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Simulating Dielectric Barrier Plasma Actuators with Varying Geometries

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Undergraduate Honors Thesis

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Abstract

The idea of Ionic Wind Propulsion has long been a topic of research for whether or not it can be used as a practical power source for flight. MIT researchers proved in 2018 that a plane with zero moving parts powered by Ionic Wind Propulsion was possible, and sustained flight could work with an internal power supply. However, due to the thin wire electrodes required to generate the ion cloud that made such propulsion possible, large amounts of drag rendered the plane extremely inefficient and impractical. Dielectric Barrier Discharge Devices (DBDs) are being investigated as to whether they can serve as a more aerodynamically efficient replacement to the wire electrodes, as they can be shaped around the wing, and multiple geometries are being tested in order to find the most efficient one for plasma generation. As physically building and testing the DBDs takes time, COMSOL Multiphysics software was used to simulate the electric field of the DBDs to see if it could serve as a quicker method to test the DBD geometries. The results from COMSOL supported the initial findings from physically testing the DBDs. In addition, multiple geometries of DBDs were tested in order to see which one could generate the strongest electric field, and thus prove more efficient for plasma actuation. These results also showed the relationship between DBD geometry and strength of electric field, providing useful data for how best to design DBDs going forward.

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Abbreviations

DBD	Dielectric Barrier Discharge Device
EF	Electric Field
AC	Alternating Current
DC	Direct Current
V	Volts
m	Meter
E	Electric Field Intensity
D	Electric Displacement
H	Magnetic Field Intensity
B	Magnetic Flux Density
J	Current Density
ρ	Electric Charge Density
t	Time

Introduction

Background

1. Ionic Wind Propulsion

Ionic Wind Propulsion is a method for creating a flow of air without any moving parts by using electrodes to ionize molecules in the air, which then are used to create thrust. Two electrodes are used to accomplish this, an emitter electrode, and a collector electrode. When a high voltage is applied, the emitter electrode will generate the ion cloud, the cloud is then accelerated backwards towards the collector. This acceleration creates air flow which can then be used to propel objects forward. Whether this phenomenon could be utilized for flight was investigated throughout the 1900's, however due to high voltage requirements, power supplies had to be external and attached with a wire rendering the technology unusable for practical means. [7] In 2018, MIT researchers successfully tested an ionic wind propelled plane that contained an internal power supply, proving that the technology could be used for powered flight with no moving parts. However, due to the thin wire electrodes used to generate the ion cloud, large amounts of drag were generated, limiting the performance and efficiency of the plane. [2]

2. Dielectric Barrier Discharge Devices

Dielectric Barrier Discharge Devices, or DBDs, use electrical plasma discharge between two electrodes, generated by high voltage alternating current, split by a dielectric barrier, to generate ozone. They were first experimented on by Ernst Werner von Siemens in 1857 for use in ozone generating applications. This first DBD used air flow through a small gap between two glass tubes, where the dielectric barrier discharge was generated from alternating electrical field, to generate the ozone. [8] Today, plasma can be generated using a "paper" like DBD, which allows for flexibility and lets the plasma generating surface be shaped around irregular surfaces, increasing their usability. [9] This flexibility has potential to be utilized in Ionic Wind Propulsion, in order to shape the ion-cloud generating device around the surface of the wing and alleviate the drag due to thin wire electrodes.

3. COMSOL Multiphysics Software

COMSOL Multiphysics is a simulation software that is used for various applications across engineering and scientific research. It combines multiphysics and single physics along with modeling capabilities in order to build and run simulations in electromagnetics, heat transfer, fluid dynamics, structural mechanics, chemical engineering, and more engineering and scientific applications. [4]

Objectives

- Building on the plane designed by MIT, investigate DBD usage as plasma actuators in Ionic Wind Propulsion to alleviate drag effects from thin wire electrodes.
- Investigate viability of various geometries of DBDs for use in plasma generation and Ionic Wind Propulsion.
- Verify that DBDs can be set up and the electric field can be simulated in COMSOL to make testing different DBDs in the future easier.

Testing DBDs in COMSOL

Generating Plasma with Physical DBDs

To begin investigating whether DBDs could be used to generate plasma for use in Ionic Wind Propulsion, some DBDs were made with a hexagonal shaped geometry in order to perform physical experiments. The DBDs used in this experiment were designed similar to parallel plate capacitors, and the thin paper plasma actuators shown in Figure 2, using a thin top and bottom conductive layer made of aluminum foil with a thin dielectric layer in between, made of Kapton film.

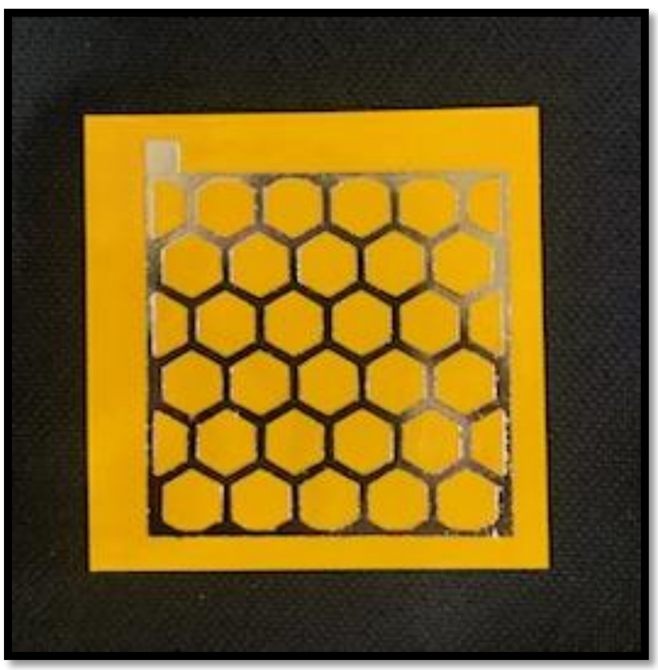
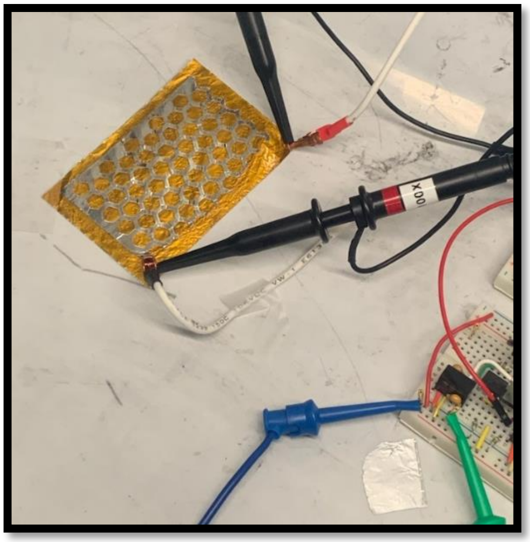


Figure 1: DBD with Hexagonal Geometry

This DBD was then tested in atmospheric conditions. The circuit used to power the DBD has a maximum voltage of 1.7 kV, and plasma was generated across varying frequencies.



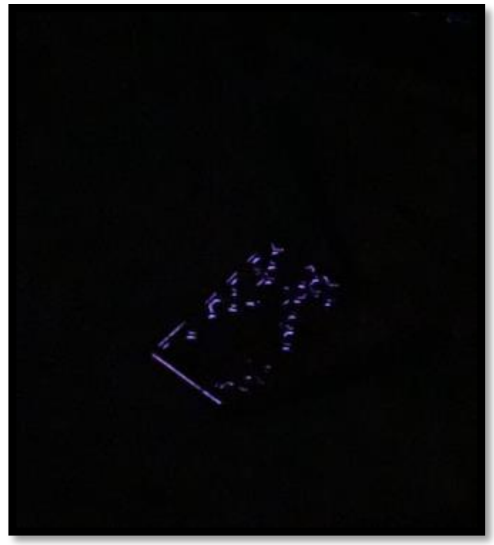


Figure 2: Plasma Actuation Test Setup

Figure 5: Surface Plasma Generated on DBD

Using COMSOL Simulation

Once plasma had been successfully generated with this DBD, work could be done to verify whether the correlating electric field could be generated through simulation. If the electric field generated by the DBD in simulation was found to be concentrated in the same locations where the plasma was generated in the physical experiment, this method of testing can then be used in order to more easily find the most efficient geometry of DBD to use for further experimentation. The hexagonal DBD was modelled in Solidworks along with other possible geometries for simulation use in COMSOL Multiphysics software.

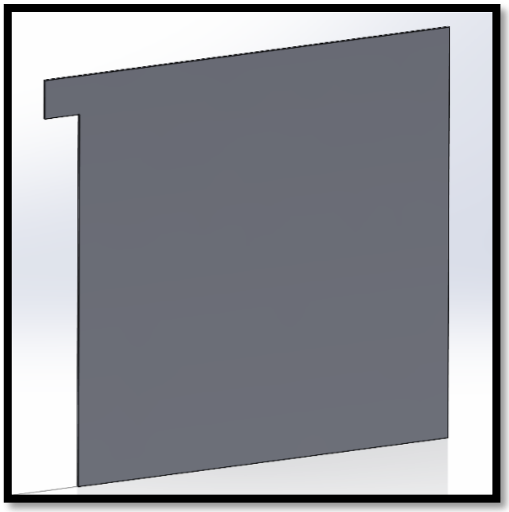


Figure 6: Dielectric Solidworks Model

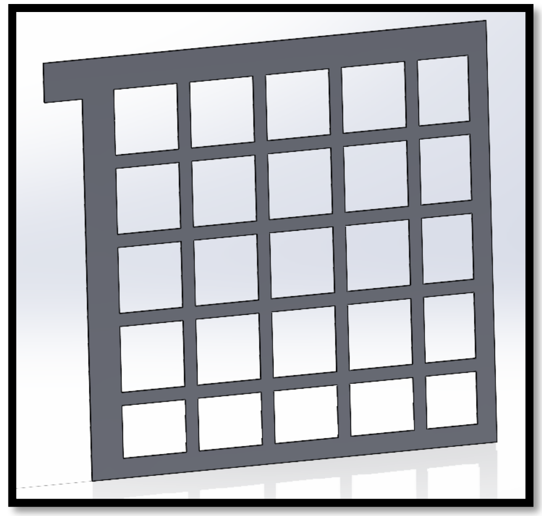


Figure 7: Square Plate Solidworks Model

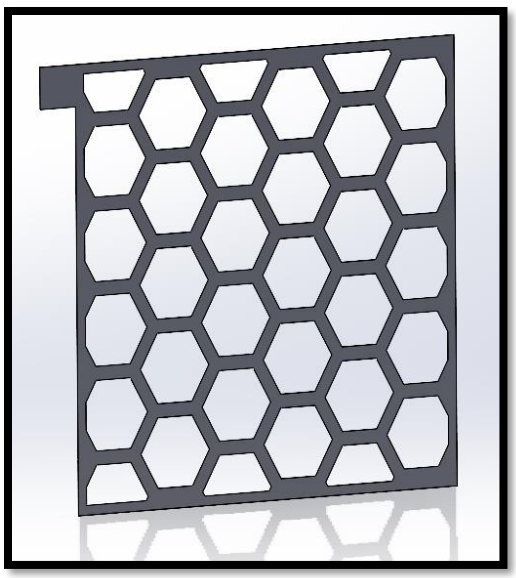


Figure 8: Hexagonal Plate Solidworks Model

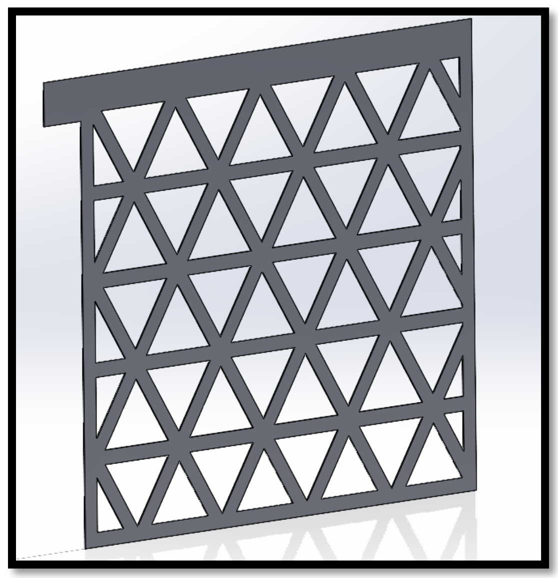


Figure 9: Triangle Plate Solidworks Model

To find the locations and strength of the Electric Field generated by the DBD in COMSOL, the AC/DC module was used. In COMSOL, the AC/DC module is used in low-frequency and static applications to simulate electric, magnetic, and electromagnetic fields. Stationary, frequency-domain, and time-domain analysis can all be run in order to analyze resistive and conductive devices, capacitance devices, electrical insulators and more. [4] Each module in COMSOL uses various differential equations, integrals, and solvers to perform its simulations, and key to the AC/DC module are Maxwell's Equations. Maxwell's equations are a set of equations that define the relationships between various key electromagnetic variables. [3]

$$\nabla \times H = J + \frac{\partial D}{\partial t} \quad \text{EQ. 1}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad \text{EQ. 2}$$

$$\nabla \cdot D = \rho \quad \text{EQ. 3}$$

$$\nabla \cdot B = 0 \quad \text{EQ. 4}$$

Equation 1 is known as Maxwell-Ampere's Law and Equation 2 is Faraday's Law. Equations 3 and 4 are each a form of Gauss' Law, the former being the electric form and the latter being magnetic. Another important equation for the AC/DC module is the equation of continuity.

$$\nabla \cdot J = -\frac{\partial \rho}{\partial t} \quad \text{EQ. 5}$$

This equation guarantees the conservation of electric charge in the presence of currents and can also tell when currents are steady. [3] The various Solidworks models were loaded into COMSOL and then positioned to match the DBD used in the physical testing – namely, conductors on top and bottom and dielectric in the middle. The materials library was then used to assign Aluminum 1050 and Kapton H film to their appropriate parts. The dielectric constant, or measure of how well a material can store electric energy in an electric field, for each of these materials was assigned. The aluminum was assigned a dielectric constant of 10.8 [1] and the Kapton film 3.4 [5]. Once the voltage of 1.7 kV was applied to the appropriate location, a frequency domain study was run to simulate the electric field across the DBDs.

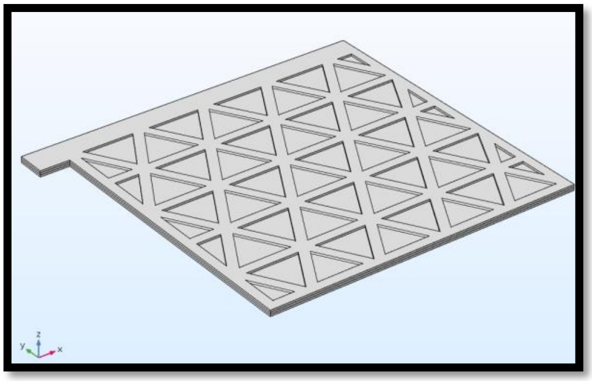


Figure 10: Triangle DBD in COMSOL

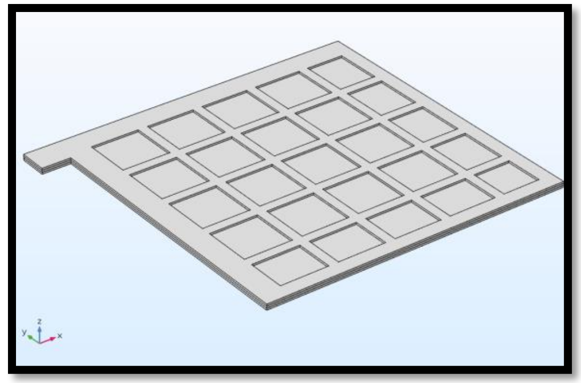


Figure 11: Square DBD in COMSOL

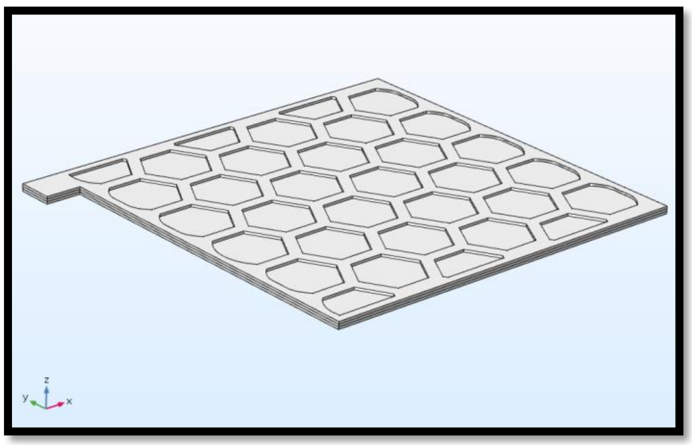


Figure 12: Hexagonal DBD in COMSOL

Results and Discussion

When conducting the simulation to find the electric field for the hexagonal DBD at 1.7 kV, it was found that the electric field was concentrated on the edges of the cutout aluminum shapes and the sides of the DBD. The same places where the plasma was being generated as seen in Figure 5.

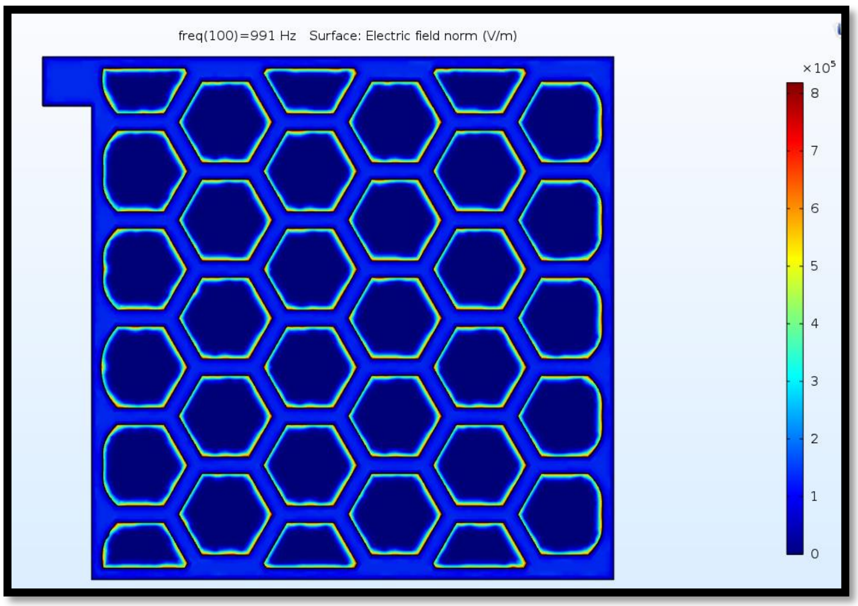


Figure 13: Electric Field Concentration on Hexagonal DBD

This confirmed that the results from the physical testing could be replicated through simulation, and that the correct electric field, indicating where plasma generation will occur, could be found. This process was then repeated for the triangle and square geometries, obtaining an electric field concentration similar to that of the hexagonal DBD.

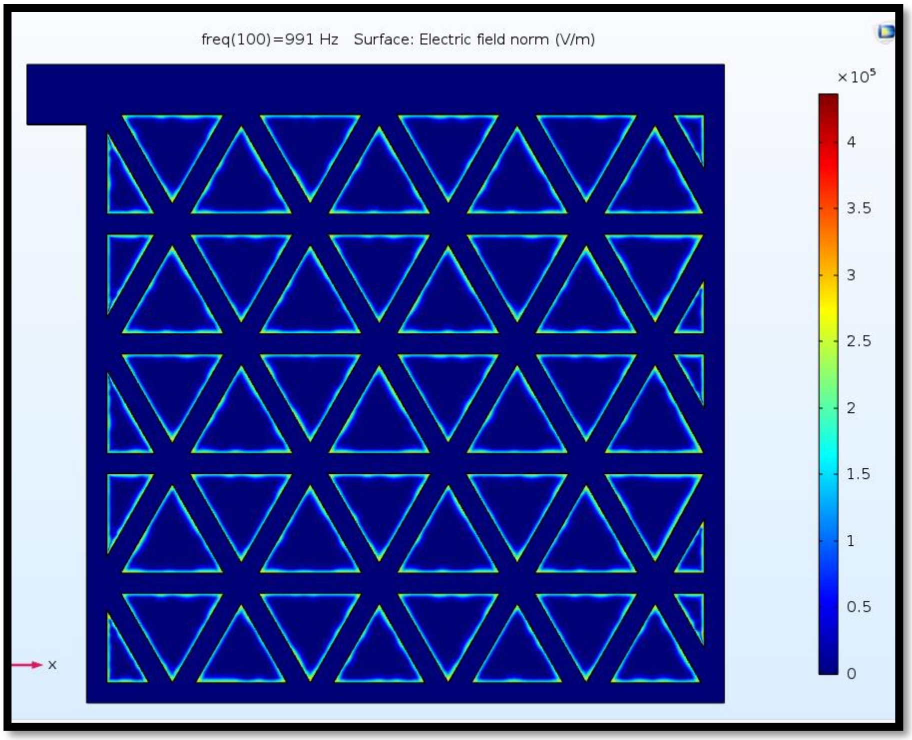


Figure 14: Electric Field Concentration on Triangle DBD

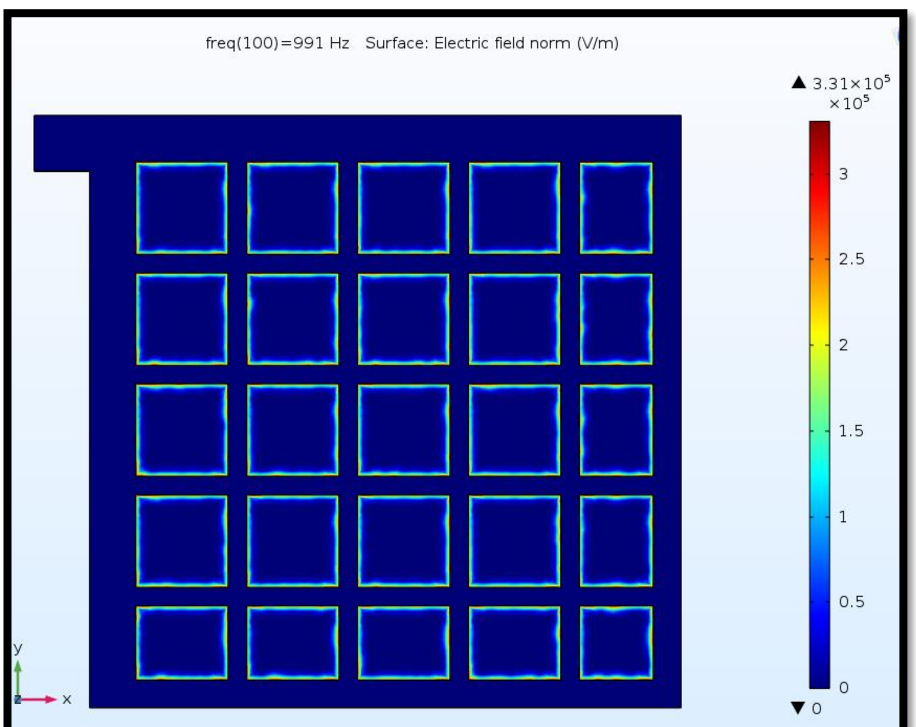


Figure 15: Electric Field Concentration on Square DBD

By further analyzing these results in COMSOL, the location and value, in V/m, of the maximum electric field strength can be found for each of the different DBDs, which then provides insight into which of the three geometries would generate plasma the most efficiently.

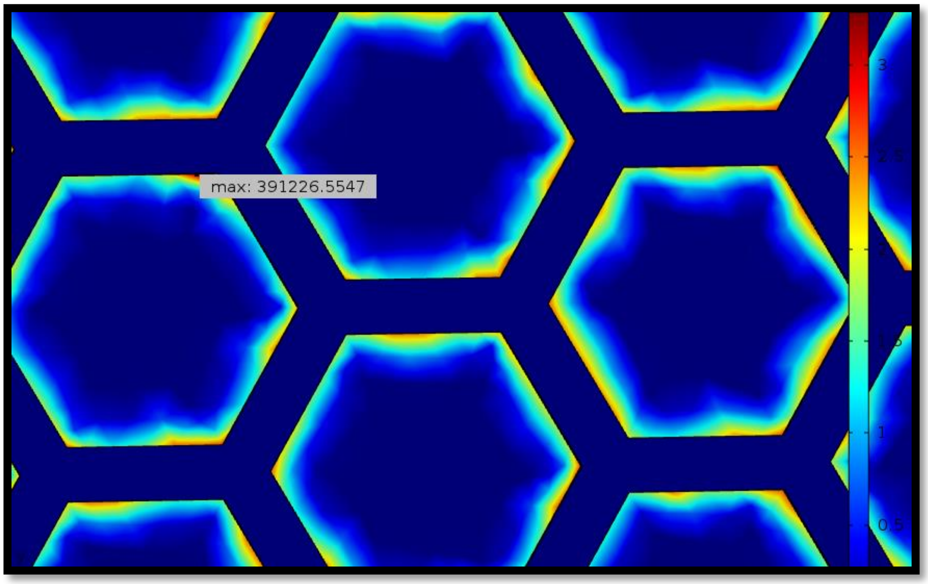


Figure 16: Location and Value of Max EF Strength on Hexagonal DBD

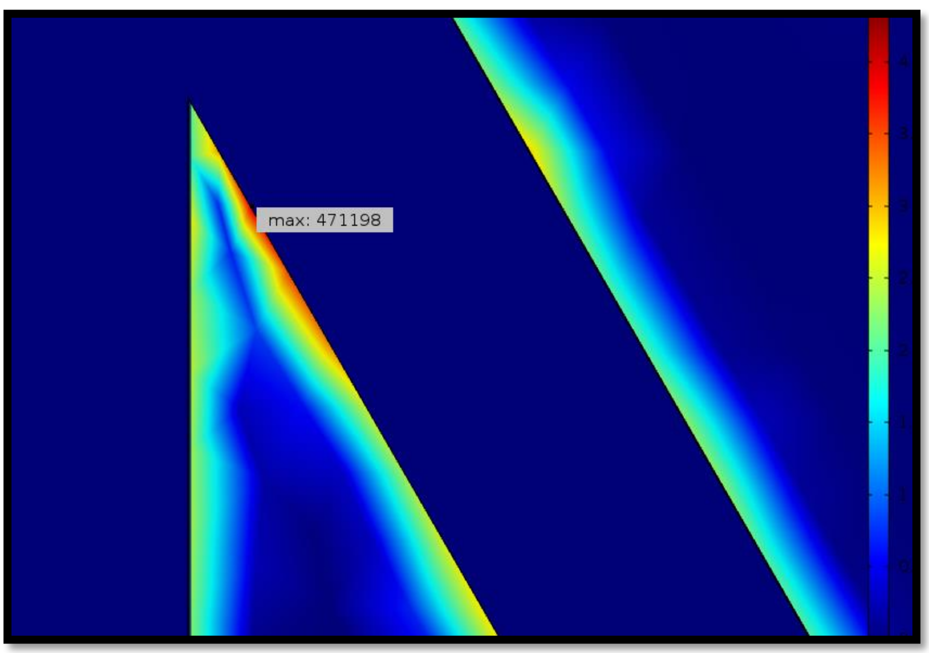


Figure 17: Location and Value of Max EF Strength on Triangle DBD

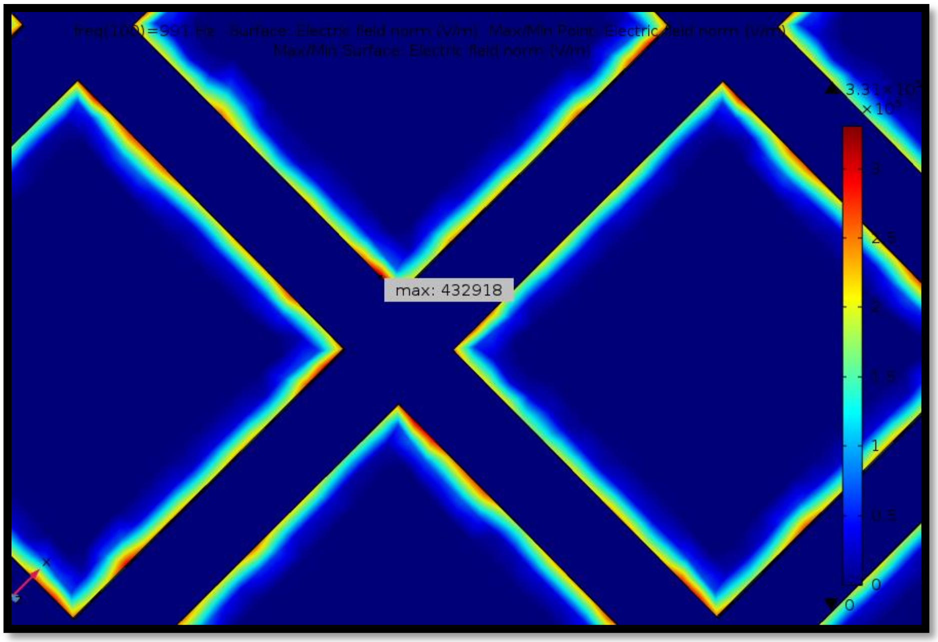


Figure 18: Location and Value of Max EF Strength on Square DBD

Max Electric Field Strength	Hex DBD	Triangle DBD	Square DBD
V/m	391226.5547	471198	432918
MV/m	0.391227	0.471198	0.432918

Figure 19: Max EF Strengths for each DBD in V/m and MV/m

These values can also be compared to a study ran by the United States Air Force Academy on the downstream electric field strength of a Plasma Actuator. In this study, the DBD setup used was very similar to the DBDs used throughout this research, with a dielectric material separating two flat plate electrodes on the top and bottom. [6] Comparing to their results, the location where the surface potential of the electrode was 1.7 kV can be found and the electric field strength at this same location can be seen. The strength of the electric field can be seen to be approximately .4 to .5 MV/m - the same range as the values found above, this correlation helps support the accuracy of the results found through simulation. [6] The strongest maximum electric field was found to be on the triangle DBD, indicating that it would be good to test this geometry in the future as opposed to only testing the hexagonal DBD shape. When looking at where the electric field was found to be concentrated on each of the DBDs, and where the locations of the maximum strength were themselves, it can be seen that it is generally the strongest on or near the corners of each shape. As the angle of each corner got smaller, the value for the maximum electric field strength also went up, from the hexagon to the square to the triangle, this could indicate that the sharper the corner there is, the stronger the electric field concentration is, thus improving plasma generation in those areas. The results of this experiment have also shown that, going forward, COMSOL can be used as an alternative to find the most efficient geometries of DBDs for plasma generation as opposed to physically building and testing the DBDs.

Conclusions

The idea to use Ionic Wind Propulsion to power a plane without any moving parts has the potential to revolutionize the effect planes have on our environment. If realized, this technology could allow for planes to fly with a vastly smaller environmental impact than they have right now, as well as reducing noise created when in flight. This project has taken steps to further this research and improve the ease at which this project can be continued in the long term.

- Investigations into the substitution of DBDs for thin wire electrodes for use in plasma actuation were done and simulated results were found that supported findings from physical experimentation.
- Simulated various geometries of DBDs and found the maximum electric field strength for each one, compared these results with outside studies to correlate and support simulated results.
- Provided a starting point for further work on simulating different geometries and improving efficiency of plasma actuation as well as improving ease of further testing.

Future Work

The next steps for this research would be to take the observations gathered here about how the electric field reacts to certain geometries of DBDs, and design/test DBDs that should generate even stronger electric fields. If the Plasma module for COMSOL is obtained, then it would also be good to work on simulating the DBDs in that module, as it can simulate the process of plasma generation itself. It would be able to provide a more accurate picture of what is happening with the DBDs as well as provide even more concrete results on which geometry of DBD can produce plasma the most efficiently.

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