PRESSURE DEPENDENCE OF PLASMA ACTUATED FLOW CONTROL

A Thesis

Submitted to the Graduate School
of the University of Notre Dame
in Partial Fulfillment of the Requirements
for the Degree of

Master of Science in Aerospace Engineering

by

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July 2010
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Abstract

by

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Novel applications for plasma actuators necessitate performance predictions that are reliable at a range of environmental conditions. An experimental setup is used to determine how Single Dielectric Barrier Discharge (SDBD) plasma actuators perform under variable ambient pressure. Measurements of plasma initiation voltage and static thrust were compared to similar data from literature. Recurring trends in the experimental thrust were evaluated against simulations from the Space-Time Lumped Element Model, which was designed strictly for atmospheric pressure. Parameters in the model affected by ambient pressure (capacitance, resistance, and Debye length of the air) were then systematically adjusted to determine their effects on the plasma-produced body force. Even with an empirical approximation of threshold voltage, the model did not predict a body force that changed with pressure in a similar manner to experiment. Filament formation, not physically represented in the model, was very prevalent at pressures above atmospheric and may be responsible for the complicated trends in data.
To my father, William L. Valerioti, Jr.
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SYMBOLS

*English*

\( A_d \) cross-sectional area of dielectric element

\( A_a \) cross-sectional area of air element

\( C_d \) capacitance of dielectric element

\( C_a \) capacitance of air element

\( d \) distance between facing electrodes

\( \vec{E} \) electric field

\( E_b \) breakdown electric field

\( e \) charge of a single electron

\( \vec{f}_b \) body force vector

\( I_p \) plasma current

\( k_b \) Boltzmann’s constant

\( k_n \) constant representing presence of plasma

\( l_n \) thickness of air element

\( n_e \) number of electrons in plasma density

\( R_a \) resistance of air element

\( t \) time

\( t_d \) thickness of dielectric element
$T_e, T_i$  temperature of electron species, ion (respectively)

$T$  period of alternating current cycle

$V_{AC}$  voltage amplitude of alternating current cycle

$V_{app}(t)$  applied voltage as a function of time

$V_n(t)$  voltage on the dielectric surface as a function of time

Greek

$\varepsilon_a$  dielectric-coefficient of air

$\varepsilon_d$  dielectric-coefficient of the dielectric barrier

$\varepsilon_o$  dielectric-coefficient of free space

$\phi$  voltage potential

$\lambda_D$  Debye length

$\rho_a$  resistivity of air

Abbreviations

AC  alternating current

SDBD  single dielectric barrier discharge
ACKNOWLEDGMENTS

I would like to thank Dr. Corke for his direction and confidence in me during the course of this investigation. Sincere appreciation is offered to Ben Mertz, Chan-yong Schuele, Brian Neiswander, and the other graduate students of the Hessert Laboratory for their assistance. I would like to thank Natalie Robnett for her editing, and her patience. And I would like to extend a special thank you to my family for their enduring support for this and all my endeavors.
CHAPTER 1:
INTRODUCTION

1.1 Motivation

The ability to predict performance is essential toward the optimization of any engineering system, including active flow control. The increasing range of applications for plasma actuators has created the demand for performance predictions at an expanding array of environmental conditions. Current computational models explore their performance at atmospheric conditions, but potential implementation into compressors and other turbomachinery could consign the plasma actuator to a high-pressure environment, where its effectiveness is less understood. The potential optimization of plasma flow control is very desirable in these systems where flow separation is extremely detrimental to overall efficiency.

1.2 Background

A Single-Dielectric Barrier Discharge (SDBD) plasma actuator is utilized to alter the airflow over its surface. Its construction features a dielectric barrier between two electrodes, one insulated and the other exposed to air. The electrodes are arranged asymmetrically, as depicted in Figure 1.1.
When the electrodes are supplied with a sufficiently high AC voltage, some of the air molecules above the covered electrode start to ionize. The ionized air, or plasma, is influenced by the presence of the electric field, and the collisions of its ions with the neutrally-charged air particles result in a force on the ambient air. The induced flow, qualitatively shown in Figure 1.1, is the mechanism for aerodynamic control [3].

Looking within the AC cycle provides a glimpse at one of the timescales governing plasma physics. For a given gas, the breakdown electric field, $E_b$, is the electric field needed to sustain electron-ion pairs through gas impact ionization. When the instantaneous voltage amplitude is enough that the electric field becomes greater than $E_b$, the gas ionizes and plasma is formed (Kunhardt [9], Kunhardt & Luessen [12], Llewellyn-Jones [14], Raizer [21]).

The breakdown voltage required for ionization was found to be a function of the product of pressure and distance between electrodes (for facing electrodes) [20]. Paschen’s curve, presented in Figure 1.2, illustrates this relationship for different gases, including air. To the right of the minimum, the breakdown voltage increases with the
Figure 1.2 Paschen's curve for breakdown voltage [20].
pressure, given a fixed spacing \( d \). This is a result of the decrease in the mean free path of the air. With a shorter distance between molecules, electrons do not accumulate enough energy to ionize neutral molecules before colliding with them – unless the voltage is increased. To the left of the minimum, electrons reach a higher energy level between collisions, but not enough collisions occur to ionize at the same voltage as at the minimum. The minimum is at the point where the mean free path is just sufficient enough to gain the energy needed for ionization [1],[9].

An indication of plasma formation is the emission of a weak blue light, a product of the recombination and de-excitation of the ionized particles [3]. Light emission tests conducted by Enloe et al. [6] revealed that ionization takes place over only part of the AC cycle. As the gradient of the AC voltage wave changes signs, the electric field is not high enough to sustain ion formation until the voltage reaches the critical initiation level in the negative amplitude direction.

Figure 1.3 Time series of photomultiplier tube output (left) over corresponding AC input (right) [6].
In the figure above, the narrow spikes are indicative of the many microdischarges that take place within each wave cycle, studied and presented by Enloe et al. [7] and Orlov et al. [18],[19]. The asymmetry between the positive- and negative-going emissions is attributed to the source of the moving electrons. During the negative-going voltage half-cycle (time 0 to $1 \times 10^{-4}$ s in Figure 1.3), the exposed electrode develops a more negative potential than the dielectric surface. Once the electric field is large enough (initiation), electrons discharge onto the dielectric. In this case the source of the electrons is the uncovered electrode. Because of the essentially endless supply of electrons from the metal electrode, the microdischarges form easily and often. In the positive half-cycle, the electrons originate from the dielectric barrier, which has only the electrons that were previously deposited. These do not come off as readily, and when they do, form fewer, larger microdischarges (reflected below in Figure 1.4b). This asymmetry can be exploited by applying a ramp, or sawtooth, voltage waveform, which has been linked in experiment to more efficient production of thrust [6]. Corresponding to the light-emission spikes are similar spikes in electrical current, which can be used as an indication of plasma formation from instrumentation. These observations are consistent with works by Massines et al. [15], Eliasson and Kogelschatz [5], and Kogelschatz et al. [10].

The asymmetry discussed above is also evident in Figure 1.5, which illustrates light-emission data from Orlov et al. [18],[19]. Each point on the vertical axis represents a stream-wise “slice” of light-emission at one instant in the AC cycle. Together these are shown as contours of constant light-emission intensity for one period, $T$. The figure presents a good summary of the extent of plasma as it progresses through the AC cycle.
Figure 1.4 Asymmetry of microdischarges between the negative-going (a) and positive-going (b) half-cycles [18].

Figure 1.5 Space-time variation of the light emission of plasma extending over the covered electrode (x-axis) of an SDBD actuator [18].
Of particular importance to verification of plasma models is the thrust of a flat-plate actuator. The flow induced from a SDBD plasma actuator creates a momentum flux away from the actuator, therefore creating a reaction force in the opposite direction. Enloe et al. [7] measured this force and correlated it with the applied AC voltage. The induced thrust was found to be proportional to $V_{AC}^{3.5}$ at atmospheric conditions. Thomas et al. [23] performed a similar experiment, but changed the apparatus to measure thrust directly into an electronic scale. The results confirmed the proportionality of thrust to $V_{AC}^{3.5}$.

![Figure 1.6 Schematic and data from measuring induced thrust from a flat-plate SDBD actuator [23].](image)

Also documented was the phenomenon of maximum thrust. Thrust followed $V_{AC}^{3.5}$ up to a certain voltage then started to trail off. Visually, the max-thrust point was marked by the appearance of bright filaments in the plasma [23]. The development of filaments
caused an increased draw in current. For fixed power systems, this increase in current limited the voltage potential experienced by the actuator, and the thrust dropped off from its $V_{AC}^{3.5}$ proportionality (Figure 1.7). Further, Thomas et al. [23] found that the voltage of maximum thrust varied linearly with driving frequency. Lower frequencies forestalled the onset of filaments and led to higher maximum thrust.

![Thrust vs. Voltage Curve](image)

Figure 1.7 (a) Induced thrust data from a flat-plate SDBD plasma actuator. Plasma during the 3.5 exponent regime is pictured in the bottom image of (b), while the top four images show filament formation at each frequency’s max-thrust point [23].

Schuele and Corke [22] studied flat-plate thrust at pressures below atmospheric. Plasma at low pressure was found to have lower initiation voltages, in accordance with Paschen’s curve. The opposite end of the voltage domain, the voltage of the max-thrust point, was similarly discovered to decrease with lower pressure. This indicated that lower pressures, like higher frequencies, have a greater tendency to form filaments.
Ibrahim et. al. [9] investigated the feasibility of plasma in a compressed environment. Plasma generation and extent were monitored on SDBD actuators for different pressures of various gases, including air. Continuing the trend of Schuele and Corke’s low-pressure results, plasma generation was found to require higher voltage amplitudes as pressure increased. Higher initiation voltages also had the effect of decreasing the extent of the plasma for higher pressures [9].

Important to the comprehension and optimization of plasma actuators is the development of predictive modeling. A thorough review and comparison of plasma simulations is presented by Mertz and Corke [16].

Enloe et al. [7] derived electrostatic equations to relate the voltage potential on the electrodes to the body force produced by the actuator. Found was the relation

\[
\overrightarrow{f_b}^* = -\left(\frac{e_o}{\lambda_D^2}\right)\phi \overrightarrow{E},
\]

where \(f_b^*\) is the body force of a single charged particle, \(\phi\) is the voltage potential, \(E\) is the electric field strength, and \(e_o\) is the dielectric coefficient of free space. The characteristic length for electrostatic shielding, \(\lambda_D\), is given by

\[
\lambda_D = \left[\frac{e^2 n_e}{e_o} \left(\frac{1}{k_b T_i} + \frac{1}{k_b T_e}\right)\right]^{\frac{1}{2}},
\]

where \(e\) is the charge of an electron, \(T_i\) and \(T_e\) are the ion and electron species temperatures, \(k_b\) is Boltzmann’s constant, and \(n_e\) is the number of electrons in the background plasma density. Known as the Debye length, \(\lambda_D\) is set to 0.17 mm for industrial plasmas at atmospheric pressure [13].
A spatial lumped circuit element model was proposed by Enloe as an attempt to model the time-varying effects of the electrostatic model [7],[19]. In this model, the air and dielectric barrier were represented as capacitive elements, with resistive element provided by the plasma. Orlov et al. [18] took this circuit network and divided it into parallel sub-circuits that stretched across the entire plasma domain. Each sub-circuit element was made up of a parallel resistor and capacitor to represent the air (plasma), and a capacitor to represent the dielectric. Each air circuit also included two zener diodes to adjust resistance depending on which direction the current flowed.

![Figure 1.8 Schematic of the electrical elements that make up the sub-circuit network within the Space-Time Lumped Element Model [18].](image)

The capacitance of the dielectric was a function of its area, $A_d$, its thickness, $t_d$, and the dielectric coefficient of its material, $\varepsilon_d$. The relationship was given by

$$C_d = \frac{A_d \varepsilon_d \varepsilon_o}{t_d}. \quad (3)$$
The value of the air capacitor was found in a similar manner, except the characteristic length was instead the distance from the exposed electrode to the dielectric surface, a dimension that changed for each $n$-th sub circuit. The equation was given by

$$C_a = \frac{A_n \varepsilon_a}{l_n \varepsilon_a^*},$$  \hspace{1cm} (4)$$

where $\varepsilon_a$ is dielectric coefficient of air, $A_n$ is the cross-sectional area of the air, and $l_n$ is the characteristic length, shown in the figure below.

![Figure 1.9 Schematic of the $n$-th air element [18].](image)

The resistance of the air, conversely, was proportional to this characteristic length. Its relationship was given by

$$R_a = \frac{l_n}{A_n \rho_a},$$  \hspace{1cm} (5)$$

where $\rho_a$ is the effective resistivity of the air.

Mertz and Corke [16] used the space-time lumped element model to test different boundary conditions for the electrostatic equations. The output of the lumped element model, an array of body force vectors, was averaged in space and time. This average was also found to follow $V_{AC}^{3,5}$. These results were loaded into CFD packages and compared
with experimental data. Validations included an impulsively started flat-plate actuator, flow control on a cross-flow cylinder, and separation control over a wind turbine blade. The simulations conducted in this report were run using the code of the Mertz & Corke model.

1.3 Objective

The limitation of the present model is its restriction to exclusively atmospheric flow conditions. The goal of this work is to explore methods of implementing accurate pressure dependence. Experiments will be conducted to record the performance of plasma actuators at different pressures. Initiation voltage will be compared for different actuators over a pressure range, and high-pressure thrust experiments will build on the work of previous literature. These results will be collectively analyzed in the effort of finding the physical effect of changing pressure and the method for its implementation into the SDBD model.
CHAPTER 2:
EXPERIMENTAL SETUP

2.1 Low-Pressure Initiation

As noted by Schuele and Corke [22], plasma at low pressure was found to have lower initiation voltages. To quantify this reduction, several geometries and materials of plasma actuators were tested for their threshold voltages at sub-atmospheric conditions.

In the computer model, the dielectric barrier is represented entirely by its capacitance, $C_d$. The actuators were selected such that a range of capacitances could be tested, with the aim of determining whether or not the initiation voltage of an actuator was purely a function of its $C_d$ and the ambient pressure. The actuators tested are presented below.

<table>
<thead>
<tr>
<th>Name</th>
<th>Dielectric Thickness (in)</th>
<th>Material</th>
<th>Dielectric Coefficient</th>
<th>Capacitance / unit area (nF/m$^2$)</th>
<th>Area of covered electrode (m$^2$)</th>
<th>Capacitance (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2</td>
<td>0.002</td>
<td>Kapton</td>
<td>2.9</td>
<td>505.4</td>
<td>0.0013</td>
<td>652.2</td>
</tr>
<tr>
<td>K6</td>
<td>0.006</td>
<td>Kapton</td>
<td>2.9</td>
<td>168.5</td>
<td>0.0013</td>
<td>217.4</td>
</tr>
<tr>
<td>K11</td>
<td>0.011</td>
<td>Kapton</td>
<td>2.9</td>
<td>91.9</td>
<td>0.0013</td>
<td>118.6</td>
</tr>
<tr>
<td>T8</td>
<td>0.008</td>
<td>Teflon</td>
<td>2.1</td>
<td>91.5</td>
<td>0.0013</td>
<td>118.1</td>
</tr>
<tr>
<td>T30</td>
<td>0.030</td>
<td>Teflon</td>
<td>2.1</td>
<td>24.4</td>
<td>0.0013</td>
<td>31.5</td>
</tr>
<tr>
<td>G90</td>
<td>0.090</td>
<td>Glass</td>
<td>3.8</td>
<td>14.7</td>
<td>0.0039</td>
<td>57.0</td>
</tr>
<tr>
<td>G250</td>
<td>0.250</td>
<td>Glass</td>
<td>3.8</td>
<td>5.3</td>
<td>0.0016</td>
<td>8.5</td>
</tr>
</tbody>
</table>
The thicknesses for actuators K11 and T8 were chosen such that both had almost identical $C_d$. In the model, therefore, these two actuators are numerically equivalent. The test was to see if the two displayed similar initiation characteristics, which would provide evidence an actuator could in fact be modeled strictly by capacitance.

The area of the covered electrode is a geometric dependency contained within the capacitance equation. All the actuators listed above had similar areas, except for G90, which was given a longer span to enhance its thrust capability. This adjustment had the additional consequence of scaling the capacitance by a value different than the other actuators.

Each actuator was placed in an airtight chamber in a dark room. Leads from the voltage source were extended into the chamber window through an airtight seal. Using a vacuum pump, the chamber was evacuated to a given pressure, and the voltage amplitude of an AC sine wave was slowly increased until the plasma glow was visible. Because plasma extends farther at low pressures, visual evidence from the naked eye was enough to determine plasma initiation.

Figure 2.1 Pressure chamber used in low-pressure initiation tests (including electronic scale utilized for thrust measurements) [22].
2.2 High-Pressure Initiation

A different setup was needed for high-pressure testing. The chamber previously used was rated for negative gage pressures only. An experimental facility rated up to 175 psi (12.1 bar) was employed, the same used in the earlier work by Ibrahim et al. [9].

The primary element of the facility was a high-pressure vessel. The cylindrical vessel was 3/8 in. thick stainless steel, with a diameter of 16 in. and a length of 24 in. A four in.-diameter sight glass was welded to the side. On the endcaps of the vessel were two safety relief valves and a gas line inlet-valve with pressure gauge.

![Image of high-pressure facility with compressed air tank.](image)

Figure 2.2 High-pressure facility with compressed air tank.

The SDBD actuator was positioned inside, its exposed electrode facing the window so plasma generation could be observed. Equipped to the side of the tank were two feed-throughs for the actuator’s high-voltage lines.
The procedure to determine initiation voltage was similar to the low-pressure tests: slowly increase AC voltage amplitude until plasma formation was confirmed. The methods of determining initiation, however, were different for the high-pressure experiments.

Because plasma extent becomes very minimal at pressures above atmospheric, the first signs of plasma initiation were almost impossible to determine with the naked eye. The first measure against this was to include a current sensor on the high-voltage line. The sensor would capture the current spikes that are indicative of plasma formation. Also, digital video of the plasma was shot through the sight-glass. When enhanced with software, the video provided a clearer indication of plasma generation. The digital video and time-dependent current output were synched in time, and the two running together were analyzed to determine a reasonable value of initiation voltage.
2.3 High-Pressure Thrust

The next step was to determine the effect of pressure on actuator thrust. An experiment was designed to measure the reaction force produced by a plasma actuator as a function of applied voltage for different static pressures. A ramp waveform was used as it had been proven as the most efficient producer of thrust [6].

A setup similar to that of Thomas et al. [23] was implemented inside the high-pressure tank. An SDBD actuator was placed upright such that its induced flow pushed air upward, resulting in downward thrust directly into an electric scale (see Figure 1.6). A serial connection to the scale was possible because of an instrumentation feed-through in the endcap of the pressure vessel. From inside the pressurized tank, the scale could deliver real-time weight readings directly to a computer in another room (about 10 readings per second).

The actuator used for thrust measurements was G90, a 90-mil thick glass actuator. The span was 6 inches, and the stream-wise length of the covered electrode was 1 inch.
The actuator was selected to produce measurable thrust while being light enough to allow the use of the high-precision scale.

![Image](image.png)

**Figure 2.5 Instrumentation feed-through [9].**

The actuator was subjected to an AC ramp wave produced by the function generator. The function generator and oscilloscope were networked and controlled via a C computer code. The result was an automated coordination between function generator, oscilloscope, scale, and computer.

The procedure for finding thrust went as follows. First, the scale was activated with no applied voltage to get a baseline weight. The function generator was then turned to a specific AC voltage amplitude, which was amplified and fed to the actuator inside the tank. The jump in weight was recorded by the scale as the measure of thrust. The oscilloscope averaged and stored the voltage / current waveforms over a 20-30 second...
time interval. The function generator was then turned off, and the sharp decrease in weight was recorded. A live digital camera captured the dynamics of the plasma during the entire trial.

Figure 2.6 Schematic for thrust experiment.

The tank was then pressurized to a new level and the thrust measurements were repeated. The experiment was reiterated at 1-bar intervals up to 9 bar (130 psi), and the results were compared.
Figure 2.7 Real-time data saved from the electronic scale during trial. The periods of high readings indicate the 20-sec intervals when plasma was on (G250, 15kVrms, 5kHz).
3.1 Initiation

The initiation properties of the actuators were documented first. The procedure was executed at both low- and high-pressures, and the results were plotted together. Data at atmospheric pressure (1 bar) was taken in both the low- and high-pressure chambers; as expected, there was no appreciable difference.

Although the execution of the procedure was very straightforward, the condition of “initiation” was somewhat subjective. Plasma did not form uniformly across the span of the electrodes, most likely a result of the nonuniformity of the copper tape on the microscopic scale. The initiation voltage was interpreted as a range and plotted as such. The low end of the range was the point at which the first speckles of light appeared on the electrode, or when the current meter showed the first evidence of a spike. The upper limit was chosen as the point when almost all of the electrode-span had generated plasma and the current showed very visible spikes at every period in the cycle. These “limits” are presented as error bars in the plots below. The fit was calculated using averages of both current and light data for several repeated trials. The lowest pressure (~0.17 bar) corresponds to an approximate altitude of about 13 km or 42,500 ft [2].
Figure 3.1 Example initiation plots for sinewave input over the range of pressures.
(a) G250, 5.3 nF/m² (b) K11, 91.9 nF/m².
As anticipated from previous literature, the voltage required to initiate plasma increased with greater ambient pressure. For all cases tested, the relationship between initiation voltage and pressure first appeared linear up to 5 or 6 bar, then leveled off. The data could be represented as two intersecting linear fits, or if a least-squares power fit is applied to the data, \( V_{\text{init}} \) is found to go as \( P^k \), where \( 0.5 \leq k \leq 0.7 \) for the range of actuators tested.

All the trials were averaged into mean values representing the combined light and current data for each actuator. The actuators were then compared based on their capacitances. To explore the effect, the initiation data was first analyzed at atmospheric pressure.

Figure 3.2 Initiation voltages at 1 bar.
In the figure above, the initiation data is presented for the seven actuators on a logarithmic scale. Each actuator is represented by its capacitance, a single point on the \( x \)-axis; for example, the data for G90 is plotted at the \( x \)-coordinate 57.0 pF.

Several facets of Figure 3.2 merit discussion. Firstly, the initiation data was similar between the two frequencies. The difference between 1 and 5 kHz driving frequency was therefore considered negligible for the scope of this investigation. Also, two actuators, K11 and T8, had the same capacitance, ~118 pF. The initiation averages of these two actuators were within 10% of each other.

Lastly, as discussed in the previous section, the electrode area of actuator G90 was different than the others, resulting in a capacitance value that was scaled disproportionately. After the above plot indicated that the initiation voltage of G90 did not follow the trend of the other actuators, the capacitance values were normalized by area and plotted again.

Figure 3.3 Initiation voltages at 1 bar, with capacitances normalized by area of the covered electrode.
For atmospheric pressure, the normalized data collapsed distinctly to a power-law trendline. The data strongly suggests that initiation voltage is a function of its dielectric capacitance per unit area, \( \frac{C_d}{A} \). (The trend is analogously reproduced using the ratio of dielectric constant to dielectric thickness, \( \frac{\varepsilon_d}{t_d} \), as these two ratios differ only by a constant). The overlying trend is actuators with higher capacitances require less applied voltage to initiate plasma. Results for low- and high-pressures were then appended to see how this relationship was affected by ambient pressure.

Figure 3.4 Initiation voltages for range of ambient pressures.
Data for a range of pressures is presented in Figure 3.4. The initiation voltages are compared with respect to the capacitance per unit area of each actuator \( \left( \frac{C_d}{A} \right) \). As expected, the initiation voltages are seen to increase for higher pressures. More interestingly, the slope (on a logarithmic scale) of the initiation voltage to \( \frac{C_d}{A} \) remains relatively constant across the range of pressures. The value originally encountered at one bar, an exponent of about -0.4, persists throughout the data.

3.2 Thrust

Next examined was the static thrust of a flat-plate actuator. The dominant metric of comparison was the exponent of the thrust-to-voltage power-law. The 3.5 power-law encountered in literature has been reproduced for different geometries at atmospheric conditions [23]. Missing from literature is how different ambient pressures affect this power-law exponent.

Sub-atmospheric thrust measurements from Schuele and Corke [22] were revisited. The data was organized to generate a thrust vs. voltage curve at each pressure, plotted in Figure 3.5. A least-squares power-law fit was then calculated, omitting the high-voltage points when thrust was reduced (because of filament formation). At one atmosphere, the measurements reproduced the 3.5 relation. As the pressure dropped, however, the exponent decreased.
Figure 3.5 Low-pressure data from Schuele and Corke [23] for a 2kHz glass actuator. At atmosphere, the thrust went as voltage to the 3.5 power, but the exponent decreased with lower pressure.
The next step was to collect thrust measurements at high pressure, using the experimental facility discussed in the previous section. The experiment was conducted using the G90 actuator, a 90-mil thick glass dielectric. The applied voltage was a ramp waveform with a 1 kHz driving frequency. To gauge the accuracy of the presented experimental method, thrust measurements were first taken at atmosphere, both open-air and enclosed in the tank.

The thrust was found to go as $V_{\text{rms}}^{3.7}$, close to the accepted value and reassurance of a legitimate experimental method.

Figure 3.6 Thrust vs. voltage data for G90 at 1 bar.
Measurements were next taken at 1-bar intervals up to 9 bar (130 psi). From the 3.7 slope at 1 bar, the exponent was found to increase for pressures between 2 and 5 bar.

Figure 3.7 Thrust vs. voltage data for G90 at 2, 3, 4, and 5 bar.
At 6 bar and above, however, the exponent stopped increasing and remained relatively constant. The magnitude of the thrust also leveled off, and the data looked very similar from 6 through 9 bar.

Figure 3.8 Thrust vs. voltage data for G90 at 6, 7, 8, and 9 bar.
Figure 3.9 presents a summary of the thrust-to-voltage exponent over the course of the plots listed above. It represents the pressure dependency of the exponent of the power-law fit between thrust and applied voltage.

Figure 3.9 The exponent (logarithmic slope) of the thrust-to-voltage power-law as it changes with ambient pressure.

The next figure takes the same thrust data and plots it against pressure. The thrust magnitude dropped significantly from 1 to 2 bar, a decrease between 65 and 85% for each voltage amplitude. A main factor in this drop is most certainly the higher initiation voltage at 2 bar, which increased by about 70%. The thrust switched directions and increased with pressure until 6 bar, when, just as the exponent did, it saturated and leveled off. The reason for this occurrence will be explored in the upcoming section.
Figure 3.10 Collective data for G90 thrust at each pressure.
Figure 3.11 Power dissipated by G90 at each pressure.
The experiment was repeated using an actuator with an equivalent 90-mil glass dielectric. The geometry was the same, except the covered electrode was extended to double its original streamwise length (thereby dubbed actuator GG90). This adjustment was made to ensure the thrust was not being limited by the termination of plasma at the edge of the covered electrode. The results are summarized in the following plots. The thrust was slightly less in magnitude, due most likely to variance in actuator construction, but the trends with respect to pressure were almost exactly the same.

Figure 3.12 demonstrates the similarity in the exponents of the thrust-to-voltage curves for each of the two actuators. Appended are the low-pressure results from Schuele and Corke [22]. These sub-atmospheric points are from an actuator with a different geometry and dielectric thickness than that of the present experiment, but they blend into the curve almost seamlessly.

Figure 3.12 Comparison of the thrust-to-voltage exponents for three experiments at different pressures.
Figure 3.13 Collective data for GG90 thrust at each pressure.
Figure 3.14 Power dissipated by GG90 at each pressure.
Here the structure of the plasma deserves a closer look. At almost all voltages, plasma at 2 bar was marked by the appearance of filaments. The studies performed with atmospheric plasma found that filaments appear after a certain voltage amplitude was reached, and their formation was consistent with a drop in thrust [23]. The most efficient thrust production was found to be within the “window” between initiation and filament formation.

When the pressure increased from one to 2 bar, however, not only did the initiation threshold increase, but the voltage of filament-formation decreased, as evidenced by Figure 3.15 (no filaments were present at atmosphere). This closed the “window” so much that it was almost impossible to produce plasma at 2 bar without also producing filaments.

The magnitude of thrust did decrease from one to 2 bar (Figure 3.10, Figure 3.13), but the exponent of the thrust-to-voltage curve actually increased from what it was at atmosphere (Figure 3.12).

Strangely, the most prevalent filaments formed during the 2-5 bar range. At pressures 6 bar and higher, the filaments were less dominant. This is evidence the voltage of filament-formation does not follow the same trend as the initiation threshold, and may be responsible for the shape of the thrust vs. pressure curve (Figure 3.10, Figure 3.13).

The high-pressure filaments differed from those observed at atmosphere. These filaments were very unstable, appearing then disappearing at different points along the span. The filaments extended much farther than the uniform plasma field. At high-end voltages, the buried electrode was covered by what would be best described as a lightning storm.
Figure 3.15 View of plasma formation for G90 actuator at different pressures. Applied voltage is constant (11 kVrms, 1 kHz).
Figure 3.16 View of plasma for GG90 actuator at higher voltage (13 kVrms, 1 kHz).
The influence of pressure had a profound effect on the dynamics of the plasma actuator. Before the results of these experiments can translate into accurate simulations, the physics of this influence must be understood. The next section will re-visit the phenomena encountered above and investigate the tendencies in data.
CHAPTER 4:
DISCUSSION OF RESULTS

4.1 Initiation

Despite the subjectivity involved in determining the condition of "initiation", the data for threshold voltage was quite consistent. Referencing the initiation vs. capacitance per unit area curves (Figure 3.4, reproduced below), seventy-seven percent of the data was within 10% of the exponential fit. These fits were close to parallel, indicating the logarithmic slopes (power-laws) were very similar. Upon closer inspection, the exponent of the power-law fit at every single pressure was within 10% of -0.4 (including those not shown).

Figure 3.4 Initiation voltages for range of ambient pressures.
What changed from pressure to pressure was the coefficient of the power-law fit. The coefficients increased with pressure, as shown in Figure 4.1. As was expected, the coefficients followed the same basic trend as the threshold voltage vs. pressure for an individual actuator: linear up to a saturation at about 5 bar.

![Figure 4.1 Coefficients for the set of thrust vs. capacitance/area curves.](image)

4.1.1 Paschen’s curve

The theory behind Paschen’s curve was detailed in the Introduction (Figure 1.2). The general trend of breakdown-voltage increasing with pressure was reproduced in the experimental data. This is explained on the microscopic level. Higher pressure, and
therefore higher density, decreases the mean free path of the air molecules. With a shorter
distance between them, electrons need higher voltage to accumulate enough energy to
ionize neutral molecules (i.e., form plasma).

Paschen’s theory, however, was based on data from two symmetrical electrodes,
with only gas in between. The experimental data does not fall on the specific Paschen
curve for air because it was taken from dielectric-barrier actuators. Proven above to be
the principal determinant of SDBD initiation voltage, the properties of the dielectric are
not taken into account in Paschen’s theory.

4.2 Thrust

The thrust experiments produced results that are best summarized as complicated.
Comparing thrust vs. pressure (Figure 3.10 and Figure 3.13), the magnitude of thrust first
decreased dramatically from 1 to 2 bar. With increasing pressure, the thrust increased
almost linearly until 5 bar when it turned and started to decrease. The local maxima at
5~6 bar only measured approximately 70-80% of the thrust registered at 1 bar.

The exponent curve (Figure 3.12) was steadier. As pressure rose up to 5 bar, the
exponent increased along the same trend as the low-pressure data from Schuele and
Corke [22]. The exponent immediately stopped increasing at 5 bar. The remaining
pressures (6-9 bar) stayed within 5% of the value at 5 bar.

On the surface, the two principal factors that arise with pressure change are the
initiation and the density. The density of an ideal gas, of course, increases linearly with
pressure. Experimental data for the initiation of actuator G90 is shown below in Figure
4.2. The largest gradient in initiation voltage was early in the pressure range. This was
likely the strongest factor in the thrust drop between 1-2 bar. The threshold voltage, though, leveled off at higher pressures, and one would have expected to see the density take over and cause the thrust to go linearly with pressure. This, however, was not the case, as the thrust actually reversed direction and decreased.

4.3 Pressure Regimes

Analysis of the experimental data saw different trends in the data among the 0-1 bar range, the 2-5 bar range, and the 6 bar or greater range. The proposition of multiple pressure regimes seems nonphysical, but the consistency of data through each regime merits discussion.

Figure 4.2 Initiation voltage curve of the actuator used in thrust experiments, G90.
4.3.1 One bar or less

At low pressures up through atmosphere, the plasma behaved consistently. The discharges were diffuse and shone with a uniform glow. The initiation voltage was fairly linear with pressure. In reference to previous literature [22], low-pressure thrust at a given voltage had a steady slope with respect to pressure, except near vacuum (Figure 4.3). The thrust-to-voltage exponent also changed linearly through this regime, including a value of ~3.5 at one bar.

Figure 4.3 Low-pressure thrust vs. pressure data from Schuele and Corke [22].
4.3.2 Two bar to five bar

The experimental data between 2 and 5 bar was marked by three noteworthy features: a sharp decrease, then increase, in thrust magnitude; an increase in the thrust-to-voltage exponent; and the strong presence of filaments.

Although the specific actuators differ, the low-pressure data of Schuele and Corke [22] suggest the thrust-drop from 1 to 2 bar may be a continuation of the trend from low-pressure. The increasing threshold voltage is the most obvious culprit in the thrust decrease. The initiation voltage, however, was practically linear up to 5 bar. Why, then, was the extreme drop in thrust only between 1 and 2 bar? The appearance of filaments may not be a coincidence.

Filaments are essentially streamer discharges with limited lifetimes, governed by the capacitance of the dielectric [5]. Filament formation in this experiment was most prevalent in the 2-5 bar pressure regime (Figure 3.15). A possible explanation is these pressures bring out the “positive-going” plasma half-cycle (see Figure 1.4). This half of the AC cycle features more prominent streamer formation, as opposed to the diffuse plasma of the “negative-going” half-cycle. The presence of filaments has been linked to high frequencies and high applied voltages, and were typically accompanied by a decrease in thrust [23].

Nonetheless, the exponent of the thrust-to-voltage curve continued to increase during this regime (Figure 3.9). The filaments, for this particular actuator, were actually most prominent at 3 or 4 bar. Why didn’t the thrust continue to decrease, when the filaments were getting stronger?
The high-pressure filaments were very unstable, and perhaps differed in structure from the low-pressure filaments. According to Thomas et al. [23], the development of filaments caused an increased draw in current. This caused the power limit to be reached, resulting in a suffering voltage potential. The filaments at high pressure, however, formed at voltages much lower than at low pressure. The power dissipated at high pressures (Figure 3.11 and Figure 3.14) was much lower than at atmosphere. The high-pressure filaments, perhaps, did not reach the power limit, and therefore did not encounter the thrust drop-off typically associated with filaments at low pressure.

4.3.3 Six bar and higher

At 6 bar, the thrust leveled off and eventually decreased. The initiation voltage, very linear up until this point, did not increase with higher pressure at the same rate (resulting a linear fit with smaller slope). The thrust-to-voltage exponent came to a standstill, holding steady from 6 through 9 bar. The magnitude of thrust had negative concavity with respect to pressure, reaching a local maximum between 5~7 bar.

Bearing note once again is the nature of the filaments. In this pressure regime, the filaments were suppressed compared to equal voltage amplitude in the 2-5 bar range. Structurally, the plasma was concentrated into “clumps” near the edge of the exposed electrode. These could have simply been an effect of the higher threshold voltage, as maybe not 100% of the span had yet to initiate. The points that did initiate, however, extended plasma farther than would have been expected at such high pressures. This suggests the possibility these “clumps” are perhaps smaller, less organized filament structures, which do not have enough electric field strength to fully develop.
Because the thrust curves cannot be fully explained by the initiation effect, one or more factors must also be in play. The computer model can be used to determine alternate variables that are affected by ambient air pressure. The next section will explore the different factors and isolate their influences on the resulting body force. Different strategies of implementing pressure-dependence will be combined and compared in an attempt to reproduce the trends observed in experiments.
CHAPTER 5:
IMPLEMENTATION INTO MODEL

5.1 Model

The computer model used in the following analysis was the Space-Time Lumped Circuit Element Model refined by Mertz and Corke [16]. The output of the model is an array of body force vectors. The spatially-averaged RMS magnitude of these body force vectors was found to go as the voltage amplitude to the 3.5 power [16], matching the thrust-to-voltage exponent at atmosphere. The goal of this section was to analyze how adjustments in the model affected the body-force average, comparing changes in magnitude and force-to-voltage exponent with trends observed in experiment.

The initial aim was to computationally recreate the experimental actuator to have direct results for comparison. Unfortunately, the most up-to-date version of the model at the time of the simulations was not compatible with the thick dielectric of actuator G90. This problem is best illustrated by Figure 5.1 below. Plots of the space-time plasma current were used as a check of accuracy as the current is directly related to the light-emission observations (see Figure 1.5). The “hashing” in the G90 plot is unlike anything seen in experiments.
The hashing is indicative of plasma alternating off and on between time steps. It was encountered at lower dielectric capacitances (above), lower frequencies, and lower air resistivities. The instability is speculated to relate to the differential equation for the time-varying voltage on the surface of the dielectric, $V_n$. This relationship is given by

$$\frac{dV_n(t)}{dt} = \left( \frac{C_{an}}{C_{an} + C_{dn}} \right) \frac{dV_{app}(t)}{dt} + k_n \frac{I_{pn}}{C_{an} + C_{dn}},$$

where $k_n$ is 1 or 0 depending on initiation. $I_{pn}$ is the current through the air resistor, given by

$$I_{pn} = \frac{1}{R_n} \left[ V_{app}(t) - V_n(t) \right],$$

where $R_n$ is the value of that resistor. Lower values for dielectric capacitance and air resistivity both magnify the influence of the $I_{pn}$ term in Equation (6). This would increase the time derivative and has the potential to change $V_n$ significantly from one time step to the next. If this change is enough to leapfrog the electric field back and forth over the critical threshold, then the plasma field would be unstable and hashing would result.
Because G90 did not produce reliable computational results, the simulations were run using a 2-mil Kapton dielectric (replicating the K2 actuator used in initiation testing). Thrust was found to go as $V_{AC}^{3.5}$ at atmosphere for different SDBD configurations [23]; therefore, it is expected the patterns for G90 thrust would extend to a range of actuators (note that the low-pressure exponents from Schuele and Corke [22] fit seamlessly into data curves from G90). The K2 simulations were thus conducted and subsequently compared to experimental results.

5.2 Parameters

The motivation of the above experimentation was to find how ambient pressure affected the initiation and thrust of SDBD plasma actuators. The computer model, however, does not have a knob to adjust for pressure. The pressure information must be stored in the series of variables used to represent the properties of the air. Three air properties are included in the model: capacitance, resistivity, and Debye length. If these three variables cannot be adjusted in concert to reproduce the performance trends seen in the experiment, then some other kind of mechanism must be inserted.

5.2.1 Capacitance

The capacitance of the air is its ability to hold electric charge. In the model, the capacitance of the $n$-th air element, as detailed in the introduction, is given by

$$C_n = \frac{A_n \varepsilon_a \varepsilon_o}{l_n}.$$  

(8)
The dielectric coefficient of air, $\varepsilon_a$, is the only factor that is not a universal constant or variable of geometry. In the above equation, a change in air pressure would affect only this parameter.

The dielectric coefficient has a very weak dependence on pressure. At 1 bar, the dielectric coefficient of air is 1.00059. At 100 bar the dielectric coefficient is 1.0548, roughly 5% larger. To be conservative, a simulation was performed with an exaggerated 10% change in the dielectric coefficient of air. Even the exaggerated change produced very little difference in the results. The exponent and magnitudes were each changed by less than 1%. This evidence concluded the capacitance was decidedly not the means of pressure dependency.

Figure 5.2 The dielectric coefficient of air negligibly affected the power law exponent.
5.2.2 Resistance

Another property of air used in the lumped element model is its electrical resistance. The resistance is calculated from

\[ R_a = \frac{l_n}{A_n \rho_a} \]  

(9)

The resistivity of the air, \( \rho_a \), is the only factor not based on geometry. It would contain, therefore, the effect of pressure.

To gauge the effect of an increasing resistivity, a simulation set was performed using different multipliers (0.5, 0.75, 0.9, 1, 2, 4, and 8) of \( \rho_o \), the resistivity of air at atmosphere. The results are displayed in Figure 5.3.

Resistivity had the most profound effect on the exponent of the force-to-voltage curve; the effect, however, was in the wrong direction. Unlike the experimental data that showed an exponent that increased with pressure (up to 5 bar), the resistivity simulation resulted in data with a lower exponent. The exponent decreased \( \sim 30\% \) from 1 to 8 bar.

In experiment, the most obvious effect of pressure was its influence on the plasma extent. Plasma extent was inversely proportional to the pressure, confirmed in the experiment above and in literature [9],[22]. For the simulation runs, Figure 5.4 displays the plasma current over one AC-cycle in terms of its percent coverage over the covered electrode. The current plots give insight into the extent of the plasma for each resistivity value. At a given time, the magnitude of the current decreased with resistivity (expected since \( V=I\cdot R \)), but the overall extent did not change. Hashing occurred for resistivity multipliers less than 0.75. The body force and extent data indicate resistivity alone is not an adequate medium for pressure change.
Figure 5.3 Simulation set adjusting the resistivity of air.
Figure 5.4 Comparison of plasma current output for changing air resistivity. The plasma extent, very dependent on air pressure in experiments, did not change, indicating it was not a function of air resistivity (6 kV$_{amp}$).
5.2.3 Debye length

The Debye length is a parameter from the model’s electrostatic equations. Its value is given by the function

\[
\lambda_D = \left[ \frac{e^2 n_e}{\varepsilon_o \left( \frac{1}{k_b T_i} + \frac{1}{k_b T_e} \right)} \right]^{-\frac{1}{2}}, \quad (10)
\]

where \( n_e \) is the number of electrons in the plasma density. The value of the Debye length was approximated to be \( \lambda_D^{\text{atm}} = 0.00017 \text{ m} \) at atmosphere [13]. The electron density was empirically found to go as pressure \( p^{5/2} \) [17], meaning \( \lambda_D \) scales as \( p^{-5/4} \).

To test the effect of a changing Debye length, another K2 simulation set was run with \( \lambda_D = \lambda_D^{\text{atm}} p^{-5/4} \) to model different pressures in bars. The results are presented in Figure 5.5. Adjusting the Debye length had only a minimal effect on the exponent (less than 5% increase at 8 bar). It did, however, significantly increase the magnitude of force at each given voltage (increase of 1000x at 8 bar). Looking at the space-time current plot (Figure 5.6), the plasma extent had no appreciable change from one Debye length to the next.

The relationship used to describe how \( n_e \) changed with pressure was an empirical fit based on data at very low pressures (< 0.1 bar) [17]. Because it is not known if this trend continues up to 9 bar, a simulation set was run based on an exaggerated Debye length. For these simulations, it was assumed that electron density \( n_e \) scaled as \( p^5 \). The results can be seen in Figure 5.7. The smaller Debye lengths produced even higher force magnitudes, but did not change the behavior of the force-to-voltage exponent. The exponent still reached an asymptote of about 3.42; the exaggerated Debye length just caused it to approach this value even faster.
Figure 5.5 Simulation set adjusting the Debye length.
Figure 5.6 Debye length had no effect on the plasma current extent (6 kV_{amp}).
Figure 5.7 Simulation set adjusting the Debye length, using an exaggerated electron density, $n_e$. 
Reduced plasma extent was a principal consequence of increased pressure. Plasma extent, however, was unaffected by a changing Debye length (Figure 5.6), evidence this parameter alone was not enough to reproduce pressure variation. Because of its ability to affect force magnitude, the Debye length was concluded to be an important factor, but only in conjunction with other parameters.

5.2.4 Initiation fit

None of the adjusted air properties produced an adequate reproduction of the experimental data trends. A closer inspection discovered the parameters did not affect the threshold voltage, a principle factor in the shape of the thrust curves. It was thus necessary to force the initiation voltage to be dependent on pressure.

The threshold in the model is based on a critical electric field needed for plasma initiation, given by

\[ E_{\text{crit}} = \frac{V_{\text{init}}}{l_{\text{init}}} \]

(11)

where \( l_{\text{init}} \) is the characteristic length of initiation. At atmosphere, the critical electric field was approximated as 1.00e6 V/m. To account for pressure, an empirical fit of the threshold voltage was introduced that was based on the initiation curves from the above experiment.

The threshold voltage was represented as a combination of two linear approximations with a division at 5 bar, shown in Figure 5.8. The characteristic length was set to whatever value caused \( E_b = 1.00e6 \) V/m at 1 bar (0.971 mm for K2). A simulation set was then run with pressure change being represented only by this variable initiation voltage.
Forcing a pressure-dependent threshold voltage resulted in plasma extent (Figure 5.10) that decreased with pressure, as observed in experiments. At high pressure, though, the increased threshold voltage caused some hashing. This creates some doubt in the accuracy of the force magnitudes at these pressures, though the data points did not seem to deviate from their low-pressure trends (Figure 5.9).

This simulation set finally saw a consistent increase in the force-to-voltage exponent. Force magnitude did not decrease as much at the higher applied voltages (68% for 10kV from 1 to 8 bar) as the lower voltages (92% for 1kV from 1 to 8 bar). This outcome created an “anchor” at the high points, allowing the lower ones to swing down and raise the exponent. The values were not to the level seen in experiment (6-bar simulation: 3.7, 6-bar experiment: 7.2), although it is possible that a high-capacitance actuator simply saturates at a lower asymptote than a low-capacitance actuator.
Figure 5.9 Simulation set with an empirical approximation of the threshold voltage.
Figure 5.10 Plasma current extent for simulations with an empirical fit for threshold voltage (6 kV\text{amp}). The extent decreased with pressure, but hashing formed at higher bar.
5.2.5 Critical electric field

Although the above simulation set was given an empirically-based initiation fit, the threshold voltage did not match that seen in experiment. At 8 bar, for example, the model predicted nonzero body-force magnitudes for 1 and 2kV (Figure 5.9); the experimental actuator did not initiate until almost 3 kV.

An investigation into the model’s threshold voltage was performed. Using the inherited critical electric field of 1.00e6 V/m, the model was given a gradually increasing voltage amplitude. The threshold voltage was identified when a nontrivial percentage of time steps showed plasma formation. For the given $E_{crit}$, the threshold was determined to be around 0.5 kV, compared to an experimental threshold of about 1.0 kV.

![Figure 5.11 Threshold voltage from model with different values of critical electric field.](image-url)
To find the critical electric field that produced the accurate threshold voltage, $E_{crit}$ was increased until the model initiated at 1.0 kV; this condition was met at a critical electric field of 2.25e6 V/m. The adjustment can be similarly understood as a change in the characteristic length, updated to 0.432 mm or a decrease of 56%.

A body-force simulation was run comparing the two values of critical electric field at atmosphere. The higher $E_{crit}$ actually resulted in a force-to-voltage exponent that more closely matched the accepted 3.5 value.

Figure 5.12 Comparison of force-to-voltage curves for different critical electric fields.

The empirical initiation fit was once again implemented, this time with the new characteristic length. The results are shown in Figure 5.13 and Figure 5.14. Appropriately, the model did not initiate under 3 kV at 6 or 8 bar. The force-to-voltage exponents increased slightly from those of the longer characteristic length. The exponents
Figure 5.13 Simulation set with an empirical approximation of the threshold voltage, using new, smaller value for characteristic length.
Figure 5.14 Plasma current extent for empirical threshold fit with higher critical electric field (6 kV\text{amp}).
of the lower pressures were affected more than the higher pressures, resulting in an overall flattening of the curve toward horizontal. It should be noted, however, that pressures that did not initiate at the lower voltages computed an exponent using only 4 or 5 points, resulting in a power-law skewed slightly toward unity.

5.2.6 Debye length + Initiation fit

In an attempt to combine the desirable effects from both the Debye length and threshold-voltage sets, a simulation series was run that allowed both parameters to change with pressure. The results are displayed in Figure 5.15 and Figure 5.16. Because the plasma did not initiate for 1kV$_{\text{amp}}$, the power-law fits at 2 and 4 bar were calculated using only the higher five voltages. Similarly, the fits for 6 and 8 bar included only the highest four voltages. The difference in the number of points considered for fitting analysis is the probable explanation behind a discontinuous slope in the exponent vs. pressure curve.

The exponent displayed only an 8 percent increase in its trend from threshold alone (six-bar threshold only: 3.64, six-bar threshold+Debye: 3.93), not near close enough to experimental results. Once again, though, the experimental actuator differed in dielectric material, thickness, and geometry; the possibility exists that a higher-capacitance actuator simply saturates at a smaller exponent than a lower-capacitance actuator.
Figure 5.15 Simulation set with both a changing Debye length and an empirical approximation of the threshold voltage. Some of the lower voltages did not initiate at higher pressures, as observed in experiment.
Figure 5.16 Plasma current extent for simulations with both an empirical fit for threshold voltage and a variable debye length (6 kV$_{amp}$).
6.1 Conclusions

The threshold voltage of plasma initiation was found to be a very strong function of capacitance per unit area. At any given pressure, lower capacitance demanded higher initiation voltage. In reference to atmosphere, actuators at lower pressure required less initiation voltage in an almost linear relationship. This linear trend continued at high pressure until about 5 bar, when the slope shifted toward horizontal. It is not known whether this saturation is the approach toward an asymptote or some unidentified experimental effect.

The thrust of a flat-plate actuator was studied next, using a 90-mil-thick glass actuator. From an earlier experiment at sub-atmospheric pressure, the thrust of a flat-plate actuator was inversely proportional to pressure (for a given applied voltage amplitude). This trend continued on to 2 bar, but at 3 bar the thrust magnitude switched directions and increased. Further pressure increase uncovered a rounded thrust curve whose local maximum shifted with pressure as voltage increased. At no point during high-pressure tests did the thrust ever reach the magnitude it had at atmospheric conditions. The complicated thrust curve may be partially explained by the formation of high-pressure filaments, which were most prevalent between 3~4 bars.

The exponent of the thrust-to-voltage curve was also found to vary with pressure, deviating from its 3.5 value at atmosphere. It increased linearly from near-vacuum up to 3
bar, then leveled off to a constant value of approximately 7.2 for all pressures between 5 and 9 bar.

An attempt was then made to adapt the computational model to account for pressure change. Electrical properties of air featured in the model were systemically adjusted to find the consequence on actuator thrust. The effects of each parameter were documented and compared.

Figure 6.1 Force-to-voltage exponents vs. pressure, comparing experimental data to computer simulations. The functions used to vary the computational parameters with pressure were estimated.
The dielectric coefficient of air was determined to have minimal effect based on its small dependence on pressure. An increase in resistivity caused the force-to-voltage exponent to decrease, opposite to the direction of high-pressure experiments. The Debye length reproduced the shape of the exponent curve, reaching an asymptote at high pressure. It did not, however, affect plasma extent, and pushed force magnitudes in the wrong direction. In the experiment, no pressure above one bar produced thrust magnitudes higher than those at atmosphere.

Since none of the physical parameters reproduced the experimental pressure effects, a simulation set was run with an empirical approximation of the initiation voltage. Using linear fits of experimental data, threshold voltage was forced on the model as a function of pressure. The results showed that with higher pressure came decreases in both force magnitude and plasma extent. The force-to-voltage exponent increased, but not to the level seen in experiment. The next procedure was to combine both the threshold fit and Debye variation, but the exponent only increased about 9% from threshold alone.

No variable alone caused the body-force profiles to resemble pressure changes in experiment. Several combinations were tried and analyzed, with only marginal results. The complicated thrust curves at pressures above 2-bar were likely the consequence of filament formation, but the low-pressure results were consistent; thrust magnitude decreased and the thrust-to-voltage exponent increased, both linearly. No parameter in the model, however, could reproduce these results in the correct direction. Only the threshold-voltage adjustment, an empirical input, scaled the thrust correctly.
6.2 Recommendations

The following list comprises recommendations that could make any future experiments on this research topic more accurate and repeatable. These include a more quantitative determination of initiation, a larger range of thrust experiments, and a closer look at filament formation.

The first recommendation is to improve the method of determining initiation. The technique used in this investigation, one based on time-synchronization of software-enhanced video, was very time-consuming and required lots of computer memory. Because subjectivity of the observer was involved, a large number of trials had to be taken to find a repeatable average. A suggestion would be to record the waveform of the actuator’s dissipated power. Before plasma forms, the actuator behaves like a simple capacitor and has a baseline power waveform. Plasma discharges disturb this waveform and cause a phase shift. A reliable measure of this phase shift could provide a quantitative indication of plasma formation.

For the thrust experiments, more insight could be obtained from tests at even higher pressure. At 9 bar, the maximum for this investigation, the thrust was on a downward slope, and it would be informative to know if this tendency continued. Also, this investigation found several transitions in data trends at about 5 bar. There is nothing obviously fundamental about this specific pressure, so additional experiments with other test rigs or actuator configurations would likely determine if the transitions at 5 bar were fundamentally physical or exclusive to this experiment.

Future work would benefit from a thorough investigation into the behavior of the high-pressure filaments, including their underlying structure and the conditions under
which they form. The presence of these filaments did not correlate to a thrust reduction like observed at atmosphere, and it would be important to know why. It is suspected that these filaments are principal to the cumulative flowfield, and if so, the computer model would need to be updated to include their effects.
REFERENCES


