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High-Voltage Ionic Wind Thruster

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by

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***Abstract*— A high-voltage ionization technique is implemented in a novel coupled, small-scale cylindrical thruster model to measure the resulting air velocity. This thrust is achieved with the use of a 100 kV voltage supply, which induces a high electric field between the anode and cathode planes of the model. In turn, the electric field transfers a high amount of energy to the surrounding air, exciting individual electrons and liberating them from the molecule. The free electrons create an air flow as they cascade into one another, resulting in a non-zero thrust to weight ratio of the thruster model. This proof of concept is empirically investigated, and the air velocity with respect to a corresponding applied voltage investigated. The gathered data is then analyzed and compared to an ideal simulated value, and the results thereof discussed.**

***Keywords*— Ionic Wind, Ionization, High Voltage Thruster, Paschen's Law, Breakdown Voltage**

I. Introduction

With a push towards more efficient modes of extraterrestrial transportation, novel electronic mechanisms of thrust have been considered; of these mechanisms, atmospheric ionization utilizing ionic wind is of keen interest. When air particles are in close proximity to an extremely high voltage source, ionic wind is created. The strength of the voltage source allows it to transfer electrons to the air particles, thus ionizing them. The movement of the ionized air particles towards the grounding plane creates interactions and collisions with neutrally charged particles, as well as the ionic wind force.

From this knowledge, the ionization process had the potential to be isolated within a chamber, accelerated through multiple stages and channeled into a single exhaust to create thrust for a device. Man-made ionization is most commonly seen in the medical environment for X-Rays, and in air purification devices to reduce airborne diseases. Beyond these uses, though, there exist further implementations for applications in the aerospace industry.

The goal of this project is to qualitatively examine the novel ionic thruster design concept, develop and meet a baseline requirement for the thrust levels necessary to lift the device off the ground, and modify the design as necessary. High-voltage circuitry was utilized to facilitate the ionization of atmospheric air to produce a desired thrust, housed by a 3-D printed modular body consisting of anode and cathode pairs to facilitate the ionization process. The first objective was that the ionic thruster would be functional, ie. that there would be a measurable wind speed at the output of the model body. The second objective was that ionization would be visible in low-light conditions. The third was that the device delivers an air velocity equivalent to or greater than five meters per second. The fourth objective was that the final design requires a thrust to weight ratio of at least ten percent. Finally, the final build will be less than or equal to five pounds

II. Theory & Simulation Design

An understanding of gaseous ionization is required before undertaking the task of creating an ionic thruster; this is, at its heart, a multidisciplinary subject involving fluid dynamics, electro-chemistry, and advanced physics. To begin, a cornerstone of

the ionization process is described in Paschen's Law- the concept of a gaseous material's breakdown voltage. Breakdown voltage is the required electrical potential difference between an anode and cathode plane in a specified medium to create a short circuit between them, and can be described by:

$$V_B = \frac{Bpd}{ln(Apd) - ln[ln(1+\frac{1}{\gamma_{se}})]} \quad (1)$$

Here, p is the pressure of the surrounding gas in Torrs, d is the distance between the anode and cathode in cm, γ_{se} is the secondary electron emission (SEE) coefficient of the material (essentially, a metric to describe the ability of the gas to release more than one ion), and A and B are empirically determined constants that are specific to a certain gas. In the simulation described below, p is taken as 760 Torr, the distance between anode and cathode is varied (this will be discussed later), and both A and B are estimated (as described in [1]) to be 7 Torr/cm and 258 VTorr/cm, respectively. The secondary electron emission coefficient is determined by backsolving the general form of Paschen's Law, applying the breakdown voltage of atmospheric air to the equation; at room temperature, low humidity, and 1 atm pressure (760 Torr), this value is generally accepted as 30kV. The SEE coefficient is found to be approximately 4.19 x 10^-4.

Considering the SEE coefficient as a function of breakdown voltage for the gaseous substance of interest- in this case, the air in the testing facility- this value can be reapplied to Paschen's Law in a form that has been evaluated to solve for pressure, as seen in (2). This pressure value is then related to wind speed by the molecular density of air, ρ, and overall aperture efficiency, A_{eff}, which was calculated to be approximately 14% by calculating the area of ionization (here, the area of the anode and cathode themselves as compared to the cross sectional area of the model, taken to be $0.011m^2$):

$$p = \frac{e\, ln(1+1/\gamma_{se})}{A\, d} \quad (2)$$

$$v = \sqrt{\frac{2p}{\rho}} A_{eff} \quad (3)$$

Such a direct relationship between a gaseous substance's applied voltage and the resulting wind speed of electrical ionization has not appeared in previous literature that the authors are aware of; the results of this calculation, therefore, are discussed in-depth in the following sections in order to examine the validity of the concept, and to ultimately determine whether or not this model is an accurate indicator for air velocity.

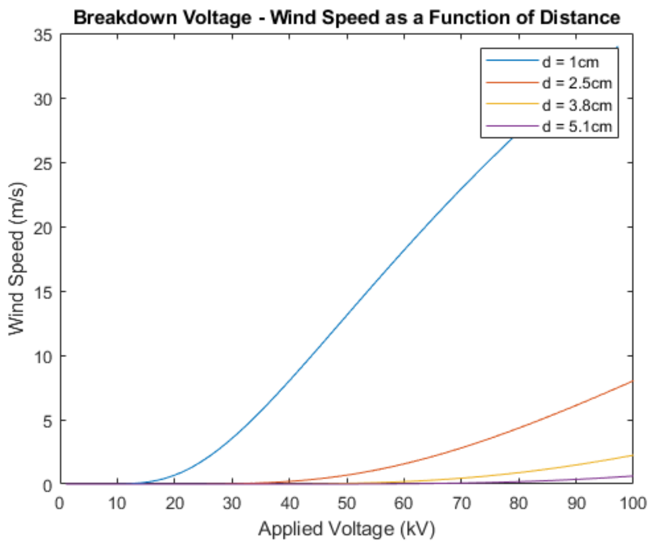
The relationships discussed above are each taken into account in the simulation of the aforementioned problem statement. In this study, MATLAB was used to generate values for various applied voltages of the system- received from the variable high-voltage supply. These values, ranging from one to 100 kV, were then applied to (1), backsolving for the SEE coefficient at that voltage. The resulting SEE can then be used in (2), and subsequently (3) from the simulated pressure difference, to approximate the output wind speed in ideal atmospheric conditions. This relationship is illustrated in figure 1 for different distances between the anode and cathode planes, and is extremely useful in gauging the accuracy and efficiency of the later empirical results. Here, each of the spacing distances used in the following experimental section are simulated; the determination of these distances as ideal testing conditions is discussed in section IV of this report.

As a matter of ensuring accurate simulation values while also preserving time by understanding any variations with the measured results, wind speed values for a 1 cm anode-cathode gap at various room air pressures were also simulated. This was done essentially using the methods above, but substituting a pressure variable in for the distance variable within the MATLAB simulation code. The results from this simulation are detailed

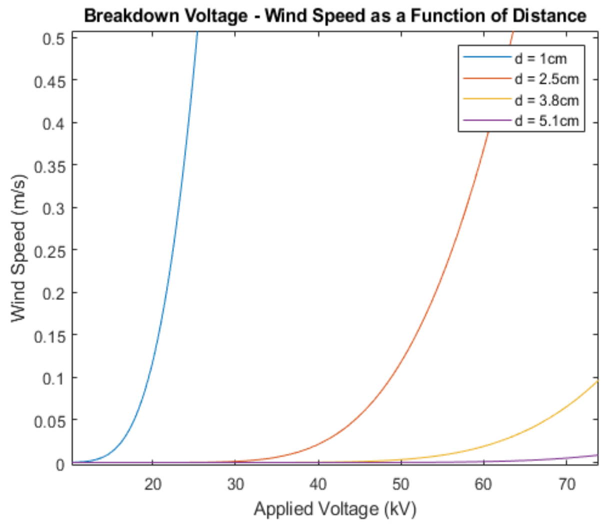
below in figure 2 of section III; the four resulting functions are representative of a typical pressure fluctuation depending on geographic location and altitude, as well as weather conditions.

III. Simulated Results

Applying the simulation described above, a baseline for the expected measured results can be developed. As can be seen in figures 1 and 3, the variable conditions of the setup and surroundings can have a rather drastic effect on the output of the system. The variation in spacer distances dramatically reduces the simulated wind speeds, requiring almost 80kV to see an output for a 5.1cm space between the anode and cathode.

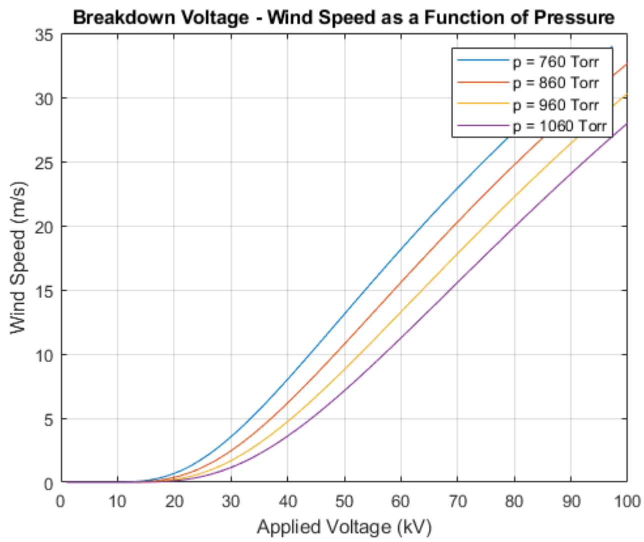


[Figure 1: Simulated Wind Speed as a function of distance]



[Figure 2: Impetus Voltages for various distances]

Less dramatic are the effects of the atmospheric pressure on the wind speeds; and, while this might account for consistent variation between the simulated and measured results, it would not be accountable for inconsistent variations between spacing distances, as this value should be a constant for individual testing sessions (this might vary session by session, again dependent on weather, etc.).



[Figure 3: Simulated Wind Speed as a function of pressure]

If this model were to prove accurate, it could be expected that any variation between the simulation and measured results to be consistent with the variations in pressure; any similarities between different spacers used would prove this model inaccurate, at least to some extent. Figure 2 provides a clearer depiction of simulated wind speeds at various distances. This relationship truly illustrates the dependency of wind speed on achieving a modicum of the breakdown voltage; as discussed above, the breakdown voltage is a value that must be achieved to generate an arc. Ionization can still occur without arcing, a fact made apparent in figure 3.

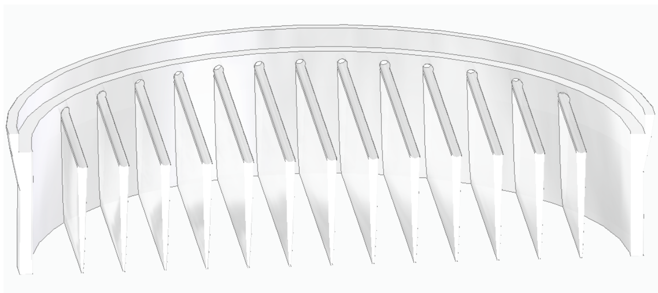
IV. Experimental Design & Testing Procedure

As a prerequisite for creating a functioning ionic wind thruster, a housing body for the anode and cathode planes were required. For the applications listed above, it was determined that a custom-built model would best serve the project; an optimal distance between these two planes needed to be found in order to generate a maximum amount of thrust. To this end, a separable anode and cathode plane were designed, with spacers to be placed between the two.

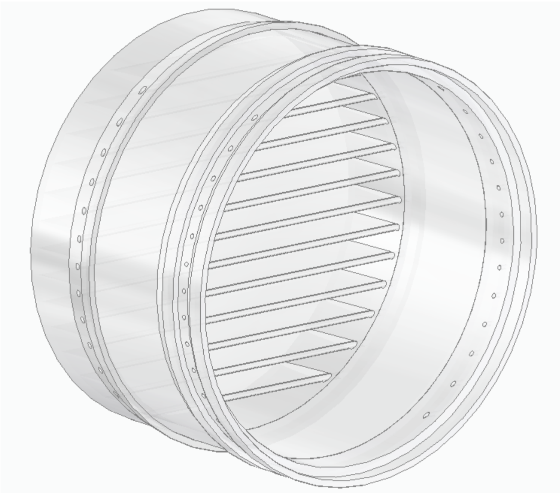
Each piece (anode, cathode, and spacer) are designed to be 122.5 mm in diameter on the inner wall of the cylindrical body, and have a locking lip on one end; the walls of each measure 3 mm in thickness. For the anode and cathode, a total of thirteen anode-cathode strand pairs will be required to house the 32 AWG and 18 AWG wire for the anode and cathode, respectively, with a spacing of 8.5 mm between each strand. Both the anode and cathode pieces are a total of 30 mm in height. The strands of the cathode will be housed at the head of an airfoil that spans from the back of the cathode towards the front lip a total length of 25 mm; this airfoil is notched in order to house half of the 18 AWG wire, the remainder of which is covered in electrical tape to provide an additional layer of insulation. The 32 AWG wire is strung in a back and forth manner through the holes of the anode.

The anode and cathode strands must sit parallel to one another for the ionization of the air between them to take place. To this end, the holes in both pieces were spaced equidistant from one another and cut linearly through the walls of both pieces, allowing for the wire being strung through the anode piece to mirror the airfoils in the cathode when aligned correctly. The distance between anode and cathode would be determined by the spacer pieces used; the size of these spacers was determined using a variation of Paschen's law, relating distance to breakdown voltage.

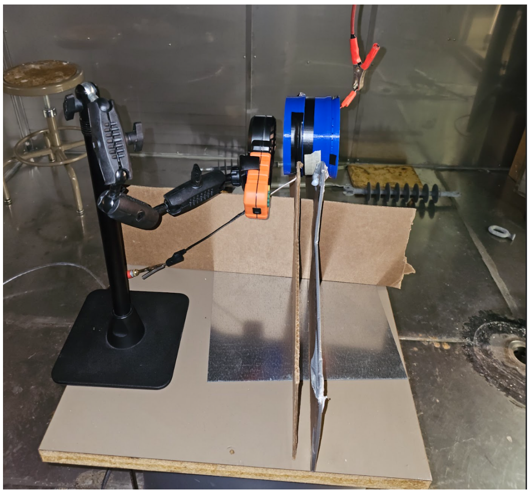
The choice of a material to print with was a critical consideration; the model would be exposed to extremely high voltages, meaning that the material could potentially experience high temperatures in concentrated areas. The model then required a printing filament that could meet such standards, but also fit the overall budgetary and weight constraints. Conveniently for testing purposes, the UAH College of Engineering maintains a supply of 3D printing filament that withstood the maximum voltage used to test the model. This material was used to construct all anode, cathode, and spacer pieces for the preliminary testing that was conducted for this project. A clear filament of equivalent voltage rating was also procured to construct a final design as a representation of future thruster model possibilities.



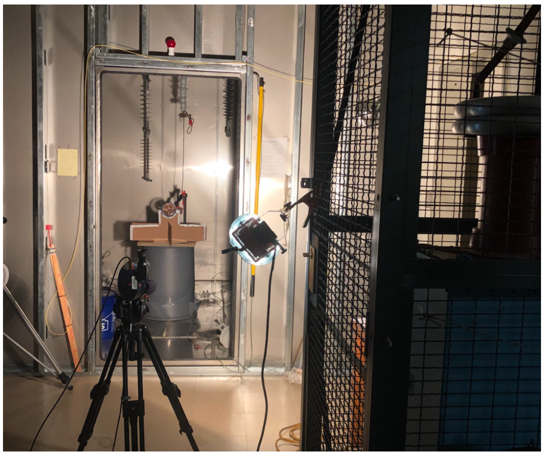
[Figure 4: Cathode]



[Figure 5: Anode and Cathode with Spacer]



[Figure 6: Test Set-Up]



[Figure 7: High-Voltage Testing Chamber]

Our systematic testing approach involves altering a single parameter per test iteration in order to attain the utmost precision in our results. Specifically, we conducted a series of tests that entailed manipulating the distance between the anode and cathode within a predetermined optimal range. This range, which extends from a proximity just beyond the arcing distance to slightly below the minimum realizable thrust produced by ionic wind, was calculated through a combination of Paschen's law and the faculty recommended range, which incorporated a judicious safety margin aimed at avoiding any unnecessary arcing events. The distances chosen were 25mm, 38mm, and 51mm; these were selected because of their relative range-38mm being the expected ideal distance, with a margin of 15mm on either side of this.

To further minimize the risk of arcing, we began our testing at a distance within the middle of the optimal range, thereby reducing the likelihood of exceeding the arcing distance and causing damage to the system. By adopting this approach, we were able to obtain highly accurate and reliable results, which we subsequently analyzed and interpreted with great care.

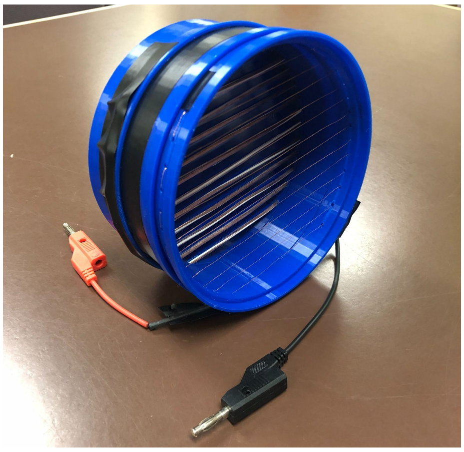
The testing procedure, prescribed by the lab coordinator, is as follows:

1. Ground the equipment properly to prevent electrical hazards.
2. Close the laboratory doors.
3. Place the prototype in the designated area for testing
4. Set up the corona camera to capture the experiment being conducted.
5. Turn on the anemometer and set it to measure the maximum level.
6. Connect the high voltage and ground cables to the equipment carefully.

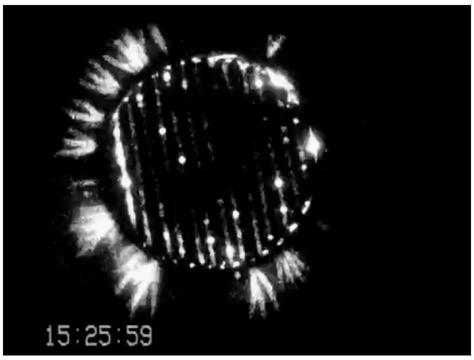
7. Remove the ground pole to prevent interference with the test results.
8. Leave the testing chamber and ensure that no one is in its near vicinity.
9. Turn off the overhead lights and initialize the high voltage source.

V. Experimental Results

Various revisions of the prototype were tested to determine if the device was effective in reaching the prototype goals. Revision 1 testing used the 38 mm and 51 mm spacer. The corona camera was set up and the entire testing session filmed. Figure 5 shows a screenshot of the visible corona effect. Unfortunately, we were unable to obtain any recordable data from the thruster during the Revision One testing as seen below in Table 1.



[Figure 8: Experimental Anode and Cathode]

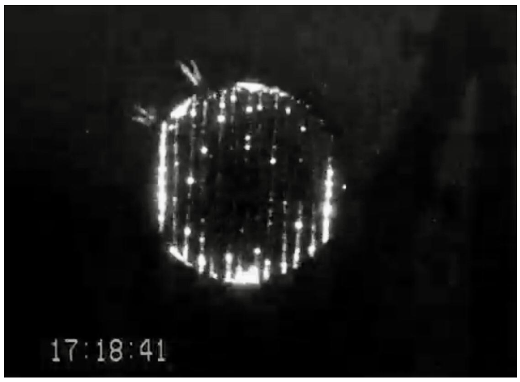


[Figure 9: Revision 1 Visible Glow Corona]

Spacer Distance (mm)	Wind Speed (m/s)	Breakdown Voltage
51	0	Not Achieved
38	0	Not Achieved
25	0	Not Achieved

[Table 1: Revision 1 Measured Results]

For testing Revision 2 of the design, we took note of the shortcomings of Revision 1. For the design of Revision 1, a corona discharge around the perimeter of the anode voltage plane was visible. This issue was diagnosed as being from windings of wire around the anode that were made before the wire entered the anode. This was originally done to attempt to prevent the wire from becoming loose. To treat this issue, the anode was rewired with new copper wire, but it was secured and insulated at the ends of the copper wire with electrical tape. They also shortened the positive voltage lead that was soldered to the anode piece for a better connection to the transformer. For the testing during this revision, the team made the decision to only use two separate spacer sizes, compared to the four sizes tested for revision 1. This resulted in much better outcomes, and measurable results that can be seen in the table below.



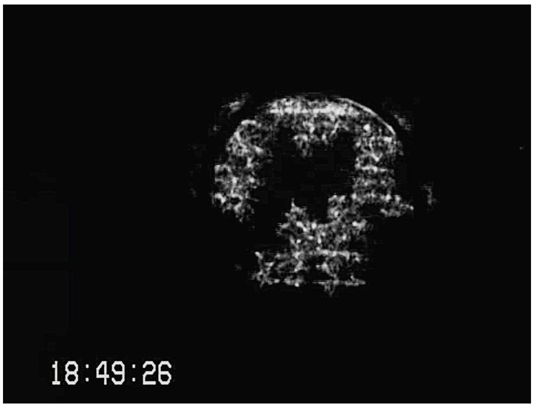
[Figure 10: Revision 2 Visible Glow Corona]

Spacer Distance (mm)	Wind Speed (m/s)	Breakdown Voltage
51	0.06	28kV
38	0.37	28kV

[Table 2: Revision 2 Measured Results]

As can be seen from the Revision 2 testing results, much better results were observed when a smaller spacer between their voltage anode and grounding cathode planes. This is likely due to the smaller distance required for an electric field to travel in order for an effect to occur between the two planes. Less corona discharge around the perimeter of the thruster was observed as well. This is believed to be a direct result of removing the exterior windings of copper wire from the anode piece.

The third and final revision of testing resulted in the best results seen to date. For this revision, the design of the cathode piece was again modified. For the Revision 1 and 2, the team had a single, 18 gauge, bare copper wire as the grounding wire going across the cathode. For Revision 3, insulated 18 gauge copper wire was applied across each of the airfoils of the cathode piece. This additional insulation allowed the model to fit with a smaller spacer size, in accordance with Paschen's Law. The results from these design changes yielded better results than even the second revision. The results are shown in the table below.



[Figure 11: Revision 3 Visible Glow Corona]

Spacer Distance (mm)	Wind Speed (m/s)	Breakdown Voltage
51	0.33	34kV
38	0.44	31kV
25	0.46	24kV

[Table 3: Revision 3 Measured Results]

The same results and conclusion can be made with the Revision 3 testing results as can be made with Revision 2. During Revision 3 testing, much greater wind speeds were seen at the output of the thruster when a smaller spacer was used. As seen in the table above for Rev. 3 testing, two separate wind speed results were measured for the 38mm spacer. Initially, a wind speed of 0.44 m/s was obtained before an arc occurred at approximately 33kV. These results were attempted again after redoing the setup for testing. However, only a value of 0.42 m/s at approximately 31.5 kV was able to be recorded. This drop in voltage tolerance for the system is believed to be due to an arc occuring at the same location for both tests, with the 38mm spacer. But after the first test, the arc caused a weakening of the thruster's insulation. This is what the team believes resulted in a lower wind speed and voltage tolerance for the second testing with the same spacer. A more even distribution of corona inside the thruster was also observed. This is believed to be from the creation of the new cathode piece. The wire that was laid along the airfoils likely contributed to the more even displacement of corona.

VI. Discussion

Further examining these results, an additional metric that would further allow comparison with other aviation technologies can be produced. The overall thrust to weight ratio of the final product was intended to be a minimum of 10%. This goal is slightly more ambitious than similar technologies, but not so lofty as to be unachievable. While a thrust to weight ratio of 100% would be required to achieve the liftoff of a vehicle, improvements could be made to the design regarding materials outside the project's current budget, as well as potential design improvements of the anode and cathode planes to optimize the produced electric field- thus,

a thrust to weight ratio of 10% is a realistic goal for early stages of research such as this.

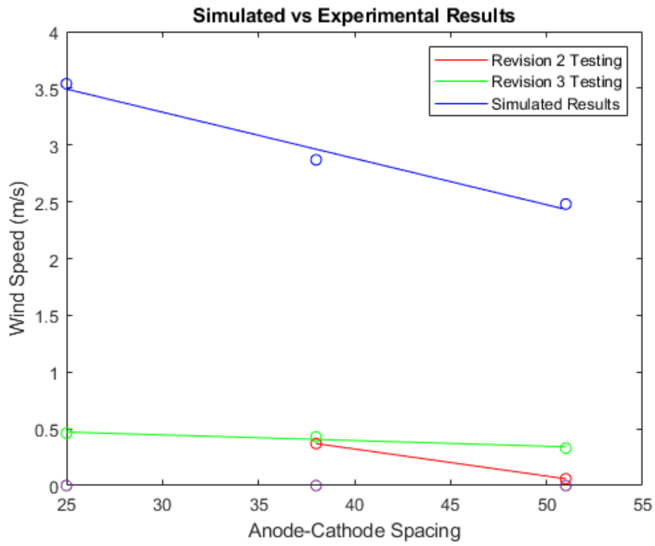
To compute the thrust to weight ratio for this system, the weight of the overall body must be converted from grams to Newtons, and the air speed must be converted to a thrust value in Newtons. This thrust value is derived from the overall wind speeds produced in combination with the surface area producing the air speed. Thrust is given by the general equation:

$$F = (A)(1.229\ kg/m^3)(v^2), \quad (4)$$

where A represents the aperture area in m^2, v is the air speed in m/s, and the middle term of $1.229\ kg/m^3$ is a proportionality constant for atmospheric air at room temperature. Using an overall open aperture area of $0.01143\ m^2$ and the top resulting wind speed of 0.46 m/s, we can derive that the achieved thrust was 0.002972 N. Converting the weight of an ideal model body (constructed of aerographite, with a density of 180 g/m^3) from grams to Newtons, we see a total weight of 0.0834 N. The resulting thrust to weight ratio from these parameters is 3.699%- not quite up to par with the goal that the team had initially set, but there are testing conditions that must be taken into account when considering this result.

The highest air speed of 0.46 m/s was produced using only one stage; as the number of stages increases, we would expect a slight exponential increase of the wind speed, following Paschen's Law. This would then result in an increased airspeed in relation to the overall thruster weight, meaning that an increased number of stages would result in a higher thrust to weight ratio. Future research on this topic would require experimentation with the number of stages to determine an optimal amount of stages for a maximum thrust to weight ratio.

Comparing these results to the simulated results, it can be seen that there are certain discrepancies among them. The final recorded values are approximately ten times lower than that of the expected; still, this was an expected result given ideal conditions. Anything from humidity levels, pressure, or voltage differences could have altered the results. The significant decrease between the simulation and measured results is most likely due to the efficiency of the constructed model body, which melted slightly between tests. It is also likely due to the humidity in the room, which would have lowered the required breakdown voltage of the air but required more energy to maintain a sufficient level of ionization. Moving forward, the simulation could be made more robust by accounting for various levels of water vapor in the air. Other notable influences might include an accurate pressure measurement of the room air at the time of testing, as well as a model body unaffected by previous tests.



[Figure 12: Calculated vs Experimental Results]

VII. Conclusion

The goal of Team Haddalayerdown was to create an ionic thruster in order to prove the concept of ionic wind. We were able to consult with subject matter experts, conceptualize the overall design, create, and test an ionic thruster. Nevertheless,

while not being able to achieve all of the project parameters, ionic wind was produced. Three model revisions and three different spacer sizes at varying voltages from 0 V to approximately 33 kV were designed and tested.

Future considerations for recreating this design in a more efficient manner should be taken into consideration. Originally, a design that involved three separate stages had been envisioned, but they were only able to develop and test one stage due to time constraints. Additional considerations could also be made for the power supply used for this project. The team realizes that a 100kV transformer limits the mobility of an ionic thruster, and future implementations of this project idea should consider alternative power sources.

Acknowledgements

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