COMPACT HIGH VOLTAGE LOW POWER IONIZING POWER SUPPLY

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To my grandma Mamang Aurora De Pedro and Uncle Pepito Nicholas. Whom, despite the turbulent years in my youth and time in university supported and spurred me in the continuation of my studies. Thank you. May they, rest in peace.

I'd like to thank Graham Town for his guidance and for exposing me to the practicalities of circuit design. As well as all the academics, family and friends who have enriched my learning. All the while making the whole experience much more pleasant.

STATEMENT OF CANDIDATE:

I, Kevin De Pedro, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Electronic Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged.

This document has not been submitted for qualification or assessment at any academic institution.

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Date: 4th September

ABSTRACT:

At high velocities, drag is the dominating factor in fuel consumption by a vehicle moving through air. Strategic design chief at the Volvo's Monitoring & Concept Center, Doug Frasher goes onto describing the drag coefficient to have decreased miles per gallon (mpg) by 1 mpg for every 0.1 increase in the drag coefficient. Plasma actuators serve as an attractive solution to this problem, as they can control the flow of air around the body they are applied to, while maintaining a relatively light-weight, quick response time and require no moving parts in their construction.

Limited knowledge is available in the application of these plasma actuators on smaller scale modes of transport. In these instances the plasma actuators must be able to sustain a glow discharge plasma in an environment inherent to cars. Functioning at an ambient pressure of one atmosphere as well having a compact and light enough build. That it does not substantially impede the functioning of the vehicle's performance and the devices actual benefit to the vehicle. Further the plasma actuator's power consumption must be efficient. As batteries are the primary manner to which vehicles receive electrical power. The compact high voltage low power ionizing power supply is to be designed to fulfil these requirements.

In the undertaking of the project, the design decisions made to the power supply closely follows existing knowledge on John R. Roth's patented *"one atmosphere uniform glow discharge plasma-(OAUGDP)"*. As well as the works of Jean-Louis Naudin and Thomas. C. Corke ET. AL. in their efforts in explaining and optimizing the details of Roth's work. Here their techniques will be assessed and evaluated through simulation and experimentation. If they are deemed favorable in fulfilling the requirements of the compact high voltage ionizing power supply, they will be incorporated into the design (CHVLPIPS).

The CHVLPIPS though is far from completed, progress has been made in the right direction. What has been achieved is the generation of plasma using a battery. That at a visual standpoint is comparable to works published in regards to plasma actuators. THE CHVLPIPS' form factor and weight that is far less cumbersome than the laboratory power supplies generally used. What has been contributed as a result of this undertaking is contributing the first but very few steps, in the potential streamlined use of plasma actuators.

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Chapter 1: Introduction

The Australian Bureau of statistics conducted a survey of motor Vehicle usage between the years of 2008 and 2014. Between these years it was apparent among private passenger vehicles that there was a decrease in fuel consumption [1]. Dropping from thirteen liters per 100 kilometers to twelve liters per 100 kilometers. The improvement in fuel economy can be attributed to refinements in newer iterations of combustion engines, consideration of the vehicles aerodynamics and fuel economy as well as the introduction of hybrid and fully electric powered vehicles.

Another potential step in this direction may be achieved by plasma actuators. Plasma actuators describe a device that consists of a power supply and electrodes separated by any dielectric. Capable of producing voltages higher than the breakdown voltage of the surrounding air. The breakdown voltage describes the phenomenon that occurs when a dielectric or normally resistive medium begins to conduct current. When voltages greater than the breakdown voltage are applied across the electrodes. The immediate air surrounding the electrodes will ionize.

Ionization describes the event where atoms have lost or gained electrons. In air this occurs when oxygen among other particles in the air splits into singular oxygen atoms and recombine into sets of three creating ozone. As a result the ozone, now negatively charged will tend towards the more positive electrode or anode, resulting in a conductive path through air between the two electrodes. It is during these events of recombination, light is released to form the glows characterized by plasma.

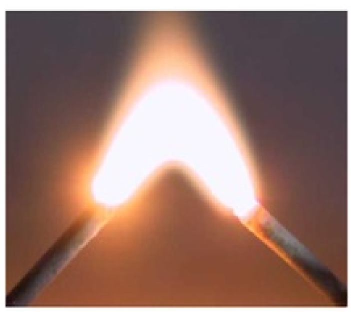


FIGURE 1
ELECTRICAL ARCING BETWEEN TWO CONDUCTORS SEPARATED BY AN AIR GAP [25]

Ionized particles together form plasma. When plasma is present it can be used to manipulate the flow of air, as air will tend to flow into the plasma. This is due to the ionized particles occupying the same amount of space of its non-ionized counterpart less densely. Using electric fields to manipulate or move the plasma, the mixture of ambient air and plasma will follow. This effect can be used to reduce effects of drag on a body moving through a fluid. In our applications the fluid is air. Roth's patented one atmosphere uniform glow discharge plasma or OAUGDP© for short, is a type of plasma that is able to efficiently achieve this effect and can be scaled to high speed applications.

When a body moves through a fluid, the fluid at some stage will produce a resistive force in the opposite direction of the object's motion, slowing it, this force is called drag. The effects of drag can be reduced by accelerating the air along the body in the direction of the incident fluid's motion. Flow detachment from the object can also be an issue, resulting in turbulence that can amplify the effects of drag. The OAUGDP panel is a construct that places a dielectric between two asymmetrical electrodes that is powered by the same power supply. The panel ensures that any airflow that would otherwise detach from the body will remain attached. This will circumvent the effects of turbulence due to flow detachment from the body in question. The OAUGDP panel achieves these effects in two ways, namely paraelectric and peristaltic flow.

In summary, paraelectric flow describes the tending nature of air to flow and mix into air that is energized or ionized [2]. This is due to a concentration gradient as a result of the highly excited state of the ionized air particles that exist in an area with far less air molecules per given volume than its non-ionized counterpart. On the other hand peristaltic flow describes the acceleration of plasma using an array of electrodes that accelerate the plasma along electrodes, excited at timed instances [3].

Plasma actuators in general are more attractive in drag reduction applications, than mechanical solutions. As they have a quick response time valued in dynamic environments, no moving parts, have a relatively simple construction, and are light weight preferable in high 'g' applications the body may be exposed to [4]. It is inherent in these qualities of the plasma actuator they are desirable for use in high speed automotive and avionic applications.

1.1 The compact high voltage low power ionizing power supply

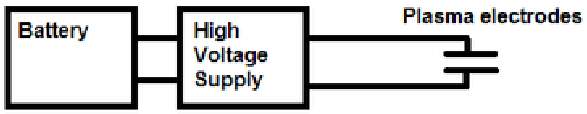


FIGURE 2 SIMPLIFIED FUNCTIONAL BLOCK DIAGRAM OF THE CHVLPIPS.

The compact high voltage low power ionizing power supply (CHVLPIPS) is a design that aims to generate plasma in the form of Roth's one atmosphere uniform glow discharge plasma. The CHVLPIPS overall must incorporate in all aspects of its design a compact form factor, lightweight and mobile usability. Fig. 2 describes very simply the main functional blocks of the compact ionizing power supply:

1. A self-contained power supply.
2. A high voltage source, needed to ionize air.
3. Electrodes or plasma actuator capable of sustaining Roth's OAUGDP and useable for aerodynamic applications.

The self-sustained power supply allows for the device to be used without another power source and can be used on a mobile platform. Since the power supply is to be used on a mobile platform a battery is an appropriate power source for the supply. Ideally the batteries to be used in this design must be light weight and compact. Intuitively lithium ion batteries are favorable in this design, having the highest power density among the commercially available types. However safety is also a factor to consider when designing the supply.

In order for the electrodes to produce OAUGDP, a high potential difference in the vicinity of the thousands to tens of thousands of volts, between the electrodes must be provided. However, batteries rarely supply voltages of greater than 12VDC. To circumvent this issue, a transformer or other means of stepping up the voltage must exist between the electrodes and the battery. This means that further circuitry must be designed in order for a DC source to be stepped up to desired voltages.

Once the required voltage is reached. The electrodes must be capable of generating plasma across its electrodes in a sustained manner, while exposing the ambient air normal to the plasma's surface. Allowing the plasma to be used for aerodynamic applications.

This thesis is an effort to expand on the work by J. R Roth and those that followed in the development of plasma actuators for use in aerodynamic applications. Roth found that paraelectric flow of the plasma is capable of reattaching air flow to a wing at 26 m/s [2]. This design aims to build a compact power supply that can generate similar voltages and operating frequencies, while adhering to the lightweight, compact form factor and battery powered mobility requirements as mentioned above. This thesis project aims to provide the groundwork to potentially expanding onto perhaps a peristaltic flow capable design. As well as provide a test bed to determine if the plasma actuator does in fact exhibit the same paraelectric Roth has published on plasma actuators.

1.2 Synopsis

Plasma actuators in general are well documented in their performance and electrode configuration. Namely the operating voltages, waveforms and frequencies as well as electrode construction. However very little information is given in the way of the power supplies used to drive them. Most documented accounts use laboratory power supplies or other devices using mains power. This thesis project focuses on designing a battery powered, compact-lightweight power supply capable of driving a plasma actuator. The chapters ahead are structured in a manner that will first build on the properties of plasma and the nature of its generation. Gradually introducing electronics concepts that bridges the logical gap between the generation of plasma and the circuity used to achieve this.

The research, design choices and results in this thesis project are heavily influenced by the works of John Reece Roth ET. Al [2] [3] [5] and Thomas Corke ET. Al. [4] [6].. These researchers have respectively, provided the conceptual ground work on plasma actuators and expansions on the optimization of these devices. In regards to power supply design Jean Naudin provided the starting point for the prototype of the plasma actuator's driving circuit.

It is in chapter two, that the notions of plasma is defined. This chapter will explore various plasmas and discuss the benefit of the use of OAUGDP in our application. And at a molecular level quantify their behaviors given changing voltages across parallel electrodes. These concepts are pertinent in understanding the underlying concepts that underpin the function of plasma actuators. This chapter essentially bridges the connection between the plasma and the circuit used to generate them.

The main issues encountered in the design of the power supply was in the optimization of Naudin's circuit [7]. Problems were apparent in terms of power consumption, componentry and power supply of the circuit. In essence although the circuit produced plasma, it did so in a fashion that was not ideal for aerodynamic applications. Further, the circuit did so in an inefficient manner. This in consequence made the circuit bulkier and heavier, how these issues were apparent and then solved will be discussed in chapter 3.

Chapter 4, will outline the current state of the CHVLPIPS. Detailing the current build and assessing whether it has evolved in accordance to the goals set out by this thesis project. As well as documenting plans for the device in the immediate future. The direction of the project will be outlined in chapter 5: Future work. Detailing further improvements that can be made to the current design.

The thesis project is supervised by Professor Graham Town, part of the department of Engineering at Macquarie University. A documented record of consultation meetings over the course of the semester and risk assessment can be found in part A, of the appendices. These meetings were used to discuss approach, progress, issues and safety in regards to the thesis project.

1.3 Project objective

The CHVLPIPS in this project is designed with the intention for use in aerodynamic applications. This is achieved by designing a high voltage power supply able to generate a plasma glow discharge that can be potentially used in drag reduction applications in vehicles. This plasma glow discharge must be sustained at 1 atmosphere. When generated must be applied uniformly across the surface it is installed. This must all be achieved from an electronics standpoint in an efficient manner. That is lightweight and compact for use in an automotive environment. With the particular intention of potentially using it for Macquarie's Human Power Vehicle Program.

The succeeding chapters will detail the foundations, approach, design decisions and progress made in meeting these requirements.

1.4 Project outcomes

As the time frame in the design of the CHVLPIPS comes to a close the following outcomes have been met at this point in time:

- A clear understanding of how the operational parameters affect the generation of plasma. These operational parameters include the operational frequency, input voltage, duty cycle and the events that cause plasma excitation.

- A more efficient means to produce the plasma, with the capability of sourcing power from a rechargeable battery.
- A compact driving circuit.
- A direction in making the design's componentry, more compact and lightweight.
- An experimental setup on the analysis of the CHVLPIPS' paraelectric capabilities.
- A conceptual basis in undertaking the peristaltic functionality of Roth's plasma actuator.

Chapter 2:
Background theory and context

This chapter will provide the background theory and context in the design of the compact high voltage ionizing power supply. Covering everything necessary to understand the design decisions made in the later chapters. Serving as the bridge to understanding what plasma is, why it is formed and how the circuitry is used to generate it. This document is heavily influenced by the works of Jean-Louis Naudin, John Reece Roth, Thomas Corke and Enloe among the many others that have conducted research on the subject of plasma actuators. Naudin's work serves as the foundation in understanding with more detail the electronic intricacies of OAUGDP generation. Naudin's circuit will heavily referenced throughout this chapter to explain the connection between plasma and electronics. Optimization, testing and the underpinning concepts of plasma generation are provided by that of Roth and Corke. Their works will be used to assess Naudin's circuit and then evaluate whether potential improvements to his design are needed. These optimizations will work towards efficient plasma generation as well as adhering to the projects requirement of form-factor, weight and mobility.

2.1 Paraelectric and Peristaltic fluid flow control in drag reduction applications:

When a body moves through a fluid a resistive force impedes the body's motion. This resistive force is drag and can be described by the following equation:

$$F_D = ½\, \rho v^2 C_D A \qquad (1)$$

Where:

- F_D is the force due to drag
- ρ is the fluid density
- v is the relative motion between the fluid and object
- A is the cross sectional area perpendicular to the direction of travel.

We notice the greater the relative velocity between the fluid and object are, an increase of drag force is apparent. Another unfavorable effect that could occur as an object moves through a fluid is flow separation. This can be exemplified by a wing as shown below.

Lift is a result of air having to flow faster over the curved surface of the wing as opposed to the air below it. This increase in speed results in less pressure being applied across the top of the wing than that of the air below it. Together with the angle attack of the wing being increased. The incident air below will be further slowed increasing the felt on the underside of the wing as well as producing a resultant upward force. However, flow separation can occur as a result of too steep an angle of attack. This separation is the space between the air flow and the wing, containing an area of stationary air. This results in the still air above the wing moving slower than the air below it, creating a higher pressure on the topside of the wing in relation to that of the bottom creating a downward force.

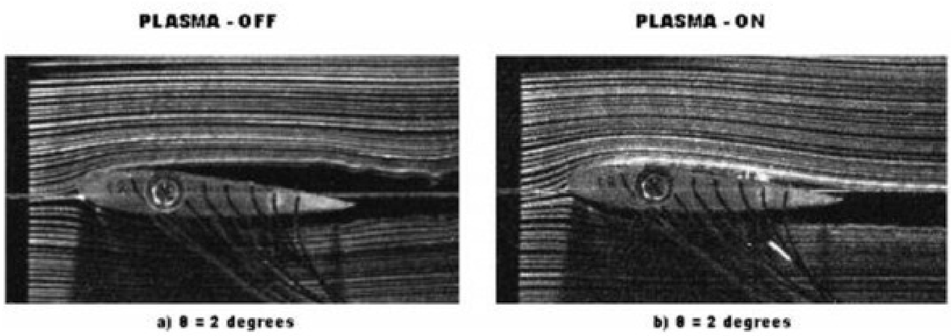


FIGURE 3 FLOW SEPARATION AND PARAELECTRIC REATTACHMENT

By calculating the Reynolds number of the object subject to some fluid flow, we can determine at what velocities the fluid's flow will begin to become turbulent. Laminar flow is the type of air flow we want. It describes the parameters that prevent flow separation and provides minimal drag across the boundary layer of the body. To determine the Reynold's number:

$$Re_D = \frac{U_\infty D}{v} \qquad (2)$$

Where

- $U\infty$ is the incident velocity of the fluid, relative to the body's motion.
- D is the tube diameter.
- 'v' is the fluid's viscosity.

A Reynolds number lying between $1 < Re < 3x10^2$ defines the flow of air over the cylinder considered to be laminar. This does not go to say that turbulent flow is non-existent in this spectrum of Reynold's numbers. It describes when the flow of fluid over an object is still predominantly laminar, yet as the number increases the turbulent flow becomes increasingly the dominant type of flow.

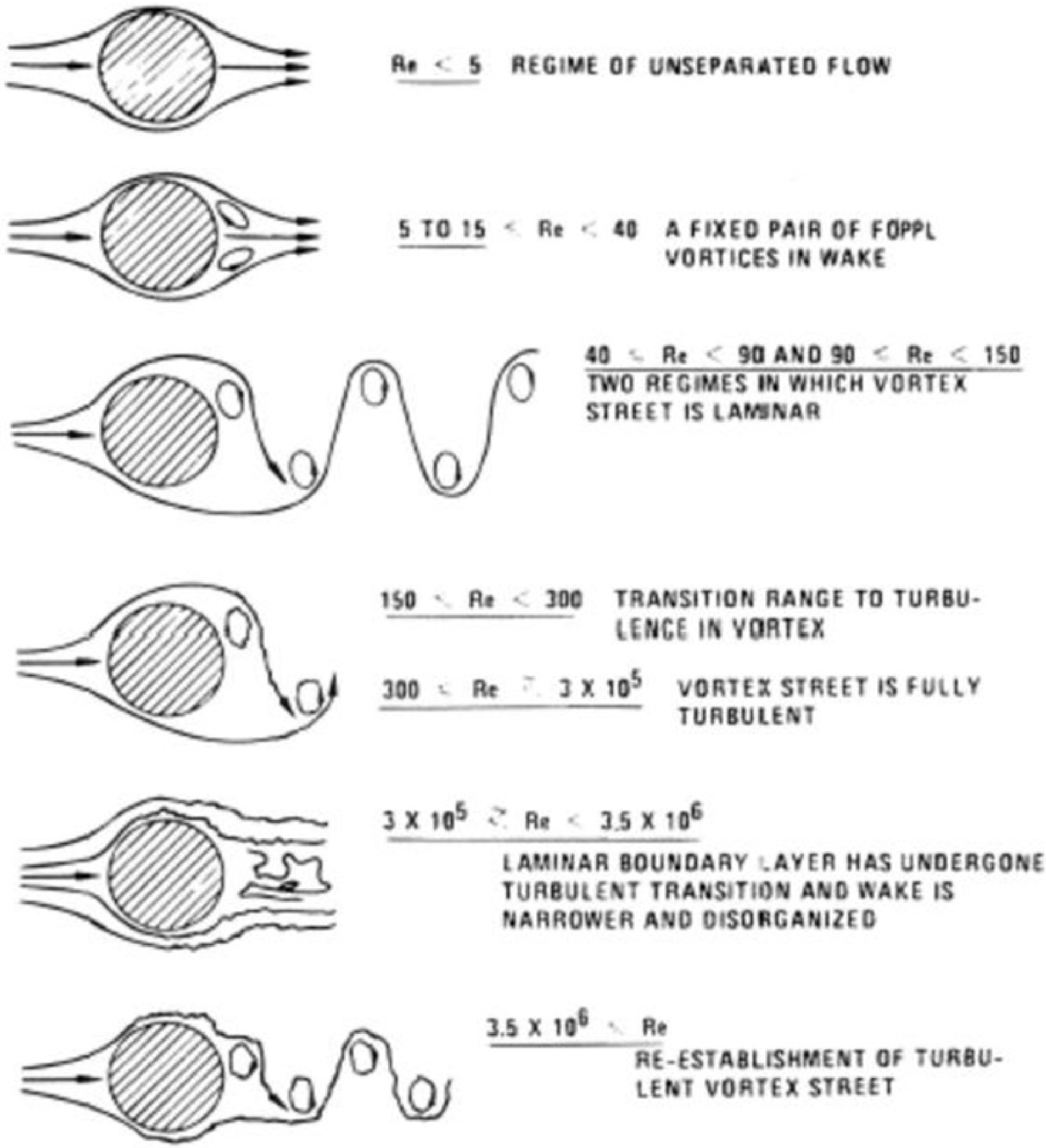


FIGURE 4 REGIMES OF FLUID FLOW ACROSS A SMOOTH TUBE [26]

The properties of plasma or OAUGDP in particular can be used to reduce the relative velocity of the fluid and object by accelerating the air nearest to the objects skin or boundary layer in the same direction as the incident air flow. This can be achieved using peristaltic and paraelectric flow control techniques.

Paraelectric flow describes the flow of plasma after the breakdown voltage has been reached. The electric field that exists between the electrodes will cause the plasma to move from the cathode towards the anode. Since ionized air has a lower area density than that of its non-ionized counterpart, the ambient air will diffuse into the plasma. The diffusion event is what prevents flow separation from occurring. However this is documented by Roth to not be effective at flight speeds. Roth states that using this method can provide drag reduction effects to speeds of up to thirty six kilometers per hour [3].

Peristaltic flow on the other hand serves to remedy this issue. By installing an array of these electrodes and exciting them in a staggered manner. Roth describes this technique to be analogous to that of 'moving light across an array of light bulbs' [5]. The result is that the plasma can be accelerated to a relative velocity comparable to that of the incident air flow. In effect reducing the Reynold's number of the system.

Paraelectric flow across the electrodes is the focus of this thesis project. As without paraelectric flow, peristaltic flow is not possible. The aim of this thesis project is to produce an OAUGDP that resembles that of the plasma actuators as shown in publications in a fashion that aligns with the projects requirements. More importantly understanding the aspects of the design that will require optimization in order to achieve results comparable to those published.

2.2 The relationship between OAUGDP plasma generation and circuit configuration:

Schematics of the electronics used to produce OAUGDP are rarely ever made available for public use. Often only citing "off the shelf" function generators and signal amplifiers designed for laboratory use. These are not compatible with the goals of this project that requires a compact, light and mobile design. Jean Naudin provides an alternative, a schematic of an OAUGDP generator that uses a 555 timer as an oscillator to provide the signal input. A transistor is used amplify its square wave output, that is then applied across an ignition coil to boost the signals voltage to the kV range. This voltage is then applied across the terminals of the electrodes to form the one atmosphere uniform glow discharge plasma. Naudin's circuit can be simplified into four functional blocks. A power source, oscillator, transformer and OAUGDP panel.

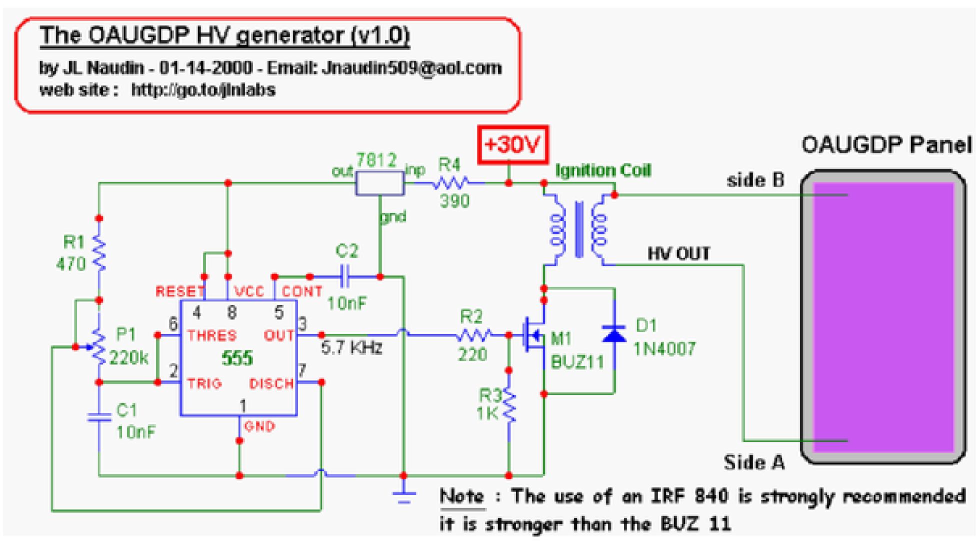


FIGURE 5 NAUDIN'S OAUGDP GENERATOR [7]

In this chapter, Naudin's circuit will be analyzed to better understand the functional blocks of his design. As well as translate the components of his circuit's contribution to plasma generation. Changes will be made to his design to meet the design goals of this thesis project and to attempt optimization techniques as discussed by research on the subject of plasma actuators.

2.2.1 Electrodes

The electrodes are essentially the part of the compact ionizing power supply that is called the plasma actuator and are wired in parallel to the ignition coil. Naudin's design utilizes 20 gauge radio wire as the plasma actuator of his circuit. Radio wires are a combination of two individual wires combined together via a part of their insulating coat from one end of the wires to the other. The radio wires corresponding ends, are tied to the head of the same wire. They are looped, ensuring that they are isolated from one another. Each of the two wires is attached to either the high voltage output or common terminal of the ignition coil. Essentially a capacitor is formed. The wires function as the electrodes of a capacitor, the insulating material and ambient air form a dielectric. Once the wires experience a high voltage across the output terminals of the ignition coil. Reaching the break down voltage of air will cause a short circuit between the two wires as electrons are emitted from the cathode's wiring insulation to that of the anodes'.

FIGURE 6 NAUDIN'S OAUGDP PANEL

Naudin's OAUGDP panel is very similar to Enloe's use of the dielectric barrier discharge electrode configuration as shown below. It consists of two strips of conductive material, placed asymmetrically over a dielectric. Enloe provides the capacitive model of this electrode configuration. Before the ionization of air occurs, the DBD behaves like a capacitor. Consisting of multiple capacitances of air and the dielectric. Once the breakdown voltage of air is reached, the air behaves as a short circuit. However the dielectrics capacitance increases with increasing voltage [4].

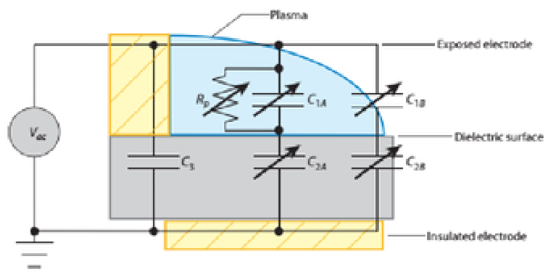


Figure 7

Lumped-element circuit model of a single–dielectric barrier discharge plasma actuator. Figure taken from Enloe et al. 2004a.

FIGURE 7 THE DIELECTRIC BARRIER DISCHARGE ELECTRODE CONFIGURATION, WITH EQUIVALENT CAPACITANCE MODEL. [4]

$$i = C\frac{dV(t)}{dt} \qquad (3)$$

Considering the equation above it is evident that during periods of increasing voltage, experienced at the ignition coils output terminals. The magnitude of current flowing through the electrodes at that instant, also increases proportionally. Corke in considering the equation above, suggests that the choice of dielectric can improve the voltage experienced by the DBD. Since the capacitor's voltage is determined by:

$$V(t) = \frac{1}{C}\int_{t_0}^{t} I(t)dt + V(0) \qquad (4)$$

And,

$$C = \frac{\varepsilon_r \varepsilon_o A}{d} \qquad (5)$$

- Where C is capacitance in farads
- $\varepsilon_0 \approx 8.854 \times 10^{-12}\ Fm^{-1}$ is the electric constant
- ε_r is the dielectric constant
- A is the area of overlap between the electrodes m^2
- d is the separation in me

The capacitance is proportional to the dielectric constant. By choosing a material with a smaller dielectric constant a larger voltage will be experienced by the electrodes. And lower current draw can be achieved.

Naudin's consists of a 1.6m wire wound around a Styrofoam panel (100mmx120mm). The distance between the two isolated copper wires across from one another is 5mm, separated by polyethylene tubing with a 2.5mm radius. Therefore taking the length of 1.6m and multiplying it with the 20 awg wire's diameter of 0.812mm. We can determine the capacitance of the panel knowing the dielectric constant of polyethylene to be 2.25. Using equation (5) yields and estimated capacitance of Naudin's panel:

$$C = \frac{(8.854 \times 10^{-12}\ Fm^{-1})(0.000812\ m)(2.25)1.6\ m}{0.0025\ m}$$

$$= 1.035 \times 10\text{^} - 11$$

The DBD electrode configuration in aerodynamic applications is more appealing in comparison to that of Naudin's use of wire. The use of copper tape is enough to be used as the electrodes for the generation of plasma. Simply attaching the wires via electric tape is enough to apply the ignition coil's voltage across them. Resulting in a lighter weight electrodes and a simpler construction. The dielectric can also be swapped, to allow for higher voltages across the electrodes. DBD configuration is also better for testing, as the electrodes do not impede the flow of air the way wounded wires do. Reducing the chance of the electrodes separating from the dielectric. The plasma formations also occur with a larger surface area, allowing for more air to mix into it. It should be also noted by applying multiple DBD's to a surface the same power supply can excite them in parallel. Or excited in a delayed manner to produce a peristaltic flow control configuration.

2.2.2 Driving signal optimization:

Plasma can be generated by both DC and AC voltage signals applied across the electrodes or what is known as the plasma actuating device. Jeffrey Gray former president of Compliance West USA, has wrote on the subject matter of Improving safety and performance with DC dielectric testing. Gray in his publication conducts tests on the break down voltage of various dielectrics ranging from air and wiring insulation, determining whether tests are more precise using DC or AC voltages. As a part of his conclusion he states "For the peak voltages to be equal, the dc voltage used in a dielectric withstand test must be 1.414 times the AC root mean squared voltage used" [8]. Paul A. Tipler among several others record the DC breakdown voltage of air to be 3x10^6 V/m or 3kV/mm [9], therefore the break down voltage for an AC is 2121 KV/mm rms. Since Naudin uses an auto transformer to step up the square wave signal. A square wave is pulsed across the input terminals of the ignition coil. When the frequency is high enough, a sinusoidal wave is shown to be approximated fig. 9.

As voltage across the electrodes increase, electrons are ejected from the electrodes creating ion pairs between the air particles and themselves. Once the peak voltage is reached and stabilizes this event begins to cease. This is due to an equilibrium of work applied to the particles across the electrodes. Reducing the number of unionized air and electrons collisions. Corke describes a saw tooth waveform with the largest duty cycle is the best waveform for this to occur [4].

The operation frequency of the circuit must be kept within a specified range to sustain the OAUGDP. If the frequency of the circuit is too low the plasma will decay and too high it will not be able to generate plasma at all [5].

In the case of determining the maximum operation frequency we must consider the collision frequency of atoms. If the operation frequency of the circuit is too low the plasma will decay too quickly and too high it will not be able to generate plasma at all [4][7]. Consider helium, its ions and electrons collide at $v_{ic} = 6.8 \times 10^9 \; and \; v_{ec} = 1.8 \times 10^{12}$ collisions per second respectively. These particles exposed to the circuit's electrodes operating at a 1-30KHZ, at appropriate voltages will ionize into OAUGDP [5]. This is due to,

$$v_{ec} > v_{ic} \gg 1 - 30\; KHz \quad (6)$$

By choosing a suitable waveform and generating the plasma at a frequency that allows appropriate time for the plasma to form, can result in a more efficient formation of plasma across the actuator

2.2.3 Waveform generator [10] [11]:

The Waveform generator used in fig.5 is a 555 timer integrated circuit run in an astable mode configuration. In astable mode the 555 timer's output pin 3, will periodically output rectangular pulses at a specified frequency. This signal is then used to drive the gate of the MOSFET, shorting the connection between the ignition coil and across the MOSFET, allowing a current to flow from the source. In effect amplifying the square wave signal at the MOSFET's gate pin, reaching a peak voltage of same magnitude as that of power source. This is very useful, as the 555 timer can only function between the voltages of 4.5-15V. Adding a MOSFET to the system allows the circuit to drive higher voltages to the ignition coil independent of the voltage of the driving signal.

However, the gate signal must be greater than that of the threshold voltage of the MOSFET's gate pin. The threshold voltage, describes the minimum voltage the gate must receive in order to turn on. If a signal cannot reach this threshold voltage it does not allow a large voltage to form across the MOSFET. Maximum voltages the MOSFET's gate, drain and source pins is rated for are also important. If not adhered to the transistor will either not switch at all or damage the transistor.

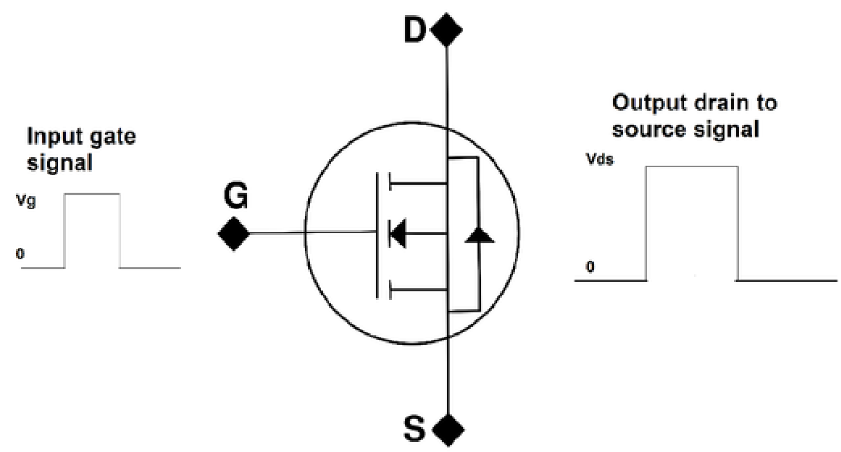


FIGURE 8 POWER MOSFET [11]

The square wave's frequency is determined by the circuit's potentiometer and resistor across pins 4 and 7 of the 555 timer in fig. 5. Allowing the frequency to be adjustable during circuit operation. The operating frequency of the circuit is described by the following equation [10]:

$$f = \frac{1}{ln2 * C * (R_1 + 2P_1)} \quad (7)$$

- Where C is the capacitor value, connected between ground and the potentiometer.
- R1 is the resistance of the resistor across pins 4 and 7.
- P1 is the resistance of the potentiometer.
- f is the square wave or switching frequency of the MOSFET.

The frequency only determines the number of times the electrodes will be excited by the square waveforms. Within the spectrum of frequencies as defined in the previous chapter, higher frequencies do not necessarily produce more plasma. In fact it impedes the production of plasma.

Corke and Naudin in their observations of the effects of the input signals and the formation of plasma across the electrodes [4] [7]. Noticed that it is during the latter half of the increasing edge of the sinusoidal waveform's crests, that plasma is formed fig. 9. This was also the case for the decreasing edge to the negative half of their sinusoidal input. Sinusoidal input signals can form plasma on both electrodes in correspondence to the increasing and decreasing edges of their respective crests and troughs. This suggests in order to more efficiently produce plasma, a smaller pulse width and steeper ramping of the waveform is favorable. What will be shown in the following chapters is plasma generation is the result of the inductive spiking in Naudin's design. In conjunction to why a smaller pulse width is favorable in the circuits' design.

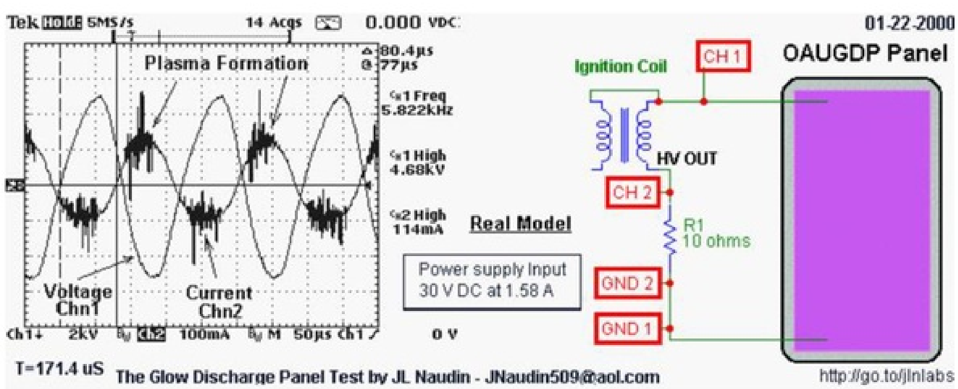


FIGURE 9 THE WAVE FORMS MEASURED AT THE OUTPUT OF THE IGNITION COIL AND ACROSS THE ELECTRODES [7].

2.2.4 The autotransformer [12]:

The autotransformer used in Naudin's design is a pair of inductive coils wound in a manner that will step up the voltage using the following relation.

$$V_p = V_s \frac{n_s}{n_p} \qquad (8)$$

- Where Vp is the voltage across the primary coil.
- Where Vs is the voltage across the secondary coil.
- $\frac{n_s}{n_p}$ is the turn ratio between the primary and the secondary.

The inductive properties of the coil describes its ability to generate an electric field to resist an introduced current flow into the coil. As the square wave voltage signal is pulsed across the ignition coil, what becomes evident is that the ignition coils inductive properties prevent an instantaneous change in current across it. When the coil has been charged and the switch is closed. The inductor will still attempt to discharge its current. This current unable to move across the MOSFET's drain and source will accumulate as a voltage at the MOSFETS drain terminal. As soon as the MOSFET is turned back on, this accumulated voltage will result in a large voltage spike or inductive kick from drain to source. Once the inductor saturates, the inductor behaves like a short, reaching a steady state voltage of zero. The voltage across the MOSFET will then return to that of the voltage of the supply until it is turned off then on again.

This voltage is important, as it will be amplified at the secondary winding of the transformer reaching peak voltages of 5-10KV [7]. This sudden increase in voltage is what generates the plasma across the electrodes, when using pulsed DC. To protect the MOSFET from excessive currents that could potentially destroy the MOSFET in its off state is through the use of an antiparallel diode across the drain and source pins of the MOSFET. This allows the accumulated charge at the drain during its off state to be redirected back to the ignition coil to be recharged or dissipated.

Pulse width modulation allows us shorten the duty cycle or high time of the pulsed DC waveform. By limiting the on time after the inductive spike, more charge can be kept on the next cycle during the MOSFETS off time. Following iterations of the compact high voltage low power ionizing power supply shown in later chapters use pulse width modulation to more efficiently produce the plasma.

2.2.5 Power supply:

The power supplies used to power plasma actuators as described by research papers thus far are connected to mains power. To adhere to the CHVLPIPS's requirements of a mobile, lightweight and compact design batteries are the best and only alternative. Secondary batteries otherwise known as rechargeable batteries will be the spectrum of batteries we must choose from. As non-rechargeable will be too expensive and too much of a hassle to replace, especially if they are cascaded. Determining the correct battery or battery pack used for our applications boils down to the following factors associated to batteries:

2.2.5.1 Power density and weight [13]:

The power density of a battery describes the ratio of extractable energy the battery can provide, given the batteries overall weight. This is measured in $Whkg^{-1}$, or watt hours per kilogram. The table below compares different rechargeable battery chemistries. We notice as the power density increases the more power can be stored and extracted from a battery with less mass. However this comes with a tradeoff of cost, thermal instability and therefore safety issues. Lithium ion batteries in theory, with the mandatory protection circuit is the most appealing of the rechargeable chemistries.

FIGURE 10 A COMPARISON TABLE OF THE PROPERT

Specifications	Lead Acid	NiCd	NiMH	Li-ion[1] Cobalt	Li-ion[1] Manganese	Li-ion[1] Phosphate
Specific energy (Wh/kg)	30–50	45–80	60–120	150–250	100–150	90–120
Internal resistance	Very Low	Very low	Low	Moderate	Low	Very low
Cycle life[2] (80% DoD)	200–300	1,000[3]	300–500[3]	500–1,000	500–1,000	1,000–2,000
Charge time[4]	8–16h	1–2h	2–4h	2–4h	1–2h	1–2h
Overcharge tolerance	High	Moderate	Low	Low. No trickle charge		
Self-discharge/ month (room temp)	5%	20%[5]	30%[5]	<5% Protection circuit consumes 3%/month		
Cell voltage (nominal)	2V	1.2V[6]	1.2V[6]	3.6V[7]	3.7V[7]	3.2–3.3V
Charge cutoff voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20 typical Some go to higher V		3.60
Discharge cutoff voltage (V/cell, 1C)	1.75V	1.00V		2.50–3.00V		2.50V
Peak load current Best result	5C[8] 0.2C	20C 1C	5C 0.5C	2C <1C	>30C <10C	>30C <10C
Charge temperature	–20 to 50°C (–4 to 122°F)	0 to 45°C (32 to 113°F)		0 to 45°C[9] (32 to 113°F)		
Discharge temperature	–20 to 50°C (–4 to °F)	–20 to 65°C (–4 to 49°F)		–20 to 60°C (–4 to 140°F)		
Maintenance requirement	3–6 months[10] (toping chg.)	Full discharge every 90 days when in full use		Maintenance-free		
Safety requirements	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory[11]		
In use since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very high	Very high	Low	Low		
Coulombic efficiency[12]	~90%	~70% slow charge ~90% fast charge		99%		
Cost	Low	Moderate		High[13]		

2.2.5.2 Charge and discharge cutoff voltage [11] [14]:

The charge and discharge cutoff voltages, describes the range of voltages the batteries can maximize the output of their useful energy while operating safely. The cutoff charge voltage defines when the battery is considered fully charged, conversely the cutoff discharge voltage defines when the battery is considered fully discharged. The cutoff voltage is determined in relation to either the circuit's lowest operational input voltage or the safest voltage the battery is considered for current to flow. The charge voltage should not be confused with nominal voltage, as nominal voltage describes the range of voltages the battery may operate at given a percentage of variance. As an example: a battery of a nominal voltage of 3.3V, can vary by ±5%.

2.2.5.3 Equivalent series resistance [13]:

Equivalent series resistance is the resistance that can be measured across the terminals of the battery in question. This is important, as it determines the maximum current that could be pulled from the battery given a circuit with particular current and voltage requirements. Suppose we wanted an idea of the maximum current that can be pulled from an E9 Energizer battery. Its data sheet suggests it can handle at most a continuous discharge of 2A or what is known as the peak current. The internal resistance of this battery from the data sheet will ideally be 150mΩ, with a nominal voltage of 1.5V. And let us suppose the circuit in question requires an input voltage of 0.8V-1.7V. We can determine the maximum current the battery could supply to the circuit using the following equations.

$$V_{load\ drop} = IR_{internal} \quad (9)$$

$$V_{source\ drop} = V_{source} - V_{load\ drop} \quad (10)$$

If $V_{cutoff} < V_{sourcedrop}$ the circuit will continue to function.

From equation the 2nd equation we know the cutoff voltage is 0.8V therefore in order to keep the circuit running, we need a voltage greater than this. We know that at this voltage, the load will experience the largest voltage drop. Let the source's voltage drop be 0.8V. Therefore the load will experience a voltage drop of 0.7V. We can determine the current drawn by the circuit by using ohm's law or the first equation. Therefore the max current draw from the battery for this system is 4.7A, this is greater than the rated continuous current. Therefore a better suited battery with a higher peak current must be chosen.

2.2.5.4 Peak current, amp hours and watt hours [13]:

Peak current is the highest discharge current at any instant the battery can handle without losing most of its energy as heat or create irreversible damage to the battery. Batteries come with a C rating, this C rating describes the discharge capability of the battery over an hour. The equation below gives us the peak current the battery can supply.

$$C_{rating} \times Ah = peak\ current \quad (11)$$

The Ah rating or amp hours describes the amount of current a battery can continuously discharge over an hour. A 4ah battery can deliver 4 amps over 4 hours. By multiplying the Ah with the nominal voltage we can get an idea of the power output of the device in watt hours or Wh.

$$Wh = Ah \times V_{nominal} \quad (12)$$

2.3 Break down voltage, Ionization, Plasma and OAUGDP:

The Compendium of Chemical Terminology published by the International Union of Pure and Applied Chemistry defines ionization as the *"process by which an atom or molecule acquires a negative or positive charge by losing or gaining an electron to form ions"* [2] [15]. This is in fact the case when electrodes or other charged objects reach a high enough voltage to turn a dielectric, in this case air, into a conductive pathway. This voltage is the break down voltage. The electrons from the cathode or negatively charged electrode, will emit electrons that will then collide with the constituent particles of air. In our example this particle will be oxygen, electrons emitted by the cathode cause oxygen atoms to gain or lose electrons in the oxygen's valence shell due to collisions between them [2]. What tends to occur after these collisions, is for two negatively charged oxygen atoms at voltages greater than air's electrical breakdown voltage, will try to bind to a positive oxygen atom forming ozone, a negatively charged molecule. As the electrons and ions are conducted from the cathode to the anode through the plasma, more ozone is produced through collisions between the emitted electrons and air particles. The ionization of these particles are collectively known as plasma, manifested in the formation of plasma arcs or filamentary discharges [16].

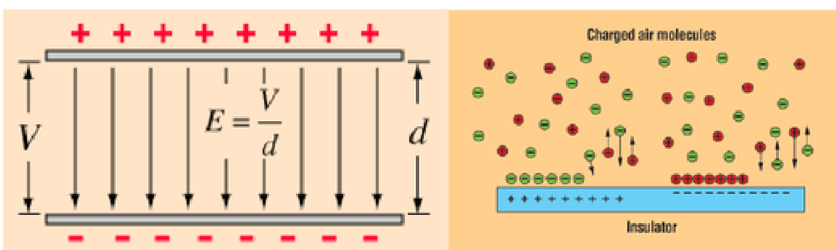


FIGURE 11 THE RELATION BETWEEN ELECTRIC FIELD AND VOLTAGE, (RIGHT) IONIZATION OF AIR

All plasmas when generated, occupy space less densely than that of ambient air. As a result, the ambient air will diffuse into the lower density region that the plasma occupies to reach an equilibrium. Mixing with the ionized particles constituent of plasma. A process analogous to that of osmosis. Plasma generally moves in the same manner as single electrons in an electric field. Moving from the negative region of the electric field to that of the more positive region of the electric field. This property allows the plasma to accelerate ambient air when the plasma ambient air mixture is under the influence of electric fields [2] [3].

Attempts to use this property of plasmas, in the form of corona discharges have already been made by El-Khabiry and Colver [2] [15]. Their experiment consisted of flat wires exposed to the ambient air. These wires were charged to high voltages along a flat surface. At these voltages coronas will form due to ionization phenomena. In the case of the wires, corona discharges appear along the normal surface of the wires. Reynolds numbers allow us to describe, given a set of variables the flow of fluid over an object. Numbers between one and one hundred are considered truly laminar or smooth flow. Anything higher begins to have turbulent flow to some degree. At low Reynolds number significant drag reduction effects were observed by El-Khabiry and Colver. However they could not be scaled to higher velocities, increasing the Reynold's number that these corona discharges were subject to. Deeming them unable to be scaled to flight conditions, their research was cancelled. Despite this, J. Reece Roth's research on OAUGDP and its application as a dielectric barrier discharge plasma has shown promising results in regards to scaling drag reduction effects at high Reynolds numbers and flight speeds using paraelectric and peristaltic fluid flow techniques.

What separates OAUGDP from corona discharges is the presence of a dielectric between two conductive plates. As opposed to coronas, that allows current to be conducted into the ambient air. The parallel electrodes allow plasma to be generated parallel in direction of the conduction of electricity. This allows for the formation of ionized particles to be directly controlled by the driving circuits operating voltage and frequency. With increased voltage, the force per unit charge increases. Allowing the electrons to move with more work between the electrodes [17]. As work is applied the electrons will accelerate from one electrode to the other. The operational frequency of the circuit determines the rate at which the emitted electrons will travel across the electrodes in a given time [5]. These concepts in relation to plasma generation are the main operational parameters when driven by a circuit. A perfect balance between voltage and frequency can overall significantly reduce power consumption by the driving circuit, resulting in an energy efficient means to generate OAUGDP.

Relationships are described by $E = \frac{F}{q}$ *and* $W = q\Delta V$ [17]

Where,

- E is electric field
- F is force
- W is work
- V is voltage

Another desirable feature of Roth's OAUGDP that sets it apart from other plasmas is the point of ignition of the plasma. As it takes advantage of the voltage requirement of 81 eV in the generation of an ion-electron pair in ambient air [2]. Electron volts or eV is a measure of energy applied to each electron in an electric field with a potential of 1 Volt. This is the Stoletow point [2], the lowest energy requirement for air to ionize. Other plasmas such as corona discharges can reach hundreds to thousands of eV to form [3]. At these energy levels, higher voltages are required. It follows that more current is more readily drawn and wasted in the form of uncontrolled coronas or plasma arcs, due to the very excited nature of electrons at these electron voltages.

In order to reap the benefits of Roth's OAUGDP, key areas of optimization must be considered and will be discussed in further details in chapter 2.3 are namely:

- The input signals waveform, pulse width, frequency and amplitude applied across the electrodes.
- Electrode configuration and construction.

These areas of optimization will inherently affect the driving circuit's componentry and may impede or improve the form factor and weight of the overall design.

In understanding how OAUGDP is formed and its properties, it can be concluded that it is the ideal plasma to be used in aerodynamic applications. It will be shown in later chapters that due to its relatively low voltage and current requirements, its circuitry is quite in favor of this thesis' projects goals. Requiring quite a simple circuit and construction.

2.4 Safety Considerations:

Plasma generation requires high voltages to reach the dielectric breakdown of air. The ensuing currents as a result of which can potentially reach amperages of 10A. Together, these are far beyond what is considered lethal to a person. Personal protective equipment though useful in mitigating risk of death by lethal voltages. Preventative measures in the undertaking of the experiments are much more effective in preventing incidents with high voltages. Ozone is a byproduct of the production of OAUGDP and is lethal at 5ppm.

When handling high voltages during the generation of plasma the following controls are applied to reduce risk:

1. When handling electronics power supply is switched off and the positive input to the power supply is removed.
2. All connections are visually inspected to ensure high voltage wires are not hazadously placed or entangled. All wires are taped down to prevent accidental contact with each other and observers.

3. Before turning on power, a lab partner is present to watch that I am not in any way near or touching the circuit.
4. At no point in time during circuit operation, the high voltage side of the circuit is handled.
5. One hand is kept in trouser pocket at all times when the circuit is active. To prevent conduction through heart.
6. Circuit is active only for the amount of time required to carry out tests.
7. Adequate ventilation is ensured by allowing air into the laboratory.

The full experimental risk assessment form is available in part A. of the appendices.

Chapter 3:
Analysis, evaluation and optimization of Jean-Louis Naudin's circuit:

This chapter focuses on the analysis and evaluation of Naudin's circuitry in terms of power efficiency and compactness. PowerSimTech's PSIM Simulation software will be used to assess the signal outputs at various components of Naudin's circuit. This will allow us to understand what to expect when the circuit is actually running. Once this is achieved, the circuit will be built to better grasp the operational parameters of Naudin's OAUGDP panel. It is then we will evaluate how best to carry out the optimization techniques as discussed in chapter 2.

3.1 Simulation:

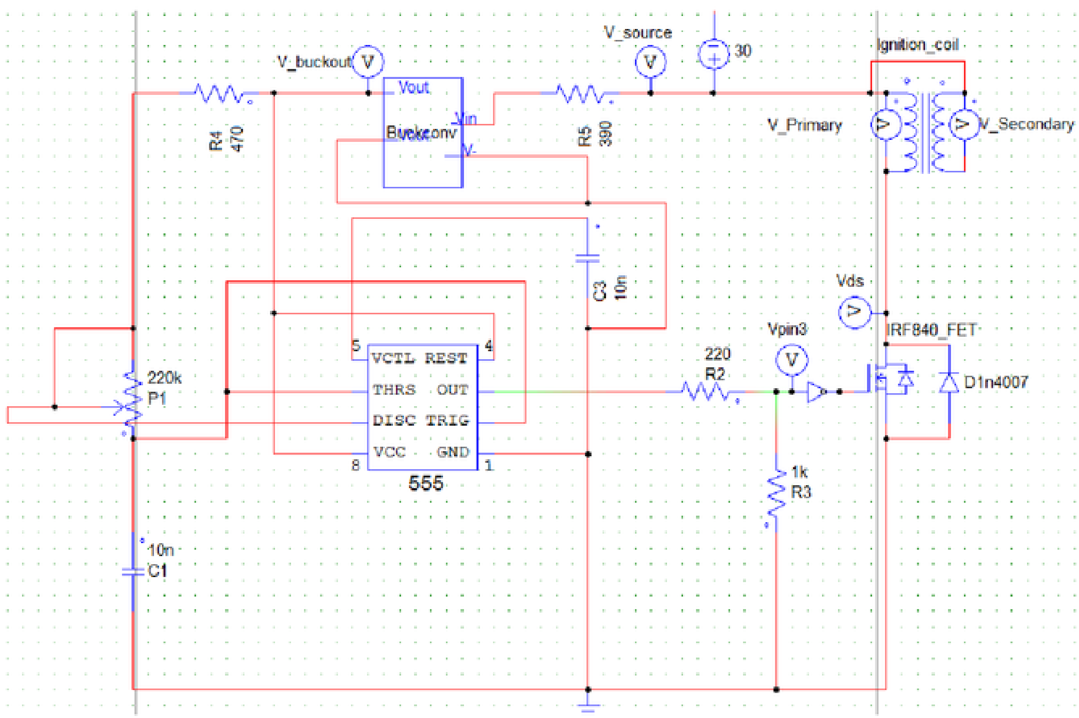


FIGURE 12 JEAN-LOUIS NAUDIN'S CIRCUIT SIMULATED IN PSIM

The above circuit is segmented into two input voltages. The probes are denoted by the arbitrarily named, circled V's in the circuit diagram shown in fig.12. 'V Buckout' represents a linear converter whose output voltage is twelve volts. The DC voltage source denoted 'V c' outputs a voltage of 30V to the linear converter and across the ignition coil. The output waveform of the 555 timer's pin three is denoted by 'V pin 3'. Its waveform is graphed in fig. 13, the 555 timer using the equation (7) has a calculated frequency of 1111.1 Hz. The duty cycle of the 555 timer output is a fixed 50%, pulsing between zero and nine volts in to the MOSFET's gate pin.

The MOSFET as discussed in the background experiences voltage spiking at the beginning of each 'drain to source' pulse. This is a result of the ignition coil being an inductive load. The drain to source voltage is denoted by 'V ds' in fig. 14 and fig. 12. Peaks of 120V are reached at its transient due to inductive spiking, at its steady-state a 70V peak is maintained. The MOSFET's drain also experiences a lag of half the period of the wave form or approximately 0.9 milliseconds.

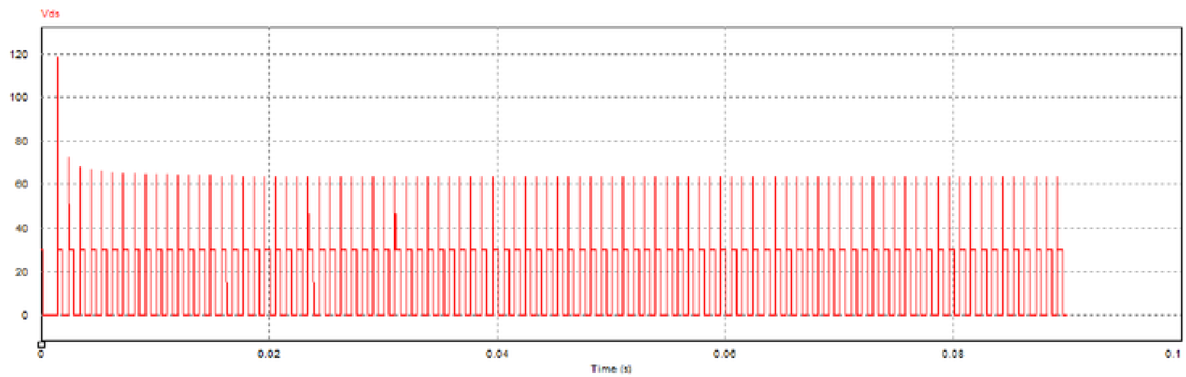


FIGURE 13 SIMULATED 555 IC ASTABLE PIN OUTPUT

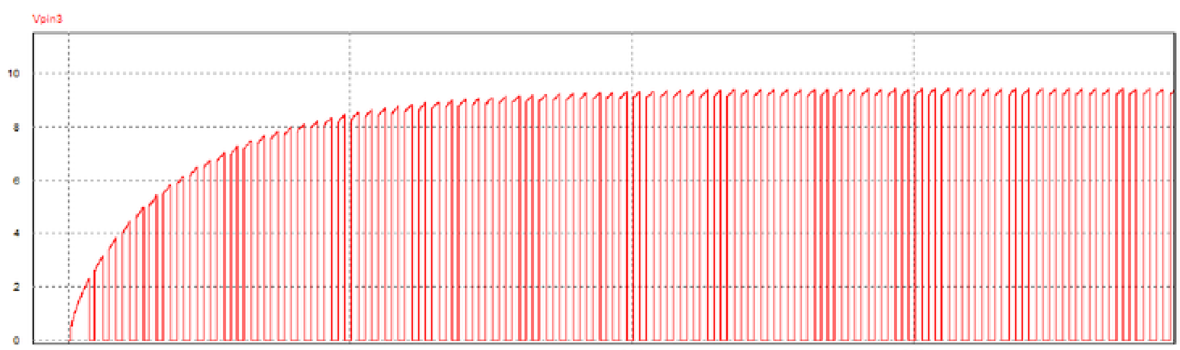


FIGURE 14 SIMULATED POWER MOSFET DRAIN TO SOURCE VOLTAGE

Figure 15 shows the voltage across the primary of the ignition coil, denoted by 'v primary' in fig. 12. What we notice is the accumulation of charge at the far end of the power supply. It is negative due the software's voltage meter taking the 30V as a positive reference point. And flow of current from the power supply is regarded as positive. Due to the diode recirculating the charge back it flows towards the supply it creates these negative spikes. Fig. 16 shows that this is reflected across the wave form and amplified by a factor of 70. Note: The ignition coil has a primary winding resistance of 5.6mH and 0.6mΩ.

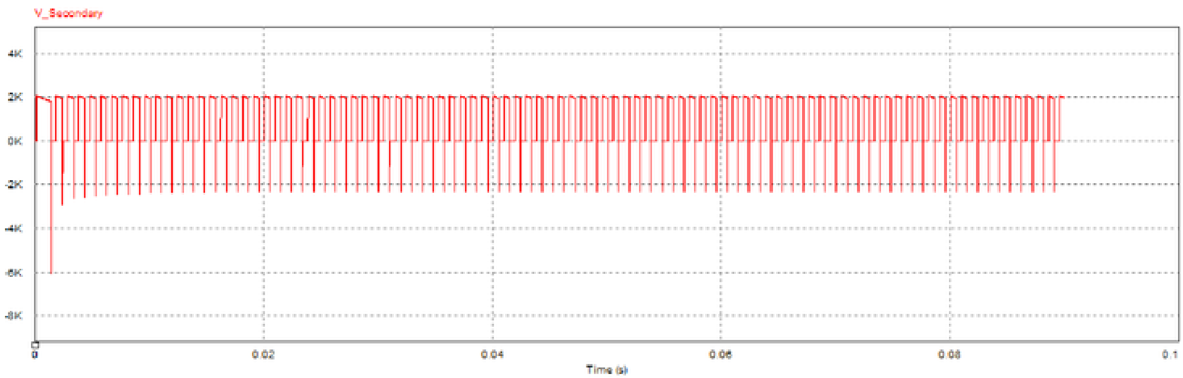


FIGURE 15 VOLTAGE WAVEFORM OF IGNITION COIL'S PRIMARY

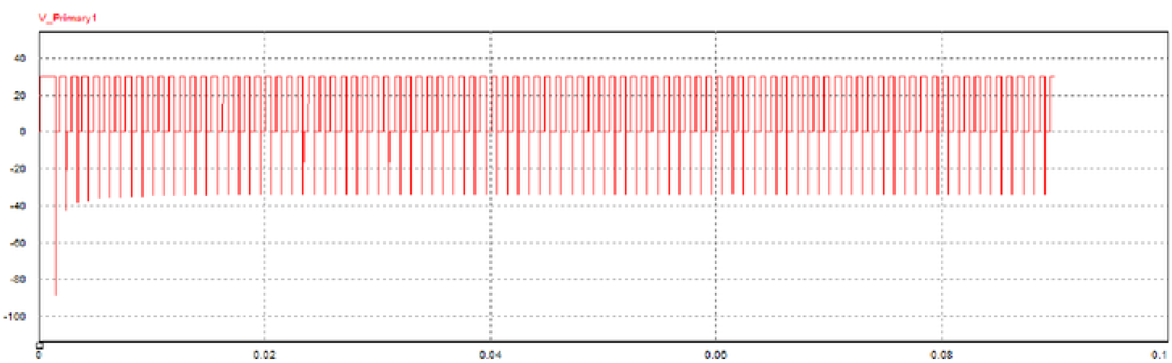


FIGURE 16 VOLTAGE WAVEFORM OF IGNITION COIL'S SECONDARY

3.2 Breadboard test of Naudin's Circuit:

Input power is the primary measure in the analysis of Naudin's OAUGDP panel circuit. What will be measured is the input current, voltage and power. These are essential in order to determine the parameters the batteries must adhere to in their design.

3.2.1 Aim:

What is of interest in the undertaking of this experiment is the input parameters of the circuit to produce the glow discharge plasma. In order to determine the lowest voltage and possible current, to achieve the brightest glow discharge at the lowest possible power cost.

3.2.2 Notable concepts:

It should be noted, that as the number of frequency increases the number of electrode excitation increases. Though plasma may not be visible, electrons still move across the electrodes after the breakdown voltage has been reached. Draining current from the supply.

3.2.3 Safety:

As the frequency increases the number of electrode excitation increases. Though plasma may not be visible, electrons still move across the electrodes after the breakdown voltage has been reached. This experiment uses lethal voltages and current. In the appendices an experimental risk assessment is appended, stating the risks and safety measures that should be considered.

3.2.4 Methodology:

1. Connect the circuit as shown in above circuit diagram.
2. Attach the oscilloscope's probe across the primary windings of the ignition coil.
3. Ensure the high voltage output cable is not crossing over with any of the lower voltage cables.
4. Check connections.
5. Turn on power supply, and set it 30V and set the circuit's frequency to 1000hz
6. Measure the peak voltage, current, brightness (1 being absent and 4 being very bright), input voltage and frequency.
7. Step the frequency by 1000Hz increments.

3.2.5 Equipment:

- Oscilloscope and probe.
- Variable voltage and current draw power supply.
- Multimeter.
- Componentry as shown in fig. 10

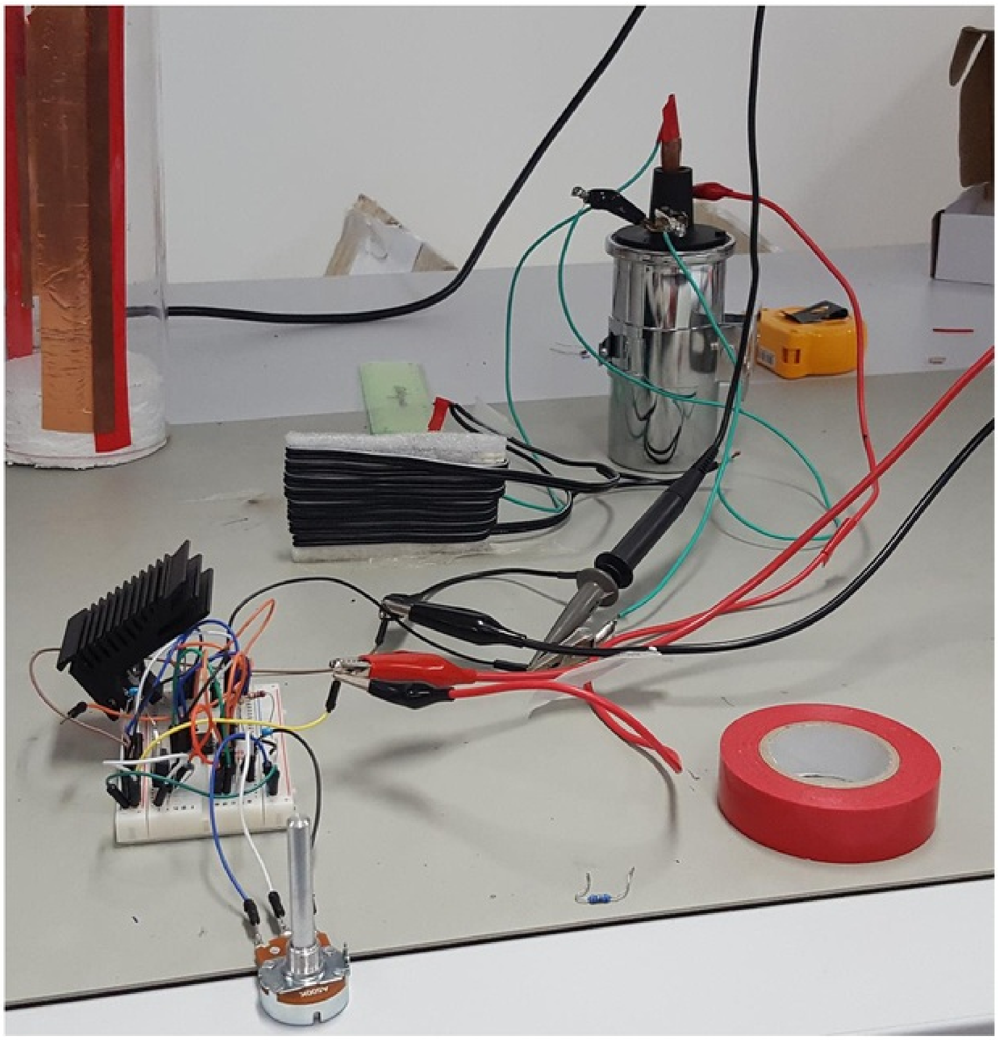


FIGURE 17 EXPERIMENTAL SETUP OF NAUDIN'S CIRCUIT

3.2.6 Results:

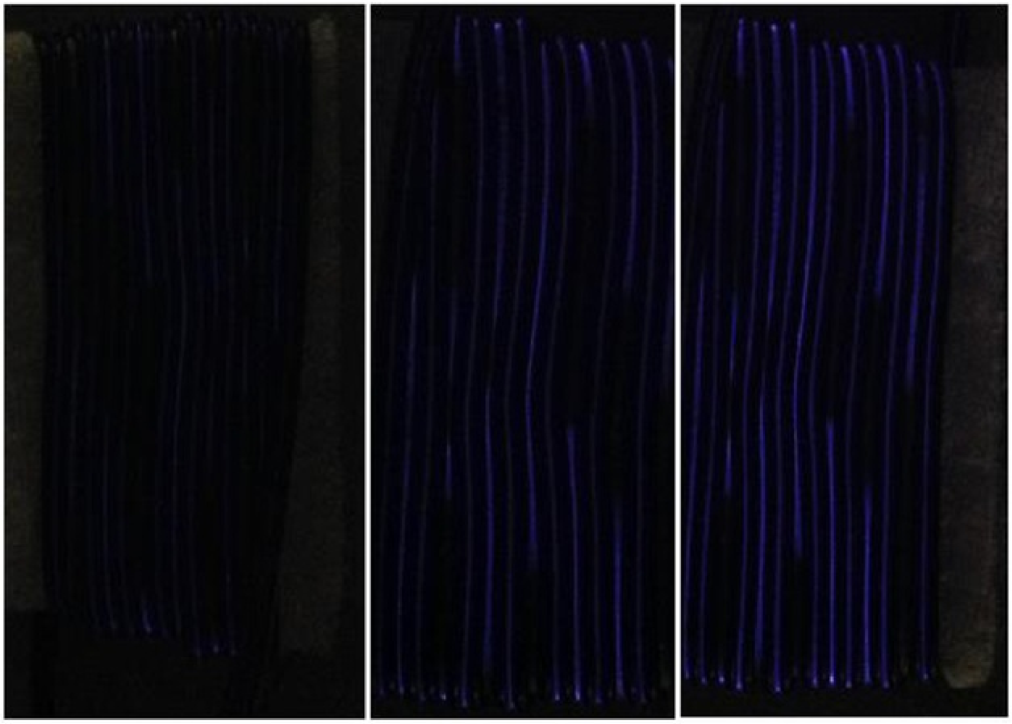


FIGURE 18 NAUDIN'S OAUGDP PLASMA FORMATIONS, FROM LEAST (1-LEFT) TO BRIGHTEST (3-RIGHT) – INCREASE MONITOR BRIGHTNESS FOR BETTER VISUAL.

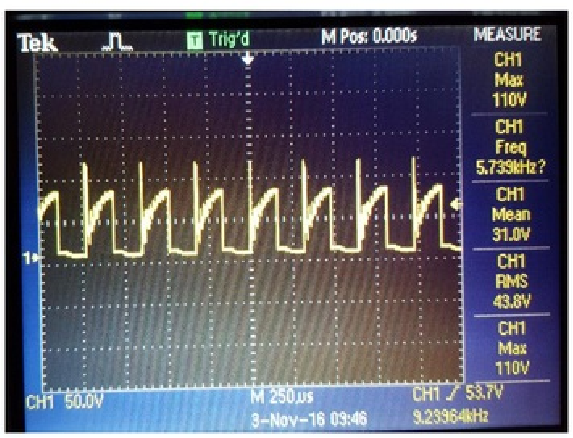


FIGURE 19 TYPICAL WAVEFORM ACROSS PRIMARY. TRANSIENT RESPONSE INCLUSIVE OF INDUCTIVE SPIKE

NAUDIN'S OAUGDP GENERATOR				
VIN	Frequency (Hz)	Peak Voltage	Brightness	Current
30	1000	36.8V	1	1.19
30	2000	36.8	2	0.46
30	3000	37.2	2.5	0.58
30	4000	37.6	2.5	0.58
30	5000	36	2.5	0.58
30	6000	37.6	3	0.57
30	7000	37	2.5	0.58
30	8000	38	2	0.52
30	9000	39	3	1.2
30	10000	40	3.5	1.5
30	11000	42	4	1.91
30	15000	110	2	2.8
30	26000	110	1	3.5

Table 1 Naudin's performance metrics

3.2.7 Design and testing:

The most apparent similarities between the simulation and Naudin's design is the presence of an inductive spike and the unchanging 50% duty cycle of the input waveform. As the frequency is increased the current draw increases proportionally as suspected, steadily climbing in brightness with increasing frequencies. At 2.5 amps the power supply was set to current limit. Since the heat sink installed on the MOSFET was not large enough to handle higher currents. Therefore higher frequencies were tested for shorter periods of time. What was found was a diminishing return on the brightness and density of plasma discharges. As shown in the table above.

Furthermore, in increasing the operational frequency of the circuit has the combined effect of increasing the frequency of ramping the electrodes are subject. The rising voltage has two composite ramping phases. The inductive spiking and the transient of the voltage increase across the inductor as it reaches its steady state. At higher frequencies, the inductors steady state is not reached. This is due to the shortening of the period, allowing the primary coil less time to reach its steady state. This is evidence that the changing voltage does indeed result in brighter thus denser plasma discharge. As the voltage increases, more work is applied to the electrons that collide with particles. It is these collisions that produce the visible purple glow, as electrons release energy as they fuse with other atoms to form molecules such as ozone.

The 30V voltage required in achieving OUAGDP is quite large, resulting in a larger battery or battery pack to supply such an input voltage. At the peak brightness, 57.3W of power is required to power the circuit. A battery pack consisting of ten 3.3V lithium ion batteries would weigh close to a kilogram and would be rather bulky. Further, the current power requirement will result in larger heat sinks needed to be required for extended use. A DC-DC converter capable of supplying such a voltage via a battery with a smaller rated voltage would also need a large heat sink. Therefore optimizations are required to achieve the same results with a smaller input voltage.

To rectify some of these issues, the duty cycle of the voltage input should be decreased. To only incorporate the transient and inductive spike of the ignition's coil primary winding. Lowering the overall RMS of the input voltage. Therefore lowering the input power requirement. This can be achieved by adding a feature to the circuit that can adjust the pulse width. This may result in a smaller voltage input requirement as well as a relatively smaller current draw. This due to the off time of the circuit becoming prolonged as the duty cycle is decreased.

3.3 Optimization of CHVLPIPS electrodes:

Naudin's plasma panel in practice is not suitable for the goals of this project. The panel is not flat, as it consists of uneven wounds of wire held by double sided tape to a Styrofoam core. This is not ideal for aerodynamic applications. At high velocities, the geometry of the uneven windings of wire will be subject to drag. The drag force overtime can result in the panel becoming unwound resulting in no plasma being produced at all. And since the windings are not streamlined, allowing air to flow across the surface of the panel unimpeded. Turbulent flow of air over the panel may be reached at slower velocities.

At an electronics perspective, the application of wires as a means to produce plasma along the surface of a body is very inefficient. The distribution of current along a very thin wire can result in excessive resistance along it. Requiring a larger voltage to ionize the air around the insulation of the wire. In order to scale the OAUGDP to larger surfaces.

It is here we consider alternatives to Naudin's electrode configuration. The dielectric barrier discharge plasma actuators as described by Roth [5] and Corke ET. Al [2], serves as a solution to these issues. A DBD plasma actuator requires only three components, the electrodes and a dielectric material between them.

FIGURE 20 PLASMA ALONG AN EXPOSED ELECTRODE [6]

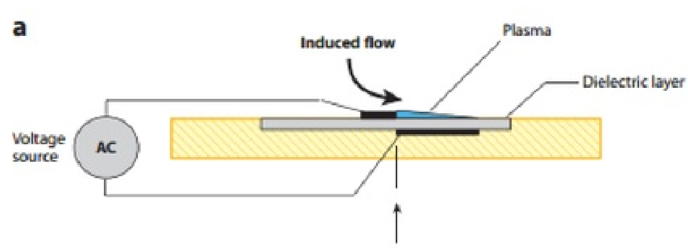


FIGURE 21 THE DIELECTRIC BARRIER DISCHARGE ELECTRODE CONFIGURATION [4]

The construction of the plasma actuator used in the following experiment consists of only a glass cylinder with a thickness of 3mm and two strips of copper tape, placed in a similar configuration see fig. 21. Both electrodes have a width of 15cms and separate heights of 2.5cms and 0.7cms. The smaller of the copper tape strips is planted on the outer layer of the cylinder. And the larger on the interior of the cylinder. The larger of the two is the anode and is offset so that the two electrodes are not vertically opposite each other, rather they meet at one another's edge. The region vertically below the smaller of the electrodes is insulated with electrical tape to prevent plasma from forming in that region fig. 22.

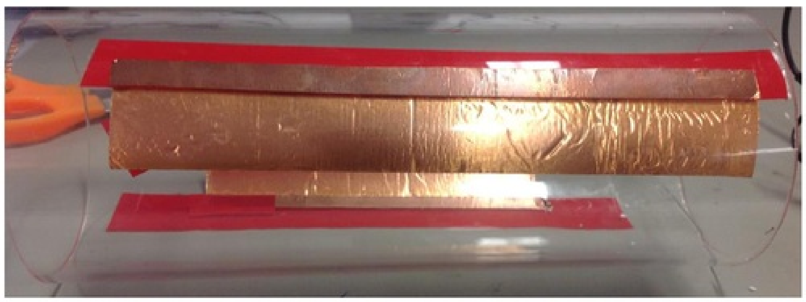


FIGURE 20 CONSTRUCTED PROTOTYPE DBD ELECTRODE CONFIGURATION.

The dielectric barrier discharge plasma actuator allows for a better idea of the plasma density across the electrode. The discharges can be described as a comb's fringe across the cathode's edge fig. 20. The density of these discharges or "comb's teeth" and brightness gives us an idea of whether the input voltage and duty cycle provided are suitable. Placing a number of these electrodes in parallel with the ignition coils' secondary allows for the use of multiple plasma actuators. If a power supply is capable of delaying the excitation of the other electrodes in relation to one another. Peristaltic functionality can be achieved [3].

This configuration is also better suited for aerodynamic applications, maximizing the surface area the plasma is exposed to the ambient air. Allowing for the paraelectric effects of the plasma to be better used. The DBD configuration allows for minimal air flow impedance, since the electrodes can be as flat as desired. The DBD plasma can be applied to geometries with known Reynolds's numbers flow regimes as shown in fig.9. The cylinder's geometry can be used to determine the corresponding Reynolds number in correspondence to the velocities it is exposed to [18]. The use of the DBD configuration allows for a viable test bench in a wind tunnel. To investigate the extent of the CHVLPIPS' paraelectric flow control capabilities at differing Reynolds's numbers.

3.4 Experiment: Observing the effects of pulse width modulation and plasma formation

The test build has been optimized in two ways. The addition of pulse width modulation and the use of the dielectric barrier discharge plasma actuators. The former, in theory should yield a smaller input voltage and current draw with a shortened duty cycle. Allowing only the voltage spike and transient response of the induction coil to occur. The shortened duty cycle has the combined effect of lowering the RMS and therefore the equivalent input DC voltage requirement. Thus allowing for a lower power (W) requirement by the circuit.

3.4.1 Aim:

To determine the effects of a shortened pulse width. Given a smaller input voltage.

3.4.2 Related work [19]:

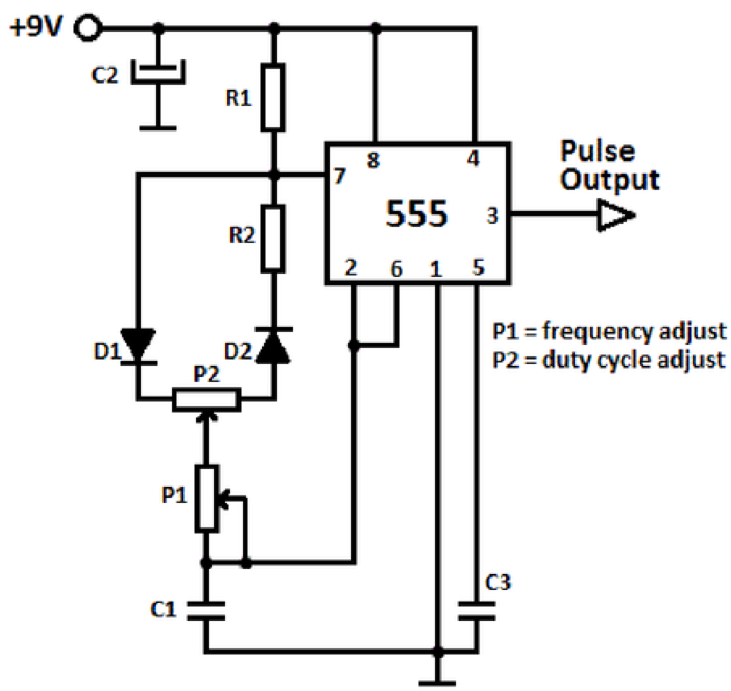
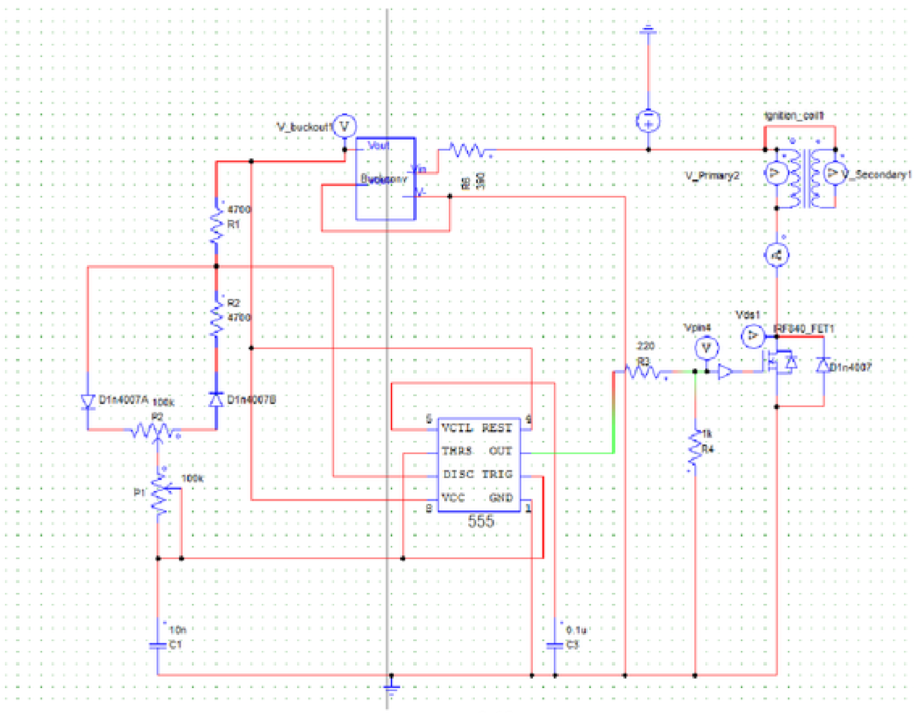


FIGURE 21 PULSE GENERATOR CIRCUIT. WITH PULSE WIDTH MODULATION CAPABILITIES [19]

To incorporate pulse width modulation into the circuit. P. Marian provides a circuit that adds a secondary potentiometer to adjust the pulse width of the rectangular waveform. The circuit values and the nature of implementation is shown below. It is essentially the same circuit structure in addition to an extra resistor, diodes and potentiometer. Note: The equation below are intended by Marian to give a very rough idea of how the circuits pulse width modulation and frequency adjust works.

$$Duty\ cycle = 1 - \frac{P2}{P1} \tag{15}$$



$$Frequency = \frac{0.69}{(2*P1 + P2 + 4.7k\Omega)*C1} \tag{16}$$

FIGURE 22 SIMULATED CIRCUIT OF PWM CAPABLE WAVE GENERATOR

Coincidentally, a Ryobi one+ Lithium polymer battery pack was made available for use by the mechanical engineering faculty's workshop. It is rated for 18V and 4ah at 1C. Testing the voltage of the battery pack at full capacity, yielded a DC voltage of 20.2V. At its low capacity state it was measured at 17.2V. The former was used as the input test voltage to determine the performance of this iteration of the CHVLPIPS.

3.4.3 Functionality:

The pulse width and frequency of the power supply can be altered via the two potentiometers P1 and P2. A flaw in the design of this circuit is the variable pulse width at differing frequencies. Therefore the pulse width is described quantitatively. These are the minimum, median and maximum pulse widths. These are dependent on the variable resistance of P1. The maximum resistance value of P2 from equation (15) yields the smallest pulse width possible.

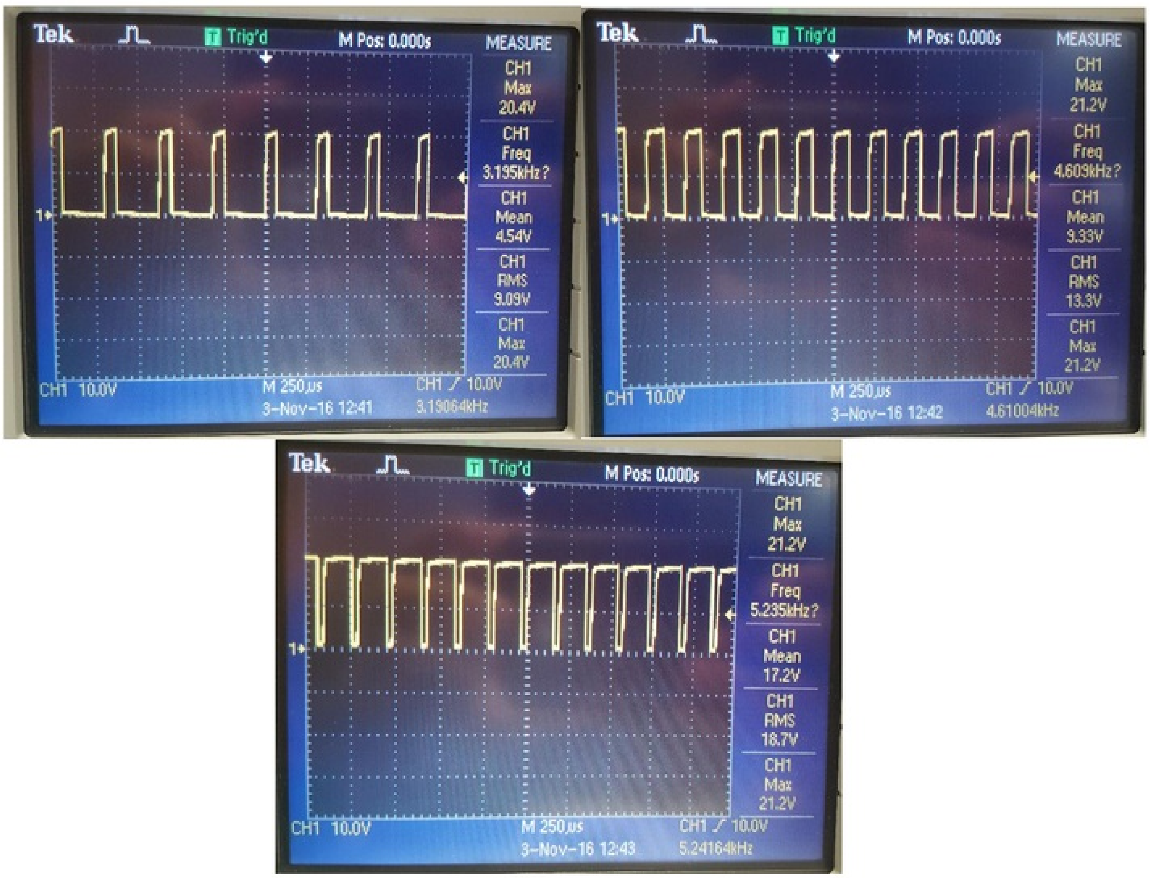


FIGURE 23(RIGHT) MINIMIZED PULSE WIDTH, (MID) MAXIMIZED PULSE WIDTH AND (LEFT) MEDIAN PULSE WIDTH

3.4.4 Safety:

Refer to appendix A.

3.4.5 Experimental setup:

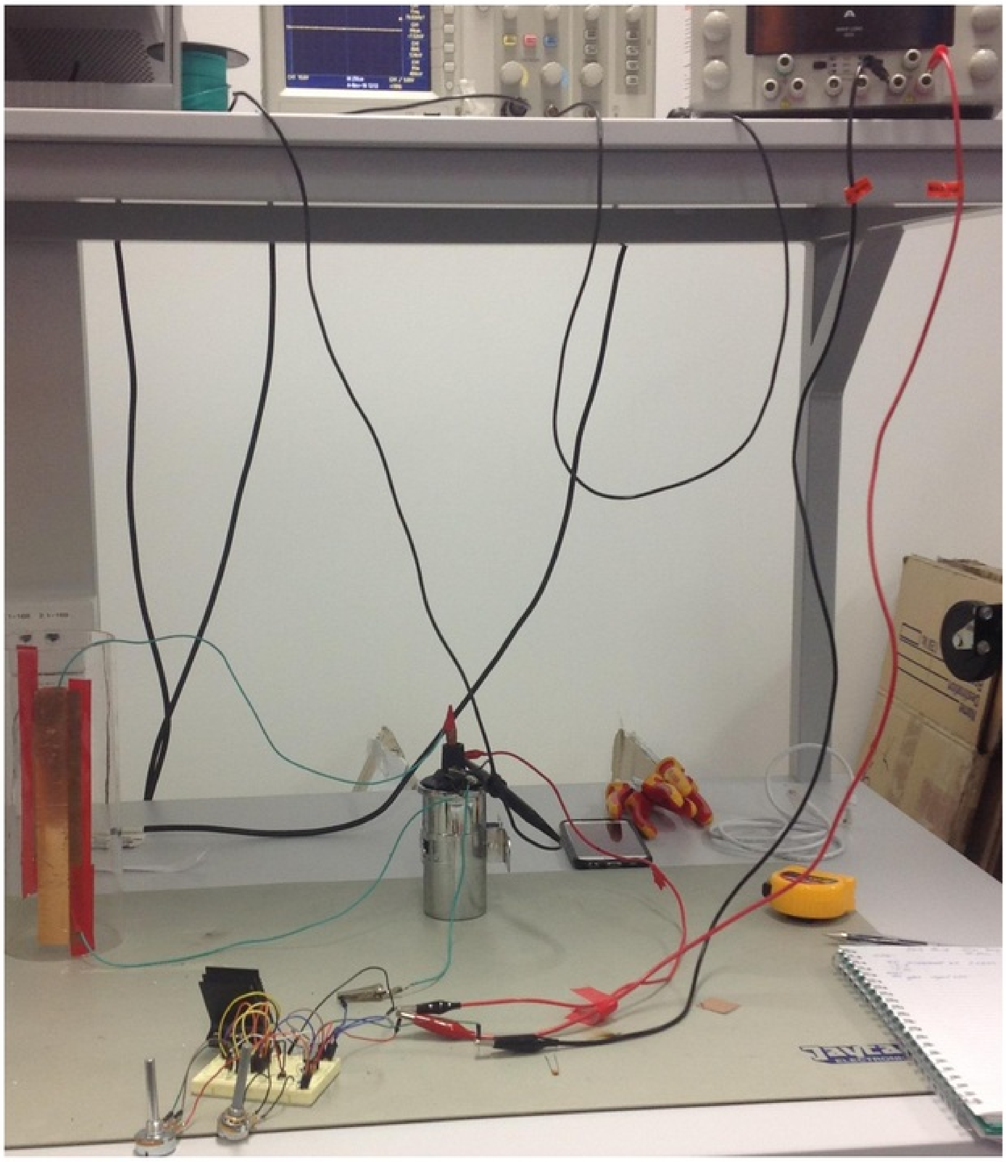


FIGURE 24 EXPERIMENTAL SETUP

3.4.6 Methodology:

1. Connect the circuit as shown in above circuit diagram.
2. Attach the oscilloscope's probe across the primary windings of the ignition coil.
3. Ensure the high voltage output cable is not crossing over with any of the lower voltage cables.
4. Check connections.
5. Turn on power supply, and set it 30V and set the circuit's frequency to 1000Hz.
6. Set P2 to its maximum value, in the above setup. This is 220kΩ in the experimental setup above.
7. Record metrics: The peak voltage, current, brightness (1 being absent and 4 being very bright), input voltage and frequency.
8. Step the frequency by 1000Hz increments. Until current limited to 2.5A.
9. Increase the P2 to the 50% value. Repeat steps 4-8.
10. Decrease the P2 to the minimum value. Repeat steps 4-8.

3.4.7 Results:

FIGURE 25 DBD PLASMA FORMATIONS, (LEFT) FROM LEAST (1) TO MOST (4) BRIGHTEST. NOTICE THE DENSITY OF THE PLASMA DISCHARGES ACROSS THE ELCTRODES.

	Minimized pulse width			Median pulse width			Maximum pulse width		
Frequency (Hz)	Peak Voltage (V)	Brightness	Current (A)	Peak Voltage (V)	Brightness	Current (A)	Peak Voltage (V)	Brightness	Current (A)
1000	110	0	0.15	110	0	0.21	110	0	0.03
2000	110	0	0.2	110	0	0.45	110	0	0.03
3000	116	0	0.24	116	0	0.65	116	0	0.04
4000	116	1	0.51	116	0	0.87	116	0	0.04
5000	116	1.5	0.56	116	0	0.91	116	0	0.05
6000	116	1.5	0.58	116	1	1.05	116	0	0.07
7000	116	2	0.85	116	2	1.15	116	0	0.07
8000	122	3	1.11	122	1	1.26	122	0	0.08
9000	126	3	1.13	126	0	1.556	126	0	0.09
10000	132	4	2.11	132	0	1.83	132	0	0.1
13000	136	4.5	2.81						
15000	140		3.2						

TABLE 2 PWM CAPABLE CIRCUITS' PERFORMANCE MEASURES

3.4.8 Design and testing:

As described in the analysis of Naudin's circuit, by decreasing the duty cycle of the input square wave the required input voltage can be decreased, thus input power can be decreased. This is evidenced by the results recorded when the pulse width set at its minimum across the frequency ranges the electrodes were subject to. At the minimum pulse width, the best OAUGDP generation achieved by far in terms of brightness and density was observed. Surprisingly the frequency to which the brightest discharge did not change too drastically. This may due to a combination of the following. Since the waveform used is pulsed DC, one plasma discharge event occurs instead of two. Thereby requiring a larger frequency to achieve a similar plasma discharge to the extent of Roth and Corke. An idea of the differing brightness levels and discharge densities are exampled in fig. 27.

The CHVLPIPS in comparison to Naudin's circuit, achieved similar results and a little more with a smaller input voltage and wattage. Further, it should be noted that Naudin's circuit represents a similar circuit with a fixed 50% duty cycle. This suggests that by decreasing the PWM by a fixed percentage may result in further reduction in the required input voltage of the circuit. Relying only on the inductive spike across the inductor. Which may be equivalent to another circuit optimization Corke describes, the use of nano second pulses [4].

In addition to pulse width modulation, when the circuit is subject to higher frequencies and currents. It produces a much brighter plasma as opposed to not producing any at all. The design overall has become more efficient in the generation of plasma, meaning more can be done with less. A DC-DC converter can be used to increase the input voltage with a battery. In order to use lower voltage packs connected in series to take advantage of the increased capacity, rather in parallel to increase the voltage. As well as achieve brighter and denser plasma discharges at a lower power requirement. This is exampled by the 4.5 achieved at 2.81 amps at an input of 20 volts, or 56.2W.Which is less than the 57.3 watts required to achieve a brightness factor of 4 using Naudin's circuit.

The shortcomings of this design are highlighted in this experiment however due to its unprecise method of changing the PWM and circuit frequency. Further wave generator optimization is needed, on order to use AC waveforms as a driving signal to the circuit. The benefits the come with AC input waveforms is the prevention of wear across the electrode [3] and the added benefit of two plasma generation events in one waveform's cycle.

Chapter 4
Current Progress:

4.1 Current iteration of CHVLPIPS:

This iteration has been reduced to two PCB's, one consisting of the pulse generator and the other the DC-DC boost converter. As well as the ignition coil. The two PCB's combined weight is no more than 150g and has a form factor of a 5cmx10cmx3cm block. The ignition coil, the heaviest of the components has a weight of 1kg and a form factor of a cylinder with a length of 14cm and 5cm diameter. The battery used in the prototype testing has an 800g mass and is sized at 12cmx7cmx10cm. The cylinder the electrodes are connected to, are not included in the size and form factor of the system. Since the electrodes can be directly applied across any dielectric surface, where OAUGDP is needed. The overall power supply thus has a combined weight of a little under 2kg.

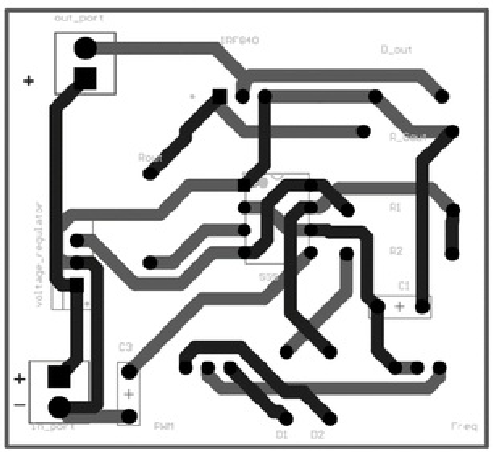


FIGURE 26 COMPOSITE GERBER FILE FOR DRIVER CIRCUIT

The addition of a DC-DC converter into the system allowed for a much higher input voltage into the system than what the battery initially provides. As a result a much brighter and denser OAUGDP is formed. The DC-DC converter is rated for an input voltage of 10V-32V and a maximum of 16A. The output ratings are 12-35V at a maximum of 10A. The heat is capable of dissipating 100W to the ambient air and is rated at 95% efficiency. Measured from a 16V input with a 19V, 2A output. Given a 20V input and 30V output, the boost converter supplying power to the system was able to 8000-10000Hz. Produce a brighter glow discharge than that of the 20V input alone at a 2.03A input. Allowing scope for the use of more compact batteries to be used to power the ionizing power supply. It should be further noted that the circuit is able to withstand 6A across the MOSFET and output terminals.

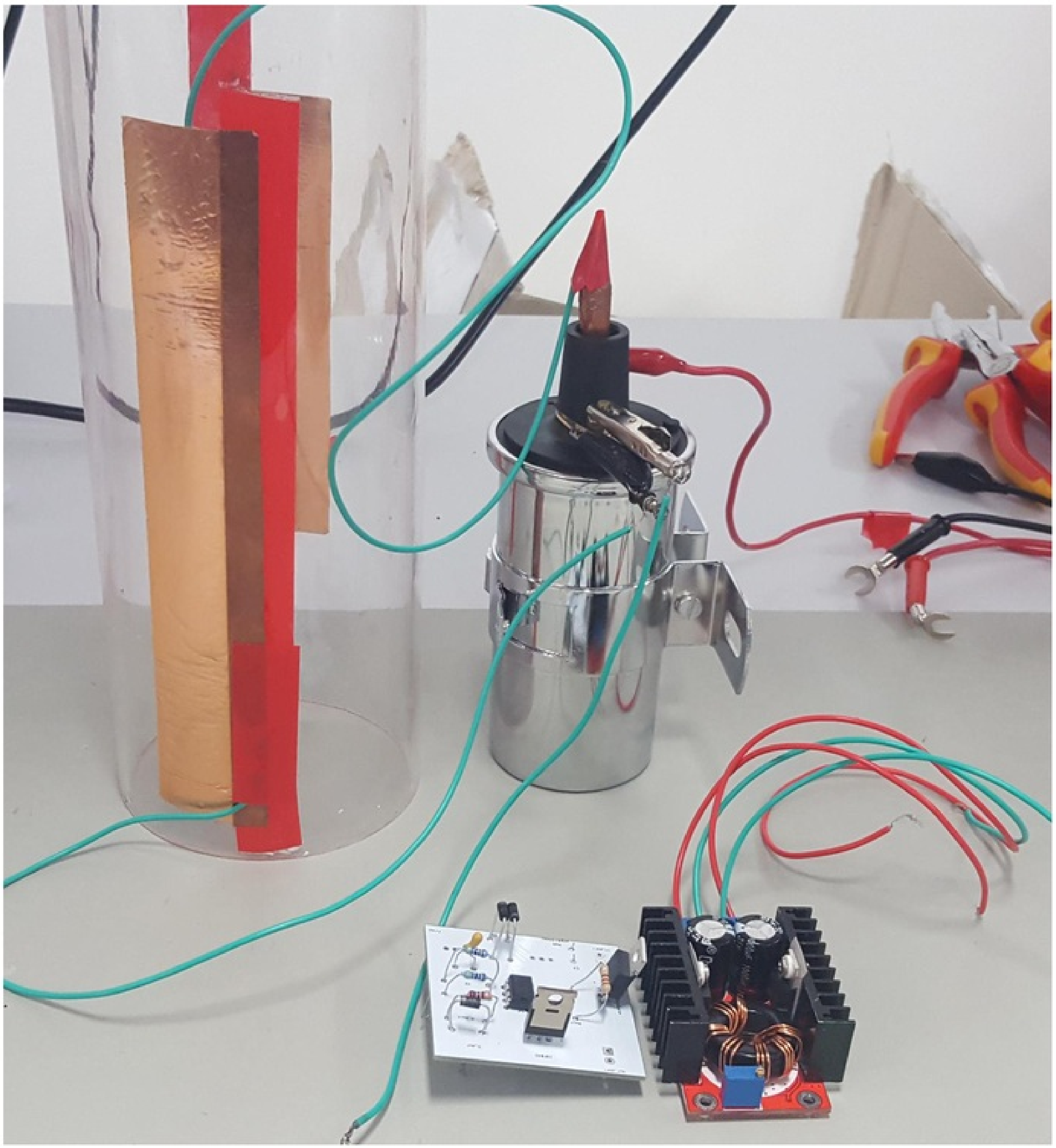


FIGURE 27 CURRENT ITERATION OF CHVLPIPS

4.2 Wind tunnel testing:

An experimental methodology in testing the flow reattachment capabilities of the CHVLPIPs has already been prepared. However, a mounting bracket that adheres to the specifications of the wind tunnel has yet to be developed.

4.2.1 Aim:

To determine the extent of the CHVLPIPS' paraelectric flow control capabilities.When subjected to different Reynold's numbers and angles of attack.

4.2.2 Related concepts:

The main underlying concepts covered in this experiment is paralectric fluid flow control and Reynolds's numbers concerning laminar and turbulent fluid flow. As covered in chapter 2.3, the fluid flow regimes for a cylinder and their transition across a spectra of Reynold's numbers are known. This is primarily the reason why a cylinder was chosen to mount the plasma actuators across the length of the cylinder. What will be measured is the angles of attack the electrodes are positioned in relation to the direction of air flow, at differing air flow velocities.

4.2.3 Equipment:

- Tektronix TDS 2012B.
- Topward dual tracking DC power supply 6306D.
- CHVLPIPS with DBD embedded on a glass cylinder 0.25m in width, 0.095m diameter and 3mm thickness
- Wind tunnel approved mounting bracket for cylinder
- Wind tunnel
- Multimeter

4.2.4 Methodology:

1. Place the cylinder in the wind tunnel, routing wires to the CHVLPIPS situated externally.
2. Check connections
3. Angle the electrodes 10-15 degrees from center of the cylinder to the normal of the incident air.
4. Allow air flow into the wind tunnel, starting at $5ms^{-1}$

5. Switch on the plasma actuators, allowing a current limit of 4A and a voltage input of 12V
6. Adjust the DC-DC converter to a 30V output.
7. Set the CHVLPIPS to the minimized pulse width, at a frequency of 7000Hz
8. Step the frequency by 1000Hz until flow reattachment is achieved.
9. Record metrics:
10. Increase velocity of air by 5ms^{-1}, until flow reattachment is no longer achieved.
11. Step the angle of the cylinder by 5 degrees, until flow reattachment is no longer achievable.

Fluid velocity ms^{-1}	Angle from normal (degrees)	Frequency (Hz)	Voltage input (V)	Current input (A)	Reynolds' Number	Flow reattached? (Yes/No)

Table 3 Results table for proposed wind tunnel test.

Chapter 5: Future work

5.1 Improvements power density high voltage converter :

The ignition coil as a means to step up the voltage to magnitudes sufficient enough to ionize air, is overall too bulky for our applications. Other methods of stepping up voltage can include the use of a line output transformer, as found in cathode ray tube televisions. A study by the University of Malaysia Sabah by Nader Barsoum and Glenn Isaiah Stanley. These are described to have a fast transient response time a very high power density and said to produce a 30KVDC output. And more importantly it is drivable by a 555 timer as shown in their study. These qualities allow us to further ramp the voltage The LOPT as a means of transforming low voltages, has been previous attempted in the undertaking of this thesis project. However, it was not successful due to failure of the LOPT after extraction.

5.2 Improvements of waveform generator:

The combined modification of the 555 timer and change of the amplification method, can result in the generation of sinusoidal or triangular outputs. By placing an inductor, that is then ground coupled with a capacitor on the output pin of the 555 timer a sinusoidal wave can be approximated. This sinusoid however can be approximated to that of a saw tooth waveform. However, MOSFETS are voltage controlled and therefore cannot effectively amplify non square wave signals. Any signal below the threshold voltage will not allow the voltage across the MOSFET to be present across these terminals. Conversely, any signal above will allow a constant voltage form the power source to flow across its drain and source terminals. To circumvent this issue, an IGBT or operational amplifier can be used instead of the MOSFET. These devices are capable of amplifying signals without distorting the signal. Allowing the ionizing power supply to take advantage of the benefits of triangle and sinusoidal signal applied to the input of the plasma actuator. These benefits include the prevention of electrode corrosion due to prolonged exposure to currents of greater than an amp [3]. And dual plasma generation events during one cycle of an alternating waveform, adding to the plasma generation efficiency of the power supply.

5.3 PCB: Refinements in spatial configuration of components

An obvious step forward in a more compact driving circuit is to use smaller components. Another is to place every functional block onto the same printed circuit board. The incorporation of the DC-DC converter onto the same PCB as the oscillator. Since DC-DC converters switched at higher frequencies result in the use of smaller componentry. This can further our goals of attaining a more streamlined and compact build for the CHVLPIPS. Incorporating multiple outputs to the power supply can allow the addition of multiple DBD plasma actuators to be excited by the same power supply. In addition to the multiple outputs could be an intermediate auxiliary circuit, capable adding a phase angle to each output signal. Allowing an array of electrodes to each excite at differing time intervals. This will allow for the CHVLPIPS to be tested for peristaltic flow control as documented by Roth, in addition to paraelectric flow.

Another possible refinement is the use of a PCB design housing the electrodes. Since the PCB is already a dielectric. Tracks can be drawn at varying levels of the dielectric, to mimic the DBD already on hand. Roth has already incorporated this in his design [5]. This configuration adds a more established connection between the intermittent functional blocks of CHVLIPS. The electrodes are also more durable in this configuration since they are embedded in the surface of the dielectric rather than by an adhesive. Further the density of the DBD's can be increased over a surface. Since they can be embedded much closely to each other. Allowing for an increase in surface area the air flow is in contact with the plasma.

5.4 Lithium-ion battery pack and control circuitry:

Having a more power dense battery pack, can massively reduce the weight and form factor of the CHVLPIPS. Lithium ion batteries have the best comparative power density in relation to other chemistries. Further they have low charge times, no charge maintenance, high cell voltages and high C ratings. Allowing lithium ion batteries to deliver the potentially high currents needed in plasma production applications. However, they are unstable below their rated charge and cutoff voltages resulting in expanding or explosions. In order to take advantage of the benefits of using lithium ion a protection circuit must be designed in order to prevent the batteries from exceeding their discharging and charging voltages and currents.

5.5 Potential use in Macquarie University's Human powered Vehicle project:

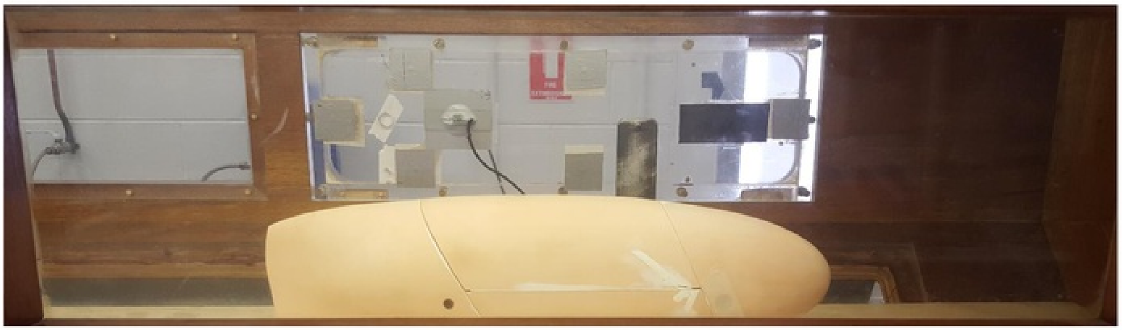


FIGURE 28 A MINIATURIZED VERSION OF THE HPV'S BODY.

If the plasma actuator is able to reattach air flow over the cylinder at speeds comparable to $26ms^{-1}$, at an angle similar to that of the rear of the human powered vehicle (HPV). It may be considered for competitive use in the HPV. This is due to the CHVLPIPS' low form factor and weight inherent in its design, required in the cramped internals of the HPV.

Chapter 6:

Conclusion

The research and discussion in this thesis document is centered around the design and development of a *'compact high voltage low power ionizing power supply'* used to produce Roth's OAUGDP in a mobile environment. Roth's OAUGDP is used to take advantage of its flow re-attachment and drag reduction capabilities favorable in aerodynamic applications. It is through the assessment, evaluation, simulation and experimentation of plasma generation techniques as mentioned in plasma actuator studies. That define the circuitry needed to satisfy the development of a more compact, lighter and efficient ionizing battery powered power supply. The outcomes of this thesis project will contribute to the initial steps of the potential main stream usage of plasma actuators s they near their maturity.

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Table of acronyms

CHVLPIPS	Compact high voltage low power ionizing power supply
DBD	Dielectric barrier discharhe
OAUGDP	One atmosphere uniform glow discharge plasma
PWM	Pulse width modulation
RMS	Root mean square

Appendices:

A. Experimental/task/Process Risk assessment form

Risk Assessment – Experiment / Task / Process Form
• A risk assessment must be carried out for each process/method involving a hazardous chemical. • The assessment is to be completed by Experimenter and Supervisor together.

General Details: Electronic Plasma generation			
Assessors Name:	Kevin De Pedro	**Telephone No:**	0414598959
Assessors Signature:		**Department:**	Science
Date of Assessment:	8 October 2016	**Faculty:**	Engineering
Supervisors Name:	Graham Town	**Building:**	E6a
Supervisors Signature:		**I certify that the risks of this experiment/task/process are negligible or adequately controlled.**	

	Description of Experiment/Task/ Process:
	An oscillator is used to drive a MOSFET to drive an autotransform. Using low voltages of magnitudes of 12V to
	30V. The 30V voltage is applied across the common and primary windings positive terminals to generate
	Voltages of up to 40,000V across the secondary coil's primary high voltage positive terminal and common
	Terminals. The voltage is applied to electrodes placed in a parallel and assymetric configuration, that are
	Seperated by a dielectric that is not easily flammable. As a result a glow discharge will form, also generating
	Ozone in the air.
	Equipment/Services to be used:
-	High Voltage Laboratory
-	30VDC Power Supply
-	Grounding Mat

- **Soldering Iron**					
- **Assortment of electronic components.**					
Substance Name	**Manufacturer**	**Catalogue No**	**Grade/ Concentration**	**Hazardous Substance (Yes/No)**	**Hazard Category**
Ozone				**Yes**	NFPA 704 (GHS code)
Controls to be applied to reduce risks:					
When handling electronics power supply is switched off and the positive input to the power supply is removed.					
All connections are visually inspected to ensure high voltage wires are not hazadously placed or entangled. All wires are taped down to prevent accidental contact with each other and observers.					
Before turning on power, a lab partner is present to watch that I am not in any way near or touching the circuit. At no point in time during circuit operation, the high voltage side of the circuit is handled.					
One hand is kept in trouser pocket at all times when the circuit is active. To prevent conduction through heart.					
Circuit is active only for the amount of time required to carry out tests.					
Adequate ventilation is ensured by allowing air into the laboratory.					

Risks identified:	**Risk:**	**When?**	**Consequence:**
Ozone inhalation/contact	Medium	During circuit operation and poor ventilation.	Death, suffocation, eye and respiratory irritation.
High voltage	High	During circuit operation.	Death, Electrical arcing through air

		Namely components that require or generate high voltages.	gap, ozone generation.
Fire hazard	Very Low	If not properly insulated live wires can ignite the copper tape or electrical tape used to conduct and connect the wires onto the electrodes.	Burns, smoke inhalation.
Cutting	Very Low	During electronics handling.	Minor cuts.

B. Attendance form:

Consultation Meetings Attendance Form

Week	Date	Comments (if applicable)	Student's Signature	Supervisor's Signature
0	28/07	Discussed info and accuracy		
1	04/08	Talked about lab access and safety.		
2	09/08	OK.		
3	16/08			
4	23/08			
5	30/08	OK,		
6	06/09	OK.		
7	13/09			away
8	20/09	OK		
9	27/09			away
10	04/10			away
11	11/10			away.
	18/10	OK.		
	3/11	OK		