DESIGN AND FABRICATION OF AN ION PROPULSION AIRPLANE

Group Members:

19-ME-057	**Zeeshan Ahmad**
19-ME-163	**Muzzamil Mehmood**
19-ME-167	**Sumroz Ali**
19-ME-187	**Azam Bilal Abbasi**

Project Supervisor

Imran Sajid Shahid Ghumman

Lecturer

MECHANICAL ENGINEERING DEPARTMENT
HITEC UNIVERSITY, TAXILA

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THESIS IS SUBMITTED TO THE FACULTY OF THE DEPARTMENT OF MECHANICAL ENGINEERING, HITEC UNIVERSITY, TAXILA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF BACHELOR'S OF SCIENCE IN MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

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Submitted by

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DEDICATION

I want to dedicate this thesis to my parents, who sacrificed what little they had to provide me with the chance to pursue higher education. I now possess a key that can be used to solve the challenges of our world, and beyond.

ACKNOWLEDGEMENTS

The journey to completing this project was challenging and full of learning, but with **ALMIGHTY ALLAH** assistance and mercy, the advice of professionals, and the support of family and friends, we succeeded.

We would like to thank our supervisor, **Imran Sajid Shahid Ghumman** for his magnificent guidance and support. Mr. Imran's guidance and advice were really helpful in our project and his continuous support was crucial, through which we tackled the hardships. We also want to thank our university for allowing us to conduct this project and providing any assistance requested. Special thanks to the Head of the Department Dr. **LIAQAT** for their continued support. We would like to thank our parents; this task was difficult without their prayers and cooperation. Their prayers and sacrifices throughout our lives have given us tremendous strength to overcome every difficulty in our life

We would like to thank our friends in university and outside the university who have helped us in completing this task, especially, Mr. Umair.

In last, we would like to dedicate this project to our beloved country Pakistan, we pray that may our country remains prosperous and achieves its goals, Ameen.

ABSTRACT

The aerospace engineering profession has made significant strides with the development of the ion propulsion system, which opens up previously unimaginable opportunities for efficient and environmentally friendly air travel. This final-year project intends to design, build and assess the viability of an ion propulsion system technology. The project involves a thorough analysis of fundamental concepts and technical features of the ion propulsion system, including the investigation of various ionization strategies and propellant possibilities. Numerical simulation will be used in conjunction with the theoretical study to analyze the performance traits, effectiveness, and operational parameters of the proposed ion propulsion system. During the design stage, the ion propulsion configuration will be optimized while considering things like environmental factors, power requirement, size, and distance. In order to ensure flawless operation and compatibility with other subsystems, the propulsion system will be integrated into the structure of the test bench for experiments. The thrust generation, energy consumption, and overall effectiveness of the ion propulsion system will be evaluated experimentally. To determine areas for additional improvement and to evaluate the accuracy of the suggested design, the experimental findings will be compared with theoretical predictions. The benefit of the technology, including lower emissions, and higher fuel efficiency have the potential to revolutionize air travel by enabling more environmentally friendly operations. Additionally, this project's research will add to the body of knowledge developing in the area of ion propulsion systems, opening the door for new development and applications in aeronautical engineering. In conclusion, this final year project aims to investigate, design and test an ion propulsion system to revolutionize air travel by offering a cost-effective and environmentally friendly alternative to conventional combustion-based propulsion systems.

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NOMENCLATURE

Abbreviation/symbol / Greek alphabet	Nomenclature
NASA	National Aeronautics and Space Administration
P	Power
V	Voltage
I	Current
J	Electric current density
A	Discharge Cross section
ρ	Charge density
v	Velocity of charges
μ	Ion mobility (Constant)
Ē	Electric field magnitude
e	Unit charge
N	Number of electrons

L	Distance Between Electrodes
EHD	Electro hydrodynamics
HVPC	High Voltage Power Supply
T	Thrust
LOPT	Line output Power Transformer
LCA	Life Cycle Assessment

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CHAPTER-1

INTRODUCTION

1.1 Electro-Aerodynamics (EAD):

The study of fluid dynamics known as electro aerodynamics, commonly referred to as electrohydrodynamic or electric wind, examines how ionized gases (plasmas) behave when exposed to electric fields. It focuses on the interactions between electrically charged and neutral particles in a gas or fluid medium.

Electro aerodynamics encompasses the study of ionized gases and their interaction with electric fields, with applications ranging from air purification to microfluidics and atmospheric physics with continued efforts to investigate its possibilities in numerous domains and deepen our understanding of plasma dynamics, it remains an active topic of research.

1.2 Corona Discharge:

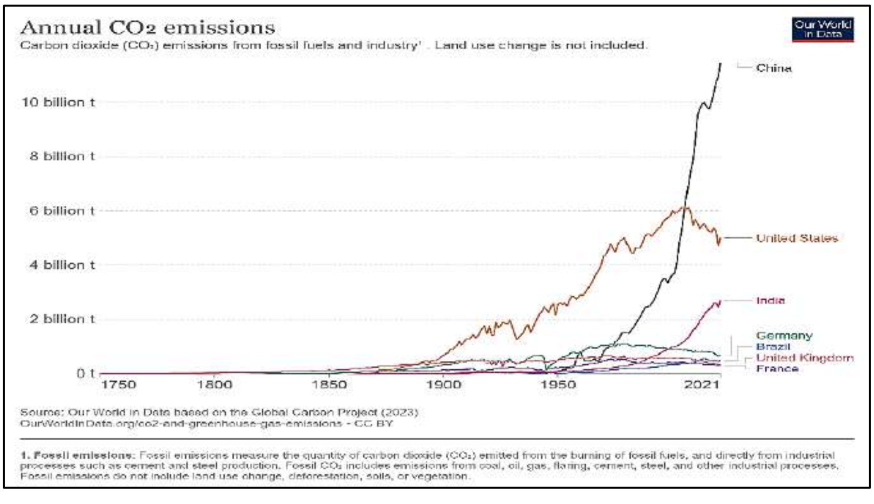
When the air around a conductor is ionized by a strong electric field, a phenomenon known as a corona discharge occurs, resulting in a visible glowing discharge or halo. It generally happens on conductors exposed to high voltages at their sharp edges or tips.

The air molecules become ionized when the electric field intensity rises above a specific limit known as the breakdown voltage. Atoms lose their electrons, resulting in positively charged ions and negatively charged free electrons. The corona discharge can occur when these charged particles flow through the atmosphere.

1.3 Environmental Impact:

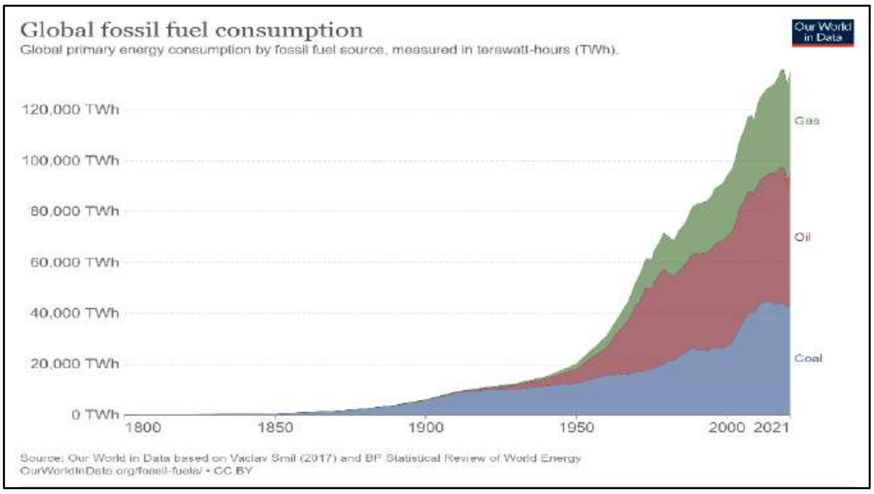
Transportation is highly dependent on fossil fuels, leading to carbon emissions and environmental degradation. Scientists believe that human activities have increased the number of carbon-containing gases in the high atmosphere as well as the number of small particles in the lower atmosphere, which are both factors in the current warming of the climate. Scientists refer to the microscopic particles as "black carbon" and believe that the lower atmosphere's ensuing layer of black particles, which acts as a blanket to trap heat, causes the warming impact.

The graph given below shows the annual carbon emissions caused by fossil fuels that strongly affected the environment and it reaches the highest-level causing air pollution it also shows the carbon emissions caused by different countries worldwide. The countries which add most of the value are highly developed countries on top of the list is China which leads to an unhealthy environment.

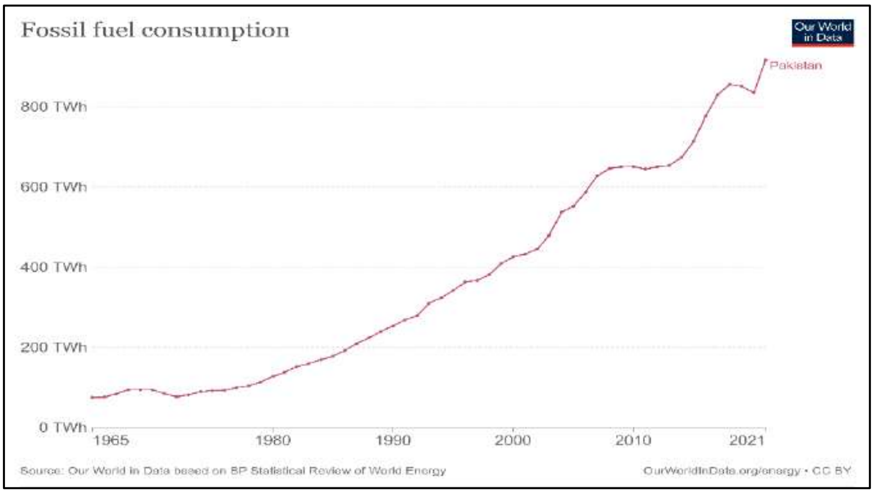


Graph 1.1: Annual CO_2 emissions

The graph shown below shows that global primary energy comes from which fuel consumption as we see gas is mostly used fossil fuel in the world and the combustion of gas produces air pollutants that damage the environment and cause global warming.



Graph 1.2: Global fossil fuel consumption



Graph 1.3: Fossil fuel consumption in Pakistan

As fossil fuel combustion is undeniably associated with significant adverse impacts on the environment. The release of greenhouse gases, such as carbon dioxide, during combustion, contributes to global warming and climate change. Additionally, the emission of air pollutants, including nitrogen oxides and sulfur dioxide, leads to air pollution and its detrimental effects on human health and ecosystems. In this context, exploring alternative technologies becomes imperative, and ion propulsion technology presents itself as promising. Ion propulsion systems, powered by electricity and utilizing ionized particles for propulsion, offer several environmental advantages. They produce minimal emissions, reducing the release of greenhouse gases and air pollutants.

1.4 Technology Advancement:

Aviation has made significant advances in more efficient and sustainable propulsion systems. As we strive to address the challenges posed by environmental concerns and resource limitations. The aviation industry is changing due to the search for engines not powered by fossil fuels. One notable development in the pursuit of greener aviation is the exploration of electric and hybrid-electric propulsion systems. These systems offer the potential for reduced carbon emissions and improved fuel efficiency. Electric aircraft, powered by batteries or fuel cells, have the advantage of zero direct emissions during flight.

1.5 Ion Propulsion:

Ion propulsion, sometimes referred to as ion thruster technology, is an electric propulsion method that produces thrust in spacecraft. Compared to conventional chemical rockets, which generate thrust by burning fuel, Ion propulsion uses electricity to ionize and accelerate propellant particles to high speeds.

Ion Propulsion technology works in a way that high voltage is applied between two conducting electrodes which ionizes the nitrogen present inside the air. The nitrogen is then made positively charged by ionizing it by removing electrons from its atoms. Electric fields are used to accelerate the ions. The ions are attracted to the negatively charged electrode and speed up as they pass through the electrode's tiny gaps and collide with the neutral particles in the air and giving them momentum to flow and produce wind.

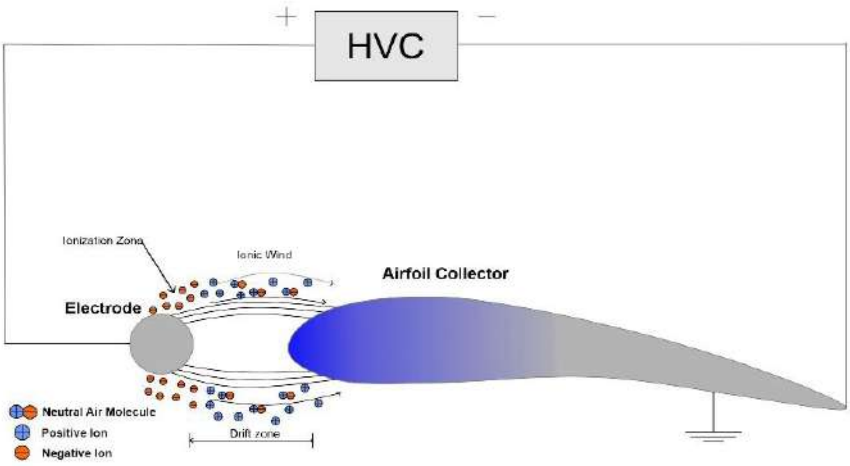


Figure 1.1: Schematic Diagram of Wind Generation between Two Conducting Electrodes

Since its origin, ion propulsion technology has been advancing. The origin of the idea can be found in Robert H. Goddard's early 19th-century work on electric propulsion and plasma physics. The development of ion propulsion was greatly aided by Harold R. Kaufman's work at the NASA Lewis Research Centre in the 1950s. Various space agencies and institutions around the world are now conducting continuous research and development to advance ion propulsion.

Ion Propulsion Technology has made great strides in recent years. As we navigate an increasingly complex and interconnected world, it becomes imperative to explore new avenues of research that contribute to our understanding and address the emerging challenges in ion propulsion technology.

1.6 Organizations Contribution

Ion propulsion technology is used by different organizations. NASA (National Aeronautics and Space Administration), European Space Agency (ESA), and Japan Aerospace Exploration Agency (JAXA) have used this technology in their spacecraft sent for space missions. This technology is also used for LED chip cooling systems.

1.7 Research Objective

The main objective of this research paper is to increase the thrust produced by the multi-stage ion thruster enabling exceptional efficiency. By extending the capabilities of ion propulsion technology beyond existing achievements, we contribute to the ongoing efforts in sustainable aviation and propulsion system innovation. Our research is also focused on understanding the feasibility and potential of ion propulsion technology in aircraft design and fabrication.

To achieve our research objectives, we do a detailed research methodology that combines theoretical analysis, numerical simulations, and experimental investigations. The methodology involves an extensive literature review to establish a solid foundation of knowledge on ion propulsion technology, existing limitations, and potential improvements. We do 1D and 2D studies on COMSOL on ion mobility. We will conduct numerical simulations to optimize the design parameters for maximizing the thrust. Additionally, we will perform prototype fabrication and testing to validate the proposed enhancements and assess the performance of the multi-stage ion thruster. The research will also consider potential challenges and safety considerations associated with the design and fabrication process.

1.8 Motivation

The motivations behind adopting ion propulsion technology lie in the urgent need to reduce emissions, minimize environmental impact, and enhance performance. Ion propulsion features unique characteristics, including reduced emissions, and improved and potential operational cost savings. Inspired by recent advancements in the field, particularly those by MIT, this research endeavors to build upon existing knowledge and contribute original insights to propel the development of ion propulsion technology.

CHAPTER-2

LITERATURE REVIEW

2.1 Jack Wilson [1]

2.1.1 Introduction:

The paper titled "An Investigation of Ionic Wind Propulsion" explores the concept and feasibility of using ionic wind propulsion for aerospace applications. Ionic wind propulsion, also known as electro-aerodynamic propulsion, utilizes electric fields to generate airflow and provide thrust. This study's goal was to see whether this thrust could be scaled to an amount that would be useful for airplane propulsion. Different types of electrodes are used for the experimentation and then compare based on their experimental performance and efficiency. This paper also shows the effect on the thrust produced by increasing the applied voltage.

2.1.2 Experimental Setup:

In the experimental setup, ionic wind tests are performed and corona discharge lifters of two types are used in the experiment.

The hexagonal lifter is the first setup that contains horizontal bars as collector electrodes and they are covered with aluminum foil. The lifter contains six equilateral triangles and, on each side, the collector electrodes are attached. Wires are used as an emitter electrode. and a high-voltage supply is attached to the setup.

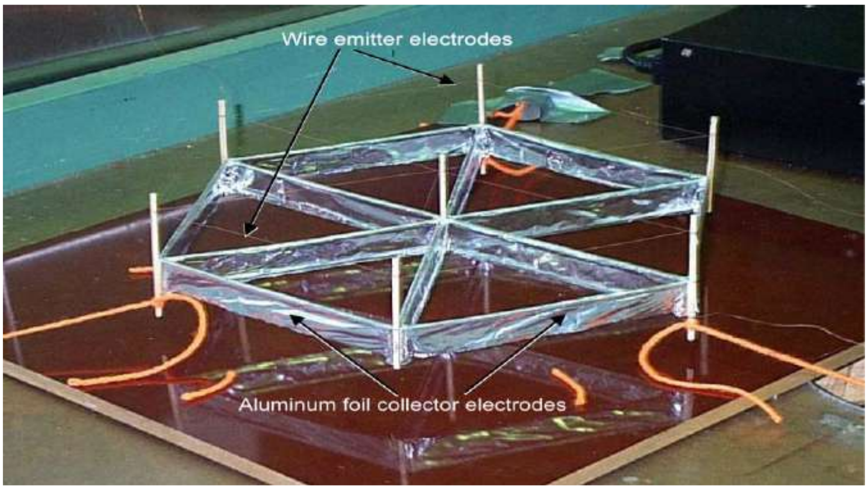


Figure 2.1.1: Hexagonal Lifter

The box lifter is the second setup in which two experiments are performed in the first experiment bow lifter contains thirteen collector electrodes that are parallel to each other to make them a conductor they are covered with aluminum foil and all these electrodes are set in a square duct and copper wires are used as emitter electrodes and high voltage supply is attached with the setup.

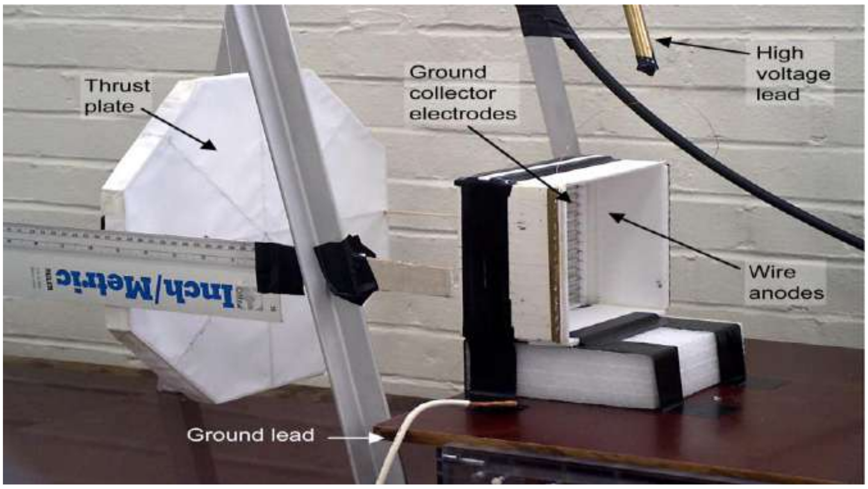
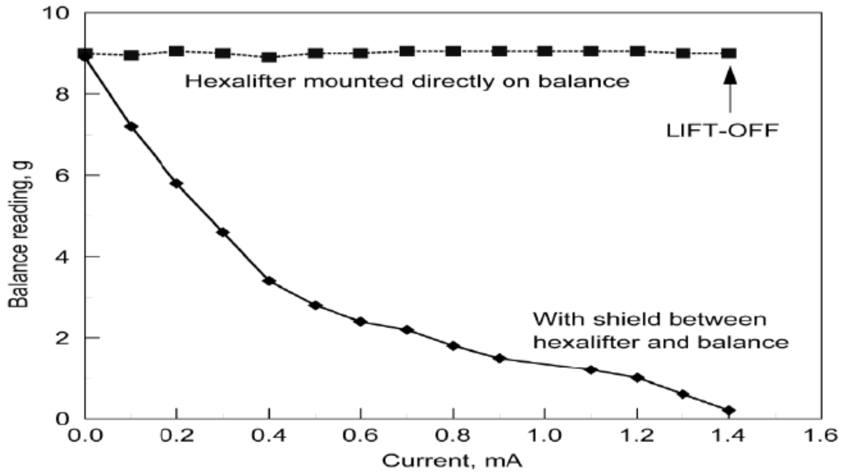


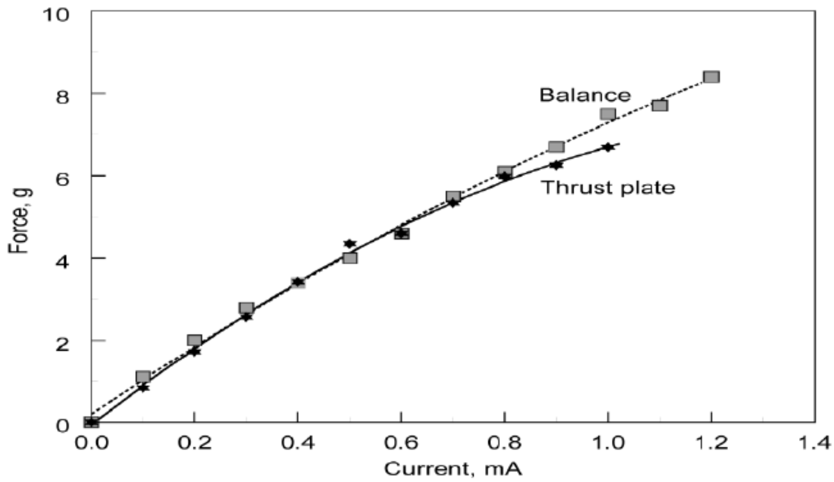
Figure 2.1.2: Box lifter

In the second experiment, there is a thrust plate also present with the box lifter that is made of basswood and covered with paper and there are shafts that are passing through the plate and the purpose of this is that the wires are attached with the end that is passing through to hold the thrust plate.

The reading taken by all three experiments are shown in the graph below



Graph 2.1.1: Balance readings versus current



Graph 2.1.2: Box lifter force on balance and thrust plate.

2.1.3 Emitters Comparison and Experimentation:

In the emitter's comparison, the author compares the pin and wire emitters and suggestions from previous studies that emitters are superior to wires so the two experiments are performed using pins. In the first experiment, there are five pins with an emitter electrode, and in the second experiment, 254 pins are attached to the brush electrode and taking various variables under consideration.

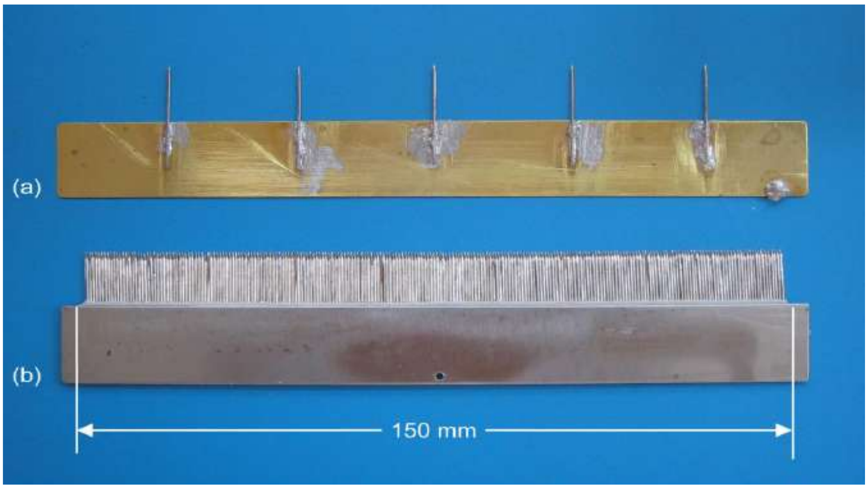


Figure 2.1.3: (a) Five pins with emitter electrode (b) 254 pins with emitter electrode

The experiment is performed for optimum separation of electrodes in which per electrode there are fifteen pins and three emitter electrodes with separation of four electrodes and pin tip radius and critical voltages for different configurations are found out. Results are shown in the tables below

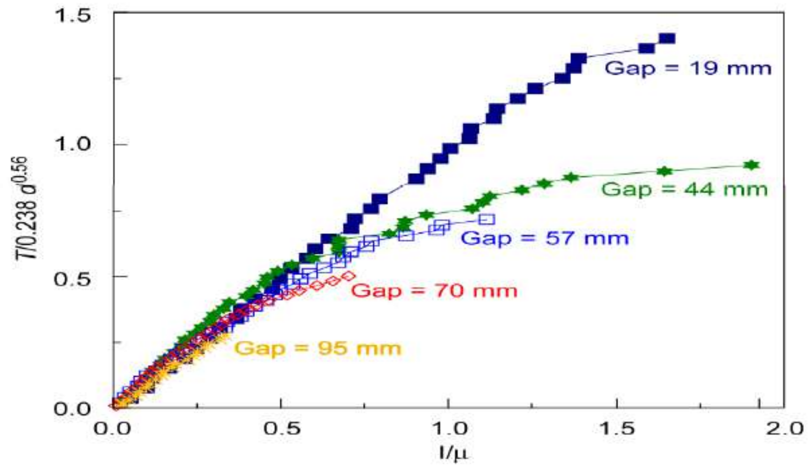
Separation, mm	Voltage, kV	Thrust, N	θ, N/kW
9.5	25.3	0.02	0.79
19	24.3	0.02	0.82
38	22.4	0.023	1.03
57	22.1	0.02	0.90

Table 2.1.1: The separation of three emitters varied results

Electrode array	Tip radius, r, μm	Critical voltage, kV
One electrode with two hundred fifty-four pins	10	12.5
Seven electrodes with seven household pins	10	10
Three electrodes with five household pins	10	7.5
Three electrodes with five tungsten pins	2	5

Table2.1.2: Critical voltages for different electrode configurations

Due to the use of pins as a collector, the thrust results are also affected by the gap size, and the value of five different sizes of the gap is taken and across them, thrust is found.



Graph 2.1.3: Thrust plotted against current/mobility

In summary, this paper provides a comprehensive investigation of ionic wind propulsion, exploring its principles, performance characteristics, and potential applications in aerospace. The findings contribute to the understanding of this innovative propulsion technology and highlight its potential as a viable alternative in the aerospace industry.

2.2 Kento Masuyama and Steven R. H. Barrett [2]

2.2.1 Introduction:

The paper titled "On the Performance of Electrohydrodynamic Propulsion" explores the performance characteristics of electrohydrodynamic (EHD) propulsion systems. EHD propulsion involves the generation of airflow or fluid flow by applying an electric field to a conductive fluid. The authors investigate the efficiency and effectiveness of EHD propulsion through a combination of experimental measurements and theoretical analysis and evaluate the performance of single-stage thruster and double-stage configuration and compare the performances of both. They focus on the relationship between the applied electric field, fluid flow velocity, and the resulting thrust generated by the EHD system and find the thrust-to-power ratio.

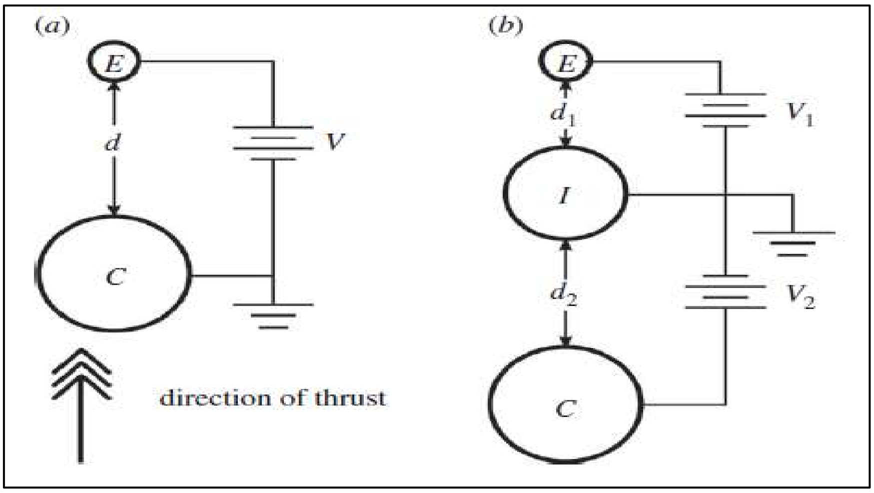


Figure 2.2.1: (a) Single-stage thruster electrodes. (b) Dual-stage thruster electrodes

2.2.2 Experimental Setup:

In the experimental setup to test both single-stage thruster and double-stage thruster, they made a frame of the square thruster and made a design in a way to allows interelectrode gap adjustments. They take an aluminum pipe as a collector and copper wire as an emitter.

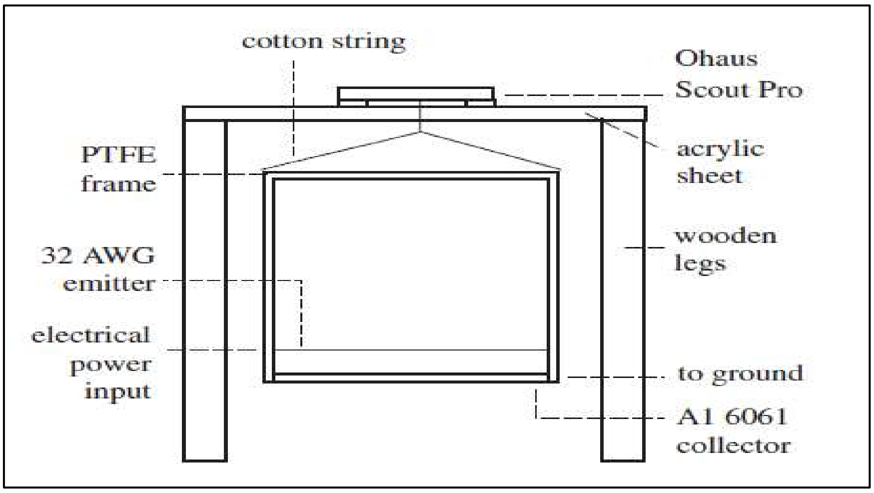
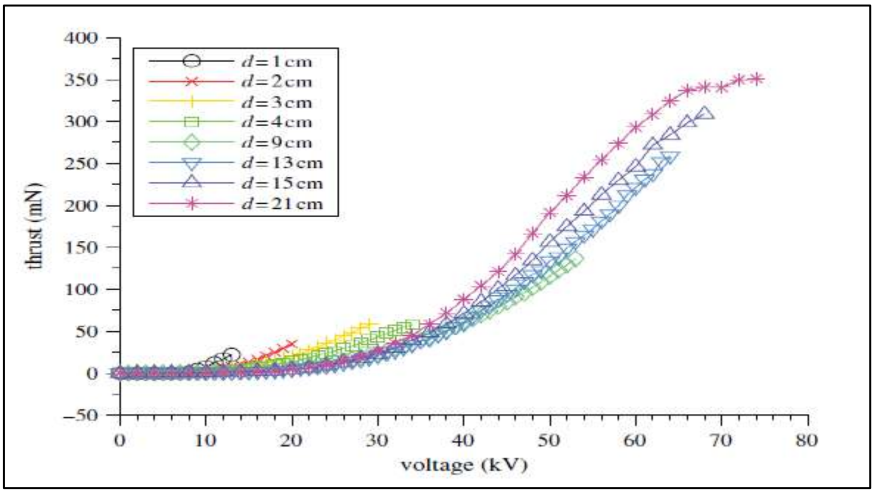


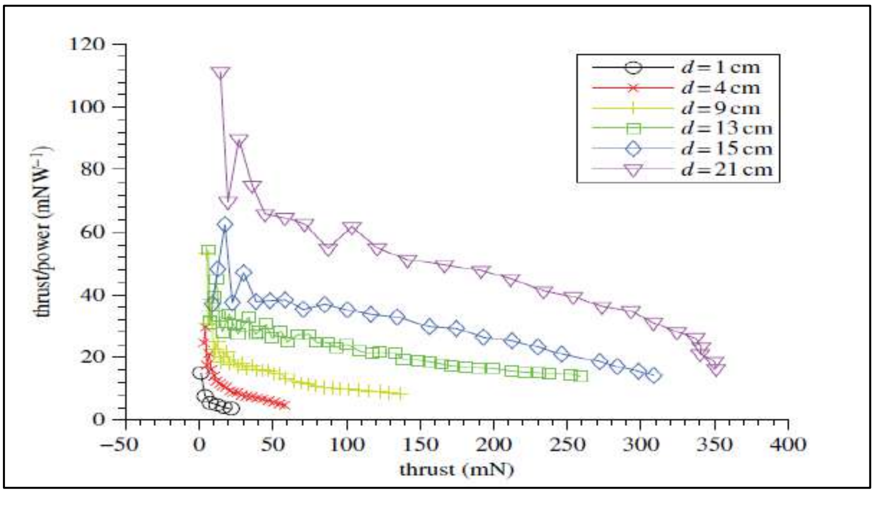
Figure 2.2.2: Overall experimental setup

2.2.3 Results:

After performing multiple trials for both the SS thruster and DS thruster results are

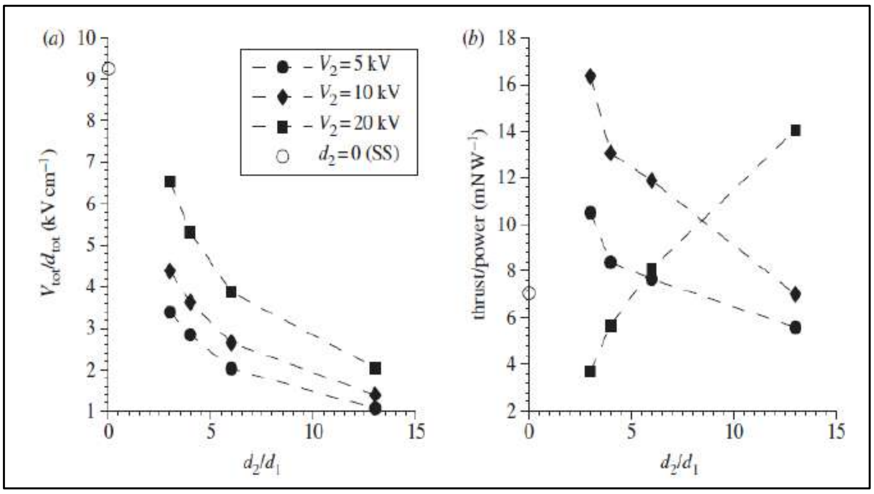


Graph 2.2.1: Voltage–thrust relationship for varying air gap, positive polarity (SS Thruster)

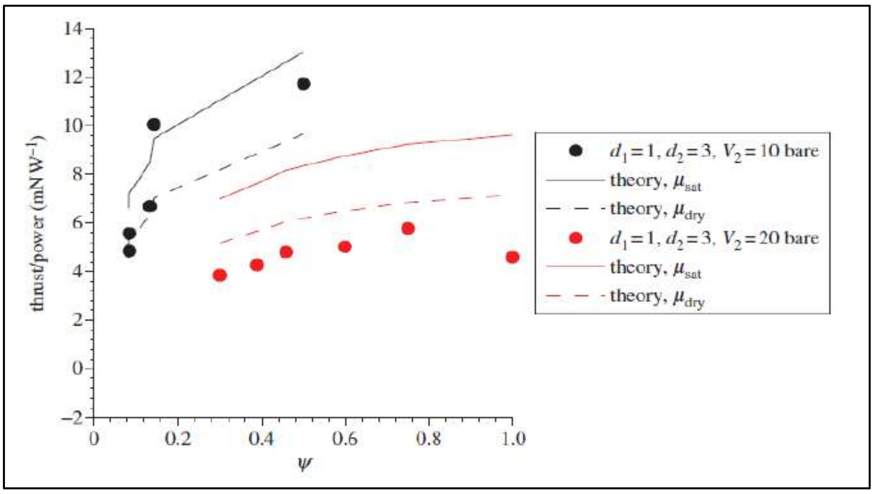


Graph 2.2.2: Variation in thrust/power (SS Thruster)

The graph shown below shows the variation of voltage across the gap between two electrodes and the thrust-to-power ratio across the gap of electrodes.



Graph 2.2.3: Variation of V/d and F/P with d2/d1 DS thruster



Graph 2.2.4: Thrust-to-power variation with ψ

Overall, the paper provides a comprehensive analysis of the performance of EHD propulsion systems. The findings contribute to the understanding of the underlying mechanisms and offer insights into optimizing the design and efficiency of EHD propulsion technologies.

2.3 Haofeng Xu, Yiou He, Kieran L. Strobel, Christopher K. Gilmore, Sean P. Kelley, Cooper C. Hennick, Thomas Sebastian, Mark R. Woolston, and David J. Perreault [3]

2.3.1 Introduction:

The paper reports the first flight of an airplane powered by solid-state propulsion, which uses electro-aerodynamic thrust to move air without moving parts or combustion. The authors describe the design, fabrication, and testing of a prototype aircraft that weighs 2.45 kg and has a wingspan of 5 m. The aircraft achieved a maximum speed of 5.4 m/s and a maximum thrust-to-power ratio of 11.6 N/kW. The paper discusses the advantages and challenges of solid-state propulsion, such as low noise, high efficiency, scalability, and reliability, as well as the need for high-voltage power supplies, air ionization, and aerodynamic optimization.

2.3.2 Experimental Setup:

The experimental setup of this paper consists of the following components:

A fixed-wing airplane with a five-meter wingspan and a mass of 2.45 kg, is made of balsa wood, carbon fiber, and polystyrene. The airplane has a conventional tail configuration and ailerons for roll control. The airplane is equipped with a radio receiver, a flight controller, a GPS module, an inertial measurement unit, and a data logger.

A solid-state propulsion system that uses electro-aerodynamic thrust to move air without moving parts or combustion. The propulsion system consists of an array of thin wires (anodes) at the leading edge of the wing and a perforated aluminum foil (cathode) at the trailing edge, separated by about 10 cm. The wires are connected to a high-voltage power converter that generates a constant potential difference of about 40 kV between the anodes and the cathode, creating a corona discharge that ionizes the air near the wires. The ions are then accelerated by the electric field towards the cathode, colliding with neutral air molecules and producing an ionic wind that propels the airplane forward. The power converter is powered by lithium-polymer batteries carried onboard.

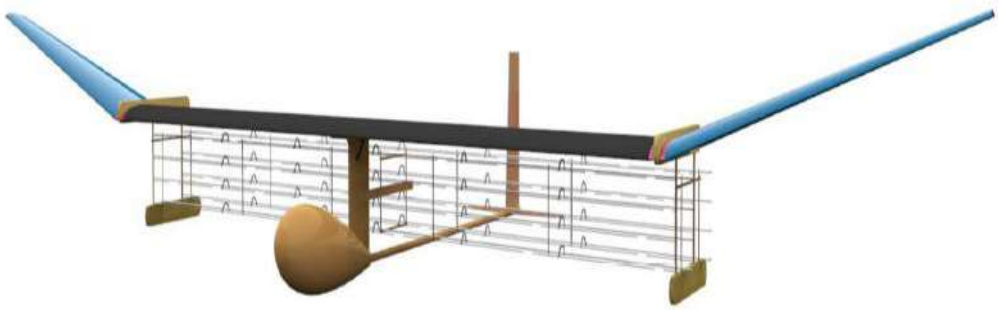


Figure 2.3.1: Design of 3D rendered EAD Airplane

Mass Budget	Total (kg)	2.45
	Power converter (kg)	0.51
	Battery (kg)	0.23
	Wing (kg)	0.63
	Electrodes (kg)	0.41
Aerodynamic Characteristics	Wing Span (m)	5.14
	Flight Velocity (m/s)	4.8 ± 0.2
	Aspect Ratio	17.9
	Drag (N)	3.0 ± 0.2
	Lift/Drag Ratio	8 ± 1
EAD Propulsion System	Thrust (N)	3.2 ± 0.2
	Voltage (kV)	40.3 ± 0.1
	Power Requirement (W)	620 ± 20
	Thrust Frontal Area (m^2)	0.9

Table 2.3.1: Engineering and Performance Parameters

This design consists of an onboard power system which is a high-voltage power converter and it consists of three stages of the series-parallel resonant inverter, a high-voltage transformer, and a Full-wave Cockcroft–Walton multiplier.

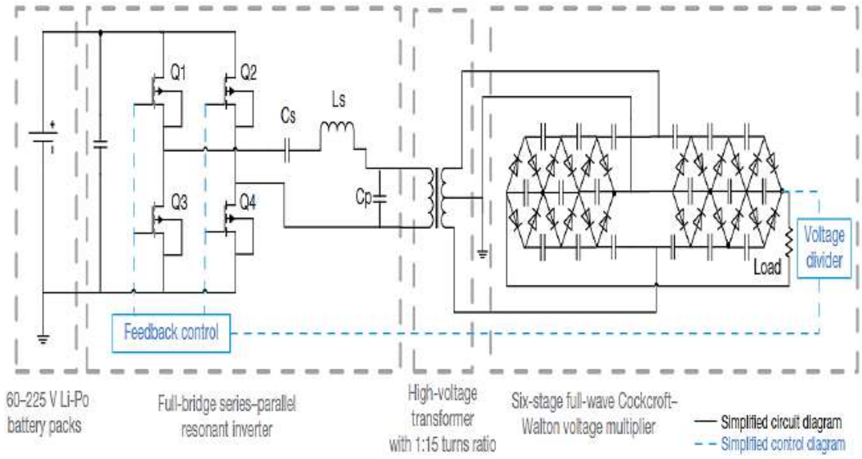
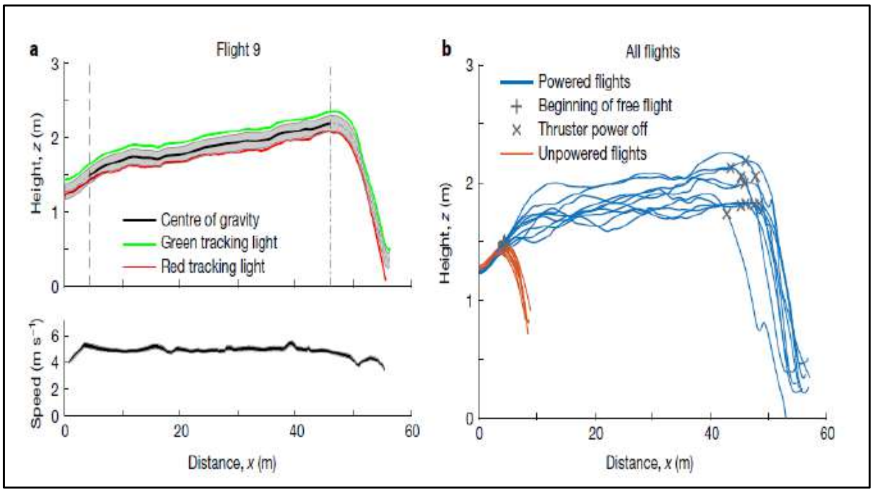


Figure 2.3.2: High-Voltage Power Converter (HVPC)

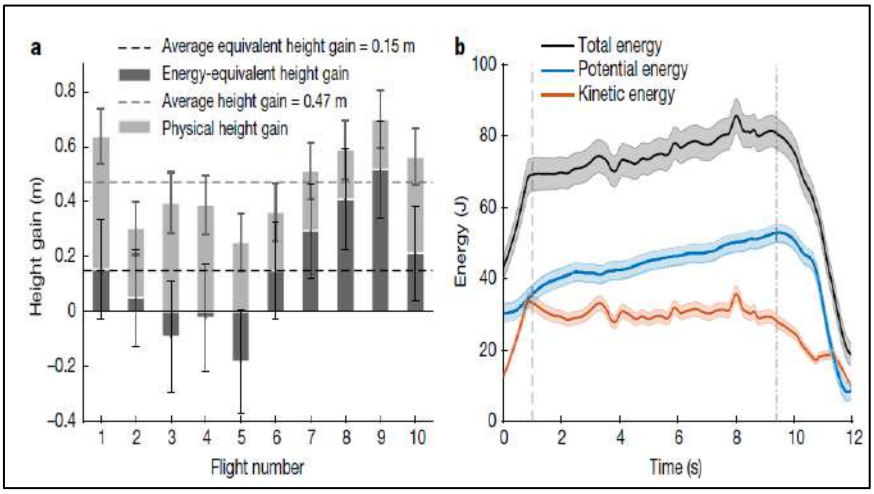
2.3.3 Results:

The results they gain from the experimental setup are:

They measure the thrust generated by the propulsion system and measure the power consumed by the propulsion system and also find the thrust-to-power ratio. The flight trajectories are measured and the height gain on every flight and the increase and decrease of kinetic and potential energy can be seen in the graphs below.



Graph 2.3.1: (a) Flight 9 trajectories at the top & speed profile at the bottom
(b) All ten powered and ten unpowered flight glides trajectories



Graph 2.3.2: (a) Physical height gain by steady flight (b) K.E & P.E variation in steady flight

The paper concludes that solid-state propulsion is a promising technology for future aviation applications that require low emissions, low noise, and high endurance. The authors open up possibilities for aircraft and aerodynamic devices that are quieter, mechanically simpler, and do not emit combustion emissions, which could have significant benefits for future aviation applications.

2.4 Haofeng Xu, Nicolas Gomez-Vega, Devansh R Agrawal, Steven R H Barrett [4]

2.4.1 Introduction:

The paper reports an experimental study of electron-aerodynamic (EAD) devices with large electrode gap spacing for aircraft propulsion. EAD devices use electric fields to accelerate ions in the air and produce thrust without moving parts or combustion. The paper shows that EAD devices with large gap spacing can achieve higher thrust-to-power and thrust density than current implementations with smaller gap spacing, which are important metrics for aero-plane propulsion. The paper also explains the discrepancy between the theory and experiment of EAD devices with large gap spacing, which is caused by three factors: leakage current, reverse corona emission, and the electric potential of the thruster relative to its surroundings. The paper proposes methods to account for these factors and to optimize the design and operation of EAD devices with large gap spacing. The paper provides a proof of concept for EAD aero plane propulsion with large gap spacing, opening up possibilities for quieter, simpler, and greener aircraft and aerodynamic devices.

2.4.2 Experimental Setup:

The paper uses a wire-to-cylinder EAD device with a variable gap spacing to measure the thrust-to-power and thrust density of EAD propulsion. The paper simulates the in-flight conditions using a wind tunnel and a force balance and measures the current and voltage of the EAD device using a current sensor and a voltage divider. The paper also accounts for the effects of leakage current, reverse corona emission, and electric potential on the performance of the EAD device.

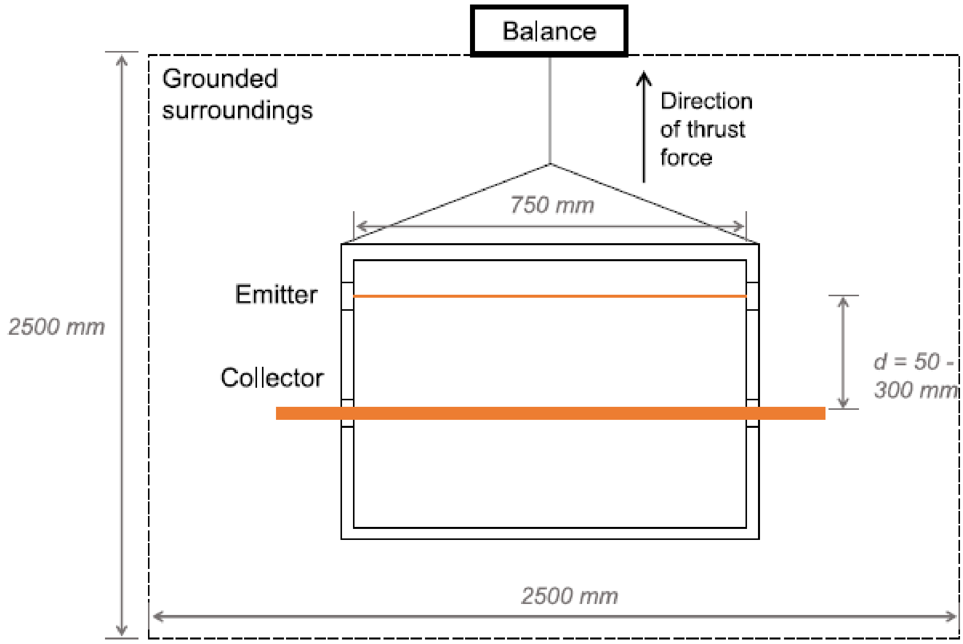
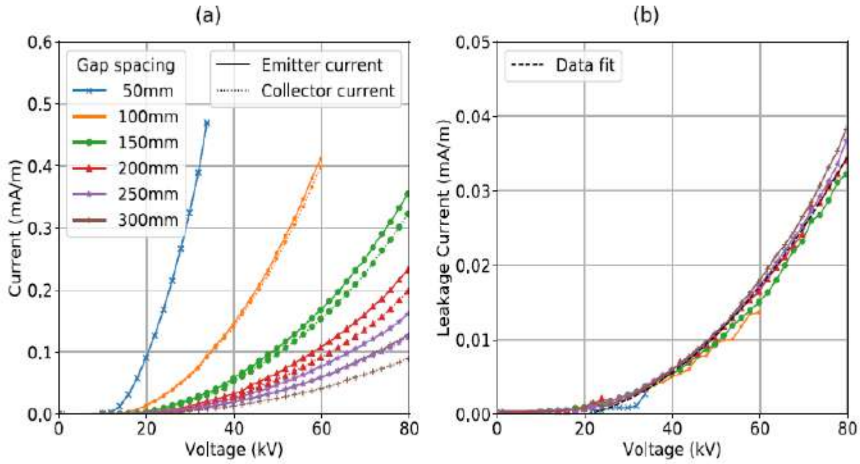


Figure 2.4.1: Schematic setup of the thruster and thrust measurement

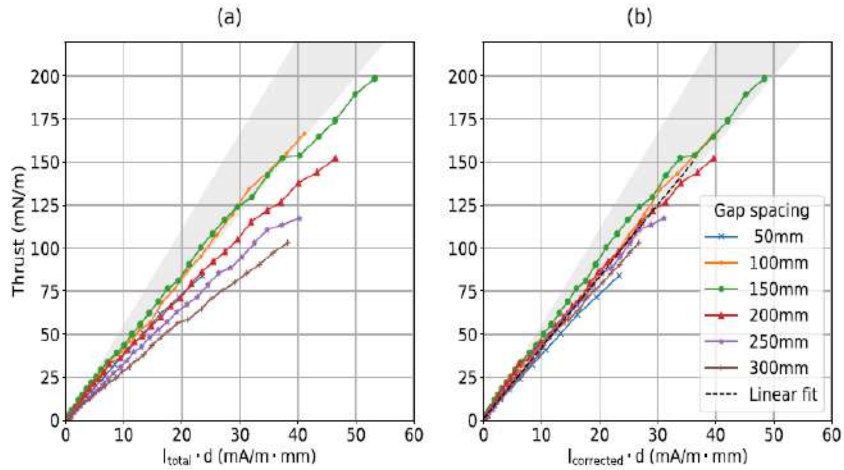
2.4.3 Experimental Results:

The paper reports the following experimental results: The paper measures the power consumed by the EAD device using a current sensor and a voltage divider and finds that it depends on the applied voltage and the current. The paper also finds that power consumption decreases with increasing airspeed, which means that the EAD device becomes more efficient at higher speeds.



Graph 2.4.1: (a) Current versus voltage at varying gap spacings (b) Leakage current versus voltage

The paper calculates the thrust-to-power ratio and the thrust density of the EAD device using the measured thrust and power, and compares them with previous theoretical and experimental studies.



Graph 2.4.2: (a) Total drawn current (b) Corrected Current

The results of the thrust-to-power ratio when the spacings are greater than 100mm is:

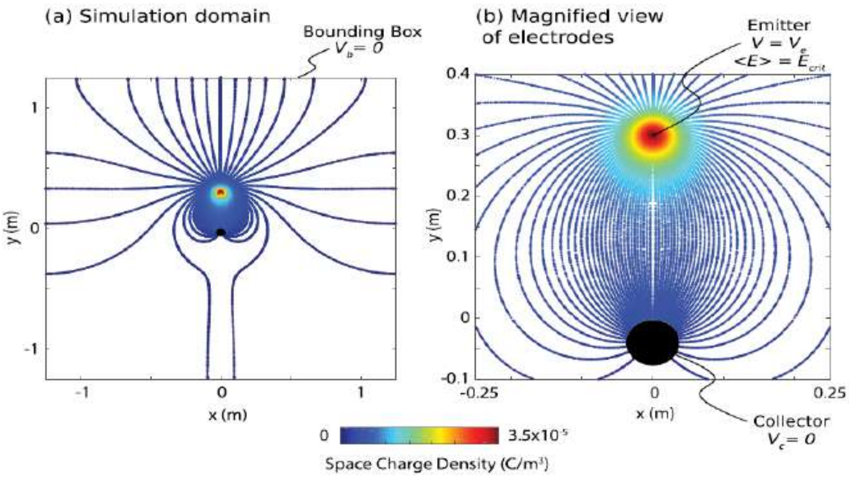


Figure 2.4.2: (a) Entire simulation domain (b) Electrodes magnified view

The paper concludes the feasibility and potential of EAD devices with large electrode gap spacing for aircraft propulsion. EAD devices use electric fields to accelerate ions in the air and produce thrust without moving parts or combustion. The paper shows that EAD devices with large gap spacing can achieve higher thrust-to-power and thrust density than current implementations with smaller gap spacing, which are important metrics for aero-plane propulsion.

2.5 Zhongzheng He, Pengfei Li, Wei Wang, Liwei Shao and Xi Chen [5]

2.5.1 Introduction:

The paper titled "Design of indoor unmanned airship propelled by ionic wind" uses ionic wind as a propulsion method. The ionic wind is a phenomenon where electrically charged particles create a thrust force in the air. The paper describes the structure, circuit, and control of the airship, which has two ionic wind propulsion devices on both sides. The paper also reports the results of a flight experiment, where the airship can perform forward and yaw motions under remote control. The paper claims that the ionic wind-powered airship has advantages such as low noise, low vibration, and high safety compared to other propulsion methods.

2.5.2 Experimental Setup:

The paper uses an ionic wind-powered airship that has a length of 1.5 m, a diameter of 0.4 m, and a volume of 0.25 m3. The airship is filled with helium gas and has two ionic wind propulsion devices on both sides, each consisting of a needle electrode and a ring electrode. The electrodes are connected to a high-voltage DC power supply and a control circuit that can adjust the voltage and polarity of the electrodes. The control circuit is connected to a Bluetooth module that receives commands from a mobile phone app. The app can send four commands: “stop”, “forward”, “forward left”, and “forward right”. The paper tests the performance of the airship in an indoor environment with no wind interference. The paper measures the thrust force, power consumption, and flight speed of the airship under different voltages and polarities. The paper also evaluates the stability, maneuverability, and noise level of the airship during flight.

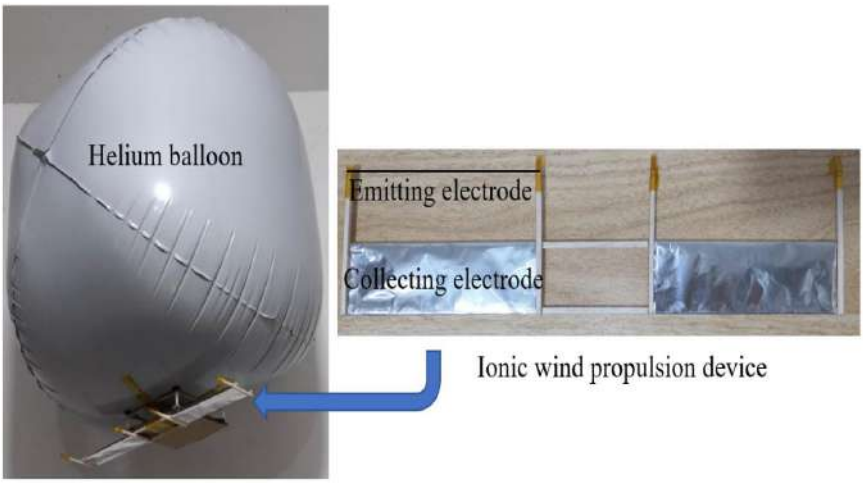


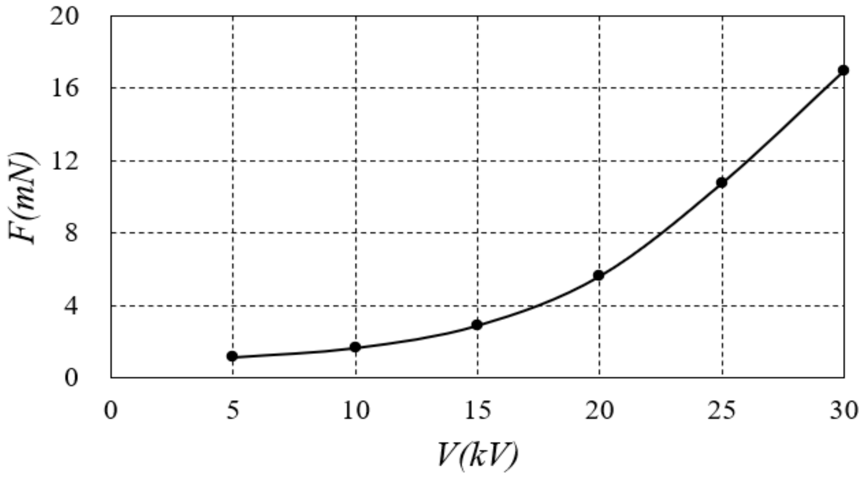
Figure 2.5.1: Airship Powered by Ionic Wind

2.5.3 Results:

The paper presents the following results and graphs:

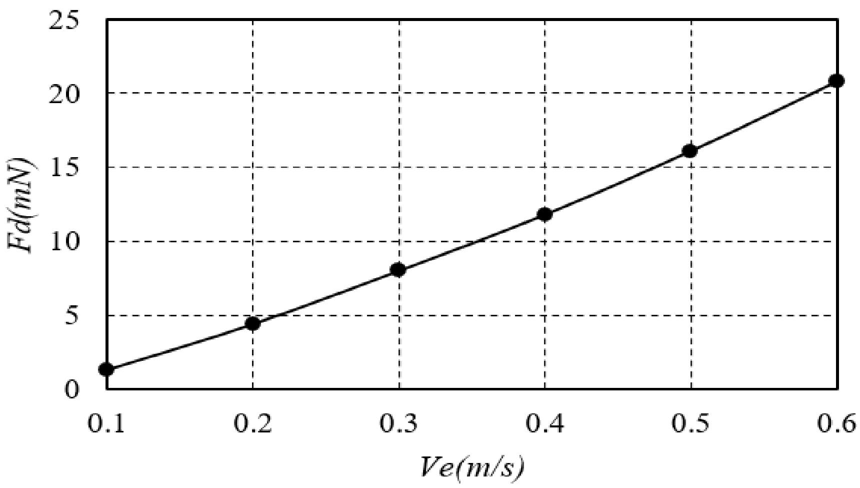
The paper tests the device with different voltages and polarities and finds that higher voltage and positive polarity give better performance. The paper also tests the airship with two ionic wind devices and shows that it can fly forward and turn left or right with a remote control.

The graph below shows that the thrust force increases with the voltage, but decreases with the power consumption. This means that higher voltage can produce more ionic wind, but also consumes more energy.



Graph: 2.5.1: Thrust to voltage graph

The graph below would show that the air resistance increases with the speed, but reaches a limit at a certain speed. This means that higher speed causes more friction between the airship and the air.



Graph 2.5.2: Speed versus air- resistance graph

The paper concludes that compared with other propulsion methods, such as propeller and bionic wing, the ionic wind propulsion device has advantages such as low noise, low vibration, and high safety. The paper also claims that the ionic wind-powered airship designed in this paper uses two ionic wind propulsion devices as power sources and can complete forward and yaw movements under remote control.

2.6 S. Coseru, D. Fabre, and F. Plouraboué [6]

2.6.1 Introduction:

The paper "Numerical Study of Electro-Aerodynamic Force and Current Resulting from Ionic Wind in Emitter/Collector Systems" presents a comprehensive numerical investigation into the electro-aerodynamic force and current generated by ionic wind in emitter/collector systems. The study aims to enhance the understanding of these phenomena, which have significant implications for optimizing the design and performance of electro-aerodynamic systems.

2.6.2 Methods:

Methods that are used in this paper are theoretical formulation and dimensionless formulation, variational formulation, and Regularization. In theoretical formulation, they set the boundary conditions and constitutive equations and use a Kaptzov approximation. Recent scientific evidence has been provided for this Kaptzov hypothesis, which asymptotically holds for the axisymmetric arrangement, and after that propulsive thrust and current intensity are measured.

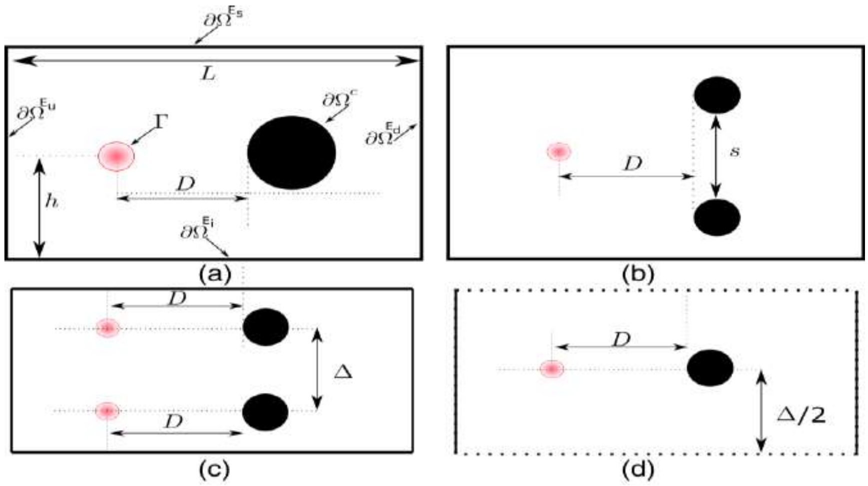


Figure 2.6.1: Various emitter and collector configurations (a) 1E/1C, (b) 1E/2C, (c) 2E/2C (d) 1E/2C

In dimensionless formulation, they use the reference length scale to make the dimensionless collector radius value equal to one and then they set the variational formulation of the problem and for replacing condition they use a regularization method.

2.6.3 Numerical Validation:

In this section, they perform axisymmetric tests that have different cases of regularization techniques and emitter configuration.

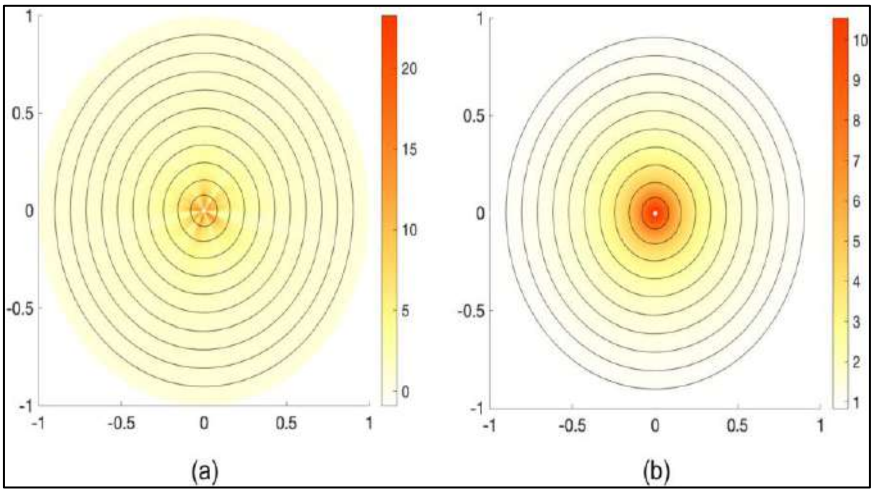


Figure 2.6.2: Computed Ion density (ρ) and electric potential (a) without regularization term and (b) with a regularization term

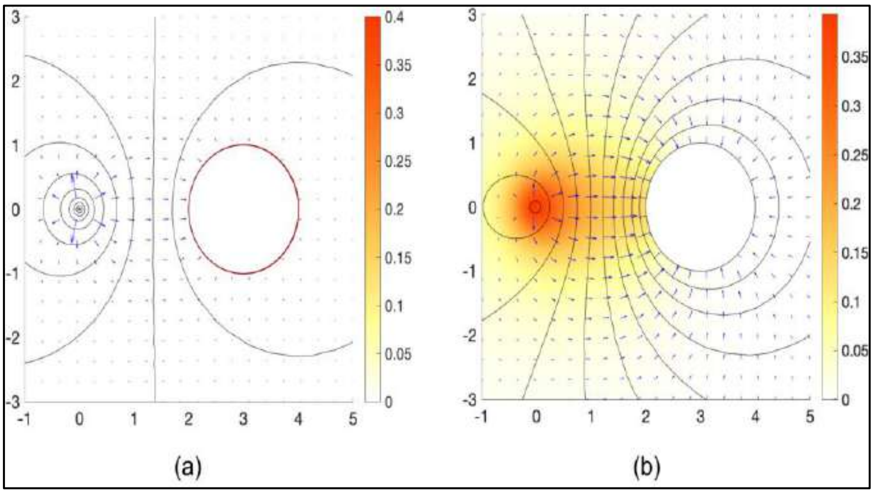
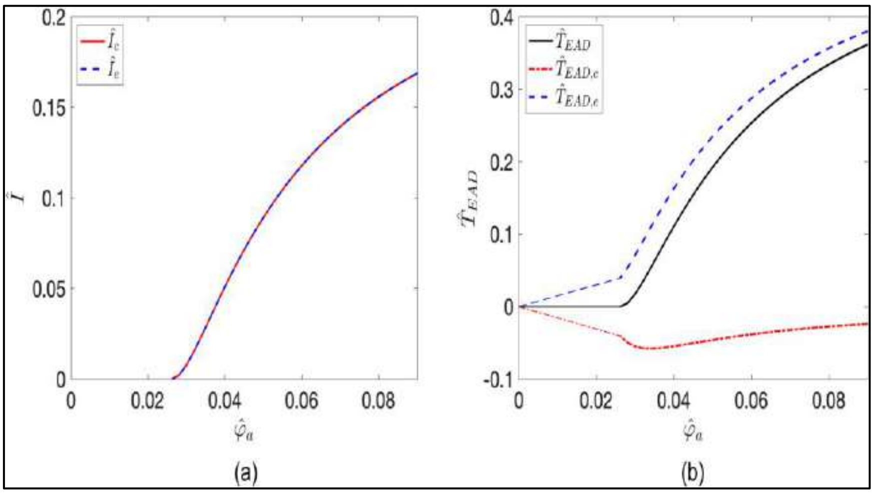


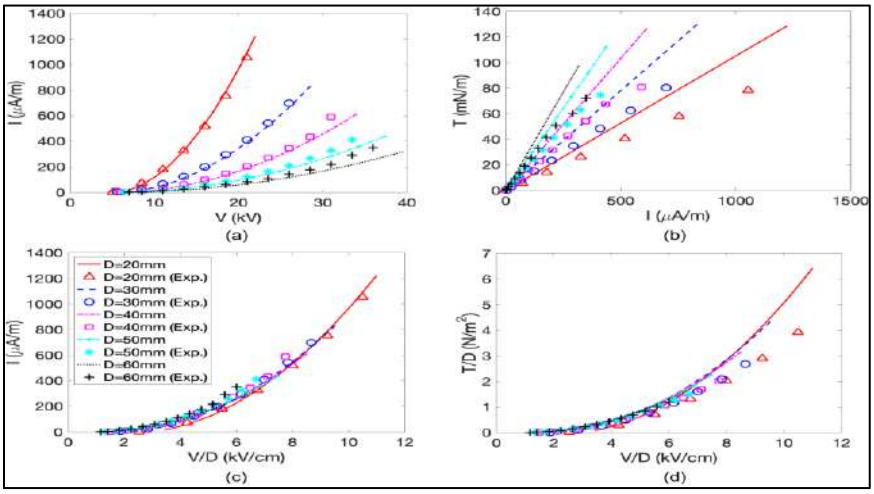
Figure 2.6.3: 1E/1C Ion density, electric potential, and electric field (a) V ¼ 6:47 kV very close, and above the onset voltage (b) V ¼ 20 kV where the corona discharge is triggered.



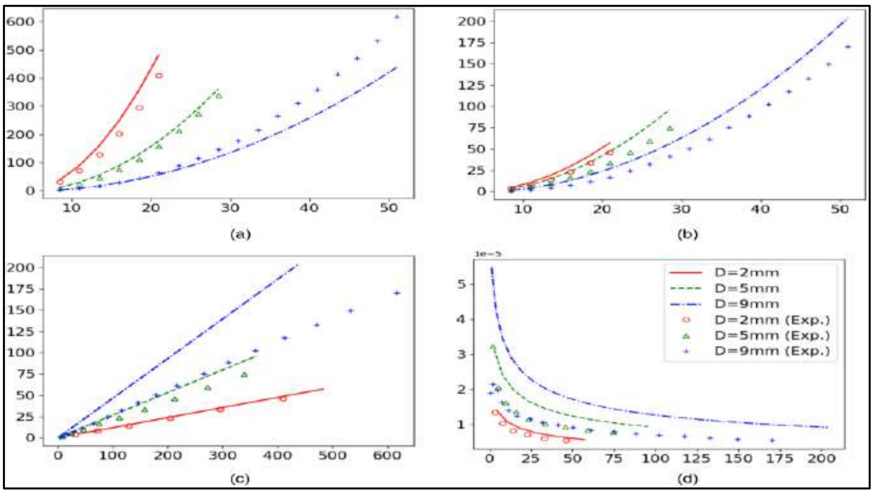
Graph 2.6.1: 1E/1C case (a) Dimensionless intensity vs dimensionless applied voltage. (b) Dimensionless Electro Aerodynamic force vs applied voltage for the same configuration and both electrodes' contributions.

2.6.4 Experiments Comparison:

There is a comparison between 1E/1C and 1E/2C in graphs in which they set the electrodes at different gaps and compare them with experimental data.



Graph 2.6.2: Results on several values of gap D for 1E1C configurations. Compared with experimental data. All panels [(a)–(d)] have the same legend as (c) not duplicated.



Graph 2.6.3: 1E2C configurations with several values of gap D. Experimental data compared. Panels [(a)–(d)] having the same legend as (d), not duplicated

In summary, this paper provides valuable insights into the numerical study of electro-aerodynamic force and current resulting from ionic wind in emitter/collector systems. The findings contribute to the broader understanding of electro-aerodynamics and offer potential avenues for further research and development in this field.

CHAPTER-3

PROBLEM STATEMENT, METHODOLOGY, AND EXPERIMENTAL PROCEDURES

3.1 Introduction:

The existing literature acknowledges the potential benefits of ion propulsion for aircraft but there is a clear research gap concerning its practical implementation, performance optimization, and safety considerations. This research gap hinders the realization of ion propulsion planes as a viable, sustainable, and commercially viable option.

We design a test bench and an HVPC for the experimentation and then experiments are done using software Design Expert and an optimum configuration is concluded and other factors affecting the efficiency of thrust generation are measured. First, we discuss the research gap and challenges for ion propulsion systems to perform in the aviation industry.

3.1.1 Research Gaps and Challenges:

Based on the literature review, several research gaps are identified regarding ion propulsion planes:

3.1.2 Power Generation and Management:

Developing efficient and lightweight power generation systems for ion propulsion planes remains a significant challenge.

3.1.3 Power Generation:

Generating sufficient electrical power for ion propulsion planes poses a significant challenge due to the high energy requirements of ion thrusters. The power source must be lightweight, compact, and capable of providing sustained power over long durations.

3.1.4 Fuel Cells:

Fuel cells offer the advantage of high energy density and long endurance. They convert chemical energy from onboard fuel such as hydrogen into electrical energy through an electrochemical reaction. Fuel cells can provide a continuous power supply for extended periods making them suitable for long-duration flights. However, challenges include the weight and storage of fuel as well as the overall efficiency of the fuel cell system.

3.1.5 Solar Panels:

Solar panels harness the energy from sunlight and convert it into electricity using photovoltaic cells. This renewable energy source has the advantage of being lightweight and environmentally friendly. However, solar power generation is subject to variations in sunlight availability making it less reliable for continuous and high-power applications. Additionally, the limited surface area of an aircraft poses a challenge in maximizing solar panel efficiency.

3.1.6 Hybrid Systems:

Hybrid power generation systems combine multiple sources, such as fuel cells and solar panels, to enhance overall power availability and reliability. These systems aim to leverage the advantages of each power source while mitigating their limitations. By combining fuel cells and solar panels, for example, the aircraft can operate using solar power during the day and rely on fuel cells for power during the night or in low-light conditions.

3.1.7 Power Management:

Efficient power management is crucial for optimizing the performance of ion propulsion systems and ensuring the effective utilization of electrical power. Power management systems monitor and regulate the distribution of electrical power to various components and subsystems, prioritizing their power requirements and managing energy storage.

3.1.8 Power Distribution:

Power distribution systems ensure that electrical power is supplied to the ion thrusters, avionics, control systems, and other onboard equipment as required. These systems must balance power demands, manage voltage levels, and prevent power fluctuations or surges that could affect system performance or damage sensitive electronics.

3.2 Propellant Efficiency and Mass Flow Control:

Optimizing ion propulsion propellants and controlling mass flow rates are critical for achieving optimal performance and range. Propellant efficiency and mass flow control are critical aspects of ion propulsion systems in ion propulsion planes. These factors directly impact the performance, thrust generation, and overall efficiency of the propulsion system.

3.2.1 Propellant Efficiency:

Propellant efficiency refers to the effectiveness with which the ion propulsion system utilizes the propellant to generate thrust. In ion propulsion, the propellant is typically a gas, such as Nitrogen usually xenon, which is ionized and accelerated to generate thrust. The propellant efficiency is determined by several factors:

3.2.2 Ionization Efficiency:

The ionization efficiency measures the ability of the ionization subsystem to convert a significant portion of the propellant gas into ions. Higher ionization efficiency ensures that a larger fraction of the propellant is utilized for thrust generation, minimizing wastage.

3.2.3 Charge Exchange Losses:

Charge exchange losses occur when the ions in the ionized propellant collide with neutral atoms resulting in the recombination of ions and a loss of kinetic energy. Minimizing charge exchange losses is crucial to maximizing propellant efficiency.

3.2.4 Beam Neutralization:

In some ion propulsion systems, beam neutralization is employed to neutralize the ion beam by injecting electrons or neutral gas into the beam. Efficient beam neutralization reduces the interaction of the ion beam with the surrounding environment, optimizing propellant utilization.

3.2.5 Recirculation and Reutilization:

Developing methods to recirculate and reutilize the propellant that has been ionized and accelerated can significantly improve propellant efficiency. This involves capturing and recycling the ionized propellant to reduce consumption and extend the operating lifetime of the propulsion system.

3.3 Thrust-to-Power Ratio:

The thrust-to-power ratio determines the efficiency of the ion propulsion system. It represents the amount of thrust produced per unit of electrical power consumed. Optimizing the mass flow rate in conjunction with the power input is necessary to achieve an optimal thrust-to-power ratio and overall system efficiency.

3.3.1 Acceleration and Extraction Grids:

Ion propulsion systems employ grids to accelerate and extract ions. The geometry, voltage potentials, and grid spacing significantly affect the mass flow rate and the resulting thrust. Precise control and optimization of these grids are essential for efficient mass flow control.

3.3.2 Magnetic Field Configuration:

Magnetic fields are often utilized to control the ion beam and improve its efficiency. The configuration of magnetic fields can influence the mass flow rate, ion trajectories, and beam divergence. Optimizing the magnetic field configuration helps ensure efficient mass flow control and enhanced thrust generation.

3.3.3 Safety and Environmental Considerations:

Comprehensive studies on the environmental impact and safety of ion propulsion planes are lacking, necessitating further research and risk assessment. Safety and environmental considerations are vital aspects that need to be addressed in the development and implementation of ion propulsion planes. As with any new propulsion technology, it is crucial to ensure that the operation of ion propulsion systems is safe for passengers, crew, and the environment.

3.3.4 Ion Beam Effects:

The ion beam emitted by the ion thrusters can interact with the surrounding atmosphere, potentially causing the ionization of atmospheric molecules and generating secondary particles. These interactions may have implications for human health, avionics systems, and other onboard equipment. Understanding and mitigating the effects of the ion beam on the aircraft and its surroundings is essential for ensuring safety.

3.3.5 Electrical Systems and Interference:

Ion propulsion systems rely on high-voltage electrical systems for ionization and acceleration. It is crucial to assess and mitigate potential risks associated with high-voltage systems, such as electrical arcing, electromagnetic interference (EMI), and compatibility with other aircraft systems. Adequate shielding and insulation measures need to be implemented to prevent hazards and ensure the safe integration of ion propulsion technology.

3.3.6 Atmospheric Impact:

Ion propulsion planes emit ionized particles into the atmosphere, potentially affecting the composition and chemistry of the surrounding air. The impact of these emissions on the environment, including air quality, ozone depletion, and climate change, needs to be carefully evaluated and compared to conventional aircraft emissions. Comprehensive environmental assessments and modeling studies are necessary to quantify and mitigate any potential negative effects.

3.3.7 Life Cycle Assessment:

Conducting life cycle assessments (LCAs) of ion propulsion planes can provide a holistic view of their environmental impact. LCAs evaluate the environmental effects of the entire life cycle of the aircraft, including manufacturing, operation, and disposal. Assessing the environmental footprint of ion propulsion planes will help identify areas for improvement and guide the development of sustainable aviation practices.

3.4 Integration and System-Level Challenges:

Integration and system-level challenges are critical aspects that need to be addressed when considering the implementation of ion propulsion systems in aircraft. These challenges involve the seamless integration of ion propulsion technology with existing aircraft structures, avionics, and control systems, ensuring compatibility and optimal performance.

3.4.1 Structural Integration:

Integrating ion propulsion systems into the existing airframe structure of an aircraft requires careful consideration of weight, size, and aerodynamic effects. Ion thrusters, power systems, and associated components need to be integrated in a way that does not compromise the structural integrity, balance, or overall performance of the aircraft. Designing and optimizing the integration process is crucial to ensure a smooth transition and compatibility with the existing aircraft structure.

3.4.2 Aerodynamic Considerations:

The addition of ion propulsion systems may introduce changes to the aerodynamics of the aircraft. These changes can affect flight characteristics, stability, and control. Evaluating and optimizing the aerodynamic effects of ion propulsion technology is necessary to maintain flight safety and performance standards.

3.4.3 Thermal Management:

Ion propulsion systems generate significant amounts of waste heat during operation. Effective thermal management is essential to ensure that excessive heat does not adversely affect the aircraft structure, avionics, or other onboard systems. Implementing proper cooling mechanisms, heat dissipation strategies, and thermal insulation is crucial for maintaining the system's efficiency and reliability.

3.4.4 Avionics Integration:

Integrating ion propulsion systems with existing avionics poses challenges in terms of compatibility, electromagnetic interference, and system communication. The ion propulsion technology must interface seamlessly with the aircraft's avionics systems, including flight controls, navigation systems, and communication networks. Ensuring proper communication protocols, signal integrity, and electromagnetic compatibility (EMC) are critical for the safe and efficient operation of the aircraft.

3.4.5 Control and Automation:

Developing control algorithms and automation systems specific to ion propulsion technology is necessary to optimize performance and ensure reliable operation. Efficient control systems are required to regulate ion thruster parameters, monitor system health, and adapt to changing flight conditions. The integration of advanced control algorithms and automation capabilities is essential to enable safe and precise control of ion propulsion planes.

3.4.6 Certification and Regulatory Compliance:

Ion propulsion planes must adhere to stringent certification and regulatory requirements. These requirements ensure that the aircraft meets safety, performance, and environmental standards. Addressing the specific challenges and considerations associated with ion propulsion technology during the certification process is necessary for regulatory approval and market acceptance.

3.5 Problem Statement:

Problem Statement Based on the identified research gaps, the following problem statement emerges: "The lack of comprehensive understanding and solutions regarding power generation, Optimization, propellant efficiency, safety considerations, and system integration hinders the practical implementation and commercial viability of ion propulsion planes.

3.5.1 Analytical Modelling:

We consider the design from the MIT plane for the calculation of the thrust-to-power ratio required to optimize the design and calculate the thrust generated by each emitter and collector. Consider two electrodes connected with High Voltage Power Supply (HVPC) that have a potential difference between ***V*** and current ***I.*** when the voltage applied ion start flowing from positive to negative with some velocity ***v.***as shown in Fig. So now power become

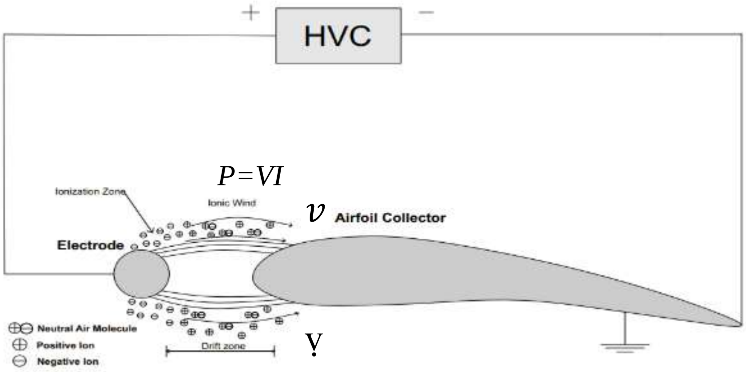


Figure 3-1 Power Flowing in ion Propulsion model

$$P = VI$$

$$P = V(JA)$$

$$P = V(\rho v A)$$

$$P = AV\rho(v)$$

$$P = AV\rho(\mu\bar{E} + \text{ỵ})$$

$$power = P = VA\rho(\mu\bar{E} + \text{ỵ})$$

In equation (3.2) we know that current is equal to electric current density in the discharge cross-section. Further equation (3.3) indicates that $J = \rho v$ in equation (3.6) we know $v = \mu\bar{E} + \text{ỵ}$. And **J** is for Electric current density, **A** for Discharge Cross section, **ρ** for Charge density, **v**=velocity of charges, **μ** is ion mobility (Const.), **Ē** for Electric field magnitude **Ỵ** for drift velocity.

Ion will experience an electrostatic force that is

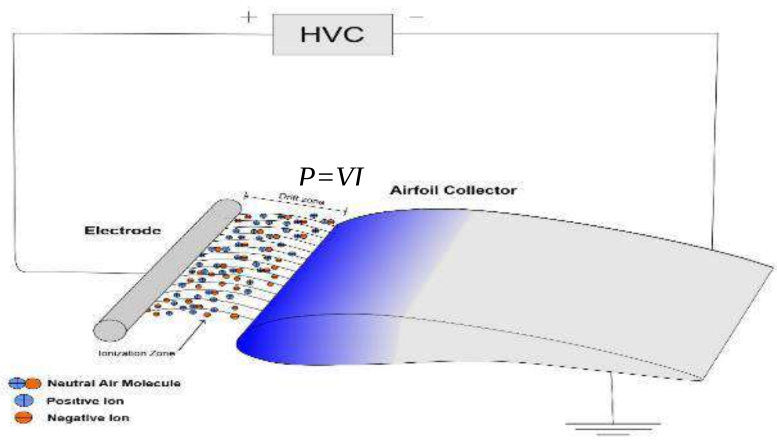


Figure 3-2 Thrust generation 3D model

$$T_i = eE$$

$$T = NT_i = NeE$$

$$T = NeE$$

$$T = (n_i Ad) * e * E * \frac{\mu E}{\mu E}$$

$$T = (\rho E)dA$$

Thrust to power ratio becomes,

$$\frac{T}{P} = \frac{(\rho \bar{E})Ad}{V(JA)}$$

$$\frac{T}{P} = \frac{\rho \bar{E} L}{V\rho(\mu \bar{E} + \underset{\cdot}{v})}$$

$$\frac{T}{P} = \frac{({}^{V}/_{L}) * L}{V(\mu \bar{E} + \underset{\cdot}{v})}$$

We get

$$\frac{T}{P} = \frac{1}{\mu \bar{\mathrm{E}} + \dot{\mathrm{v}}}$$

Where ***T*** is thrust, ***P*** is power, ***E¯*** is the average electric field strength, ***A*** is the thruster area, and ***d*** is the inter-electrode distance. A low average electric field strength ***E¯*** gives a higher thrust-to-power ratio, but too low an electric field strength results in no corona inception. As a result, the thrust-to-power ratio that may be achieved by utilizing the corona discharge has a limit. Masuyama and Barrett5 conducted experiments and discovered that a thrust-to-power ratio as high as 50 N kW-1 was feasible at the laboratory scale. This is equivalent to conventional propulsion; whose usual performance is 3 N kW-1 for jet engines and 50 N kW-1 for helicopter rotors.

3.6 Experimental Procedure:

First of all, we design the test bench to measure the different parameters and their relations such as voltage and thrust, distance and thrust, and stages ad thrust. There were many different types of shapes tested and experimented with so that an optimum shape is declared and used which is efficient and provides maximum efficiency. We have designed a 4-stage thruster to test and then we have to design the power supply that can generate the high voltage. we cannot experiment without this HVPC so we search the available options for high-voltage power supplies that are

1. Van de Graaff Generator
2. Marx Generator
3. Tesla Coil
4. Flyback Transformer
5. Cockcroft-Walton Generator

3.7 Thruster Design:

Different types of shapes have already been discussed and evaluated experimentally by different scientists and engineers. So after carefully studying and monitoring the ups and downs of different shapes, the type of shape proposed and used in this experiment we choose to design the in parallel stages with the thin copper wire as an emitter and 0.6cm copper pipe as a collector. It consists of 4 stages with sliding contact so we can change the distance between electrodes from 1 to 5 cm as shown in Fig 4.

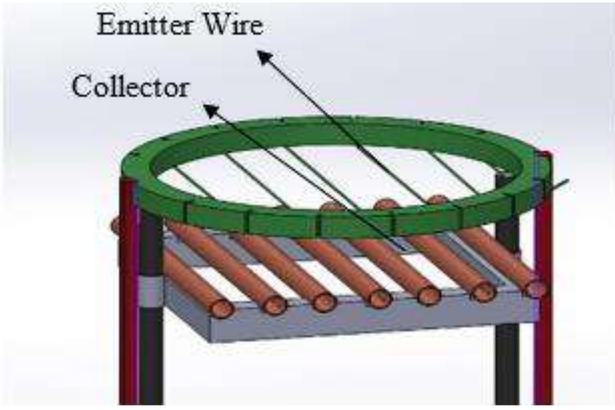


Figure 3-3 Single stage 3D model

The material used in the model was plastic and laser cutting are used to cut the desired dimensions then fabricated as a test bench for experimentation to achieve the optimum configurations for efficient thrust generation.

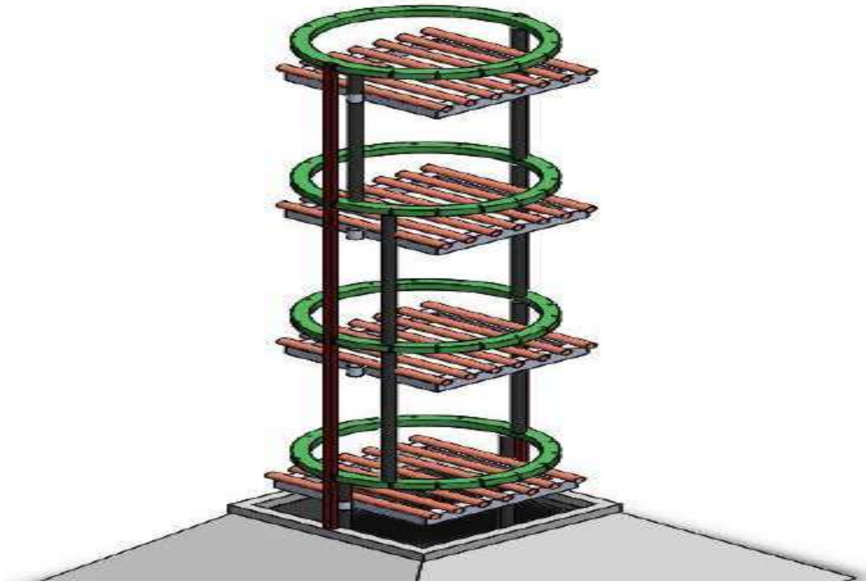


Figure 3-4 Four stage ion thruster 3D model

3.8 Power Supply:

3.8.1 Van de Graff Generator:

A Van de Graaff generator is an electrostatic device invented by Robert J. Van de Graaff in the 1920s. It consists of a large metal sphere on top of an insulated column. Inside the column, a motor-driven rubber belt carries a positive charge from a power source to the sphere. The rubbing action between the belt and rollers generates high voltage through electrostatic induction. The generator can produce voltages ranging from tens of thousands to millions of volts, which can be used for scientific experiments, particle acceleration, and educational demonstrations. Van de Graaff generators create impressive electrical discharges, but they produce low currents. We didn't choose this option because of limited resources.

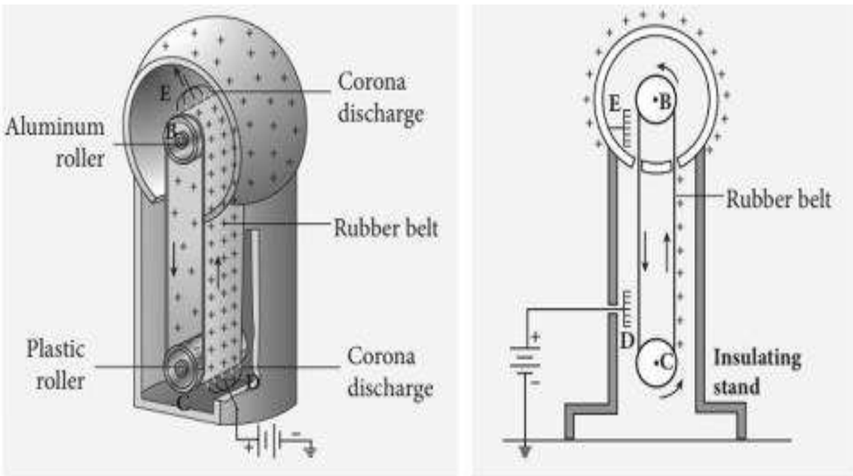


Figure 3-5 Van de Graff mechanism

3.8.2 Marx Generator:

The Marx generator is an electrical circuit that generates high-voltage pulses. It consists of capacitors connected in parallel and spark gaps. During the charging phase, the capacitors store energy, which is then discharged in series through the spark gaps, resulting in a high-voltage pulse. Marx generators are used in applications requiring precise timing and control of electrical pulses, such as high-energy physics experiments and pulsed power systems. Safety precautions are crucial due to the high voltages involved.

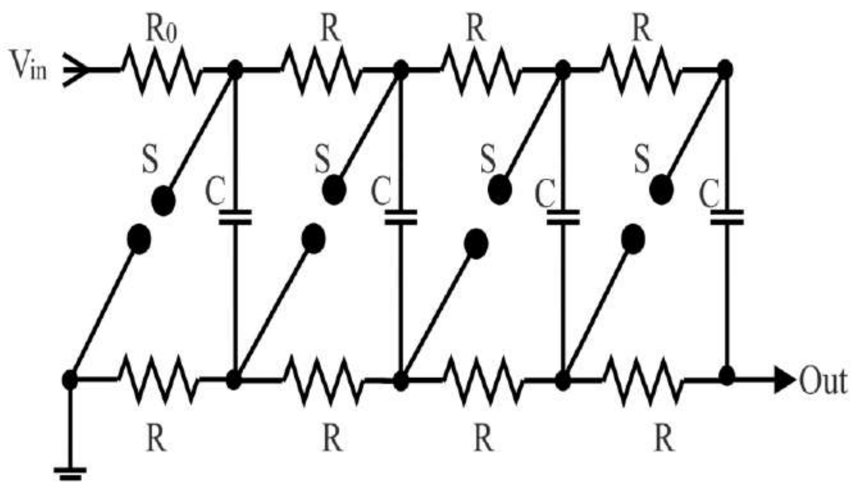


Figure 3-6 Marx Generator

This generator was not suitable for our experiment because it generates pulse only and we require continuous high-voltage flow for our experiment.

3.8.3 Tesla Coil:

A Tesla coil is an electrical device invented by Nikola Tesla that produces high-voltage, low-current, and high-frequency electricity. It consists of a primary coil connected to a power source and a secondary coil wound around a central core. The changing magnetic field in the primary coil induces a high voltage in the secondary coil through electromagnetic induction. This results in the production of spectacular electrical arcs or sparks. Tesla coils are used for educational demonstrations, entertainment, and scientific experiments, but caution must be taken due to the high voltages involved. A new approach to obtaining high-

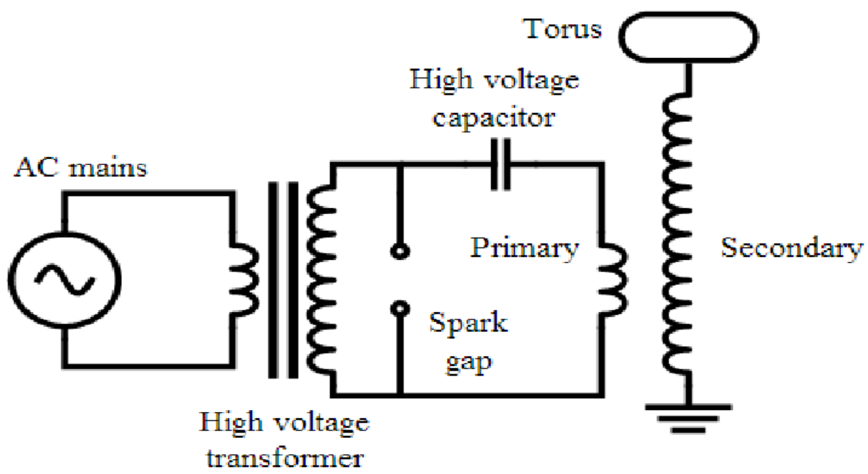


Figure 3-7 Tesla coil

voltage current was adopted because the research budget did not allow for such substantial costs.

3.8.4 Fly-Back Transformer:

A flyback transformer, also known as a line output transformer (LOPT), is a type of transformer used to generate high-voltage pulses. It stores energy in its magnetic field when the primary winding is energized and releases it when the current flow is interrupted. Flyback transformers are commonly found in CRT displays, power supplies, and voltage conversion circuits. They require careful design and consideration for efficient energy transfer and safety precautions due to the high voltages involved.

We used the old monitor to get the flyback and drive it for a high-voltage power supply to perform the experiment. Old kinescope monitor cathode tubes charge their cathode tubes to voltages greater than 24 kV. A little alteration is required to convert such equipment to a power source:

Figure 3-8 Old CRT TV

An outdated Panasonic monitor (fig) was purchased from a nearby electronics shop. The input connector on this particular display was broken. The disassembly procedure was started in order to use the high voltage inside. The wire that connects the cathode tube to the flyback transformer (fig 3-9.) has to be

Figure 3-9 Fly back transformer

directly accessible. Because it is difficult to access and heavily isolated, the monitor must be disassembled.

After taking apart the monitor and gaining access to the fly-back transformer wire shown on the top, it was checked to make sure the grounding wires were in place before closing the monitor shell. After making sure the case is closed, a few tests were run to make sure the power supply and high voltage are generated. Everything seems to be in order.

3.8.5 Cockcroft-Walton Generator:

The Cockcroft-Walton generator is an electrical circuit invented by John Cockcroft and Ernest Walton in the 1930s. It uses capacitors and diodes arranged in a ladder configuration to multiply low-voltage inputs into higher voltages. As voltage progresses up the ladder, it accumulates and increases with each stage. The generator is commonly used in applications requiring high DC voltages. However, it has limited current output and requires careful design and safety precautions when working with high voltages.

The basic principle behind the Cockcroft-Walton generator is voltage multiplication through a series of charge and discharge cycles. Each stage of the ladder charges the next capacitor to a voltage equal to the sum of the previous stage's voltage and the input voltage. As the voltage progresses up the ladder, it accumulates and increases with each stage.

The output voltage of a Cockcroft-Walton generator can be significantly higher than the input voltage, depending on the number of stages. The voltage multiplication factor is determined by the number of capacitors and diodes in the ladder configuration.

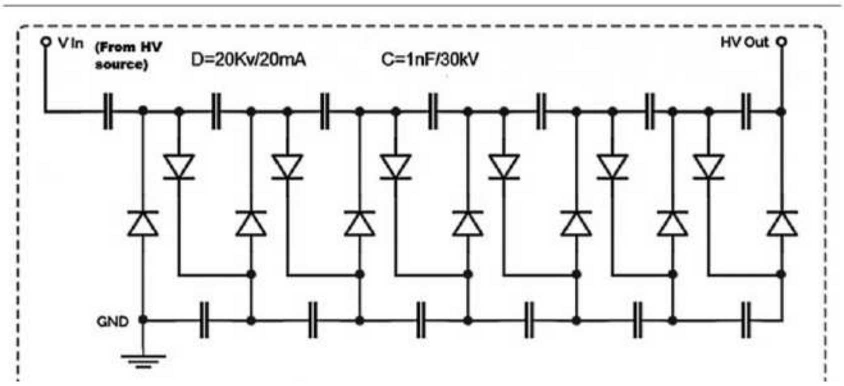


Figure 3-10 Cockcroft-Walton voltage Multiplier

We have designed the circuit to get multiple or variable voltages to perform the experiment and check the best configurations possible. We generated 24kV and then used its multiple for the experiment up to 192kV.

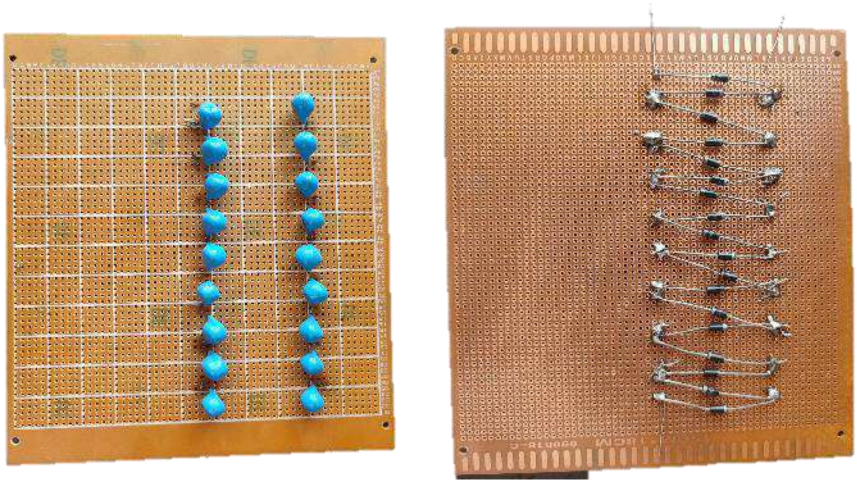


Figure 3-11 Physical model of Cockcroft -Walton voltage Generator

CHAPTER-4

CALCULATIONS AND RESULTS

4.1 EXPERIMENTAL UNIT AND DESCRIPTION:

The experimental study was carried out from a test bench constructed to carry out experimentation and monitor the changes and Configurations. There were many different types of shapes tested and experimented with so that an optimum shape is declared and used which is efficient and provides maximum customization. Voltage is applied to the test bench and velocity is measured using the anemometer.

4.2 EXPERIMENTAL RESULTS:

First, we are going to discuss the factors which affect the experimental results of the Ion Propulsion test bench.

The main factors, which affect the thrust generation are power, voltage, distance between electrodes, humidity, and number of stages. We only consider the three factors in our experiment due to limited resources which are distance, voltage, and number of stages. We performed the following experiments on Design Expert.

4.3 Input Factors:

Table 4.1: Input factors for Design of experiment

Factor	Name	Units	Type	SubType	Minimum	Maximum	Coded Low	Coded High	Mean	Std. Dev.
A	Voltage	kV	Numeric	Discrete	24.00	168.00	-1 ↔ 24.00	+1 ↔ 168.00	92.40	55.76
B	Stages		Numeric	Discrete	1.0000	4.00	-1 ↔ 1.00	+1 ↔ 4.00	2.55	1.19
C	Distance	cm	Numeric	Discrete	1.0000	5.00	-1 ↔ 1.00	+1 ↔ 5.00	2.90	1.62

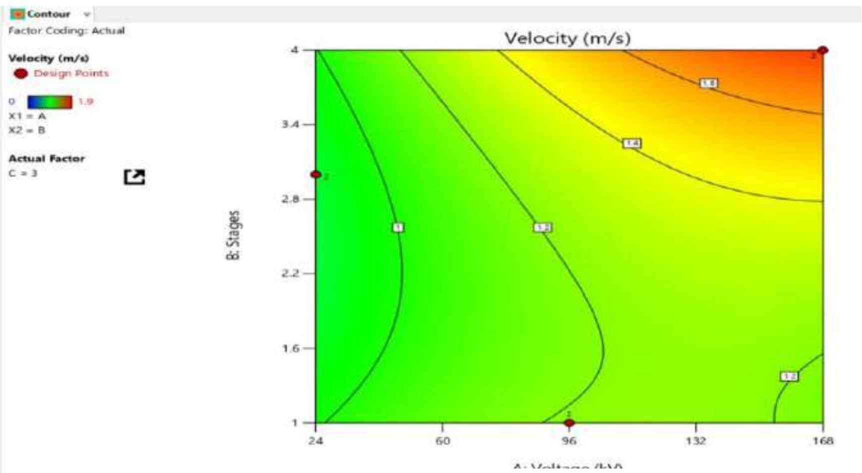
Response	Name	Units	Observations	Minimum	Maximum	Mean	Std. Dev.	Ratio
R1	Velocity	m/s	20.00	0	1.9	0.5935	0.6179	N/A

Now the Experiments performed for the optimum results

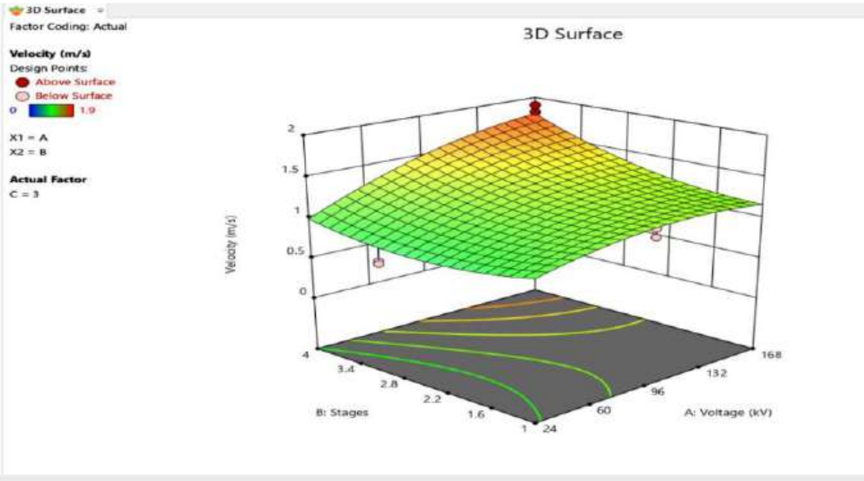
Table 4.2: Experiment performed for Design of experiment

	Factor 1	Factor 2	Factor 3	Response 1
Run	A: Voltage	B: Stages	C: Distance	Velocity
	kV		cm	m/s
1	168	2	1	0.1
2	96	3	5	0.2
3	168	4	3	1.9
4	24	3	3	0.67
5	96	1	3	1.1
6	168	1	5	0.3
7	120	3	2	1.3
8	72	2	1	0
9	24	1	1	0
10	120	3	2	1.29
11	24	4	5	0.1
12	168	4	1	0.3
13	24	3	1	0
14	72	4	1	0.3
15	168	4	3	1.81
16	96	1	5	0.2
17	24	3	3	0.7
18	96	3	5	0.3
19	24	1	5	0.1
20	96	1	3	1.2

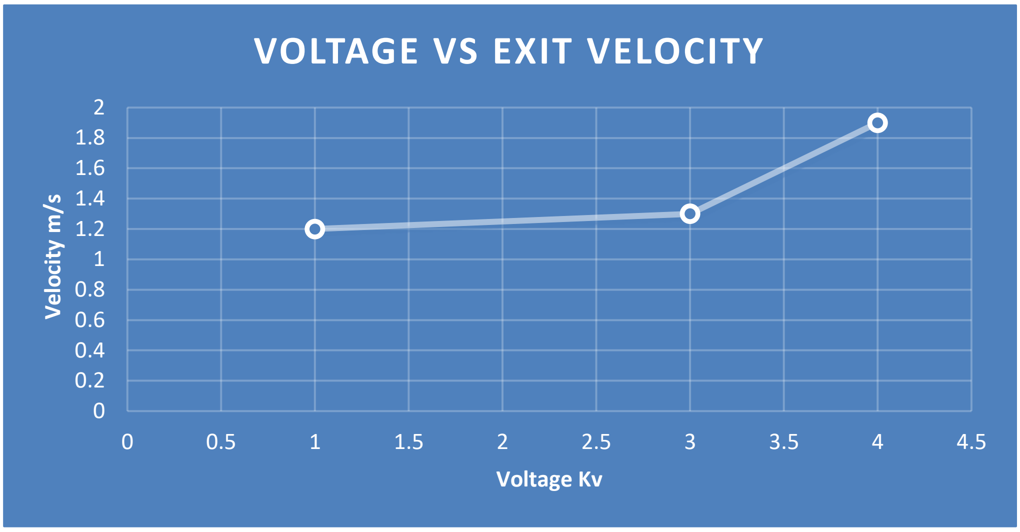
4.4 Results:



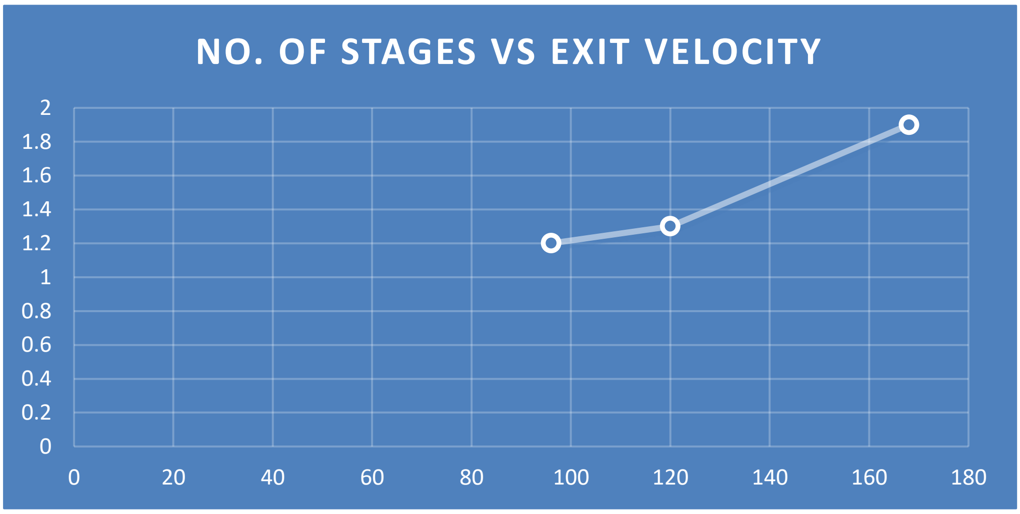
Graph 4.1: Surface plot



Graph 4.2: 3D plot surface plot



Graph 4.3 Voltage VS Exit velocity



Graph 4.4 No. of stages VS Exit velocity

CHAPTER-5

ANALYSIS OF RESULTS

ANALYSIS OF RESULTS

The analysis of result obtained from experimentation on the ion propulsion system give information about performance and optimization. This section analyzes the results, focusing on patterns, significant variables, and implications for development and use.

First, we have built a test bench for an ion propulsion system in which there are four stages of the electrode, in each stage, there are electrodes (Cathode and anode).

For the experimentation we make a list of experiments on Design Expert, there were about 20 experiments that we performed with different configurations of different factors. The factors were voltage, number of stages, and distance between the electrodes. There were about 20 experiments on these factors. It was discovered that operating the system with three stages as opposed to four resulted in the system performing at its best. This unexpected result calls into question the widely held belief that a greater number of stages inevitably results in better performance. The system demonstrated improved efficiency without sacrificing thrust generation by dropping one stage. The system's overall power consumption and complexity were both reduced as a result of the fewer phases. It is important to be able to produce equivalent or better outcomes with three stages since it allows for more streamlined and useful ion propulsion system designs.

The electrode spacing of each stage significantly impacts the effectiveness of an ion propulsion system. Maximum thrust generation occurs at an ideal of 2 to 3 cm, while performance is affected by distance outside this range. Accurate electrode alignment and arrangement are crucial for effective ionization and propulsion and systems should be calibrated and maintained carefully.

The link between electrode distance and performance is explained by considering electrostatic interactions and ionization processes. The ideal distance range ensures good electric field dispersion and efficient propellant ionization. However, increased ion recombination or excessive electrical breakdown can hinder thrust creation, while distances beyond the ideal range reduce ionization efficiency and limited contact with the electric field.

The analysis's findings significantly impact ion propulsion system design and operation, offering flexibility in stage number and electrode space. We can enhance thrust-to-power ratio and efficiency, benefiting space exploration and satellite propulsion applications.

The analysis suggests that ion propulsion systems may have other factors affecting performance that require further research. Investigating propellant composition, voltage levels, and airflow rates is crucial for better understanding. Computer modeling and simulations can help gather information on electric field distribution, ion trajectories, and propellant utilization for accurate optimization and control.

CHAPTER-6

BUDGETING AND COSTING OF THE PROJECT

5.1 Budgeting and costing:

Due to a combination of factors, we have experienced a budget deficit that has deviated from our initial projections. The recent hike in prices across various sectors, driven by economic conditions, has significantly increased our expenses and the cost of goods and raw materials. In addition, the rise in the value of the dollar and the subsequent currency exchange rate fluctuations have further strained our budget planning, leading to higher costs for imported goods and services. Furthermore, the unexpected ban on imports has disrupted our supply chain, forcing us to explore alternative, often more expensive, sourcing options. Finally, the ongoing crisis in Pakistan, characterized by socio-economic turmoil and political instability, has created an unpredictable business environment, impacting consumer purchasing power and revenue streams. Despite these challenges, we are actively working to address the budget deviations by implementing cost-saving measures and seeking alternative solutions. We appreciate your understanding and support as we navigate these circumstances and strive to maintain fiscal prudence.

Initially, our overall budget was about PKR 20,000

The budget of each group member was PKR 5,000

Here is the detailed costing of our final year project

Table 1 Budgeting and Costing

Category	Item/Description	Quantity/Duration	Rate/Unit Cost (PKR)	Total Cost (PKR)
1. Personnel contributions				
Zeeshan Ahmad	Project costing	Overall contribution		6240

Muzzamil Mehmood	Project costing	Overall contribution		6230
Sumroz Ali	Project costing	Overall contribution		6240
Azam Bilal Abbasi	Project costing	Overall contribution		6200
2. Equipment and Supplies				
	Copper tube	200 inches	10Rs/inch	2000
	Acrylic sheet	2	600	1200
	Copper wire	120 inches	1Rs/inch	120
	GMSA glue	1	280	280
	Grinder Blade	1	160	160
	Fiber sticks	4	65	260
	Capacitors	20	150	3000
	Diode	20	90	1800
	Mosfet	3	50	150
	Heat sink	2	20	40
	Single core wire	1	50	50
	Resistors	10	2	20
	Vero board	1	150	150
	Copper wire	4	200	200
	Metal Nails	26	5	130
	Flyback supply	2	700	1400
	HVPC lite	2	950	1900
	Monitors	2	1400	2800
	Thermophore sheet	1	320	320

			Subtotal	**15980**
3. Travel expenses				
	Travel Expenses			
	Destination 1	Fiber sticks		300
	Destination 2	Sheet cutting		450
	Destination 3	Electrical accessories		500
	Destination 4	Equipment		850
	Destination 5	For manufacturing		1000
	Destination 6	Transportation of project		550
4. Communication and Utilities			**Subtotal**	**3650**
	Communication Expenses			
	Phone			500
	Internet			1000
			Subtotal	**1500**
5. Rents				
	Tools rental			2800
			Subtotal	**2800**

6. Miscellaneous Expenses				
	Sheet cutting			800
	Printing			180
			Subtotal	**980**
7. Total Project Cost			**Grand Total**	**24910**
8. Funding Sources				
	IGNITE funding			pendin g
			Total Funding	**pendin g**
9. Budget Summary				
	Equipment and Supplies			**15980**
	Travel Expenses			**3650**
	Communication and Utilities			**1500**
	Rents			**2800**
	Miscellaneous Expenses			**980**
			Total Project Cost	**24910**

CHAPTER-7

CONCLUSION

CONCLUSION:

- Experimentation on the ion propulsion system test bench revealed significant discoveries and conclusions. It aimed to maximize system performance by examining electrode layout and spacing in each stage.
- The experiments revealed that the ion propulsion system performed best with three stages, reducing complexity expenses by reducing the fourth stage’s contribution to thrust generation and efficiency.
- The performance of the ion propulsion system is significantly influenced by electrode spacing. A 2 to 3-cm ideal spacing produces the best thrust generation and ionization efficiency. System performance decreases when the range is exceeded, emphasizing the importance of carefully selecting electrode spacing during design and construction.
- The study found that electrode layout flexibility in each step improved system performance. Experiments show that different configurations like electrode size and shapes, affect ionization and total thrust. Further, electrode design could improve performance and efficiency.
- The ideal electrode spacing for practical application is 2 to 3 cm, considering factors like mechanical stability, electrical insulation, and manufacturing viability. Balancing performance and pragmatic factors are crucial during system implementation.
- The ion propulsion system test bench revealed optimal construction with three stages and electrodes spaced 2 to 3 cm apart. This advanced knowledge in ion propulsion technology can guide further research and advancement in this area

CHAPTER-8

RECOMMENDATIONS AND FUTURE PROSPECTS

7.1 Recommendations:

- **Adequate power supply:** Make sure the test bench has a dependable power supply system that can deliver enough voltage and current to the ion propulsion system. For best performance and precise test results, this is essential.
- **Control environment:** Pay care full attention on control environmental factors and condition which doing experiment. Consider factors such as wind, moisture and temperature with specific propellant and operating conditions.
- **Propellant handling and storage:** To handle and store the propellant material safely, establish correct processes and storage guidelines. Create and put into use a special propellant storage system that ensures clean delivery of propellant to the ion propulsion system during testing while minimizing contamination.
- **Electrode configuration and material selection:** Make the electrode design for each stage of ion propulsion system as efficient as possible. To maximize ionization efficiency and reduce power consumption, consider elements such as electrode form, size and spacing. To ensure continued functioning, choose appropriate electrode material with good durability and low sputtering rates.
- **Control and monitoring system:** Develop and comprehensive monitoring system for ion propulsion, controlling factors like voltage, current and flow rate and implementing safety measures.
- **Performance characterization:** Develop performance indicators for ion propulsion, collect data through testing and compare with theoretical forecasts or benchmark data to assess effectiveness.
- **Efficiency improvement strategies:** Explore ion propulsion system optimization, improve propellant delivery, and implement innovative electrode topologies, evaluate system effects using computational modeling and simulation tools.

- **Safety measures:** Ensure safety in test bench design, construction and use by implementing measures like emergency shutdown, operator protection and inspections. Ensure compliance with regulations and recommendations.
- **Collaboration and knowledge sharing:** Encourage cooperation with other research organizations or groups working on related subject. Utilize combined skills by sharing knowledge and experience at conference, workshop and forum.
- **Documentation and reporting:** Maintain detailed records of project aspects, including design decisions, experimental setup, test outcomes and alterations. Write a concise outlining goal, methodology findings, and conclusions using illustrations, tables and graphs for clarity.
- **Continues research and development:** Ion propulsion technology requires continuous research and development to enhance effectiveness, dependability and scalability. Stay updated on upcoming technologies, materials and electric propulsion developments to stay informed and stay ahead of the curve.

7.2 Future prospect:

- **Enhance efficiency:** As ion propulsion technology is developed through research and development, one of the most promising future prospects is to raise the system's efficiency. Reduce power consumption, improved thrust to power ratio and minimum propellant usage can all be the target of efforts. Longer trips, lower fuel consumption, and improved spaceship maneuverability would all be made possible by this development.
- **Interplanetary Travel:** Ion propulsion system are extremely promising for facilitating interplanetary travel. Robotic trips to other planets in our solar system can travel much faster thanks to ion thruster high specific impulse and minimal fuel requirements. Possibilities for the future include creating stronger ion engines that can power bigger spacecraft to investigate locations like Mars, the outer planets and their moons.

- **Deep space exploration:** Ion propulsion system is good choice for long duration deep space missions, which is deep space exploration. Future mission to explore asteroids, comets and other celestial bodies could greatly benefit from ion propulsion because to improvement in power generation and the miniaturization of thruster components. It is possible to perform complex movements and effective and precise trajectory correction, it is the capacity to sustain a continuous low-thrust acceleration for long period of time.
- **Satellite movement and station keeping:** Ion propulsion technology has a potential to completely transform satellite movement and station keeping operations in Earth's orbit. Satellite can more precisely alter this orbit, increase the length of their operational lives and effectively retain their placements by using low thrust ion thruster. Future prospect includes the creation of ion thruster designed especially for constellations of tiny satellites, allowing for more agility and mission flexibility.
- **Solar electric propulsion for human mission:** For future crewed missions beyond Earth's orbit, such as lunar exploration and perhaps manned expeditions to Mars, ion propulsion technology show substantial promise. Ion engines are the best options for long duration missions where resupplying propellant is problematic due to their grate efficiency and low fuel consumption. Reduced travel time, improves spaceship movement and increase mission safety are all benefits of advancing ion propulsion technology for human space exploration.
- **CubeSat applications:** CubeSats are compact, standardized spacecraft with ion propulsion system, offering new opportunities for orbital transfers, station keeping and interplanetary missions. Future ion propulsion systems could improve capabilities, expanding their potential applications.
- **Alternative propellant Options:** Ion propulsion system primary use xenon, but research and development can explore more affordable

propellant like krypton or argon, leading to lower mission costs and widespread use of ion propulsion technology in future space missions.

- **Integration with other propulsion technologies:** Integrating ion propulsion system with other technologies, such as ion thruster and chemical propulsion can enhance future space missions by creating hybrid propulsion architectures that combine the advantages of both technologies. This result in more flexible and adaptive propulsion system.
- **Advancement in power generation:** Ion propulsion system requires significant electricity, but advancement in power generation technologies like storage system, solar arrays and nuclear powerplants may enable higher power levels, increasing thrust and reducing mission duration.
- **Commercial space application:** Ion propulsion systems offer a future opportunity for commercial space industry development, improving satellites performance, lowering launch cost and boosting income generation for space enterprises. Affordable, dependable and scalable ion thruster are essential for mass production.
- **In-Situ Resource utilization (ISRU):** ISRU method can be combined with ion propulsion system to utilize resources on planets like the moon or Mars. Ion engines can harvest an ionize gases, reducing Earth based propellant resupply and increasing the viability and sustainability of long duration missions and colonization initiatives.
- **Environmental consideration:** Ion propulsion technologies have potential to overcome environmental issues and promote sustainable, responsible use of space debris and surrounding environment. Research should focus on developing propulsion technologies minimal negative impact

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