1.004×10^{15} molecules/sec. This production rate is about 3.213 times of that of electrons. The energy efficiency of producing an ozone molecule is 0.12%.

Similar calculations can be made when other gases are used. Table 5.7 shows the discharge conditions (V , I , and P), the detection made (d_t over t), and the corresponding calculated values of R_{ozone} , $R_{electron}$, R_{oe} , P , W , and W_{eff} for air, helium, argon, and nitrogen gases used in the experiment.

Amongst the gases used, helium has the highest ozone production rate of 8.05×10^{16} O₃ molecules/sec followed by argon's 1.15×10^{16} O₃ molecules/sec. Both values are an order of magnitude higher than that of air at 1.004×10^{15} O₃ molecules/sec. Nitrogen has the lowest rate of 6.84×10^{14} O₃ molecules/sec. For the R_{oe} ratios, the values are 32.2, 30.7, 3.21, and 1.09 O₃/electron respectively for helium, argon, air, and nitrogen.

Table 5.8. Production of ozone inside the enhanced corona discharge apparatus with different gas feeds.

Gas	Discharge Condition	Ozone detection	Ozone production rate R_{ozone}	Electron Production rate $R_{electron}$	$R_{oe} \equiv R_{ozone} / R_{electron}$	$W \equiv$ Energy used to produce one O_3 molecule	$W_{eff} \equiv$ Energy efficiency
Air	$V = 25$ kV $I = 0.05$ mA $P = 1.25$ watt	$d_t = 0.50$ ppm $t = 243$ sec	1.004×10^{15} (O_3 /sec)	3.125×10^{14} (electrons/sec)	3.213 (O_3 /electron)	7.78×10^3 (eV/ O_3)	0.13%
Helium	$V = 15$ kV $I = 0.4$ mA $P = 6$ watt	$d_t = 0.99$ ppm $t = 6$ sec	8.05×10^{16} (O_3 /sec)	2.5×10^{15} (electrons/sec)	32.2 (O_3 /electron)	466 (eV/ O_3)	2.15 %
Argon	$V = 25$ kV $I = 0.06$ mA $P = 1.5$ watt	$d_t = 0.99$ ppm $t = 42$ sec	1.15×10^{16} (O_3 /sec)	3.75×10^{14} (electrons/sec)	30.7 (O_3 /electron)	815 (eV/ O_3)	1.23 %
Nitrogen	$V = 25$ kV $I = 0.1$ mA $P = 2.5$ watt	$d_t = 0.3$ ppm $t = 214$ sec	6.84×10^{14} (O_3 /sec)	6.25×10^{14} (electrons/sec)	1.09 (O_3 /electron)	2.28×10^4 (eV/ O_3)	0.044 %

CHAPTER 6

STERILIZATION TEST

As described in chapter 2, the standard laboratory testing of sterilization methods usually involves three steps. These steps are: a) growing the samples of the particular microorganisms in a culture medium, b) subjecting the microorganisms to the sterilizer for treatment, and c) analyzing the effectiveness of the sterilization by determination of the death rate. By adhering to these steps, this chapter describes the conduction of the sterilization test on *Escherichia coli* and *Bacillus subtilis* using an enhanced corona discharge apparatus similar to that described in chapter 4. The result is later compared to those obtained by other researchers who have used different atmospheric plasma discharges for the treatment of the microorganisms.

It must be emphasized herewith that it is not the author's intention to subject the apparatus to a wide range of sterilization tests. Such a task is more suited for microbiologists. The main purpose of this chapter is to establish that the apparatus is indeed effective in killing the two microorganisms mentioned above.

6.1 Why *Escherichia coli* and *Bacillus subtilis*

Escherichia coli and *Bacillus subtilis* are respectively the standard bacteria and endospore employed in most of the testing of a particular sterilization process.

E. coli is a common bacterium that normally inhabits the intestinal tracts of humans and animals but can cause infection in other parts of the body. One strain, sometimes

transmitted in hamburger meats and unpasteurized juices, can cause serious infection resulting in diarrhea, anemia, kidney failure and death. Outbreak of *E. coli* is quite frequent. In the last few years, there had been up to 30 outbreaks annually in America, resulting in thousands of sick people and hundreds of deaths [6.1, 6.2, and 6.3]. The health-science community, food industry, and the public are thus interested in preventing the *E. coli* contamination.

Thus, most often than not, *E. coli* is used as the initial important indicator for testing the effectiveness of a particular sterilization process. *B. subtilis*, on the other hand, is used because an important criteria of any effective sterilization process is its ability to kill the bacteria endospores, as they are considered to be the most resistant cell to any lethal antimicrobial agent.

Both *E. coli* and *B. subtilis* are therefore used in the testing of the effectiveness of the enhanced corona discharge. The following sections describe the testing process.

6.2 Preparation of the sample microorganism

For laboratory test, most bacteria or endospores can be produced on a suitable artificial culture medium in the laboratory. The growth medium used in our sterilization test was LB (Luria Bertani). The liquid media solidified to a gel by the addition of agar in Petri dish for isolation of the microorganism.

After the culture medium LB agar had been inoculated with material containing bacteria, it was incubated at the optimum temperature of 37°C for 24-36 hours. Cell division occurred at 20 minutes intervals doubling the population each time. The number of bacteria reached a maximum at $10^8 - 10^{10}$ per milliliter of broth culture. Exhaustion of

oxygen or an essential nutrient, or the accumulation of metabolic waste products slowed and eventually terminated multiplication. The saturated medium had approximately 10^{10} cells/ml.

6.3 Subjecting the microorganisms to the sterilizer for treatment

A sterilizer is an apparatus that utilizes a particular antimicrobial agent to sterilize or disinfect the microorganisms. In this investigation, the sterilizer is the enhanced corona discharge apparatus itself and the biocidal agent is the plasma discharge.

The electrode used in the apparatus is shown in Figure 6.1 [6.4]. This electrode with an array of multiple lines of pins has a dimension of 24 cm x 11.5 cm x 2.2 cm. The heads of the pins are mounted on one surface of the conducting plate while the sharp points protrude through tiny holes on the opposite plate. The pins have a length of 2.7 cm and are separated from each other by 0.5cm.

The pin electrode can be positively biased and separated from the grounded electrode with a varied gap distance. The assembly of the testing apparatus is shown in Figure 6.2 [6.4]. The DC power dissipated as a function of applied voltage for different gap distance between the pins and grounded electrode is shown in Figure 6.3 [6.4]. With proper gap distance and gas feed, the enhanced corona discharge can be initiated between the electrodes where a sample is placed for sterilization test.

For sterilization test, the *Escherichia coli* cells were mixed with sterile tryptic soy broth (TSB) containing 2 % agar and poured into sterile petri plates, and allowed to be hardened. Agar plugs (3-5 mm thick and 15 mm diameter) containing approximately 10^8 cells were exposed to the enhanced corona discharge for defined exposure times. The

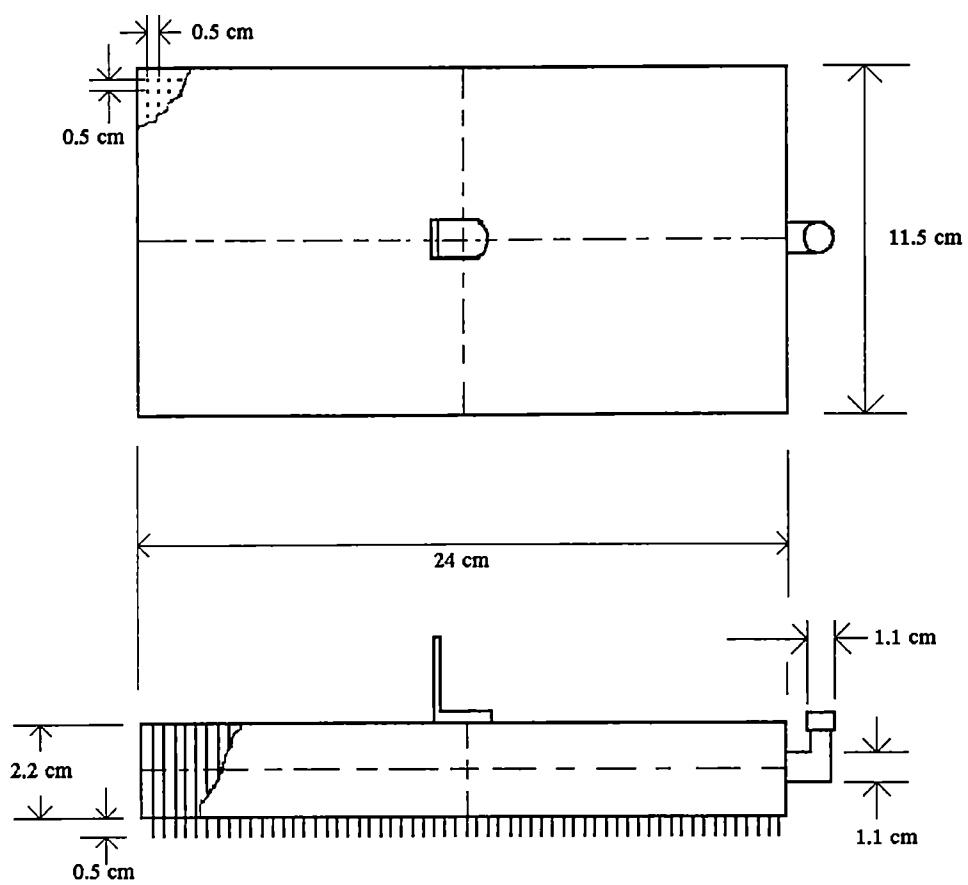


Figure 6.1. Electrode with multiple lines of pins.

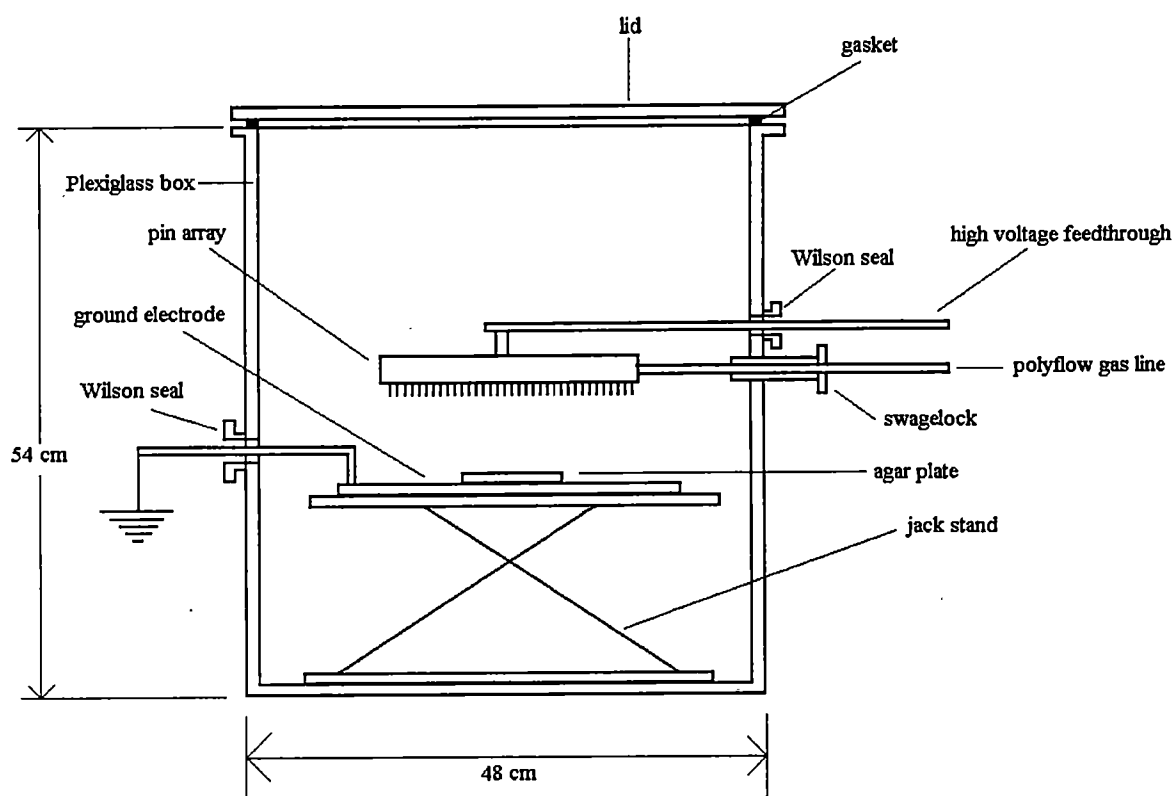


Figure 6.2. Apparatus used to conduct sterilization tests.

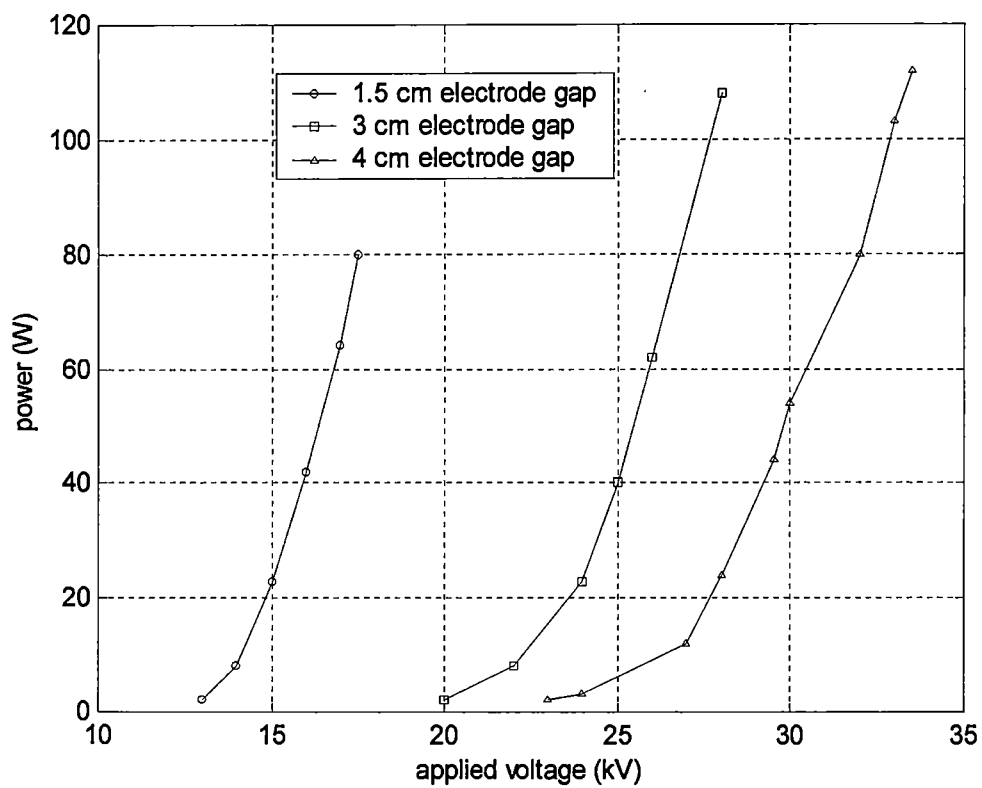


Figure 6.3. DC power dissipated at different gap distance between the electrodes of the apparatus shown in Figure 6.2.

physical nature of the agar was not visibly altered after plasma exposure. Each exposed agar plug was added to 5 ml of TSB in a sterile plastic test tube and macerated. The supernatant containing any remaining viable cells was removed from the macerated agar, and the number of survivors was determined by serial dilutions and standard plate counts on tryptic soy agar. The plates were incubated at 37°C for 18-36 hours and the percent survival was determined.

6. 4 Sterilization results

As described in chapter 2, the determination of death rate is needed to evaluate the effectiveness of the killing of microorganisms. The rate at which an antimicrobial agent reduces the number of viable cells in a microbial population is determined by counting the survivors in samples obtained after treatment. The initial count and the sample counts are usually plotted on a logarithmic scale against the exposure time and a line is drawn through the separate points to obtain a death curve. The death rate is quantified as D value as a measure of the sterilization effectiveness. The D value, or Decimal Reduction Time, is the time taken to cause a tenfold reduction in the number of viable microorganisms, which is equivalent to a 90% kill.

The sterilization capability of the enhanced corona discharge was assessed accordingly. Figures 6.4 and 6.5 show the survivability of *Escherichia coli* and *Bacillus subtilis* respectively under the treatment using apparatus shown in Figure 6.2. The gap distance between the electrode and agar plate was set at 4 cm and the treatment gas was that of atmospheric air. It must be emphasized here that they are just preliminary results.

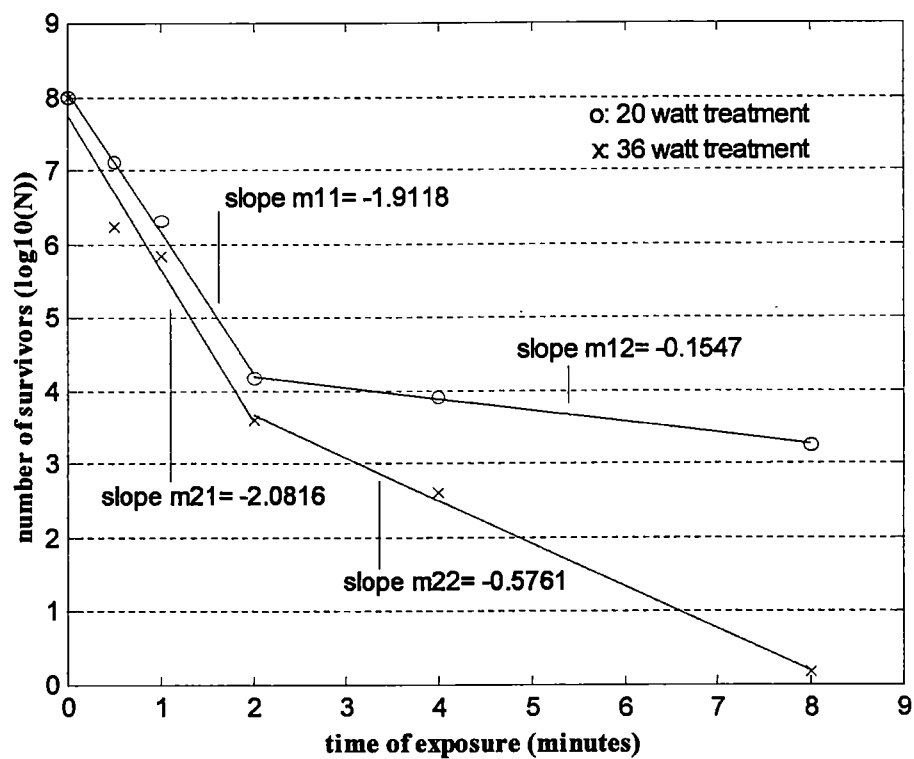


Figure 6.4. Survivability of *Escherichia coli* under enhanced corona discharge treatment in air.

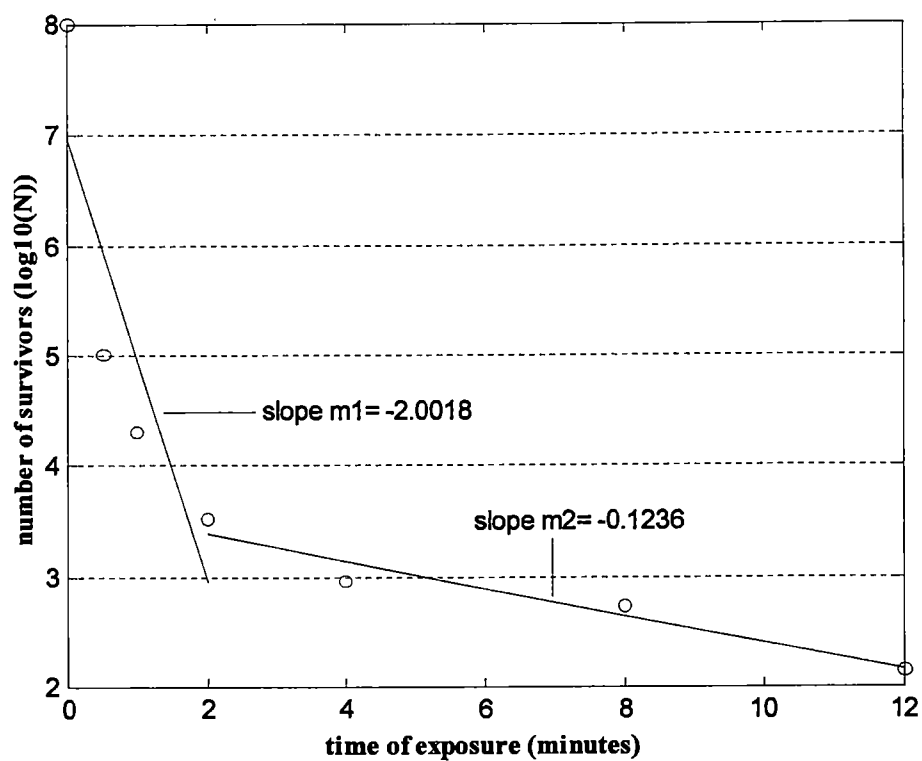


Figure 6.5. Survivability of *Bacillus subtilis* under enhanced corona discharge treatment in air.

Though several runs had been performed for each of the microorganisms, each of the figures shown is not the result of the average run but the result of just a typical run.

The data points in Figures 6.4 and 6.5 are plotted with least-squares analysis. In each of the figures, a bi-phasic curve emerges with two distinct slopes representing two distinct killing rates. These killing rates are represented as D_1 and D_2 shown below.

From Figure 6.4, the D values of *E. coli* are

$$\begin{aligned} D_1 &= 1/|\text{slope } m_{11}| \\ &= 1/1.9118 \\ &= 0.52 \text{ minutes (or 31 seconds)} \end{aligned}$$

and

$$\begin{aligned} D_2 &= 1/|\text{slope } m_{12}| \\ &= 1/0.1547 \\ &= 6.5 \text{ minutes (or 388 seconds)} \end{aligned}$$

for the 20-watt curve. Similarly, it can be shown that

$$\begin{aligned} D_1 &= 1/|\text{slope } m_{21}| \\ &= 1/2.0816 \\ &= 0.48 \text{ minutes (or 29 seconds)} \end{aligned}$$

and

$$\begin{aligned} D_2 &= 1/|\text{slope } m_{22}| \\ &= 1/0.5761 \\ &= 1.74 \text{ minutes (or 104 seconds)} \end{aligned}$$

for the 36-watt curve.

Note that the D_1 values are approximately the same for both cases. However, a shorter D_2 value for the higher 36-wattage curve indicates that a higher power can induce a quicker second phase killing.

The D values for *Bacillus subtilis* can be evaluated similarly. From Figure 6.5, the values are

$$\begin{aligned} D_1 &= 1/|\text{slope } m_1| \\ &= 1/2.0018 \\ &= 0.50 \text{ minutes (or 30 seconds)} \end{aligned}$$

and

$$\begin{aligned} D_2 &= 1/|\text{slope } m_2| \\ &= 1/0.1236 \\ &= 8.1 \text{ minutes (or 485 seconds)}. \end{aligned}$$

For the enhanced corona discharge treatment, both figures show an initial faster exponential killing curve (D_1 value) followed by a second phase that exhibits a much slower killing response (D_2 value).

6.5 Comparing with results from other atmospheric plasma sterilization methods

The survivability curves of Figures 6.4 and 6.5 are not unique. They are similar to other survivability curves of the same microorganism species embedded in the same material but exposed to the treatment of a different atmospheric plasma discharge.

Figure 6.6 shows the *Escherichia coli* survivability curve when the microorganism is embedded in agar and exposed to the treatment of one atmospheric uniform glow

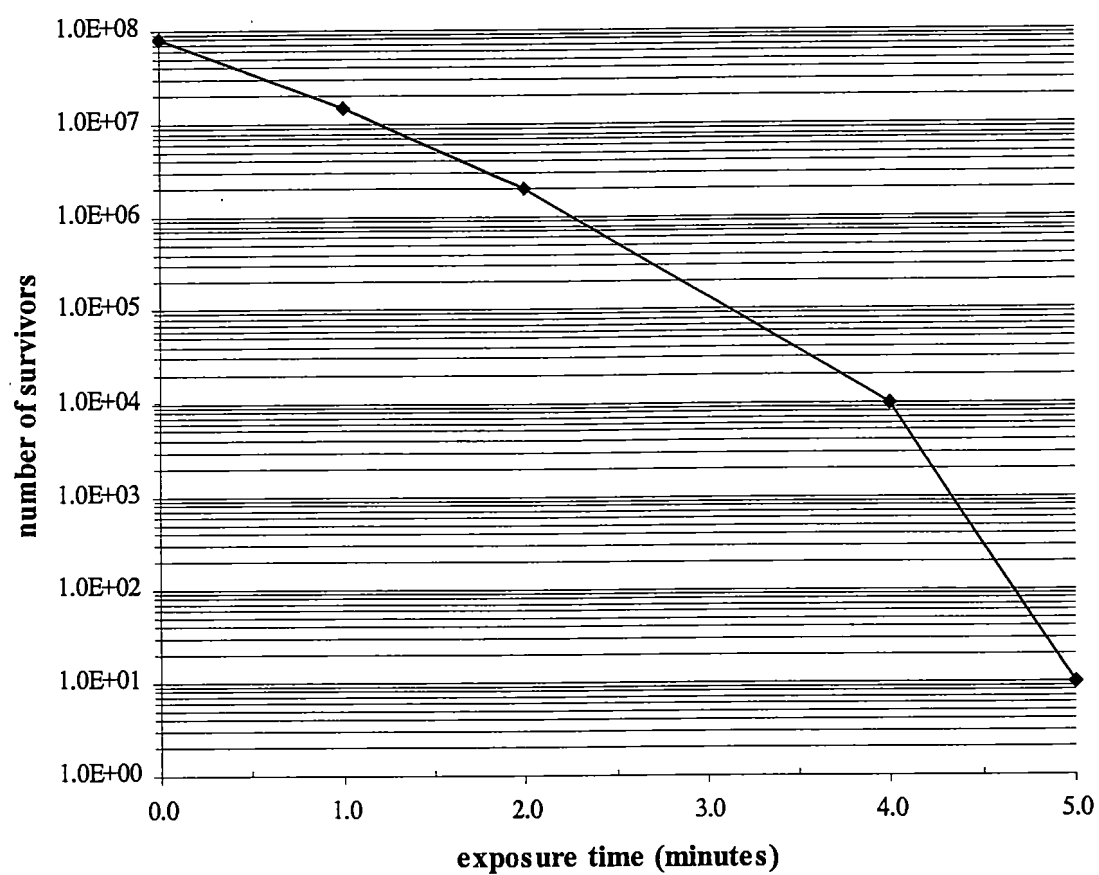


Figure 6.6. Survivability of *Escherichia coli* under OAUGDP treatment [6.5, 6.6]

discharge plasma (OAUGDP) [6.5, 6.6]. The D_1 and D_2 values for the K12 *E. coli* strain are approximately 70 and 17 seconds respectively, as interpreted from the figure.

Figure 6.7 shows the *Bacillus subtilis* spore survivability curve when the microorganism is embedded in agar and exposed to the same OAUGDP treatment [6.5, 6.6] mentioned above. The D_1 and D_2 values for *B. subtilis* are 3.3 minutes (198 seconds) and 0.3 minutes (18.2 seconds) respectively, as interpreted from the figure.

Both Figures 6.6 and 6.7 show an initial slower exponential killing curve (D_1 value) followed by a second phase that exhibits a much faster non-specific killing response (D_2 value). The reverse is true for the same microorganism undergoing enhanced corona discharge treatment described in the previous section. The difference is presumably due to the different nature of the plasma discharge.

Despite this difference in the bi-phasic nature of the survivability curve, Figure 6.4 shows a 4.8 minutes and Figure 6.6 shows a similar 4.7 minutes to reach a 6-log reduction in *E. coli* population under the enhanced corona discharge and OAUGDP treatment respectively. For *Bacillus subtilis*, a 3-log reduction in population requires a 1.5 minutes of treatment in enhanced corona discharge as indicated in Figure 6.5 and a 3.7 minutes of treatment in OAUGDP as indicated in Figure 6.7. Since one is more interested in the higher-log reduction (6-log for example) of the microorganism population for the assurance of a successful sterilization, the similar time taken to attain that reduction in both treatments is significant.

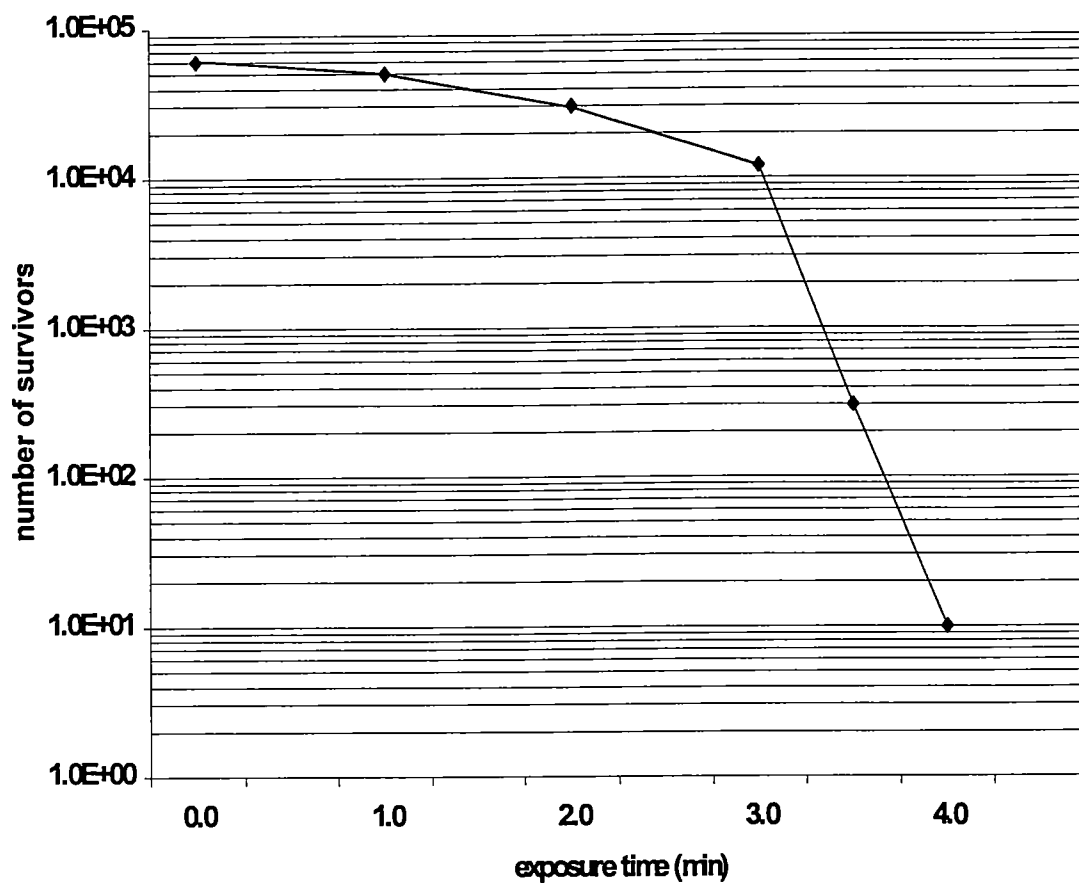


Figure 6.7. Survivability of *Bacillus subtilis* under OAUGDP treatment [6.5, 6.6].

CHAPTER 7

CONCLUSION

The application of plasma discharge for biological sterilization is an exciting and growing field of research. In investigating the feasibility of constructing a novel, efficient and potentially cost-effective sterilization apparatus using a DC-fed enhanced corona discharge at atmospheric pressure and ambient room temperature, the author has setup four main objectives. These objectives include: 1) to investigate the physical principles behind enhanced corona discharge, 2) to design the discharge electrodes and construct the discharge apparatus, 3) to characterize the plasma discharge in the apparatus, and 4) to subject the apparatus to antimicrobial testing. All these objectives have been met and are discussed in chapters 3, 4, 5, and 6 respectively.

This concluding chapter will begin with the discussion on the nature of enhanced corona discharge (ECD), followed by the sterilization results and findings obtained from both the ECD and other atmospheric plasma treatment. ECD is then compared with other plasma-aided sterilization as well as the conventional methods of sterilization. The mechanisms that are most likely responsible for the antimicrobial action, as well as other unresolved issues in the ECD and other plasma-aided sterilization, are discussed. The interdisciplinary nature of the research in plasma-aided sterilization is stressed. Future research works are suggested at the end such that more database will be available in establishing the antimicrobial mechanisms and aiding in the design of enhanced corona discharge apparatus for sterilization.

7.1 Nature of enhanced corona discharge

As described in chapter 3, corona discharge occurs in regions of high electric fields near sharp points, edges, or wires in electrically stressed gases prior to the point of electrical breakdown. In the single-species corona discharge, what is produced is a steady stream of ions, positive from positive electrode and negative from negative electrode. These two streams can be combined to produce dense synthesized plasma in the atmospheric air. The combining of both positive and negative ions into plasma overcomes the density limitation that occurred because of space charge saturation in a single-species corona discharge. While two-species corona discharge overcomes the space-charge limitation occurred in the single-species discharge; a further enhanced discharge can be achieved by replacing the air surrounding the corona points by non-electronegative gases. Non-electronegative gases reduce or get rid of the electron attachments that occurred at atmospheric air. Such enhanced corona discharge usually produces a plasma density that is an order of magnitude higher than original corona discharge.

7.2 Sterilization results from enhanced corona discharge

In the sterilization test using enhanced corona discharge apparatus, both *Escherichia coli* and *Bacillus subtilis* were embedded in agar and exposed to the plasma treatment. As described in section 6.4, the resulting survivability curves showed a bi-phasic killing rate with an initial faster exponential killing curve (D_1 value) followed by a second phase that exhibits a much slower non-specific killing response (D_2 value). The

values of D_1 and D_2 are 29 seconds and 104 seconds respectively for *E. coli* whereas the values are 30 seconds and 485 seconds respectively for *B. subtilis*.

These D values are somewhat different when compared to that obtained under the treatment of One Atmosphere Uniform Glow Discharge Plasma (OAUGDP). Treatment using OAUGDP has similar bi-phasic curves but with an initial slower exponential killing curve followed by a second phase that exhibits a much faster non-specific killing response. The D-values for *E. coli* are 70 and 17 seconds for D_1 and D_2 respectively, while *B. subtilis* has the values of 198 and 18.2 seconds.

The difference of the D-values and bi-phasic survivability curves obtained from these two different apparatus is probably due to the difference in the nature of the discharge. ECD is operated by DC, while OAUGDP is achieved by RF activation. However, when higher-log reductions in the viable microorganism are compared between these two apparatus, the values are surprising comparable to each other as described in section 6.5.

The purpose of only using *E. coli* and *B. subtilis* embedded in agar for the sterilization test in the enhanced corona discharge is to establish the capability of the discharge for antimicrobial action. To obtain a broader database, one may perhaps conduct more tests using microorganisms embedded in other culture mediums. Such tests are not included in this dissertation but the similar database using other means of atmospheric plasma discharge is available in the literature. The following section describes some of the important results using other forms of atmospheric plasma treatment for sterilization.

7.3 Some important results from other atmospheric plasma treatment

In other atmospheric plasma treatment, it is found that microorganisms survive differently when seeded in different cultures. The exposure time required depends on the type of organism and the type of substrate and varies from several seconds to several minutes. For *E. coli* seeded on polypropylene in the OAUGDP investigation, a 30-sec exposure time is enough to effect a 6-log reduction in population whereas a longer 4.7 minutes is needed to effect the same reduction when the bacteria are embedded in agar [7.1]. The differences in exposure times on different surfaces can perhaps be attributed to the time of diffusion of active species and the nature of the treated cellular surface.

In the same OAUGDP investigation, electron micrographs are used to assess the effects of sub-lethal doses on *E. coli* cells, which show cell lysis and the presence of cell debris [7.2, 7.3]. The microbe destruction mechanism appears to be attacked by atomic oxygen produced by the discharge. The rate of microbe destruction begins slowly due to initial stress to the organism, followed by rapid destruction through membrane rupture.

7.4 Plasma-aided sterilization versus conventional method of sterilization

A number of industrial and university research groups have already demonstrated the remarkable ability of relatively cold ionized gases to rapidly kill bacteria cells while avoiding the problems or difficulties associated with the current conventional methods of sterilization. The available conventional techniques must deal with such problems as thermal sensitivity and destruction by heat as in dry heat [7.4] sterilization, damage due to moisture as in saturated steam sterilization [7.4], formation of toxic by-products as in

gaseous chemical sterilization [7.5], cost and inefficiency in performance as in sterilization by ionizing radiation [7.6].

The enhanced corona discharge can greatly reduce or eliminate high temperature, thermal sensitivity, moisture, toxic compounds, or harmful high-energy radiation associated with the standard sterilization processes mentioned above. This new approach may offer major advantages for both defense and commercial medical applications.

7.5 Antimicrobial mechanism and other unsolved issues

The antimicrobial or killing mechanism by the enhanced corona discharge on microorganism is not investigated at this moment. Perhaps, one can postulate that the discharge achieves its treatment effects as a result of the interaction of one or more active species from the plasma with the surface of interests. Such interaction causes cellular damage to the cellular sites reacting with the plasma-generated active species.

The active species may include: a) neutral particles such as monoatomic oxygen that is present in the plasma, b) the charged particles generated by ionization events or charge exchange, and c) the free radical such as molecular fragments generated by plasma-chemical reactions.

These active species are more chemically reactive and more energetic than the species associated with conventional chemical processing. It may not be a surprise if they play a major role in the killing of microorganisms by attacking the cellular sites.

The suggested putative plasma susceptible cellular sites include lipids, proteins, and/or DNA that encounters their respective peroxidations. For lipid peroxidation, the unsaturated fatty acids are susceptible to the attack by hydroxyl, generating lipid peroxide

that results in membrane (structural) damage and eventual cell-lysis. For protein peroxidation, most amino acids are susceptible to oxidation, resulting in loss of enzyme function and structural damage. DNA peroxidation results in oxygen adduct formation of nucleotide bases [7.1].

The unsolved antimicrobial mechanism is not typical in the enhanced corona discharge treatment of microorganisms. All plasma-aided processes for sterilization probably share the same but yet undetermined antimicrobial mechanisms.

Besides the antimicrobial mechanisms, there are other issues bothering the enhanced corona discharge as well as other plasma-aided processes for sterilization. One would like to know, for example:

1. Which plasma regime is most effective?
2. Which physical process plays the dominant sterilization role?
3. What biological and chemical processes induce the death of the cells?
4. What type of gas is more desirable for a particular application?

Microbiologists will more appropriately answer some of the questions posted above. However, it appears that plasma-aided sterilization requires shorter exposure times, is potentially practical and inexpensive, and is probably environmentally friendly. Applications could include medical (reusable medical tools), laboratory research, and environmental (soil and water treatment) usage.

7.6 Interdisciplinary nature of the plasma-aided sterilization research

It has been shown that plasma discharge at atmosphere pressure is a very effective sterilization agent. But more tests and an in-depth study of this process are needed to

settle the antimicrobial mechanisms and other issues posted in the previous section. Due to the complexity of constructing and testing of the apparatus and the sterilization test on microorganisms, the endeavor of plasma sterilization research should be conducted by multidisciplinary collaboration between physical and biological scientists, as well as practicing engineers. The more "biology" oriented works such as the preparation of the microorganisms and the analysis of the testing results should be conducted by microbiologists. Plasma scientists or engineers on the other hands are more at ease in building and characterizing the sterilization apparatus. When the sample is under sterilization test, both physical and biological scientists are ideally needed at the testing site. The isolation of the antimicrobial or killing mechanisms needs to be discussed thoroughly by both the physical and biological scientists, drawing their individual expertise to the quest for new method of sterilization.

7.7 Suggested future work

As described in chapter 6, the sterilization tests of only *Escherichia coli* and *Bacillus subtilis* embedded in agar have been performed using the enhanced corona discharge apparatus. This dissertation places quite an emphasis on the theory and the characterization of the enhanced corona discharge, and the design and construction of the discharge apparatus. Such emphasis is as essential as the sterilization test itself. Selected testing on *E. coli* and *B. subtilis* embedded in agar is just sufficient to establish initially the sterilization capability of the enhanced corona discharge.

While the preliminary testing result is encouraging, more tests need to be conducted by exposing different microorganisms embedded in different surfaces to the

discharge. To gather a broader spectrum of data, exposures of other bacteria (*Staphylococcus aureus* besides *Escherichia coli*), endospores (*Bacillus pumilus* besides *Bacillus subtilis*), and yeast on various porous and non-porous surfaces including polypropylene, paper strips, solid culture media, and glass should be performed. Bacteria endospores are needed for testing the effectiveness of the sterilizer because they are considered one of the most resistant cells to any lethal agent. Yeast such as *Saccharomyces cerevisiae* and *Candida albicans* can be tested to assay the aspect of the plasma on larger microorganisms of more complex structure. Polypropylene (PP) is selected as a seeded surface because it is an important material used in the medical and packaging industry.

Endeavor of these scopes could only be accomplished with the interdisciplinary cooperation between bio-scientists and physical scientists or engineers. With more testing data available and the interaction between the researchers, only can the antimicrobial mechanisms be fully investigated and understood. In the event that more data are available and the killing mechanism fully understood, an improved version of the enhanced corona discharge apparatus can be constructed, finally offering it as an alternative method of sterilization.

REFERENCES

REFERENCES

- [1.1] S. S. Block, ed., *Disinfection, Sterilization, and Preservation*, Lea & Febiger, Philadelphia, 1983.
- [1.2] J. F. Gardner, and M. M. Peel, *Introduction to Sterilization and Disinfection*, Churchill Livingstone, New York, 1986.
- [1.3] P. D. Nair, "Currently Practiced Sterilization Methods – Some Inadvertent Consequences," *J. of Biomaterials & Applications*, vol. 10, no. 2, Oct. 1995, pp. 121-135.
- [1.4] L. Joslyn, "Sterilization by Heat," in *Disinfection, Sterilization, and Preservation*, ed. by S. S. Block, 3rd edition, Lea & Febiger, Philadelphia, 1983, pp. 3-46.
- [1.5] J. F. Gardner, and M. M. Peel, *Introduction to Sterilization and Disinfection*, Churchill Livingstone, New York, 1986, pp. 64-82.
- [1.6] M. Laroussi, "Sterilization of Contaminated Matter with An Atmospheric Pressure Plasma," *IEEE Transaction on Plasma Science*, vol. 24, no. 3, June 1996, pp. 1188 – 1191.
- [1.7] P. E. Haney, B. A. Raymond, and L. C. Lewis, "Ethylene Oxide: An Occupational Hazard for Hospital Workers," *AORN Journal*, vol.51, no. 2, pp. 480-486, 1990.
- [1.8] W. R. Cline, and V. Coffey, "Why We Stopped Using EtO," *Materials Management in Health Care*, vol. 4, no. 1, 1995.
- [1.9] G. J. Silverman, "Sterilization by Ionization Irradiation," in *Disinfection, Sterilization, and Preservation*, ed. by S. S. Block, 3rd edition, Lea & Febiger, Philadelphia, 1983, pp. 89-105.
- [1.10] *The Economics of Sterilization in Healthcare*, Communicore, Friday Harbor, WA, 1998.
- [1.11] F. F. Chen, *Introduction to Plasma Physics and Controlled Fusion*, vol. I, Plasma Physics, 2nd edition, Plenum, New York, 1985.
- [1.12] National Research Council, *Plasma Processing of Materials: Scientific Opportunities and Technological Challenges*, National Academic Press, Washington, D.C., 1991.

- [1.13] National Research Council, *Plasma Science: From Fundamental Research to Technological Applications*, National Academic Press, Washington, D.C., 1995.
- [1.14] N. Hershkowitz, "Role of Plasma-Aided Manufacturing in Semiconductor Fabrication," *IEEE Transaction on Plasma Science*, vol. 26, no. 6, Dec. 1998, pp. 1610-1620.
- [1.15] *The National Technology Roadmap for Semiconductor Technology Needs*, Semiconductor Industry Association, 1997 Ed.
- [1.16] M. M. Jensen, D. N. Wright, and R. A. Robinson, "Microbiology for The Health Sciences," Prentice Hall, Upper Saddle River, NJ, 1997.
- [1.17] T. T. Chau, K. C. Kao, G. Blank, and F. Madrid, "Microwave Plasma for Low-Temperature Dry Sterilization," *Biomaterials*, vol. 17, no.13, 1996, pp. 1273-1277.
- [1.18] "Research Interests of the Air Force Office of Scientific Research and Broad Agency Announcement 97-1", Air Force Office of Scientific Research, Arlington, Virginia, VA, 1997.
- [1.19] K. H. Schoenbach, S. Liu, and R. J. Barker, "Announcing a Special Issue of IEEE Transactions on Plasma Science on Nonthermal Medical/Biological Treatments Using Electromagnetic Fields and Ionized Gases," *IEEE Transaction on Plasma Science*, vol. 26, no. 6, December 1998.
- [2.1] M. M. Jensen, D. N. Wright, and R. A. Robinson, "Microbiology for The Health Sciences," Prentice Hall, Upper Saddle River, NJ, 1997.
- [2.2] The American Heritage Dictionary, 2nd College Edition, Dell Publishing, New York, 1983.
- [2.3] S. S. Block, "Definition of Terms," in *Disinfection, Sterilization, and Preservation*, 3rd edition, edited by S. S. Block, Lea & Febiger, Philadelphia, 1983, pp. 879-880.
- [2.4] J. F. Gardner, and M. M. Peel, *Introduction to Sterilization and Disinfection*, Churchill Livingstone, New York, 1986, p. 3.
- [2.5] J. F. Gardner, and M. M. Peel, *Introduction to Sterilization and Disinfection*, Churchill Livingstone, New York, 1986, pp. 8-9.
- [2.6] J. F. Gardner, and M. M. Peel, *Introduction to Sterilization and Disinfection*, Churchill Livingstone, New York, 1986, pp. 4-6.

- [2.7] J. F. Gardner, and M. M. Peel, *Introduction to Sterilization and Disinfection*, Churchill Livingstone, New York, 1986, pp.14-29.
- [2.8] C. R. Stumbo, *Thermobacteriology in Food Processing*, 2nd edition, Academic Press, New York, chap. 7, p. 74, 1973.
- [2.9] S. S. Block, ed., *Disinfection, Sterilization, and Preservation*, Lea & Febiger, Philadelphia, 1983.
- [2.10] J. F. Gardner, and M. M. Peel, *Introduction to Sterilization and Disinfection*, Churchill Livingstone, New York, 1986.
- [2.11] L. J. Joslyn, "Sterilization by Heat," in *Disinfection, Sterilization, and Preservation*, 3rd edition, ed. by S. S. Block, Lea & Febiger, Philadelphia, 1983, pp. 3-46.
- [2.12] J. F. Gardner, and M. M. Peel, *Introduction to Sterilization and Disinfection*, Churchill Livingstone, New York, 1986, pp. 57-63.
- [2.13] C. W. Bruch, M. G. Koesterer, M. K. Bruch, "Dry Heat Sterilization: Its Development and Application to Components of Exobiological Space Probes," *Developments in Industrial Microbiology* 4: pp. 334-342, 1963.
- [2.14] H. Shaner, "Pollution Prevention for Nurses: Minimizing the Adverse Environmental Impact of Health Care Delivery," *Vermont Registered Nurse*, vol. 62, no. 4, 1996, pp. 1-9.
- [2.15] M. McCally, P. Orris, J. Thornton, and J. Weinberg, "Dioxin Prevention and Medical Waste Incinerators," *Public Health Reports*, July/August, 1996.
- [2.16] J. F. Gardner, and M. M. Peel, *Introduction to Sterilization and Disinfection*, Churchill Livingstone, New York, 1986, pp. 64-82.
- [2.17] B. Bolding, "Steam Sterilization Systems: How They Work, Part 1," *Canadian Operating Room Nursing Journal*, vol. 6, no. 3, June 1988, pp. 9-12.
- [2.18] H. D. Probst, "The Effects of Bacterial Agents on The Sterility of Surgical Linen," *Am. J. Surg.*, vol. 86, 1953, pp. 301-308.
- [2.19] C. W. Bruch, "Gaseous Sterilization," *Anna. Rev. Microbiol.*, vol.15, pp. 245-262, 1961.
- [2.20] C. R. Phillips, "Gaseous Sterilization," in *Disinfection, Sterilization, and Preservation*, 2nd edition, ed. by S. S. Block, Lea & Fibiger, Philadelphia, 1977.

- [2.21] R. A. Caputo, and T. E. Odlaug, "Sterilization with Ethylene Oxide and other Gases," in *Disinfection, Sterilization, and Preservation*, 3rd ed., ed. by S. S. Block, Lea & Febiger, Philadelphia, 1983, pp. 47-64.
- [2.22] D. A. Gunther, "The Chemistry and Biology of EtO Sterilization," *Medical Device & Diagnostic Industry*, 2(12): 31-35, 1980.
- [2.23] J. F. Gardner, and M. M. Peel, *Introduction to Sterilization and Disinfection*, Churchill Livingstone, New York, 1986, pp. 83-98.
- [2.24] *United States Pharmacopeia*, 20th rev., Mack Publishing Company, Easton, 1980, p. 1039.
- [2.25] G. T. Michael, and C. R. Stumbo, "Ethylene Oxide Sterilization of *Salmonella senftenberg* and *Escherichia coli*: Death Kinetics and Mode of Action," *J. Food Sci.*, vol. 35, 1970, p. 631.
- [2.26] V. M. Steelman. "Ethylene Oxide, The Importance of Aeration," *AORN Journal*, vol. 55, no. 3, 1992, pp. 773-783.
- [2.27] "Explosion Kills One, Injures 69," *The News-Sun* (Kendallville, Ind), June 25, 1997.
- [2.28] H. E. Bryant, N. D. Visser, and K. Yoshida, "Ethylene Oxide Sterilizer Use and Short-term Symptoms Amongst Workers," *J. of Social and Occupational Medicine*, vol. 39, no. 3, 1989, pp. 101-106.
- [2.29] R. E. Haney, B. A. Raymond, L. C. Lewis, "Ethylene Oxide: An Occupational Health Hazard for Hospital Workers," *AORN Journal*, vol. 51, no. 2, 1990, pp. 480-486.
- [2.30] G. R. Holyoak, S. Wang, Y. Liu, and T. D. Bunch, "Toxic Effects of Ethylene Oxide Residues on Bovine Embryos in Virto," *Toxicology*, vol. 108, 1996, pp. 33-38.
- [2.31] C. Hogstedt, L. Aringer, and A. Gustavsson, "Epidemiologic Support for Ethylene Oxide as A Cancer Causing Agent," *JAMA*, vol. 255, 1986, pp. 1575-1578.
- [2.32] Occupational Safety and Health Administration, "Occupational Exposure to Ethylene Oxide: Final Standard," *Federal Register*, vol. 49, 1984, pp. 25734-25809.
- [2.33] Occupational Safety and Health Administration, "Occupational Exposure to Ethylene Oxide: Final Standard (Amended)," *Federal Register*, vol. 53, 1988, pp. 11414-11438.

- [2.34] Environmental Protection Agency, "National Emission Standards for Hazardous Air Pollutants for Ethylene Oxide Commercial Sterilization and Fumigation Operation: Final Rule," *Federal Register*, Doc. No. 94-29823, 1994.
- [2.35] J. F. Gardner, and M. M. Peel, *Introduction to Sterilization and Disinfection*, Churchill Livingstone, New York, 1986, pp. 99-115.
- [2.36] G. J. Silverman, "Sterilization by Ionizing Irradiation," in *Disinfection, Sterilization, and Preservation*, 3rd edition, ed. by S. S. Block, Lea & Febiger, Philadelphia, 1983, pp. 89-105.
- [2.37] J. Maesfield, "Advances Made in Cobalt-60 Gamma Sterilization," in *Sterilization of Medical Products*, Vol. II, edited by E. R. L. Gaughran and R. F. Morrissey. Montreal, Multiscience Publ. Ltd., 1981.
- [2.38] J. Henkel, "Irradiation: A Safe Measure for Safer Food," *FDA Consumer*, vol. 32, no. 3, May/June 1998, pp. 12-17.
- [2.39] I. L. Shechmeister, "Sterilization by Ultraviolet Irradiation," in *Disinfection, Sterilization, and Preservation*, 3rd edition, S. S. Block ed., Lea & Febiger, Philadelphia, 1983, pp. 106-124.
- [2.40] W. Ham, *Biological Effects of UV Radiation*, Cambridge U. Press, New York, 1980.
- [2.41] K. C. Smith, and C. Hanawalt, *Molecular Photobiology: Inactivation and Recovery*, Academic Press, New York, 1969.
- [2.42] R. Dulbecco, "Photoreactivation," in *Radiation Biology*, vol. 2, ed. By A. Hollaender, McGraw Hill, New York, 1955, pp. 455-486.
- [2.43] J. F. Gardner, and M. M. Peel, *Introduction to Sterilization and Disinfection*, Churchill Livingstone, New York, 1986, pp. 116-130.
- [2.44] J. F. Gardner, and M. M. Peel, *Introduction to Sterilization and Disinfection*, Churchill Livingstone, New York, 1986, pp. 131-149.
- [2.45] P. D. Nair, "Currently Practiced Sterilization Methods – Some Inadvertent Consequences," *J. of Biomaterials & Applications*, vol. 10, no. 2, Oct. 1995, pp. 121-135.
- [2.46] *The Economics of Sterilization in Healthcare*, Communicore, Friday Harbor, WA, 1998.

- [2.47] W. R. Cline, and V. Coffey, "Why We Stopped Using EtO," *Materials Management in Health Care*, vol. 4, no. 1, 1995.
- [2.48] R. Seavey, "Out of Gas: Replacing EtO Sterilization," *Today's Surgical Nurse*, vol. 9, no. 2, 1997, pp. 27-32.
- [2.49] *ElectroMed99 Symposium Record Abstract*, First International Symposium on Nonthermal Medical/Biological Treatments Using Electromagnetic Fields and Ionized Gases, Norfolk, VA, April 12-14, 1999.
- [2.50] B. Elinsson, and U. Kogelschatz, "Nonequilibrium Volume Plasma Chemical Processing," *IEEE Transaction on Plasma Science*, vol. 19, no. 6, Dec. 1991.
- [2.51] W. P. Menashi, "Treatment of Surfaces," *United States Patent*, No. 3,383,163, 1968.
- [2.52] S. J. Fraser, R. B. Gillette, R. L. Olson, "Sterilizing and Packaging Process Utilizing Gas Plasma," *United States Patent*, No. 3,851,438, Dec. 1974.
- [2.53] G. Boucher, M. Raymond, "Seeded Gas Plasma Sterilization Method," *United State Patent*, No. 4,207,286, Jan. 1980.
- [2.54] R. M. Bithell, "Plasma Process Pulse Sterilization," *United State Patent*, No. 4,348,357, Sept. 1982.
- [2.55] P. T. Jacobs, and S. M. Lin, "Hydrogen Peroxide Plasma Sterilization System," *United State Patent*, No. 4,643,876, Feb. 1987.
- [2.56] P. T. Jacobs, and S. M. Lin, "Hydrogen Peroxide Plasma Sterilization System," *United State Patent*, No. 4,756,882, July 1988.
- [2.57] P. T. Jacobs, S. M. Lin, and D. Timm, "Hydrogen Peroxide Vapor and Low Temperature Gas Plasma Method for Sterilization Medical Devices Without Leaving Toxic Residue," *Proceedings of the Largest International Non-woven Technology Conference*, 1998, Assoc. Non-woven Fabrics Ind., Cary, NC, USA, pp. 17.1-17.15.
- [2.58] P. T. Jacobs, "Mechanism and Validation Issues in Gas Plasma Sterilization," in *Frontiers in Sterilization Practice: The Future of Low-Temperature Technology*, ed. D. S. Robins, Communicore, Newport Beach, CA, 1996, pp. 73-84.
- [2.59] P. T. Jacobs, *STERRAD® 50 Sterilization System*, Advanced Sterilization Products, Irvine, CA 1999.

- [2.60] Private conversation with Professor Igor Alexeff of the University of Tennessee.
- [2.61] Y. Ku, H. Tong, K. Kelly-Wintenberg, T. C. Montie, and J. R. Roth, "Sterilization of Materials with a One Atmosphere Uniform Glow Discharge Plasma," *Bulletin of the American Physical Society, Plasma Physics*, vol. 40, no. 11, Oct. 1995, paper 2R5, p. 1685.
- [2.62] Y. Ku, C. Brickman, K. Kelly-Wintenberg, T. C. Monte, P. Tsai, L. Wadsworth, and J. R. Roth, "Sterilization of Material Using a One Atmosphere Uniform Glow Discharge Plasma," *IEEE Conf. Record-Abstract*, 1996 IEEE ICOPS, 96CH35939, June 1996, paper 2IP15, p. 175.
- [2.63] M. Laroussi, "Sterilization of Tools and Infectious Waste by Plasma," *Bulletin of the Am. Phys. Soc., Plasma Physics*, vol. 40, no. 11, Oct. 1995, paper 2R6, p. 1685.
- [2.64] M. Laroussi, M. Rader, F. Dyer, M. Dever, and I. Alexeff, "Plasma Aided Sterilization," *Bulletin of the Am. Phys. Soc., Plasma Physics*, vol. 40, no. 7, Nov. 1996.
- [2.65] M. Laroussi, "Sterilization of Contaminated Matter with An Atmosphere Pressure Plasma," *IEEE Transaction on Plasma Science*, vol. 20, no. 3, June 1996, pp. 1188-1191.
- [2.66] J. R. Roth, P. Tsai, C. Liu, M. Laroussi, and P. D. Spence, "One Atmosphere Uniform Glow Discharge Plasma," U. S. Patent, No. 5,414,324, May, 1995.
- [2.67] A. Carr, J. R. Roth, C. Brickman, K. Kelly-Winterburg, T. C. Monte, P. Tsai, and L. Wadsworth, "Killing Microorganisms in A Sealed Sterilization Bag with a OAUGDP," 1997 IEEE ICOPS, 97CH36085, June 97, paper 4Q20, p.230.
- [2.68] G. Karet, "R and D: Research and Development Kobe Steel Engineering Reports," vol. 41, no. 1, Jan. 1999.
- [2.69] K. Sorge, J. R. Roth, K. Kelly-Wintenberg, T. C. Montie, P. Tsai, and L. Wadsworth, "Broad Spectrum Killing of Microorganisms with One Atmosphere Uniform Glow Discharge Plasma (OAUGDP)," *Proceedings of IEEE International Conference on Plasma Sciences*, 1998, IEEE, Piscataway, NJ, USA, 98CH36221, p. 288, paper 6P61.
- [3.1] L. B. Loeb, *Electrical Corona – Their Basic Physical Mechanisms*, University of California Press, Berkeley, LCCCN 64-18642, 1965.
- [3.2] R. S. Sigmond, and M. Goldman, "Corona Discharge Physics and Applications," in *Electrical Breakdown and Discharges in Gases*, E. E. Kunhardt and L. H. Luessen, Eds., Plenum Inc., New York, 1983, pp. 1-64.

- [3.3] J. S. Chang, P. A. Lawless, and T. Yamamoto, "Corona Discharge Processes," *IEEE Trans. on Plasma Sci.*, vol. 19, no. 6, Dec. 1991, pp. 1152-1166.
- [3.4] W. L. Kang, M. Rader, and I. Alexeff, "An Air Plasma," *Bulletin of the Am. Phys. Soc. Plasma Physics*, Vol. 39, No. 7, Nov. 1994, paper 6T7, p. 1689.
- [3.5] M. Rader, I. Alexeff, P. P. Tsai, and L. C. Wadsworth, "Electrostatic Charging Apparatus and Method," United States Patent, No. 5,592,357, Jan. 7, 1997.
- [3.6] I. Alexeff and W. L. Kang, "An Enhanced Ionizer," *IEEE Trans. on Plasma Sci.*, Vol. 27, No. 1, Feb. 1999, pp. 32-3.
- [3.7] J. M. Meek and J. D. Craggs, ed., *Electrical Breakdown of Gases*, John Wiley & Sons, New York, 1978.
- [3.8] E. E. Kunhardt, and L. H. Luessen, eds., *Electrical Breakdown and Discharges in Gases*, Plenum Inc., New York, 1983.
- [3.9] J. Reece Roth, *Industrial Plasma Engineering, Volume 1, Principle*, IOP Publishing Ltd., Bristol and Philadelphia, 1995, p. 149.
- [3.10] M. A. Lieberman, and A. J. Liechtenberg, *Principles of Plasma Discharges and Materials Processing*, Wiley, New York, 1994.
- [3.11] E. Kuffel, and W. S. Zaengl, "High Voltage Engineering – Fundamentals," Pergamon Press, Oxford, 1992, p. 360.
- [3.12] J. D. Cobine, *Gaseous Conductors*, Dover Publications, Inc., New York, 1958, p. 163.
- [3.13] J. Reece Roth, *Industrial Plasma Engineering, Volume 1, Principle*, IOP Publishing Ltd., Bristol and Philadelphia, 1995, p. 266.
- [3.14] F. Carreno and E. Bernabeu, "On Wire-to-Plane Positive Corona Discharge," *J. Appl. Phys. D*, vol. 27, no. 10, pp. 2136-2144, 1994.
- [3.15] F. Pontiga, C. Soria, and A. Castellanos, "Electrical and Chemical Model of Negative Corona in Oxygen at Atmosphere Pressure," *J. Electrostatics*, vol. 40-41, pp. 115-210, June 1997.
- [3.16] E. Kuffel and W. S. Zaengl, *High Voltage Engineering – Fundamentals*, Pergamon Press, Oxford, 1992, p.382.

- [4.1] M. Rader, I. Alexeff, P. P. Tsai, and L. C. Wadsworth, "Electrostatic Charging Apparatus and Method," *United States Patent*, No. 5,592,357, Jan. 7, 1997.
- [5.1] G. Francis, "The Glow Discharge at Low Pressure," in *Encyclopedia of Physics, Gas Discharges II*, vol. XXII, S. Flugge Ed., Springer-Verlag, Berlin, Germany, 1956.
- [5.2] S. Ramakrishnan and M. W. Rogozinski, "Properties of Electric Arc Plasma for Metal Cutting," *J. Appl. Phys. D*, vol. 30, pp. 636-644, 1997.
- [5.3] M. Goldman and R. S. Sigmond, "Corona and Insulation," *IEEE Trans. Elect. Insulation*, vol. EI-17, no. 2, pp. 90-105, 1982.
- [5.4] R. S. Sigmond and M. Goldman, "Corona Discharge Physics and Applications," in *Electrical Breakdown and Discharges in Gases*, E. E. Kundhardt and L. H. Luessen, Eds., Plenum Inc., New York, 1983, pp. 1-64.
- [5.5] F. F. Chen, *Introduction to Plasma Physics and Control Fusion*, Plenum Press, New York, 1990, p.67.
- [5.6] B. Chapman, *Glow Discharge Process*, John Wiley & Sons, New York, 1980, p. 109.
- [5.7] J. D. Cobine, *Gaseous Conductors: Theory and Engineering Applications*, Dover Publications, Inc., New York, 1958, p. 38.
- [5.8] D. L. Book, *NRL Plasma Formulary*, Naval Research Laboratory, Washington, DC, 1990, p. 15.
- [6.1] J. Kluger, "Anatomy of An Outbreak," *Time*, vol. 152, no. 5, August 3, 1998, pp. 56 - 62.
- [6.2] V. D. Smith, "The New *E. coli* Nightmare," *Good Housekeeping*, vol. 226, no. 4, April 98.
- [6.3] T. Morganthau, "*E. coli* Alert: Beef Recall Due to Hamburger Contamination of Hudson Foods Patties," *Newsweek*, vol. 130, Sept 1997, pp. 26-32.
- [6.4] E. Garate, K. Evans, O. Gornostaeva, I. Alexeff, W. L. Kang, M. Rader, and T. K. Wood, "Atmospheric Plasma Induced Sterilization and Chemical Neutralization," *IEEE Conference Record-Abstracts, 1998 IEEE International Conference on Plasma Science, 98CH36221*, June 1998, paper 3D02-03, p. 183.

- [6.5] K. Kelly-Wintenberg, T. C. Montie, C. Brickman, J. R. Roth, A. Carr, K. Sorge, L. Wadsworth, and P. Tsai, "Room Temperature Sterilization of Surfaces and Fabrics with A One Atmosphere Uniform Glow Discharge Plasma," *Journal of Industrial Microbiology and Biotechnology*, vol. 20, no. 1, 1998, pp. 69-74.
- [6.6] T. C. Monte, K. Kelly-Wintenberg, and J. R. Roth, "An Overview of Research Using a One Atmosphere Uniform Glow Discharge Plasma (OAUGDP) for Sterilization of Surfaces and Materials," *ElectroMed99 Symposium Record Abstract*, First International Symposium on Nonthermal Medical/Biological Treatments Using Electromagnetic Fields and Ionized Gases, Norfolk, VA, April 12-14, 1999, p. 27.
- [7.1] T. C. Monte, K. Kelly-Wintenberg, and J. R. Roth, "An Overview of Research Using a One Atmosphere Uniform Glow Discharge Plasma (OAUGDP) for Sterilization of Surfaces and Materials," *ElectroMed99 Symposium Record Abstract*, First International Symposium on Nonthermal Medical/Biological Treatments Using Electromagnetic Fields and Ionized Gases, Norfolk, VA, April 12-14, 1999, p. 27.
- [7.2] K. Kelly-Wintenberg, T. C. Montie, C. Brickman, J. R. Roth, A. Carr, K. Sorge, L. Wadsworth, and P. Tsai, "Room Temperature Sterilization of Surfaces and Fabrics with A One Atmosphere Uniform Glow Discharge Plasma," *Journal of Industrial Microbiology and Biotechnology*, vol. 20, no. 1, 1998, pp. 69-74.
- [7.3] M. Laroussi, G. S. Sayler, B. B. Glascock, B. McCurdy, M. E. Pearce, N. G. Bright, and C. M. Malott, "Images of Biological Samples Undergoing Sterilization by A Glow Discharge at Atmospheric Pressure," *IEEE Transaction on Plasma Science*, vol. 27, no. 1, Feb. 1999, pp. 34-35.
- [7.4] P. D. Nair, "Currently Practiced Sterilization Methods – Some Inadvertent Consequences," *J. of Biomaterials & Applications*, vol. 10, no. 2, Oct. 1995, pp. 121-135.
- [7.5] P. E. Haney, B. A. Raymond, and L. C. Lewis, "Ethylene Oxide: An Occupational Hazard for Hospital Workers," *AORN Journal*, vol. 51, no. 2, pp. 480-486, 1990.
- [7.6] *The Economics of Sterilization in Healthcare*, Communicore, Friday Harbor, WA, 1998.

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