MINIMIZING MAGNITUDE OF CURRENT SPIKES RESULTING FROM ARGON NON-THERMAL PLASMSA DIELECTRIC BARRIER DISCHARGE JETS

An Undergraduate Research Scholars Thesis

by

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The electrical current profiles of two mediums, helium and argon, in a sinusoidally driven floating electrode dielectric barrier discharge jet acting on a substrate were examined for differences. It was noted that the argon plasma resulted in current spikes and more tactile electrical pain than the helium plasma. System inductance was varied by the addition of a 4.5mH coiled wire inductor between the electrode and the high voltage power source in an effort to minimize these current spikes. This effort was successful and resulted in a 6.9mA (71%) reduction in argon current spike magnitude. Since tactile pain due to electrical stimulation is a known effect of current magnitude, minimizing the spikes should reduce the pain caused by argon plasma. Such a reduction would make argon much more feasible as a plasma medium for medical applications in particular, but industrial applications as well.
ACKNOWLEDGEMENTS

I would like to thank Dr. David Staack for his assistance, feedback, and teaching both with this project and with others. He gave me my first taste of what it is like to work in a true lab and I do not know what my life would be like without that.

Additionally, I also need to thank the ever helpful Matthew Burnette for his assistance with finding all the things I need in the lab.
<table>
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<td>DBD</td>
<td>Dielectric Barrier Discharge</td>
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<tr>
<td>PEDL</td>
<td>Plasma Engineering &amp; Diagnostics Laboratory</td>
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<tr>
<td>ID</td>
<td>Inner Diameter</td>
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<tr>
<td>OD</td>
<td>Outer Diameter</td>
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<td>QV</td>
<td>Charge-Voltage</td>
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SECTION I
INTRODUCTION

Background
Non-thermal plasma is already in use in a variety of industries, usually in low pressure environments. Research to develop stable non-thermal plasmas at atmospheric pressure has progressed significantly in recent years, promising potential medical applications [1, 2]. By inducing rapid oxidization as well as other chemical and physical reactions, such plasma could be used for sterilization purposes [3]. This has been demonstrated for both point locations, such as root canals[4] and other surfaces [5], as well as in flowing fluids, such as air in a ventilation system [6, 7].

A problem lies in the primary gas used to generate these plasmas, helium. While thoroughly tested and proven to be effective, helium is expensive and is likely to become more so in the future [8]. For non-thermal plasma to be practical for medical purposes, a cheaper gas needs to be proven feasible. Argon has been proposed but our preliminary studies have suggested that it causes tactile pain, posing a problem for medical applications. Argon is commonly used in various industrial plasma applications but has not found significant usage in these lower temperature medical applications. Helium’s lighter atomic mass and higher excitation potential of its first excited state allow for a lower electron density than argon plasma at the same operating conditions. This also allows for helium to deviate significantly from the Saha equilibrium and thus for lower bulk temperatures to be achieved than most plasmas [9].
A comparison of argon and helium plasmas in a dielectric barrier discharge (DBD) jet may be seen below in Figure 1. The current spikes visible in the argon plasma support the theory that the induced pain is of primarily an electrical, not thermal, origin. Since the amplitude of the argon current does not exceed that of helium, it is thought possible to minimize this pain by suppressing the current spikes through adjustments to the operating conditions of the plasma, specifically the characteristics of the circuit that includes the plasma.

Figure 1. Comparison of argon and helium plasma from a preliminary test with the DBD jet. Slight time offset applied to sinusoidal to make both waveforms visible.
While tactile pain will not be directly measured in this experiment, the relationship between current and tactile sensation has been demonstrated previously to follow Steven’s Power Law [10], which can be seen below in Equation 1:

\[ \psi(I) = kI^a \]  

Where \( \psi \) is the perceived magnitude of a sensation (pain in this study), \( I \) is the magnitude of the physical stimulus (in this case, current in amps), \( k \) is a constant to maintain units, and \( a \) is an exponent dependent on the type of stimulation. For tactile sensations dependent on electrical signals, the value of \( a \) is 3.5. Any reduction in the current spikes should thus result in a significant reduction in tactile pain. For example, according to Equation 1, a 50% reduction in current magnitude should result in a 91% decrease in tactile sensation.

Previous work has been done to model dielectric barrier discharge jets as circuits [11] and a diagram of such a circuit can be seen below in Figure 2. In this diagram, \( C_g \) is the gas gap capacitance, \( C_d \) is the discharge capacitance, and \( R \) is a variable resistor. Collectively \( C_g \) and \( R \) model the behavior of the gas gap. It is believed that by adjusting the circuit parameters, such as capacitance and inductance in particular, the electrical behavior of the plasma itself can be adjusted as well. It should be noted that any such adjustments should take place upstream of the plasma (i.e. between the voltage source and the DBD) because in medical applications it may not be feasible to place adjustments downstream of the plasma since that is where the biological target, such as a person’s skin, would be.
Objectives

The objective of this project is to determine if, through the insertion of additional inductance upstream of the plasma, the current spikes of argon plasma can be reduced. The goal of the project is to alter argon plasma so that it does not cause tactile electrical pain. This project is primarily a screening experiment and is not intended to result in a definitive quantitative relationship between these parameters and their impact on the discharge.
SECTION II

METHODOLOGY

Experimental Apparatus

A sinusoidally driven floating electrode DBD jet was used for this study, which took place in Dr. David Staack’s Plasma Engineering and Diagnostics Laboratory (PEDL). The base configuration of the jet consisted of a 0.25” outer diameter (OD) 0.125” inner diameter (ID) alumina dielectric tube, a copper tube supply voltage electrode, and a stainless steel target surface attached to ground through a 254Ω voltage shunt. This voltage shunt was used to measure current downstream of the plasma using a LeCroy PP007-WR 10:1 voltage probe (10MΩ, 9.5pF). Additionally, between the high voltage source and the ground was similarly measured using a North Star High Voltage PVM-4 @ 1000:1 voltage probe (400 MΩ, 10pF). The data from both of these probes was recorded using a LeCroy WaveRunner 204MXi 2Ghz Oscilloscope. The gas medium flowed through the dielectric tube and was converted into plasma by the electrode before discharging unto the substrate. Additionally, a Teflon insulating square was placed between the electrode and the substrate to prevent current discharges through the air. Sinusoidal voltage was applied by an Amazing1 PVM/DDR Plasma Driver as a high voltage power source. The schematic of this apparatus may be seen in Figure 3

Inductance was varied through the addition of a coiled wire inductor of 4.5mH (53pF).

Frequency and applied power were maintained at 21.6 kHz and 60W, respectively. The inductor was added “upstream” of the plasma (i.e. between the plasma and high voltage source). This is
because in medical applications, changes downstream of the plasma would either be invasive to the target (i.e. the human body) or would not prevent the current spikes from reaching the target.

All cables are wires are kept as short as feasible and kept in place were possible in order to avoid small changes in capacitance or inductance from affecting the test results. A photograph of a portion of the primary portion of the test set-up with the inductor in place may be seen in Figure 4.

Figure 3. Diagram of test apparatus
Experimental Procedure

Both helium and argon plasmas were created and the induced current and relevant voltages were measured. The plasma was not allowed to run for longer than one minute and a minimum of one minute waiting period was in place between each measurement. This was to prevent any thermal effects from impacting the results. This process was then repeated for each of the configurations. The sequence of gases and voltages was randomized for each configuration to minimize any confounding factors. Where tests occurred different days, the base configuration was rerecorded and any data processing from those days tests was conducted in reference to this base in order to correct for potentially confounding factors such as room temperature or humidity.
**Data Processing**

Several metrics were used to determine the impact that the inductor had upon the resultant current signal. For one, the maximum recorded current in each sample was noted, as was the average peak current magnitude, and the average sinusoidal current amplitude. This last measurement should not be directly relevant to tactile sensation but is important as changes that reduce the tactile sensation may very well have other effects on the plasma that inhibits its usefulness. Additionally, a Lissajous plot of charge versus electrode voltage was created for each configuration. This was used to calculate the capacitance of the system to insure that the addition of the inductor did not significantly impact the capacitance as well and to determine the effect if it did. Lastly, the maximum charge transferred across the gas gap was calculated using variations of the equations developed by Pipa et al.[11], which are based on the equivalent circuit found in the Introduction.

For each test configuration, multiple tests were performed, to enable statistical analysis and to quantify variance. For the single value measurements, such as average peak current, ANOVA tests were conducted in order to confirm significance of reported differences.
SECTION III

RESULTS

Initial Helium-Argon Comparison

An initial comparison of the helium and argon plasmas at the base setup was conducted in a more controlled and thorough environment than that used in the preliminary study discussed in the Introduction. It should be noted that, for all inter-test comparison plots shown in the Results of this thesis, waveform offsets were added for visual legibility and should not be taken as representative of any phase shift. For all intra-test comparisons, however, waveform offsets are presented as recorded and thus demonstrate phase shifts.

To begin with a 4.5kV, 21.6kHz sinusoidal voltage was applied to the base setup. Figure 5 shows the resultant plasma currents for both helium and argon. In this plot, the significance of the current spikes is made evident. While the sinusoidal aspects of both the helium and argon waveforms are similar, with statistically identical peak values of approximately 0.4ma, the spikes in the argon plasma go more than an order of magnitude larger. In this setup, it appears that the argon spikes are largely one-sided, with the breakdown only occurring at each peak, rather than at each trough. Furthermore, the positive spikes are not consistent, but rather seem to shift between two different regimes. These positive spikes are, on average, approximately 9.8mA with a stand deviation of 6.7mA. The negative spikes, which are present though smaller, are on average 1.3mA with a smaller standard deviation of 0.2mA. The orientation of these spikes was not consistent between tests but they were always nonsymmetrical. The determining factor of the orientation could not be determined as is believed to be stochastic.
For visualization purposes, Figure 17 and Figure 18 of the Appendix provide zoomed-in views of Figure 5. The former shows a two period segment while the latter highlights the sinusoidal aspect of the waveforms by cutting off the spikes. In Figure 18 in particular, the location of the spike is evident, occurring slightly before each sinusoidal peak.

A comparison of each plasma’s current with its respective source voltage may be seen in Figure 15 and Figure 16 of the Appendix. While the timescales and voltage scales are the same, the current scales are not. There the phase shift caused by the plasmas slightly capacitive nature can be seen.

Figure 5. Plasma current comparison for base set-up argon and helium.
In order to examine the capacitive differences between the two gases, a QV Lissajous plot was constructed, as seen in Figure 6. The current spikes in the argon complicated the error correction process and resulted in some progression. Despite this, the general shapes of both curves is apparent. They appear to have similar slopes during the charging sections (and thus capacitance) but the argon curve exhibits sudden cuts inwards, corresponding to the discharging current spikes, that the helium curve does not. This capacitance is approximately 0.47pF.

Figure 6. Q-V Lissajous comparison of base set-up argon and helium.
Photographs were taken of both of the plasmas during the tests as can be seen below in Figure 7, using a 1 second exposure time and a f-setting of 40. The argon plasma exhibits more filaments that move around the area while the helium maintains a constant steady stream that is thicker than an individual argon filament.

Addition of Inductor
The next series of tests were performed with the addition of a 4.5mH inductor upstream of the plasma, as shown in Figure 3 of the Methodology section. The applied voltage was the same frequency and same power with the resultant currents for both argon and helium shown below in Figure 8. Once again, the sinusoidal aspects of both waveforms appear similar with a peak magnitude of approximately 0.4mA. While the helium waveform appears the same as without the inductor, except for a phase shift as seen in Figure 19 of the Appendix, the argon waveform has been altered in several key ways. First and foremost, the average magnitude of the current
spikes has been dramatically reduced. An additional change is that the negative spikes have increased slightly in magnitude, resulting in a more symmetric waveform. No statistically significant difference at 95% certainty could be found between the positive and negative spikes from this test. All of absolute magnitudes of the spikes here average at 2.8mA with a standard deviation of 0.9mA. This represents a 6.9mA, or 71% decrease, compared to the base setup. This difference was confirmed using an Analysis of Variance (ANOVA) with 99% certainty. A direct visual comparison of the argon waveforms with and without an inductor may be made using Figure 9 which has both on one plot.

Similarly to the base setup test, zoomed versions of Figure 8 are available in Figure 21 and Figure 22 of the Appendix, while source voltage – plasma current comparisons may be found in Figure 19 and Figure 20 of the Appendix for helium and argon respectively.

![Figure 8. Plasma current comparison for inductor argon and helium.](image)
Two Lissajous plots, one comparing argon to helium using the inductor setup and one comparing argon with an inductor to argon without an inductor may be seen below in Figure 10 and Figure 11 respectively. While the helium curve seems relatively unchanged, the argon curve now appears smaller, with more pronounced cuts on the lower side. This is believed to be due to the increase in magnitude of the negative current spikes. Once again the capacitances are the same at approximately 0.5pF.
Figure 10. Q-V Lissajous comparison of inductor argon and helium.

Figure 11. Q-V Lissajous comparison of base setup and inductor argon.
In order to better understand the effects of the addition of the inductor to the system, individual argon current spikes from both the base setup and inductor setup were compared. While multiple spikes were examined, only one representative one is shown and discussed here for illustrative purposes. Figure 12 shows this single peak comparison, with both normalized to an initial zero current for effective comparison. The specific spikes examined here are the second spikes from both tests. It is evident that not only is the inductor decreasing the magnitude of the current spike, but it is increasing the duration of the spike. This is to be expected as the inductor, by its very nature, resists changes in current.

Also calculated was the charge over time for these individual peaks, as shown in Figure 13. Here it is evident that the inductor not merely spreading out the charge over an increased span of time, but also decreasing the absolute magnitude of charge conveyed. It should be noted that this difference is only present when the spikes of the inductor set-up are compared to the larger positive spike regime of the base set-up. When the overall positive spikes of the base setup are compared to the spikes of the inductor set-up, the difference vanishes. The average charge conveyed during each spike is approximately 0.9pC with no significant difference between the base set-up and inductor set-up at 95% certainty. This is in line with expectations that both set-ups would convey similar total charge, just distributed differently, resulting in different currents.
Figure 12. Single spike current comparison for base setup and inductor argon. Taken from the second current spikes of Figure 16 and Figure 20 respectively.

Figure 13. Single spike charge comparison of base setup and inductor argon. Calculated from the second current spikes of Figure 16 and Figure 20 respectively.
Just as with the initial comparison, photographs were taken of both the helium and argon plasmas with the inductor in place. A comparison of all four combinations may be seen below in Figure 14. The addition of the inductor appears to have made a minimal impact on the helium plasma and seems to have made the argon plasma seem to have become more concentrated, similarly to the helium. Note that some of the argon filaments remain though they are fainter.

Figure 14. Photograph comparison of helium and argon plasmas with and without the inductor. All photos taken with 1 second exposure and f-setting 40.
SECTION IV

DISCUSSION

The addition of the 4.5mH inductor significantly decreased the argon current spikes and therefore fulfilled the objective of this study. Using Steven’s Power Law [10], the recorded 71% decrease in current spike magnitude equates to a 98.6% decrease in perceived tactile electrical sensation, though it should be noted that this was not confirmed using human test subjects.

Furthermore, the addition of the inductor does not seem to have significantly affected the system capacitance, charge conveyed, or the sinusoidal magnitude. The additional plasma characteristics that the inductor did affect, such flow geometry, brought the argon behavior more in line with that of helium, which is desirable for the intended applications of this research.

Several limitations of this study should be noted. First, while other sizes of inductors were tested, insufficient data was recorded in order to quantify a more general relationship between argon current spike magnitude and inductance. Second, neither bulk temperature nor electron temperature were measured to see in what ways those parameters were affected by the addition of the inductor. If the bulk temperature in particular was significantly increased, it may make the argon unsuitable for the sterilization and bandaging of wounds. Lastly, since human test subjects were not used to gauge the effect of the additional inductance on tactile sensation, the applicability of Steven’s Power Law to this mechanism could not be confirmed.
The addition of a 4.5mH inductor between the electrode and high voltage source of a sinusoidally driven floating electrode dielectric barrier discharge jet acting on a substrate served to decrease observed current spike magnitudes in argon plasma from 9.7ma to 2.8ma, a 71% decrease. According to Steven’s Power Law, this corresponds with a 98.6% decrease in electrical tactile sensation. The inductor did not significantly affect system capacitance or the behavior of the current sinusoid. Further research is warranted to both develop a quantitative correlation between argon current spike magnitude and inductance as well as to confirm the minimization of tactile sensation using human subjects. Additionally, it is possible that other altered parameters, such as adding additional capacitance in parallel with the DBD system, would similarly serve to diminish the argon current spikes as well.
REFERENCES


APPENDIX

Figure 15. Source voltage and plasma current comparison for base set-up helium.

Figure 16. Source voltage and plasma current comparison for base set-up argon.
Figure 17. Two period segment of plasma current comparison for base set-up argon and helium. See Figure 5 for full plot.

Figure 18. Sinusoidal segment of plasma current comparison for base set-up argon and helium. See Figure 5 for full plot. Note that the argon spikes exceed bounds of plot.
Figure 19. Source voltage and plasma current comparison for inductor helium.

Figure 20. Source voltage and plasma current comparison for inductor argon.
Figure 21. Two period segment of plasma current comparison for inductor argon and helium. See Figure 8 for full plot.

Figure 22. Sinusoidal segment of plasma current comparison for inductor argon and helium. See Figure 8 for full plot. Note that the argon spikes exceed bounds of plot.