Comparing Configurations of Multiple Array Plasma Actuators by Velocity and Flow Visualization

Elizabeth A. Matthews[1]

West Virginia University, Morgantown, WV, 26506, USA

Research on dielectric barrier discharge (DBD) plasma actuators has incurred interest in recent years for flow control and active lift control. This paper investigates three different configurations of plasma actuators using arrays of three actuators. Multiple array actuators have the potential to increase performance, but in many cases, adding more actuators has seen an increase in cross talk between actuator pairs. This paper looks at the advantages of using three-actuator arrays, and two possible ways of mitigating back plasma/cross talk. Two configurations tested differ in the way that the high voltage is connected, and one differs in the use of electrical insulation. These are then compared to a basic single-actuator array design. All the configurations are compared based on schlieren flow visualization and velocity measured from pitot probes, which reveal differences in quantitative performance and qualitative features. Backwards facing plasma is observed in the first configuration without electrical insulation, and backwards velocity is also measured in those areas. When electrical insulation is applied, the first configuration gives similar results to the second configuration (with alternative high voltage connections), and max velocity is increased across the three actuators. When comparing the three-actuator arrays to a single-actuator array, the three-actuator array increases peak velocity significantly.

I. Nomenclature

AC	=	Alternating Current
DC	=	Direct Current
DBD	=	Dielectric Barrier Discharge
f	=	Frequency
GND	=	Ground Connection
HV	=	High Voltage
V	=	Voltage/Volts
U	=	Velocity
x	=	*x* axis, along the streamline
y	=	*y* axis, height above the actuator
z	=	*z* axis, across the streamline

II. Introduction

Dielectric barrier discharge (DBD) plasma actuators have been a topic of interest in recent years. Research has been focused on working with plasma to help increase flow control [1]. Plasma actuators have also been found to

[1] Undergraduate, Mechanical and Aerospace Engineering, AIAA Student Member 1328464.

have the potential to help with changing the aerodynamics of the flow, boundary layer transitions, and other properties [2]. The plasma actuators used and studied in this report are created by having an exposed and covered electrode with a dielectric material placed in between of them, an example is shown in Figure 1. The experiments detailed in this report use borosilicate glass as the dielectric material. Applying a high voltage to the electrode will cause plasma and an electrohydrodynamic wind, which results in velocity being induced [2].

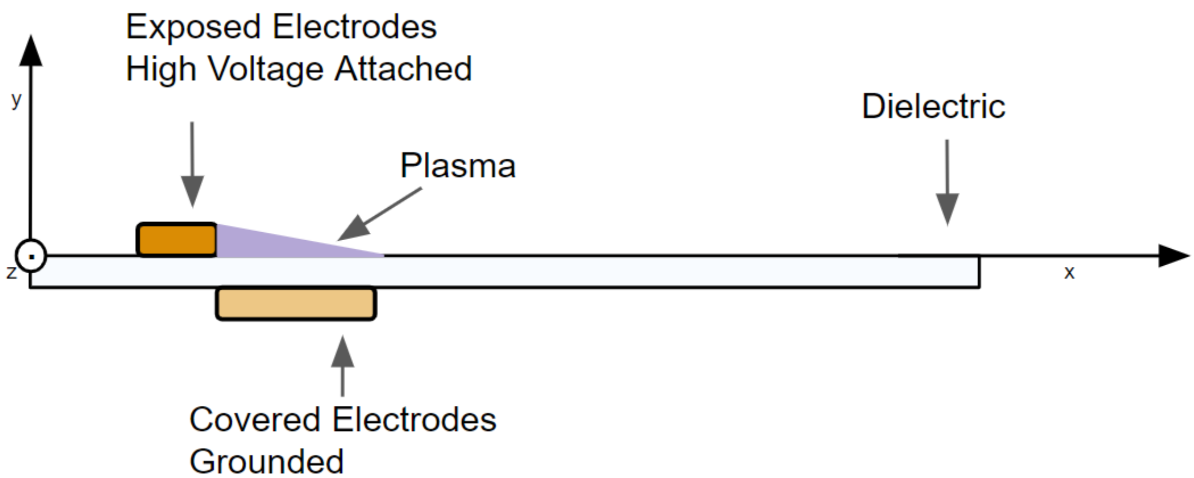


Figure 1: Example of a Single-Actuator Array

The basic DBD plasma actuator setup consists of one exposed electrode and one covered electrode. To attempt to improve the advantages that the plasma actuators bring to flow, this setup can be modified. In the paper by Debien [3], two different modifications to the plasma actuator setup are tested. These modifications involve adding a third electrode, which is an exposed electrode which is placed farther along the *x* axis, to the right of the covered electrode. When tested, adding the third electrode resulted in increasing maximum velocity. A study by Benard [4] shows the value of adding even more electrodes in a row. The paper by Benard shows DBD actuators that consist of a total of eight electrodes, alternating between exposed and covered. The benefits of using multiple arrays of actuators were studied and found in this paper. These benefits included the extension of plasma discharge and an increase in velocity. Benard also attempts to find a way to mitigate the cross talk between electrode pairs, a problem also addressed in this paper, by using embedded electrodes.

Following in the footsteps of other researchers, this report uses the same basic principles to create plasma using the DBD plasma actuator method listed above. Plasma is generated on top of a glass dielectric with strips of carefully placed copper tape on the top and bottom. Velocity is then induced because of the generated plasma. This velocity is measured and compared for the different configurations of voltage application on the electrodes. In this report, there are two different three-actuator configurations and one configuration with a single actuator. Similar to the configurations in Benard's paper [4], there are six electrodes in total, alternating between exposed and covered to make a three-actuator array. All configurations are compared to attempt to observe which configuration produces a higher velocity, and to examine the airflow and behaviors of each. This is completed by quantitatively measuring which configuration produces the most velocity with a pitot probe system, and by qualitatively examining the airflow using schlieren to find suitable behaviors.

Experimental Setup

The DBD plasma actuators are made using borosilicate glass, which acts as the dielectric material. The glass sheets are six inches wide (in the *z* axis), three inches long (in the *x* axis), and 43 mils thick (in the *y* axis). The electrodes consist of copper tape placed on the dielectric material, both exposed (on top of the glass sheets) and covered (below the glass sheets). The exposed copper tape is 0.25 in wide (spanning down the *x* axis), while the covered copper tape is 0.5 in wide (spanning in the *x* axis). The overlapping area where plasma is formed is 2.5 in long (going in the z direction into Figure 2). There is no gap placed in between the strips of tape in the x direction, as seen in Figure 2. A side view of an actuator is shown in Figure 2 below. This figure looks along the *z* axis and shows where the tape sits on both sides of the actuator.

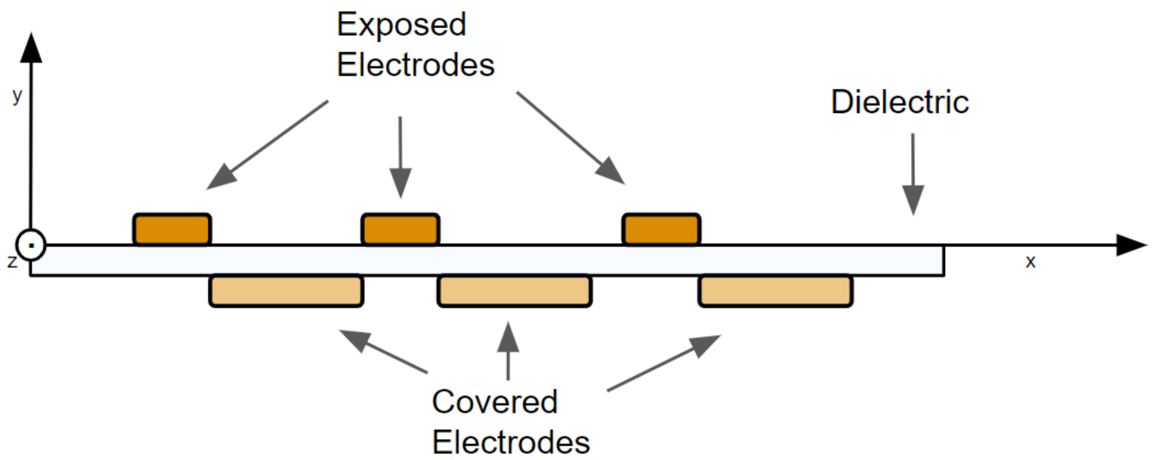


Figure 2: Three-Actuator Array From the Side

The actuator is powered with high voltage in the form of the AC wave shown in Figure 3. This voltage is applied to the actuator using a Minipuls system. The Minipuls 2.2 system used can deliver voltages in the 5-20 kHz range and up to 20 kV (10-kV amplitude, 20-kV peak to peak). The specifications used in this paper delivers a 12-kV (peak to peak) voltage at a frequency of 15 kHz during all of the experiments shown in this paper.

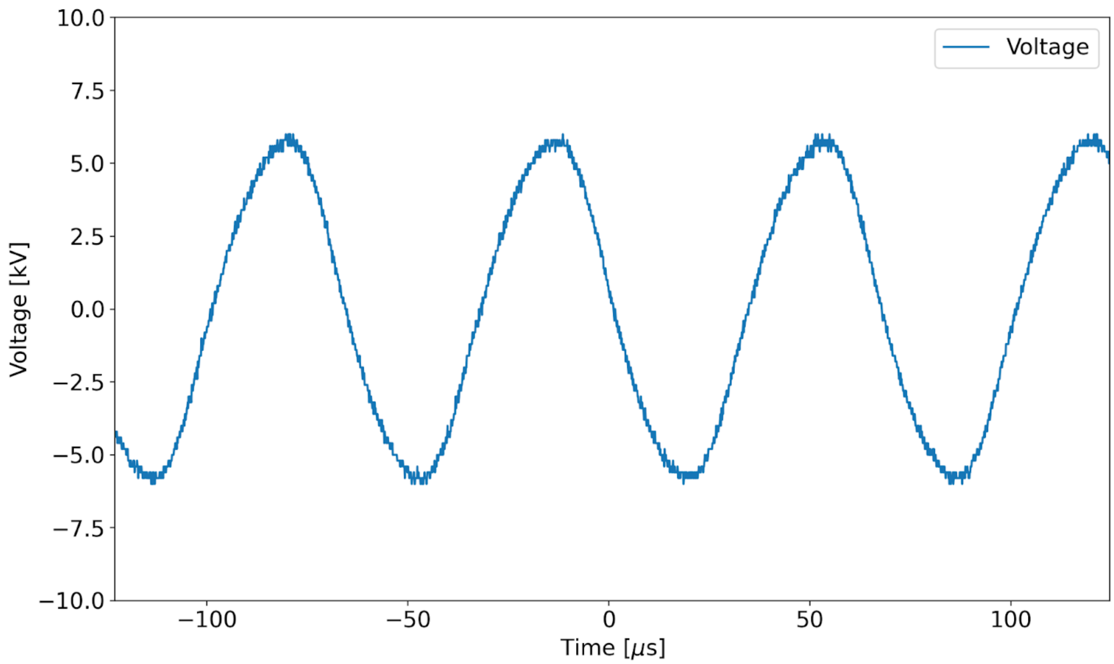


Figure 3: AC Voltage Applied by Using the Minipuls 2.2 System

There are four different actuators tested and compared in this report. The first is shown in Figure 4. This actuator has alternating connections of high voltage and ground. The first connection is high voltage (labelled as HV) and the last is ground (labelled as GND). This can all be seen in the figure below. There are six electrodes in total, three being exposed and connected to high voltage, and three are covered and connected to ground. The first actuator experiment has no electrical insulation on the top edge of the exposed electrodes.

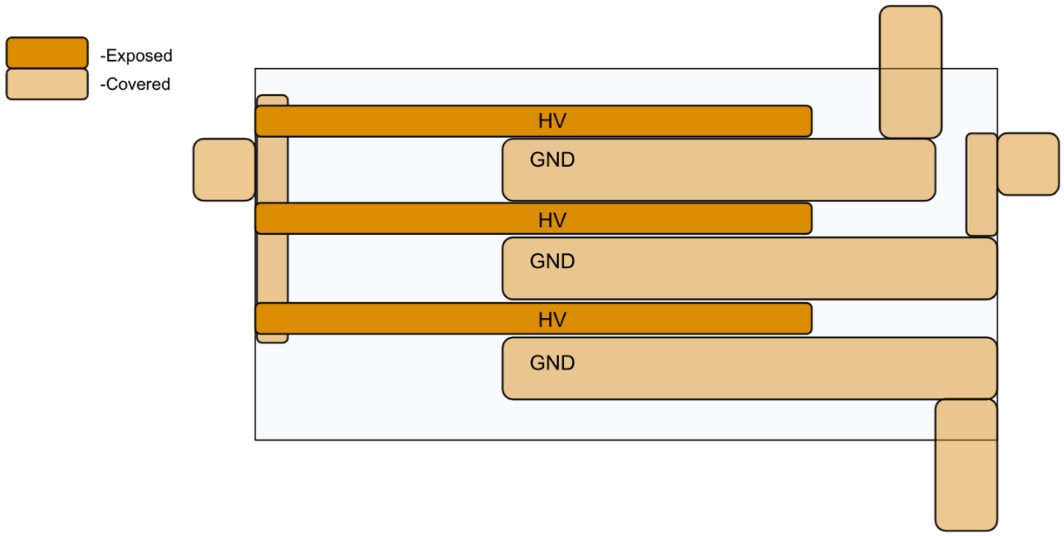


Figure 4: Experiment 1, Configuration 1 - No Electrical Insulation

Figure 5 shows the second actuator that is tested. This actuator is identical to the first, except each exposed electrode has electrical insulation covering its leading edge. The insulation (polyimide tape) is placed to attempt to lessen cross talk between arrays, which has been studied in the report by Benard [4]. The insulated actuator schematic can be seen in Figure 5. The high voltage connections are identical, where high voltage and ground connections are alternating across the six electrodes.

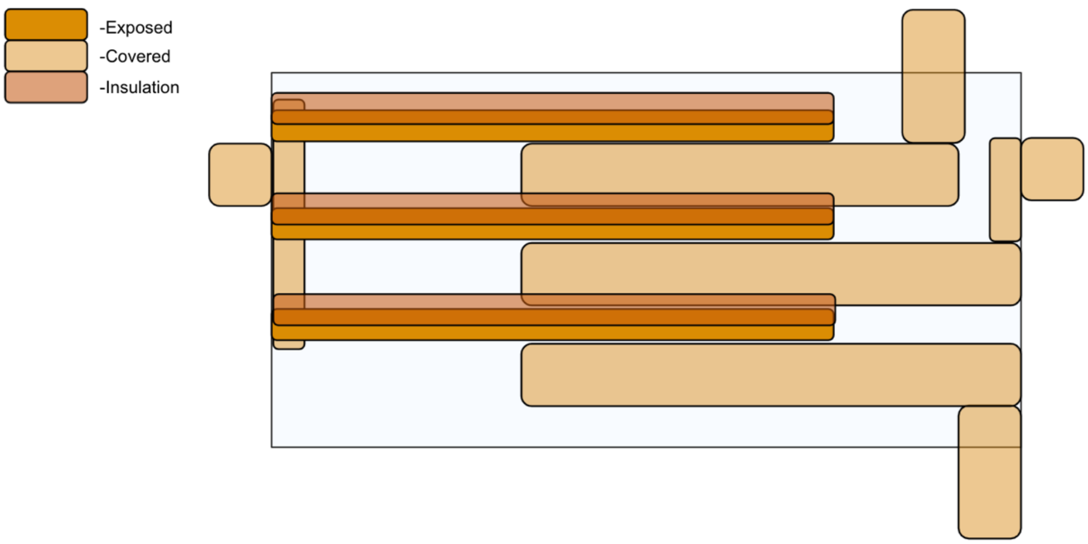


Figure 5: Experiment 2, Configuration 1 – Electrical Insulation

The second configuration is shown in Figure 6. This configuration has a different way of connecting the electrodes to the high voltage. The main reasoning of this configuration is to try to mitigate cross talk, this is done by attempting to avoid creating a voltage differential in between the first covered and second exposed, and the second covered and the first exposed. This is shown in the figure below. Each covered electrode and the following exposed electrode will attach to the same connection.

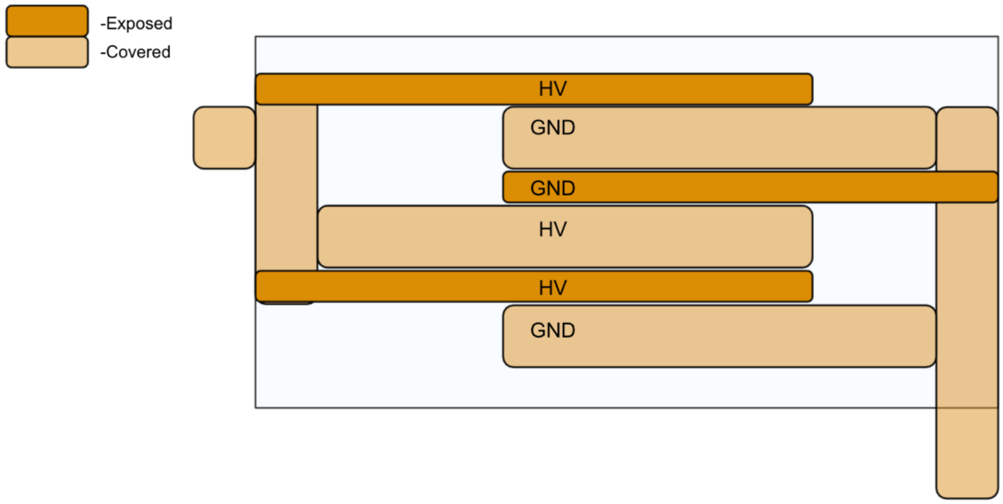


Figure 6: Experiment 3, Configuration 2

A picture of the completed actuators is shown in Figure 7. This figure shows Configuration 1 at the top (insulated), and Configuration 2 at the bottom.

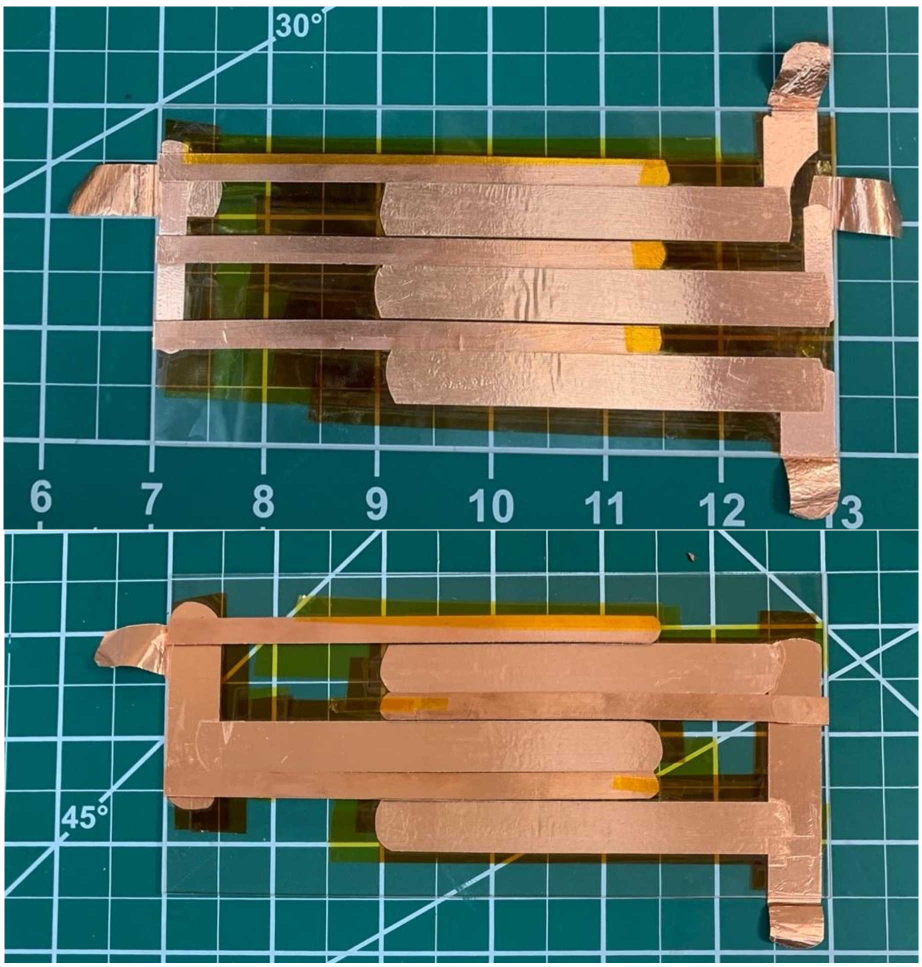


Figure 7: Configuration 1 (top) and Configuration 2 (bottom)

The last experiment conducted was one with a single-actuator array. This is shown in Figure 8. The exposed electrode is connected to the high voltage and the covered is connected to ground. This is a good control to see how using three-actuator arrays are different from single-actuator arrays. Comparing the multiple array actuators to the single-actuator array will allow for the disadvantage or advantage of multiple arrays to be seen.

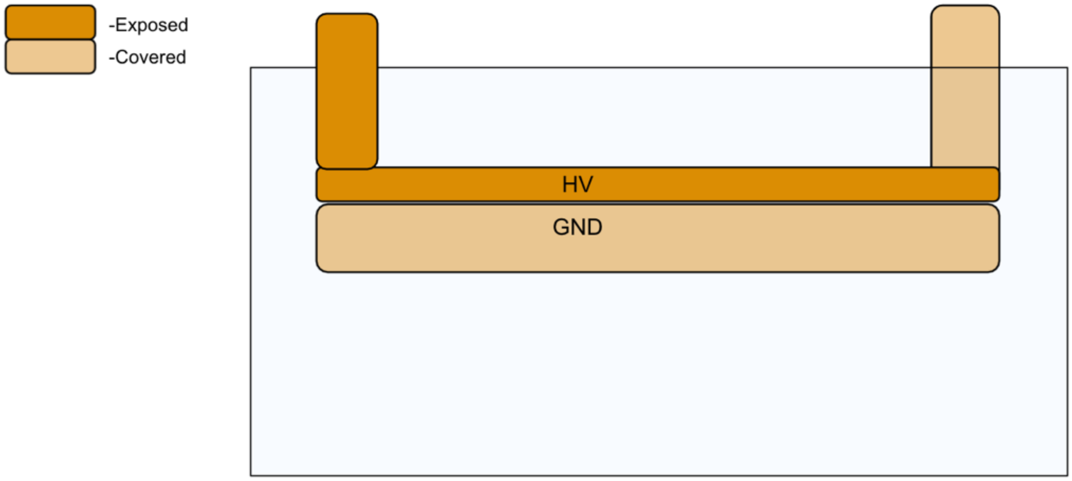


Figure 8: Experiment 4, Single Actuator

III. Experimental Procedure

The testing parameters include taking streamwise velocity measurements (parallel to the *x* axis), photographing the plasma from above, and taking schlieren photos from the side. For the velocity measurements, a linear actuator is used to smoothly scan the pitot probes along the streamline profile. This set up is shown in Figure 9. Starting at the edge of the first exposed actuator, the pitot probes measured from 0 mm (right at the trailing edge of the first exposed electrode) to 60 mm (from the trailing edge of the first electrode). The pressure differentials are measured using the pitot probes which are connected to pressure transducers to calculate velocity. The pressure transducers are connected to a LABVIEW program which allows the data to be stored and analyzed.

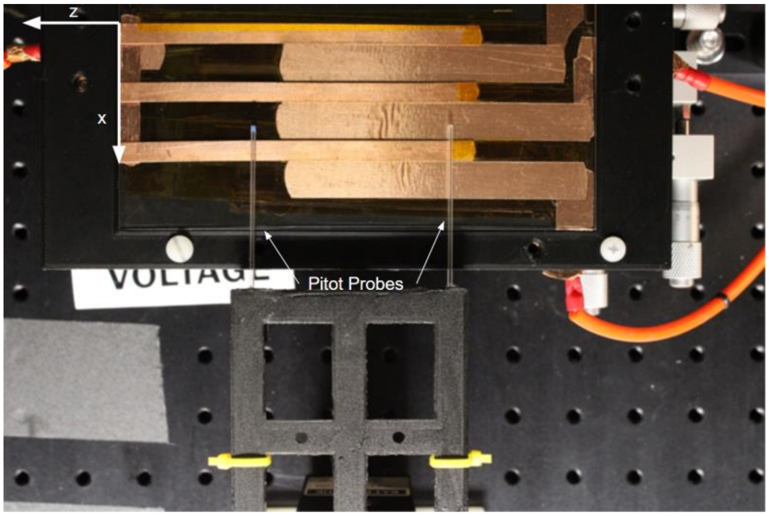


Figure 9: Pitot Probe and Actuator Set Up

The schlieren images are done using a Z-type schlieren technique, with the actuator placed in the test zone. The light from the schlieren goes across the actuators lengthwise, allowing flow to be visualized and documented. Mirrors with diameters of 10.5 cm are used in the experiment, resulting in a field of view of around 10 cm. A drawing of the setup [5] is shown in Figure 10.

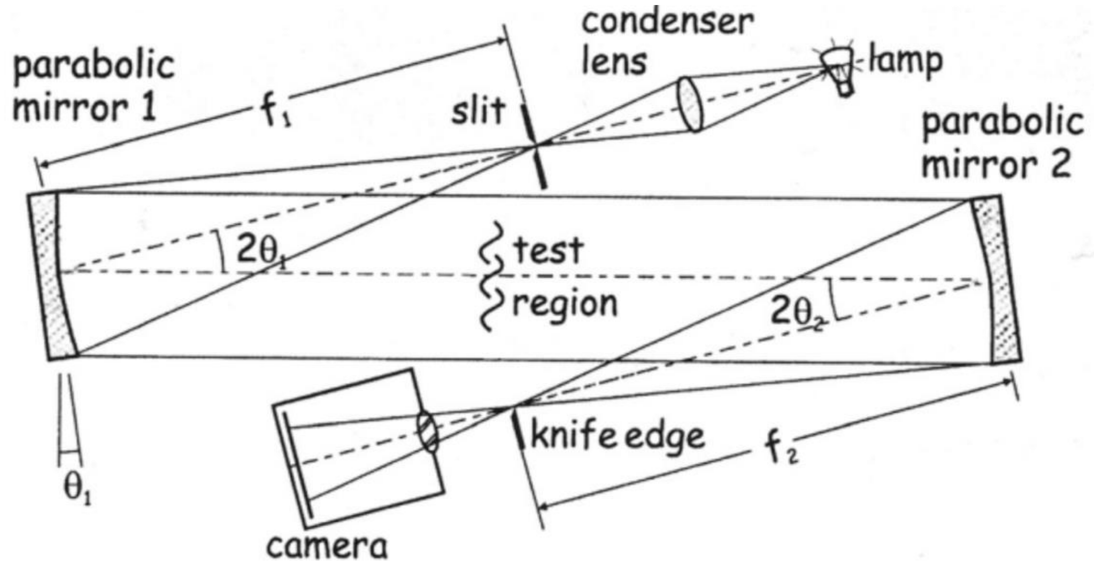


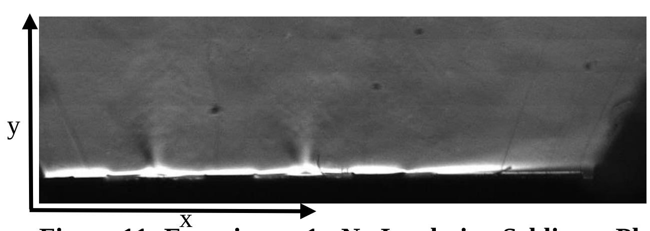
Figure 10: A Drawing of a Z-type Schlieren Setup [5]

Each experiment was done using the same settings and the same process. The high voltage and ground connections were connected, and high voltage was applied. The velocity profile was then taken along the *x* axis and schlieren photos along with photos of the plasma were taken at the same time.

To observe back flow, the entire actuator was rotated 180 degrees around the *y* axis, and the velocity was measured facing the opposite direction to allow for any possible backwards facing velocity to be measured.

IV. Results

Results are compiled for all testing parameters. This includes schlieren images, plasma photos, and pitot probe velocity readings. Schlieren images allow the flow visualization to be photographed for each of the four cases. Schlieren images can be seen in the figures below of each case's steady state flow.



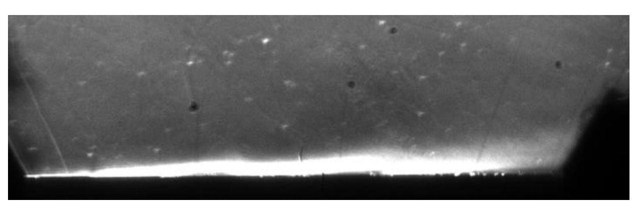
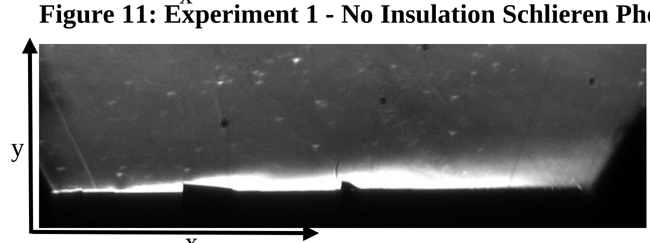


Figure 11: Experiment 1 - No Insulation Schlieren Photo; Figure 12: Experiment 3: Schlieren Photo



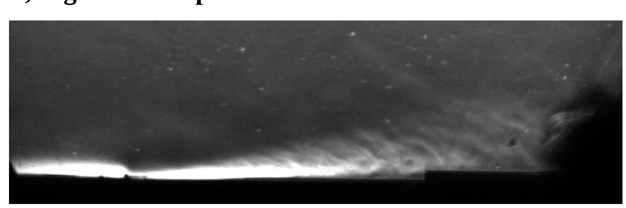


Figure 13: Experiment 2 - Insulation Schlieren Photo; Figure 14: Experiment 4

The non-insulated case in Figure 11 shows the air flow going into the positive y direction straight above. The comparison of this photo and the other three shows that none of the others have a flow going in that same direction. The other three figures all have flow going mostly in the positive x direction. Even the insulated case with the same high voltage connections, is shown going to the right. The startup process for each configuration was recorded and compiled. This allows the formation of flow to be observed, to see the primary direction of flow during the startup process and afterwards. The photos in Figure 15 shown below, were taken 1 ms apart and show the formation of the flow, the first 4 ms are shown. The flow begins with a vortex forming right after the plasma is turned on and begin to steady out after the plasma is allowed to run. Steady state is observed to take around 25-30 ms to reach.

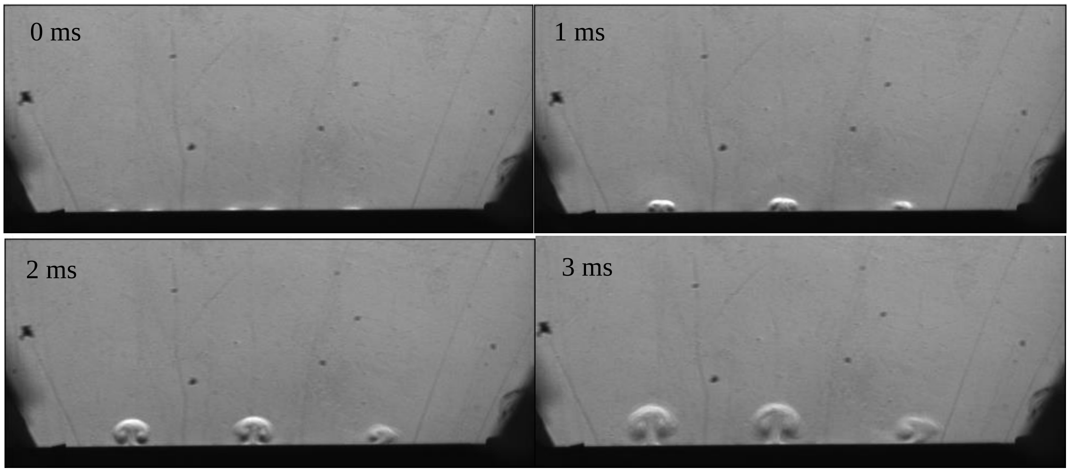


Figure 15: Experiment 1: Non-Insulated Start Up Photos, Time After Plasma is Turned On

Looking at plasma photos can give an estimation of the plasma's intensity and direction. The following figures show photos from each experiment.

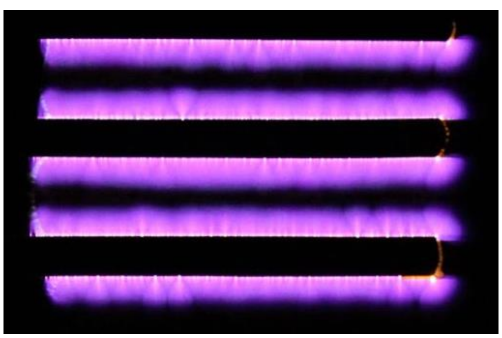


Figure 16: Experiment 1 - No Insulation Plasma Photo

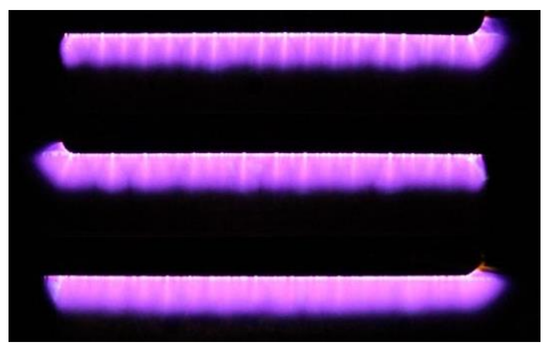


Figure 17: Experiment 3: Plasma Photo

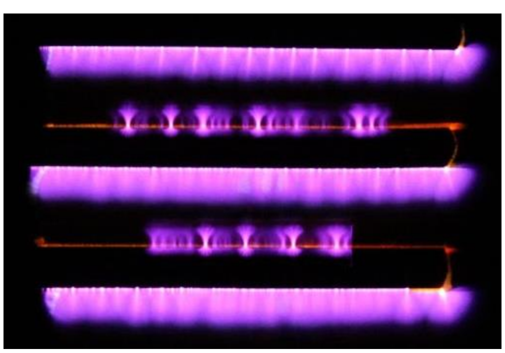


Figure 18: Experiment 2 - Insulated Plasma Photo

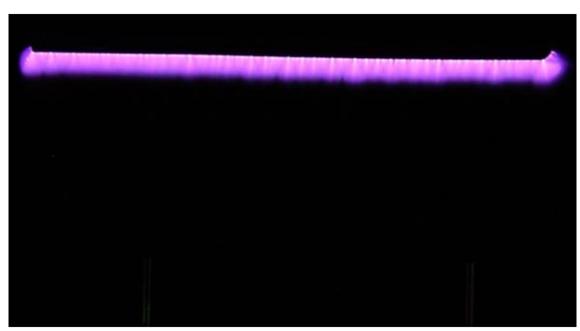


Figure 19: Experiment 4 - Plasma Photo

The previous figures, Figure 16 to Figure 18, show the differences in plasma formation between each experiment. The non-insulated case shows cross talk between actuators, meaning there is plasma facing in the positive and negative x direction, while the third and fourth experiment only show forwards. The second experiment, the insulated case, shows small streams of plasma facing backwards.

The velocity profiles, which were measured, are shown in Figure 20. This figure shows each experiment's velocity profile compared to one another. Experiment 1 shows both positive and negative flow of around equal magnitudes. Experiment 2 shows the suppression of the negative flow shown in the non-insulated case. Each actuator array increases the Experiment 2's velocity by a portion. Experiment 3 hits the maximum velocity at the first actuator and steadily decreases the peak velocity in across actuators. Experiment 4 shows one peak where the single actuator is located, followed by a steady decline.

For the first experiment, there was a need to measure both positive and negative flow. Since there was not a device available that could measure both directions at the same time, two different runs were measured right after each other. To measure the flow in the opposite direction the entire actuator was turned 180 degrees and the pitot probes were used to measure velocity from the end of the actuator to the beginning, allowing the negative flow results to be measured.

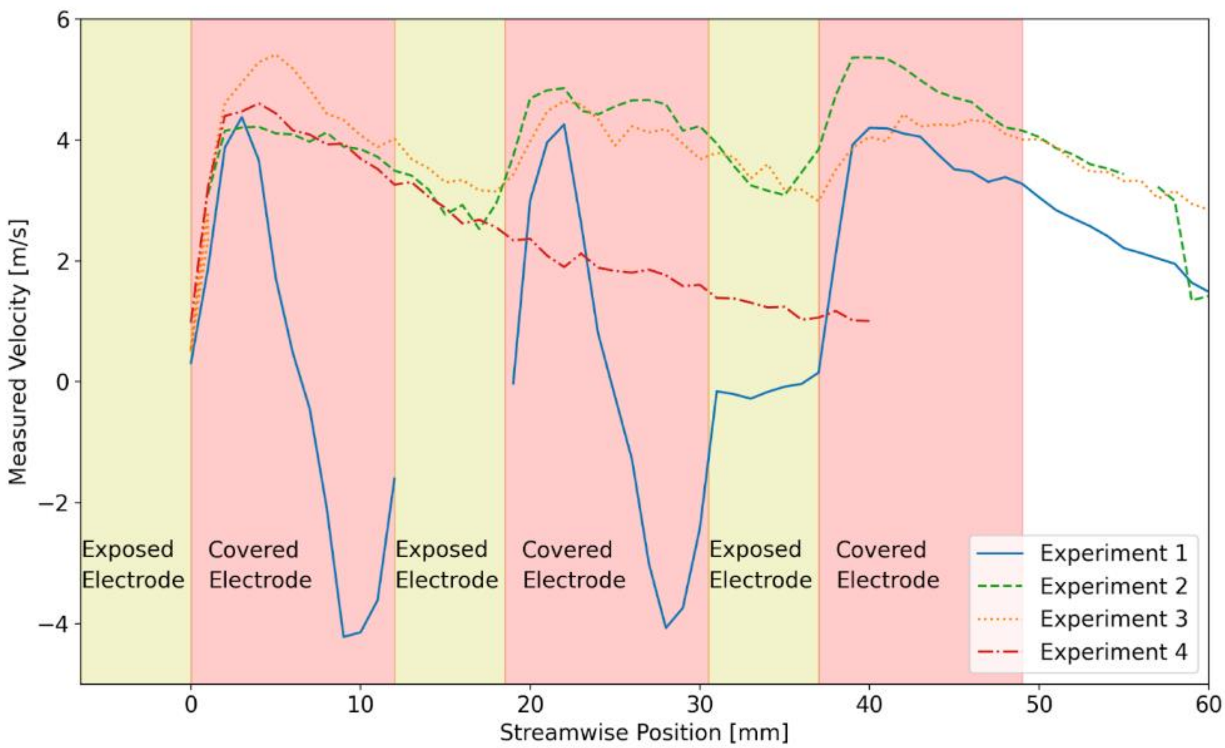


Figure 20: Velocity Profiles

Along with the velocity profiles, the peak velocity and the streamwise position where peak velocity occurs are found and shown in the table below. Experiment 2 and 3 have the highest peak velocity, while Experiment 1 has the lowest and Experiment 4 is the second to lowest. The velocity ranges were found by finding the mean velocity measured and the standard deviation of each experimental run.

Table 1: Peak Velocities

Configuration	Pitot Probe Position	Peak Velocity, U (m/s)

	(mm)	
Experiment 1: No Insulation	4 ± 1	4.47 ± 0.05
Experiment 2: Insulation	40 ± 1	5.37 ± 0.20
Experiment 3	5 ± 1	5.42 ± 0.13
Experiment 4	4 ± 1	4.61 ± 0.22

Using all of the compiled data, the configurations and experiments can be compared together. The flow behavior is first compared together using the schlieren photos in Figure 11 to Figure 13. Focusing on the non-insulated case, there is flow seen going straight up above the first two covered electrodes. This shows that without electrical insulation the second electrode also creates flow backwards and forwards, in the positive and negative x direction. This can also be shown on the non-insulated plasma photos. There are two sets of plasmas that face each other, causing their flows to meet in the middle adding together to move in the positive y direction. The point of adding the electrical insulation is to mitigate this back plasma and back flow. Looking at the insulated schlieren photos and plasma photos, we can see the insulation mostly worked. While the plasma photos show a small amount of back plasma, most of the plasma has been suppressed by the insulation. When looking at the schlieren photos, the flow is seen going towards the positive direction, and no flow is observed going in the negative direction. This shows the purpose of the electrical insulation and its effectiveness. If all backwards facing plasma needs to be mitigated, more insulation will be added.

The second comparison to focus on is the insulated case and the case with the altered high voltage connections, Experiment 2 and 3. When looking at the schlieren photos, there is little to no difference observed. Both flows are moving in the positive x direction. When looking at the plasma photos, one can see that there are still remnants of backwards facing plasma in the insulated case, and Experiment 3 has no backwards facing plasma at all. This proves that the differing of high voltage connections allows backwards facing plasma to be eliminated. The similar schlieren photos also show that the use of electrical insulation causes the flow to act similar to cases where the high voltage connections do not allow backwards facing plasma formation.

In Figure 20, each experiment's velocity profile is shown. Comparing Experiment 1 and 2, it is shown that the non-insulated case causes negative velocity which does not allow for a buildup in velocity over arrays. The second experiment, the insulated case, gains more velocity after each array, which can then be compared to the fourth experiment, where there is only one array. The maximum velocity potential in an array of three plasma actuators, is higher than it is for only one array. While one array gave a maximum velocity measurement of 4.61 m/s, Experiment 2 gave a maximum of 5.37 m/s. This proves that using three actuators allows for velocity to build up over distance.

When looking at Experiment 3, the different voltage connection experiment, it is observed that it acts in the opposite way from Experiment 2. While Experiment 2 built up velocity after each array, Experiment 3 started with its peak velocity and decreased as it went down the streamline. This shows there are some differences in the two flows and that they behave differently. The peak velocity for both cases is similar and show improvements from the single-actuator case.

Experiment 2 gives a good built-up flow that can reach higher velocities while going down the streamline. This is most commonly used in the literature for flow control, involving both low and high-speed flows.

V. Conclusion

The results from the experiments listed in this paper give valuable flow information about plasma actuators via flow visualization and velocity profiles. There is an improvement in plasma actuators when using electrical insulation and when using multiple actuator arrays. This is shown in the schlieren images taken and the velocity profiles measured. The use of plasma comes from a need to induce velocity and being able to induce higher velocities is a valuable tool. The electrical insulation mostly mitigates all back flow, which brings an advantage to using this configuration. The insulated configuration with alternating high voltage connections was shown to be the best velocity inducer of the configurations tested. This is based on the need to have the peak velocity at the end of the actuator.

Future work would involve using the same configurations with increasing voltage and/or frequencies to see the full potential of the actuators, while measuring more parameters such as power consumption. Another direction would be adding more arrays to the configuration, using the same high voltage setup, to see how the peak velocity would change and possibly increase.

Acknowledgments

This material is based upon work supported by the U.S. Department of Energy, Advanced Research Projects Agency – Energy under Award Number DE-AR0001011. This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

I'd like to thank Arctura for the opportunity to learn about plasma actuators and get to work with them on this level. I'd especially like to thank John Cooney and Pascal Mickelson from Arctura. John encouraged me to write this paper and has supported me through the process, answering questions and helping to brainstorm. Pascal has taught me everything I know about the subject and has been an excellent mentor the past year, helping me conduct experiments and apply research, encouraging me to think bigger and allowing me the space to do so.

References

[1] Corke, Thomas C., Enloe, C. Lon, and Wilkinson, Stephen P., "Dielectric Barrier Discharge Plasma Actuators for Flow Control," Annu. Rev. Fluid Mech. 2010. 42:505–29, 2009.

[2] Benard, Nicolas, and Moreau, Eric, "Electrical and mechanical characteristics of surface AC dielectric barrier discharge plasma actuators applied to airflow control," Exp Fluids (2014) 55:1846, November 2014.

[3] Debien, A, Sosa, R., Benard, N.,and Moreau, E., "Electric wind produced by sliding discharges," Proceeding of 2nd ISNPEDADM new electrical technologies for environment, Nouméa, Jan 2011.

[4] Benard, N., Jolibois, J., Mizuno, A., and Moreau, E., "Innovative Three-Electrode Design for Definition of Multiple Dielectric Barrier Discharge Actuators" Non thermal plasma – Paper #P1.17, 2009.

[5] G. S. Settles, "Schlieren and Shadowgraph Techniques," Springer, 2001.