EXPERIMENTAL STUDY ON THE IMPACT OF DBD PLASMA ACTUATOR GEOMETRY AND ELECTRICAL INPUT ON THRUST GENERATION

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DECLARATION

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LIST OF SYMBOLS

d	Distance between the plates
E	Electric field
F	Electrostatic force
K	Ion mobility
r	Distance between the charged bodies
V	Voltage
V_{p-p}	Peak-to-peak Voltage
V_{rms}	Root mean square voltage
q	Electric charge
ε_0	Permittivity of the vacuum
ε	Absolute permittivity

LIST OF ABBREVIATIONS

AC	Alternating current
DBD	Dielectric Barrier Discharge
DC	Direct current
EHD	Electrohydrodynamic
HV	High voltage

ABSTRAK

Dielektrik Penggerak Plasma (DBD) telah membuktikan dirinya sebagai peranti terkenal untuk kawalan aliran dalam aerodinamik. Kerana kualiti istimewanya, penggerak plasma DBD telah digunakan dalam pelbagai jenis kajian. Sebagai contoh, penggerak plasma DBD ialah peranti yang menjanjikan tanpa komponen bergerak yang mengionkan aliran dengan cepat, fleksibel dan mempunyai jisim yang sangat rendah. Penggerak plasma DBD telah digunakan untuk banyak aplikasi kawalan aliran, termasuk kawalan aliran pada aerofoil, kawalan aliran di sekeliling silinder atau badan tebing, dan meningkatkan prestasi aerodinamik, terutamanya dalam industri automotif. Matlamat utama kajian ini adalah untuk memperkenalkan dan menyiasat secara eksperimen penggerak plasma DBD sebagai peranti kawalan aliran aktif kerana peranti ini terkenal dengan keupayaannya untuk melambatkan pengasingan aliran dengan mendorong tujahan. Penyelidikan ini memberi tumpuan kepada penilaian kesan geometri penggerak plasma DBD dan input elektrik ke atas penjanaan tujahan, kedua-duanya untuk setiap pembolehubah reka bentuk dan interaksinya. Kesan voltan , ketebalan dielektrik dan jurang dielektrik masing-masing telah disiasat. Model eksperimen yang digunakan dalam penyelidikan ini melibatkan penggunaan penggerak buatan sendiri dan untuk pengukuran tujahan dijalankan dengan menggunakan ukuran tujahan terus yang terdiri daripada neraca daya elektronik berketepatan tinggi. Dalam konteks ini, tujahan yang dijana oleh penggerak digunakan sebagai ukuran prestasi untuk penyelidikan ini. Telah didapati bahawa ketebalan bahan dielektrik mempengaruhi tujahan yang dihasilkan oleh setiap penggerak yang direkodkan. Walaupun dibekalkan dengan voltan gunaan tinggi, penggerak yang dibuat dengan lapisan dielektrik tebal yang terdiri daripada 6 lapisan Kapton mengalami kesukaran mencipta pengeluaran plasma. Di samping itu, jurang elektrod juga nampaknya menjadi penyumbang utama kepada bacaan tujahan sifar, terutamanya dalam ketebalan dielektrik yang tebal. Penggerak yang direka dengan jurang elektrod 1mm atau 6 lapisan ketebalan dielektrik menghasilkan nilai tujahan yang rendah, dan dalam beberapa keadaan, bacaan nilai tujahan sifar. Ini menunjukkan bahawa interaksi negatif wujud antara lapisan dielektrik tebal dan jurang elektrod yang melebar. Ini menunjukkan bahawa penggerak telah berjaya dikendalikan untuk pengeluaran tujahan pada lapisan dielektrik nipis dengan jurang elektrod sifar, tanpa mengira nilai voltan yang digunakan.

ABSTRACT

Dielectric Barrier Discharge (DBD) plasma actuator has established itself as a well-known device for flow control in aerodynamics. Because of its special qualities, the DBD plasma actuator has been employed in a large variety of studies. As an example, the DBD plasma actuator is a promising device with no moving components that ionises flow streams quickly, is flexible, and has an astonishingly low mass. DBD plasma actuators have been employed for many flow control applications, including flow control on airfoils, flow control around cylinders or bluff bodies, and enhancing aerodynamic performance, particularly in the automotive industry. A primary goal of this study is to introduce and experimentally investigated the DBD plasma actuator as an active flow control device since this device is well known for its capability for delaying flow separation by inducing thrust. This research focused on the evaluation of the impact of DBD plasma actuator geometry and electrical input on thrust generation , both for each design variable and their interactions. The effects of applied voltage, dielectric thickness and dielectric gap are each examined . The experimental model used in this research involves the use of the self-made actuators and for the measurement of the thrust was conducted by using direct thrust measurement consisting of a high precision electronic force balance. In this context, the thrust generated by the actuator is used as the performance measure for this research. It was discovered that the thickness of the dielectric material influenced the thrust produced by every recorded actuator. Even when provided with a high applied voltage, actuators made with a thick dielectric layer comprised of 6 layers of Kapton have difficulties creating plasma production. In addition, electrode gap was also seeming to be the primary contributor to zero thrust readings, especially in thick dielectric thickness. The actuator designed with a 1mm electrode gap or 6 layers of dielectric thickness results in a low thrust value, and in some instances, a thrust value reading of zero. This demonstrates that a negative interaction exists between the thick dielectric layer and the widened electrode gap. This implies that the actuator was successfully operated for thrust production on the thin dielectric layer with zero electrode gap, regardless of the applied voltage value.

CHAPTER 1

INTRODUCTION

1.1 Research background

Boundary layer control is a technique used to control the behaviour of fluid flow boundary layers (Boundary-Layer Theory (Hermann Schlichting), n.d.). In the study of Fluid Mechanics , when an object travels through a fluid, or as a fluid passes past a body, the molecules of that fluid are disturbed and move around the object. Thus, the molecules near the surface are brought to rest due to the viscosity of the fluid .Once the fluid passes a solid body, the molecules near its surface adhere to it and condition of no slip occurs. In this case, the fluid velocity at the boundary will be the same as the boundary velocity. This slowing down appears the velocity gradient and limited to a thin layer near the surface that called as boundary layer. The boundary layer is a thin layer of fluid that forms next to a solid body in a flowing fluid. This thin layer is moving in the same direction as the solid body, with a velocity varying from zero to free stream velocity. At a certain point, the boundary layer may have difficulty adhering to the surface due to friction. Also known as boundary layer separation, this phenomenon occurs when a boundary layer is on the verge of separating from the surface.

Flow control refers to manipulating a flow in order to achieve the desired result. The separation region is typically reduced through manipulation of the boundary layer and shear flow on a suction surface. Many flow control technologies have been developed, either passively or actively such as vortex generators (Castellanos et al., 2022; Godard & Stanislas, 2006; Magill et al., 2003) and synthetic jet actuators (Glezer & Amitay, 2001; Koopmans & Hoeijmakers, 2014; F. F. Rodrigues et al., 2016). Despite their ability to increase maximum lift coefficients, these technologies are still compromised by their complexity, heavy weight, volumetric waste, and the ability to cause airframe noise and vibration. Therefore, plasma actuators would prove to be a more effective alternative as a substitute for simple and low-cost technologies.

Actuators based on plasma have been successfully used as flow control devices, including lift augmentation and drag reduction on a swept wing (Zhao et al., 2015), turbulent boundary layer separation control of wing-body configuration (Zhang et al., 2016), and unsteady vortex generation and airfoil leading-edge separation control(Corke et al., 2009). In previous work, plasma actuators have been found to be capable of altering the aerodynamic behaviour of an airfoil by inducing thrust and jetting the flow and delaying the separation of the flow on the airfoil as a result (Corke et al., 2009). As a result of today's innovations, the actuators have developed to be clearly lighter than the conventional methods of flow control. With these features, plasma actuators are being used in a wide variety of applications other than automobiles, like imparting the ability to control tip movement in turbines and wind turbines. As a result, Dielectric Barrier Discharge (DBD) is considered to be the best control method for replacing traditionally used stream control methods like vortex generators, slats, and flaps. Perhaps the use of actuators can generate momentum comparable to that of any other typical mechanical device.

This actuator consists of just two materials that are layered over a dielectric surface, and the entire device is powered by electrical energy. In the past, this flow control has proven itself to be lightweight and versatile, and it can be applied to various types of aerodynamic shapes and designs. Therefore, Dielectric Barrier Discharge (DBD) has been positioned as the best control tool to replace traditional stream control mechanisms such as vortex generators, slats, and flaps. Perhaps the use of actuators can generate momentum comparable to that of any other typical mechanical device.

1.2 Problem Statement

The key concept behind boundary layer flow control is to energize the boundary layer for delaying flow separation. In this study, the DBD plasma actuator will be introduced and experimentally investigated as an active flow control device since this device is well known for its capability for delaying flow separation by inducing thrust. This research will be focused on the experimental study of the impact of DBD plasma actuator geometry and electrical input on thrust generation .The effects of applied voltage, dielectric thickness and dielectric gap are each examined . The metric used to evaluate the performance of the actuator in each case is measured actuator-induced thrust which is proportional to the total body force.

1.3 Research Objectives

The general objective of this study is to conduct an experimental study on the DBD plasma actuator as an active flow control device . The thrust that is created by the plasma actuator plays a very significant part in the regulation of the separation and for this reason, the enhancement of thrust is intensely explored. In order to achieve this aim, two specific objectives were set up as follows:

I. To measure the thrust induced by DBD plasma actuator.

II. To evaluate the impact of DBD plasma actuator geometry and electrical input on thrust generation , both for each design variable and their interactions.

1.4 Scope of The Project

The scope of project will be more focused on the experimental study on the geometry and electrical input of Dielectric Barrier Discharge Plasma Actuator in producing the induced thrust that plays as an important role in flow separation. The experimental model used in this research involves the use of self-made actuators. In this context, the thrust generated by the actuator is used as the performance measure for this research. Finally, the impact of DBD plasma actuator geometry and electrical input on thrust generation , both for each design variable and their interaction will be evaluated and analysed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The second chapter is devoted to the structuring of references related theory and project scope. This literature study is accomplished by reading a range of books, journals, published knowledge, and other written sources pertaining to this experiment's findings. This research will concentrate on the DBD plasma actuator, which covers the geometry and configuration of the actuator as well as the DBD plasma actuator expansion technology. In addition, the history and background of this plasma actuator will be described in this chapter.

2.2 Fundamental of DBD plasma actuator

Essentially, plasma consists of positively and negatively charged particles of partially ionized gas. Interestingly, it has been largely affected by electromagnetic fields, as it is an acceptable form of transmitting electricity compared to ordinary natural gas. Streamlined performance is important especially in aerospace and automotive. The separation of the flow is particularly detrimental to aircraft and vehicles' streamlined performance. The research on flow separation using mechanical devices such as flaps, vortex generators, and microelectromechanical systems (MEMS) has gained popularity among researchers (Moreau, 2007).Contrary to passive flow control that can impact the design and weight of the device, an actuator that controls flow actively is more effective in preventing flow separation.

DBD plasma actuators have been widely examined over the years and have emerged as fundamental strategies in noise reduction, lifting increase, and transition control. In the past, J R Roth's group has investigated an atmospheric pressure dielectric barrier discharge and created an actuator for streamlined extension of the plasma (Roth et al., 1998) .In addition, the DBD plasma actuator is defined as an effective tool because of its physical properties, such as no moving parts, quick reaction time, and capability to control flow separation. Plasma actuators based on DBD are traditionally composed of two insulated electrodes that are separated by a thin, dielectric film.

Plasma actuator is designed with one electrode being exposed to air, while the other electrode is covered with a dielectric film. At this point, the plasma actuator is energized by applying AC voltage power with required frequency.

DBD plasma actuators are a technology that consists of two electrodes arranged in specific configurations which a dielectric layer namely an encapsulated electrode that is applied to the grounded electrode, followed by a second electrode namely an exposed electrode that is layered on top. This configuration is shown in Figure 2.1. Copper foil tape is typically used as an electrode material while the dielectric layer is commonly made up of Kapton . The actuator operates with high voltage AC power to the exposed electrode, which results in plasma formation. During the operation, the ionic wind was discharged across causing the air to blow over the actuator. This actuator is capable of inducing a flow that draws air toward its surface and accelerates this air downstream in a direction tangential to the dielectric in still air condition. Instead of its wide range of applications, the most exciting feature of this actuator is its utilization of plasma, in which electric and magnetic fields are used to exert force on electrically charged ions and electrons in order to generate thrust that will be the performance measure for these studies. The thrust that is created by the plasma actuator plays a very significant part in the regulation of the separation., for this reason, the enhancement of thrust is intensely explored.

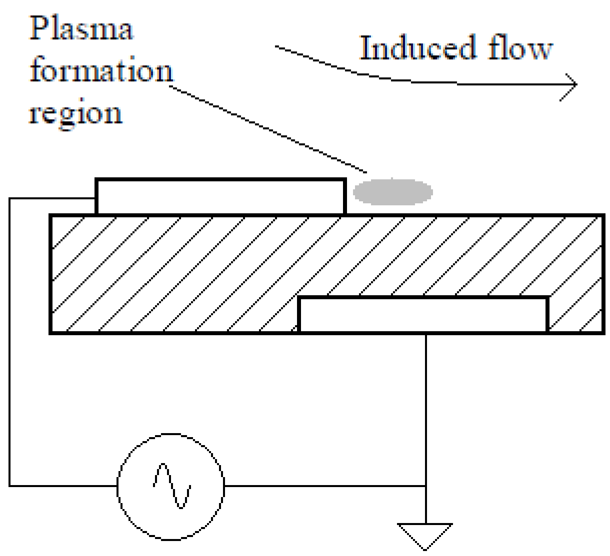

Figure 2.1 - The configuration of DBD plasma actuator (Ferry & Rovey, 2010)

2.3 Formation of the plasma by the DBD plasma actuator

The term plasma was introduced in 1928 by Darrow, (1948) to refer to an area of a gas discharge that included equal numbers of ions and electrons in their charges. This indicates that there are about the same number of positively charged and negatively charged species present in the plasma area. Ionization of a gas leads to the formation of plasma, which may be produced by applying sufficient amount of energy to molecules or atoms. As a consequence of this, a gas consisting of electrons, positive and negative ions, free radicals, gas atoms and molecules in the ground state or any higher state will be produced (excited). It is able to sustain in conditions comprising a very broad temperature and pressure range. It is possible to create it at low pressure or at atmospheric pressure by applying energy to a gaseous medium using a variety of methods, including mechanical, thermal, chemical, radiant, nuclear, electric, or electromagnetic, or through a combination of these methods.

In the duration of one cycle of alternating current (AC), the electrons that are released by the air-exposed electrode make their way to the surface of the dielectric that is located above the encapsulated electrode before making their way back. Ionization of the particles occurs as a result of the exposed electrode discharging electrons into the surrounding air while the voltage is in the negative section of the cycle. The negatively charged exposed electrode subsequently repels the negatively charged species toward the surface of the dielectric layer. Since charged particles tend toward the exposed positive electrode during the positive going half of a cycle, the previously stored electrons at the surface of the dielectric make their way back into the circuit. This process is emphasised in Figure 2.2, which depicts both half cycles.

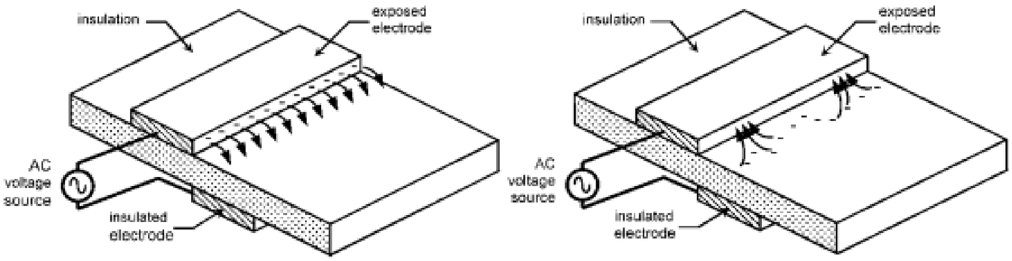

Figure 2.2 - DBD actuator when (a) the negative-going half cycle is occurring and (b) the positive-going half cycle is occurring (Enloe et al., 2003)

2.4 Plasma actuator as flow control devices

Plasma actuators are widely used in a variety of industries, most notably the automotive and aeronautical industries. Active flow control, such as plasma actuators, are dominating topics in aeronautics due to their superiority and development associated with industrial demand over other mechanical devices. In spite of the rapid expansion of plasma actuators nowadays, their usage was relatively unknown before the year 2000. Research during that period frequently emphasized flow control called DC surface corona discharges which act similar to plasma actuators in the late 1990s and is historically the first plasma actuator. A historical context for plasma actuators can be identified in the 1990s when the DBD plasma actuator was built by J R Roth's group which is now the foundation of the DBD actuator's operating guidelines for streamlined features stream control (Roth et al., 1998).

Plasma actuators provide a great number of benefits that can be demonstrated to control the detachment of the outer stream and the disturbance of the outer stream around the surface, altering the speed shape in the limit layer, a basic device that can minimise the creation and support costs, utilize the ionized air, does not contain mechanical elements to limit the weight construction, and encouraged the wind closely to the body's surface wall to allow the flow to be accelerated. It has been demonstrated previously by the author about the capability of DBD plasma actuator on improving the lift coefficient while lowering the drag coefficient, diminish the conveyance of the pressure , control the angle of stall positions for airfoil of plane and to control the stream around the feign body (Akansu et al., 2013; He et al., 2009; Kozlov & Thomas, 2009).

A recent development in active flow control has been increasing attention as it allows direct control of the flow around an object when it is desired . Research has been intensively conducted on DBD plasma actuators for its capability of controlling active flow recently. DBD plasma actuator are used in such applications as vehicle aerodynamics development (Roy et al., 2018) .Aerodynamics deals with fluid flow and the forces exerted on an object in the boundary layer by various fluids. It has been the subject of intense research to control the flow over the vehicle spoiler as the right arrangement yields an incredible number of benefits on the vehicle performance. It is, however, vital to improve the spoiler in terms of streamlining as well as to address any other issues that may interfere with its effectiveness . As a result, active flow control has been demonstrated in the past decade by modifying the spoiler with a DBD plasma actuator in order to increase its aerodynamics performance (Roy et al., 2018).

2.5 Parameter studies of DBD plasma actuator on thrust generation

A great deal of research has been conducted recently on DBD plasma actuators. In the published work, parametric optimization has been a major focus. Various operating parameters have been compared in these studies to examine how they influence actuator thrust. There is numerous factor that contributes to affecting the performance of DBD actuator in producing thrust. However, by filtering on the past literature studies, this literature will be more focus on some of the most influential parameters that significantly affect the thrust generation of DBD plasma actuator operation which are the applied voltage, actuator configuration, and the dielectric material and thickness used.

2.5.1 Effect of the applied voltage

Research by Qi et al., (2017) experimentally investigates the surface dielectric performance of DBD plasma actuator that operates by AC high voltage with a superimposed positive pulse bias voltage. A measurement of actuator-induced thrust of the applied AC voltage is made for different pulse voltage values. The results reveal that the thrust force produced by "AC + Positive pulse bias" voltage is way up than that by a single-AC voltage at the same AC voltage. Following the positive pulse bias voltage, the value of the thrust force is enhanced due to the glow-like discharge in the half-cycle of AC voltage, adjacent to the cycle where a bias voltage pulse has been applied.

Meanwhile, research by Nakano & Nishida, (2019) investigates how the performance of the DBD plasma actuator can be improved by altering the voltage waveform to increase the actuator thrust. Nine different waveform variations are defined, each with steep and gradual voltage slopes as shown in Figure 2.3. Both negative-going voltage period and positive going voltage period give different significant values on the thrust production. In terms of thrust generation and efficiency, a gradual steep voltage profile performs much better than a zero gradient for maintaining the electric field strength, which is required for body force generation. In terms of producing stronger thrust, it can be seen on the voltage waveform where the steep gradual contributes effectively for negative-going voltage period while for the positive-going voltage period it mainly depends on the negative-going voltage profile. In that case, if both the negative-going voltage profile and positive-going voltage profile experience with gradual steep, the voltage waveform profile will thus possess a stronger thrust than the other profiles.

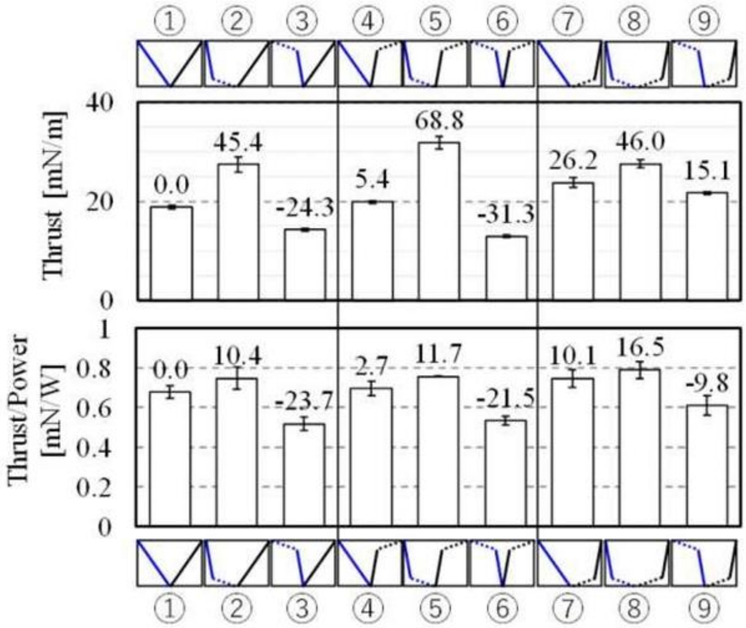

Figure 2.3 - Nine different waveform variations , each with steep and gradual voltage slopes (Nakano & Nishida, 2019)

Another research by Grosse & Angland, (2020) ,investigate how high applied voltage and high frequency effects on the thrust generation by using the method Design of experiment (DOE) by applying the voltage with the range from 10 -16 KV p-p. The thrust generation is analyzed using the square root of the thrust to satisfy the normal distribution of residuals. It was found that 91% of the variance of the results was affected from nine parameters and interactions which included the voltage effects on the thrust generation. In this paper, the results gained also indicate the relationship between the voltage and frequency in which the thrust increased by 0.16 mN/m/kHz at 10 kVpp but gained 1.21 mN/m/kHz at 16 kVpp. This indicates that charged particles transferred to the neutral gas by the high voltage are more numerous and transfer more momentum. This is related to their higher collision frequency and velocity which the charged particles collide more frequently at high AC frequencies. Consequently, based on the results of the experiment, it can be stated that an increasing value of the voltage will increase the electric field across the electrodes, and thus increase the ion drift velocity.

2.5.2 Effect of the electrode configurations

One of the limitations of the active flow control of the DBD plasma actuator is the struggling of producing enough ionic wind for flow control. Therefore, a proposed solution was conducted by Sato et al.,(2019) to experimentally investigate the effect of a DBD plasma actuator consists of multiple electrodes as shown in Figure 2.4 . As an effect of a discharge between a covered electrode and an exposed electrode , a phenomenon known as counter ionic wind is generated. When there is no gap between the actuator modules, the counter wind collapses onto the main flow and defects wind. In this study, the DBD plasma actuator consists of multiple electrodes was used to generate Electrohydrodynamic (EHD) force that acts as an active flow control of the fluid for thrust generation by inducing ionic wind. The findings from these studies show a positive value of thrust generated which following the numerical simulation results, the thrust increased linearly with the increase in electrodes at all frequencies. Due to the enhanced electric field downstream as a result of the exposed electrode absorbing the surface charge leads to the increasing value of thrust.

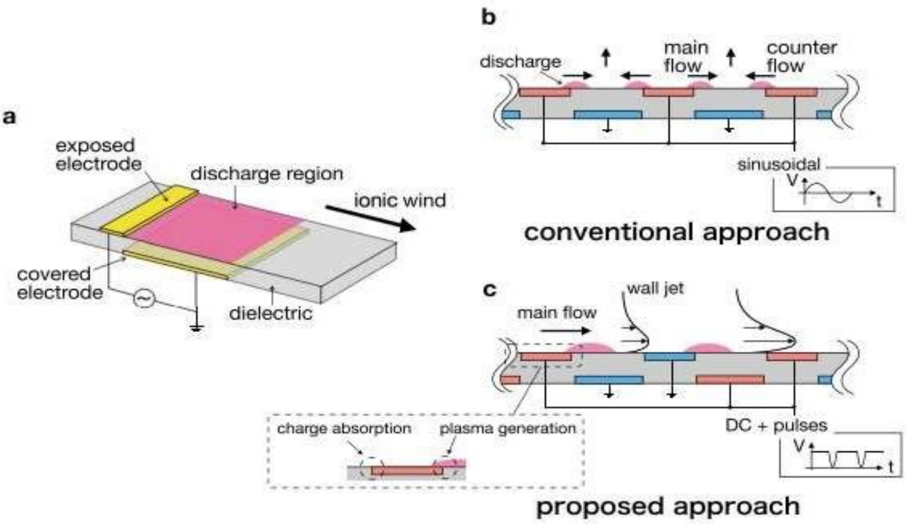

Figure 2.4 - The difference between the original arrangement of DBD plasma actuator and with multiple electrode arrangement (Sato et al., 2019)

On the other hand, with the same goal, research by F. Rodrigues et al., (2019) used a new concept of actuator configurations with stair-shaped dielectric barrier discharge actuator. The dielectric layer in this concept decreases along the width of the covered electrode, which increases the plasma discharge extension and maximum induced flow velocity instead of using a layer of constant thickness as shown in Figure 2.5. According to this paper, the plasma discharge was found to be 20% longer by applying a stair-shaped dielectric layer with a specific dimension which is 7◦ slope of angle and 1.92mm thickness. From this type of dielectric configuration, it is possible to increase the maximum induced flow velocity and decrease the power consumption when compared to the conventional DBD plasma actuator. Additionally, by employing a stair-style dielectric barrier discharge configuration, the cold capacitance of the device is reduced, and the effective capacitance is progressively increased as the voltage increases. These results, which show that the stair-shaped actuators present a bigger plasma extension and higher electron density, lead us to conclude that the plasma discharge directly contributes to the effective capacitance.

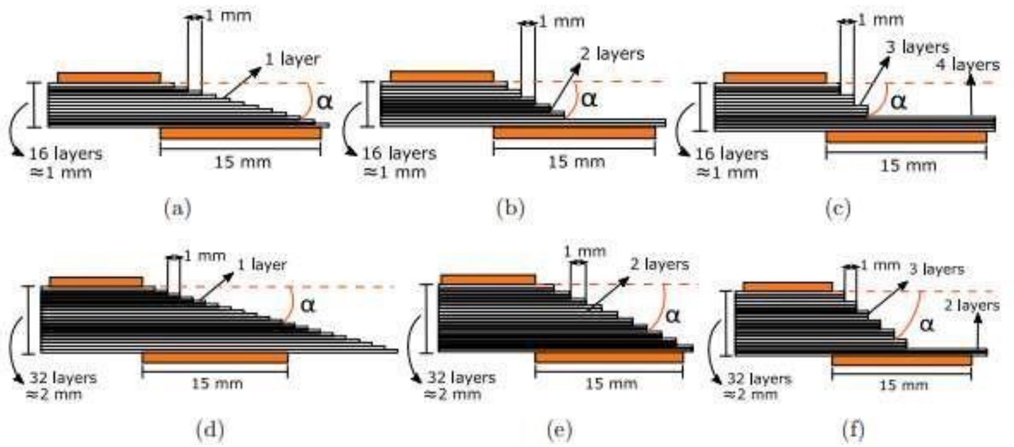

Figure 2.5 - The geometric of the stair shaped dielectric barrier discharge actuator (F. Rodrigues et al., 2019)

Furthermore, another research by Grosse & Angland, (2020) investigate how different parameter of the actuator configuration affects the thrust produced by the DBD plasma actuator. The parameter was studied by using the Design of Experiment method. The investigated parameter, which is exposed electrode width, covered electrode width, electrode gap, exposed electrode height, covered electrode height, and the dielectric layer thickness is measured. Based on the design of the experiment, the exposed electrode geometry was found to be influenced by the thrust generation of the plasma actuator which specifically depends on the height and width of the exposed electrode. The results indicate that for generating an increasing value of thrust, the exposed electrode must be designed with a thin and narrow air electrode.

In addition, there are multiple studies shown that the distance between the electrodes has a significant impact on the maximum velocity created by a DBD actuator (Corke et al., 2010; Forte et al., 2007). A tiny positive gap may improve the DBD's performance. Negative gaps or "large" positive gaps (more than 5 mm) often lower the highest velocity achievable.

2.5.3 Effect of dielectric material and thickness

Considering the limitation of the past research studies on the dielectric material used which are Kapton, a research study was conducted by F. F. Rodrigues et al., (2018) to investigate the alternative dielectric materials for DBD plasma actuator. In this analysis, three type of dielectric material was proposed which are made of polyisobutylene (PIB) rubber, acetoxy silicone and poly-lactic acid (PLA) . The electrical characteristics and induced flow velocity of these alternative dielectric materials were analyzed experimentally, and the results was then compared with the common dielectric material which are Kapton. In term of electrical characteristics, two of the three measured dielectric material which are the (PIB) rubber actuator and the acetoxy silicone are able to be operating at higher voltage with better durability when compared to the convenient Kapton dielectric material. Instead, in the terms of the induced flow velocity, none of the alternative material are able to achieve higher maximum velocities of the convenient actuator. Lastly, the results verified that in terms of efficiency, both of the (PIB) rubber actuator and acetoxy silicone achieve higher efficiency among the others. Overall, the studies suggested that the suitable alternative dielectric material that can replace the convenient actuator in the terms of high efficiency and voltage are the dielectric made of (PIB) rubber actuator and acetoxy silicone.

Later, a continuous study of the dielectric material of DBD plasma actuator was conducted again with the different types of dielectric material which are made of polyvinylidene fluoride (PVDF) and polystyrene (PS) for active flow control and heat transfer applications (F. F. Rodrigues et al., 2021) .With the same goal, the dielectric material was measured to analyze their behavior in terms of electrical characteristics, generated flow velocity, mechanical efficiency, and thermal efficiency, and the results were then compared to the conventional Kapton actuator. Polystyrene actuator showed the lowest power consumption in terms of power consumption when compared for both Kapton and poly(vinylidene fluoride) (PVDF) actuator while the highest power consumption is the poly(vinylidene fluoride) (PVDF). Instead, in terms of the induced flow velocity, as a result, the experiences obtained demonstrate the ability of polystyrene to produce flow velocities of similar magnitude as Kapton actuators, which lead to similar mechanical efficiencies. By comparing the significant factor on active flow control of the DBD plasma actuator, the mechanical efficiency and induced flow velocity are measured as the crucial factor. Therefore, a polystyrene actuator seems to be a good approach to replace the convenient actuator since this actuator can operate in high voltage and is capable to achieve maximum induced flow velocity that is good measure for thrust generation.

On the other hand, another research by Barbosa Moreira et al., (2020) presents a comparative experimental study between the dielectric material properties used as a dielectric layer which are Kapton and “PIB” rubber actuator. Both the actuator is measured based on the electrical parameters and induced velocity field. The findings from these studies show that it is similar to a capacitor in its electrical behavior, and its power consumption exhibits an exponential development with the growth of the operated voltage. In addition, the findings reveal that PIB actuators have a lower power usage than Kapton actuators. In comparison with Kapton, it can be seen from Table 2.1, the versatility of the PIB which can operate at higher voltages for both dielectric thicknesses which are 0.5mm and 1.0mm which indicates that the PIB presents as the actuator that has better efficiencies.

Table 2-1 - A comparison of dielectric materials used in plasma actuators, with regard to their mechanical power and efficiency (Barbosa Moreira et al., 2020)

Dielectric Material / Thickness	Applied voltage (KVpp)	Electrical Power (W)	Mechanical Power (mW)	Efficienc y(%)
Kapton 0.5mm	7	7.11	0.0000124	0.0002
	8	13.01	0.0005038	0.0038
PIB 0.5mm	5	1.25	0.000004	0.0003
	6	2.93	0.0001989	0.0068
	7	6.28	0.0011857	0.0189
	8	11.63	0.0019114	0.0164
Kapton 0.5mm	8	4.77	0.0000309	0.0006
	9	7.34	0.0003324	0.0045
	10	11.21	0.0020163	0.018
	11	15.82	0.0028734	0.0182
	12	20.69	0.0047499	0.023
PIB 1mm	8	1.99	0.0000099	0.0005
	9	3.85	0.000807	0.021
	10	5.05	0.0015613	0.0309
	11	6.28	0.0032467	0.0517
	12	8.79	0.0040237	0.0457

Varying the configuration of the dielectric layer alters the capacitance of the DBD directly. Consequently, it may affect performance by allowing for larger induced velocities and by lowering losses via the dielectric material. It was revealed that a thick dielectric layer with low relative permittivity increases the maximum attainable thrust, even if a thin layer with high permittivity may generate a greater thrust at low voltage. According to the findings of one of the investigations carried out by Thomas et al., (2009), the actuator exceeds the threshold performance as soon as the discharge transforms from a homogenous glow into a filamentary discharge of streamers. When the thrust output is at saturation, increasing the voltage or frequency has very little influence on the output, but it does increase the amount of energy that is used. The greater the frequency for a particular DBD, the lower the voltage achievable before approaching saturation. At a certain voltage and frequency, it was discovered that a thinner dielectric with a greater permittivity produces more thrust. It was noticed that the saturation thrust increased roughly linearly with the applied voltage but decreased approximately when the frequency inverted.

2.6 Review studies on DBD plasma actuator for thrust measurement

During the last few years, the exploration of DBD with the majority of work focusing on thrust generation have been the focus of intense research. Research by Ferry & Rovey, (2010) focusing on the efficiency of DBD Plasma Actuator for thrust generation and analyze the limitation of a plasma actuator-based control system. Based on the results of this work, the power consumption of the actuator and thrust measurement were measured. The power consumption measurement of the actuator was estimated through modelling the actuators as jet flaps while the thrust was measured by using the weighing scale as shown in Figure 2.6 below. This method's primary benefit is its simplicity. To separate the force sensors from the high voltage sources, the actuator must be mounted on a platform. As the measured forces are small, this demands the employment of costly equipment with a wide enough dynamic range to accurately measure the thrust generated. In this experiment, the lever configuration in which the plasma actuator blows transversely to an arm that amplifies the force measured at the opposite end of the lever was used. To bring the system in mechanical equilibrium and ensure that friction does not cause hysteresis in the readings, a detailed calibration was performed to ensure the accuracy of the thrust measurement system. Some promising results were found in the experimental portion of the study which the increased voltage was observed to increase actuator effectiveness. It was found by the increasing of the actuator thrust is affected by the increasing actuator voltage levels. Through increasing actuator voltage levels, it is possible that will affect the actuator effectiveness as well.

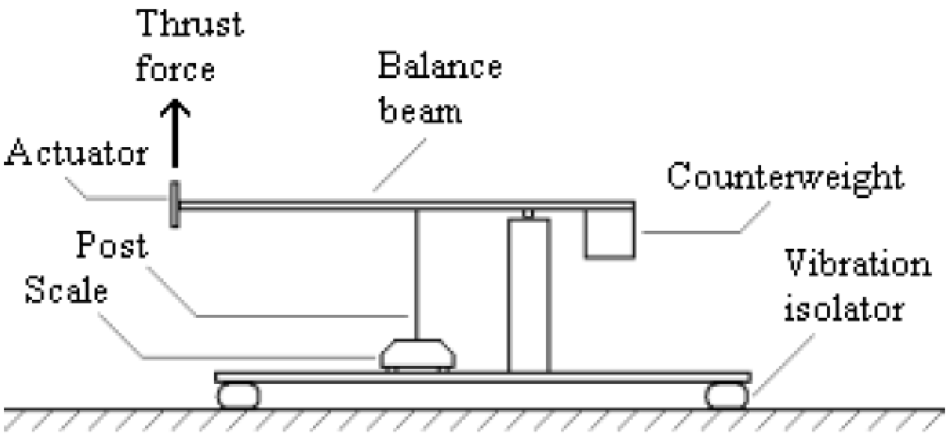

Figure 2.6 - Thrust measurement experimental setup (Ferry & Rovey, 2010)

Another research by Durscher & Roy, (2012) comparing two commonly used experimental techniques to measure the plasma-induced thrust of DBD Plasma actuator. By utilizing a force balance, a direct measurement of thrust is made, which is then compared against the measurement from particle image velocimetry data. In direct force balance experiments as shown in Figure 2.7 below, the plate length on plasma-induced wall jets was explored. At the upper range of voltages, it was observed that the thrust increased as the plate length was reduced. These findings indicate that plate length is an important factor to consider when making comparisons to experimental data. For indirect thrust measurement, a single actuator of the DBD type with a variety of voltages was also subjected to PIV measurements, providing time averaged data sets of the induced flow field. A control volume analysis was then performed on the velocity fields to infer the resultant thrusts. An analysis of the results revealed a significant dependence on volume size, with a particular focus on width. The calculated tangential thrust agreed well with the direct thrust measurements regardless of input voltage as long as the volume control extended downstream.

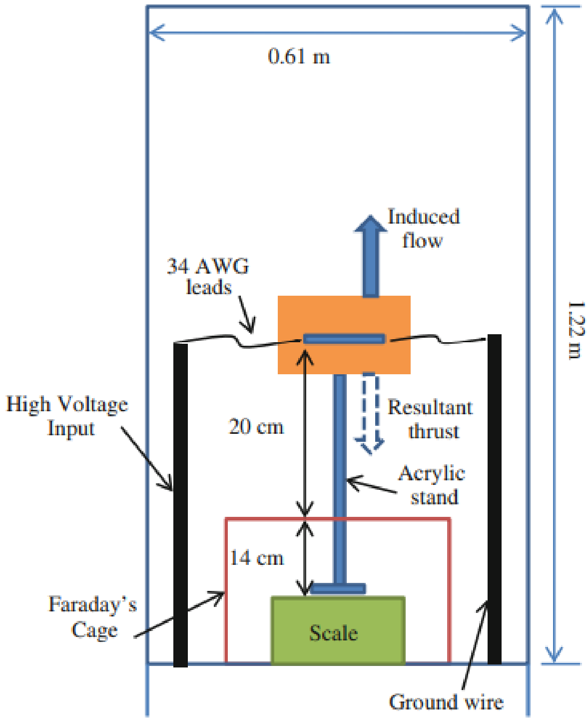

Figure 2.7 - Experimental setup for direct thrust measurement (Durscher & Roy, 2012)

A study by Thomas et al., (2009) that used the direct measurement revealed that a force balance may be used to measure the produced thrust, in contrast to the difficulty and restrictions of the other approaches. A load cell or an analytical balance may serve as the force balance. However, it is difficult or impossible to obtain load cells that have the appropriate resolution, range, and tare weight capacity.Therefore, an analytical balance is the most suitable methodology used for this purpose becuase of its simplicity and reliability. In conclusion, thrust measured by a force balance has been identified and recognised by the scientific community as a reliable metric for determining the aerodynamic performance of a DBD plasma actuator. It is a simple, cost-effective, practical, and convenient technique that enables rapid measurements and performance comparisons of a large number of actuators.

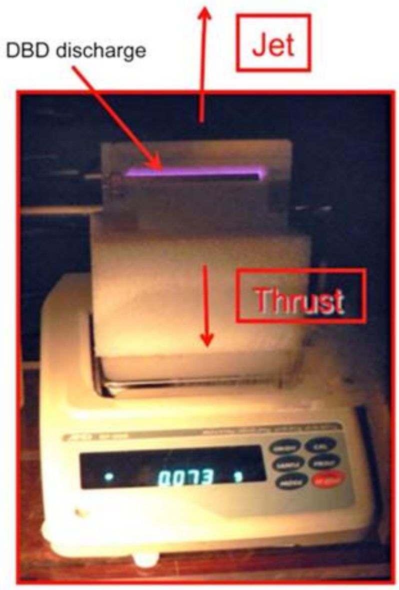

Figure 2.8 – Direct thrust measurement setup of an actuator on an analytic balance (Thomas et al., 2009)

CHAPTER 3

METHODOLOGY

3.1 Introduction of the experimental setup

The experimental setup needed to satisfy two requirements in order to investigate the plasma behaviour and thrust of the actuator. To begin with, the actuator had to be powered by supplying a high voltage alternating current (AC) signal to the exposed electrode while the covered electrode must be grounded. Second, the experiment had to be capable of measuring the thrust generated by the plasma actuator.

3.2 Actuator configuration

The copper tape electrodes with the Kapton dielectric layer were employed in the actuators made by hand for this work. The dielectric was built by layering it over both covered and exposed electrodes, creating a thickness for the dielectric. The electrodes were positioned to ensure there is no overlap on the electrode with one another . A PVC foam-core board with thickness of 5mm was used as the substrate of the actuator. The width of the exposed and covered electrodes was each 20mm. The covered electrodes were only a little bit longer than the exposed electrodes, which are 120 mm in length, while the exposed electrodes were 100 mm long.

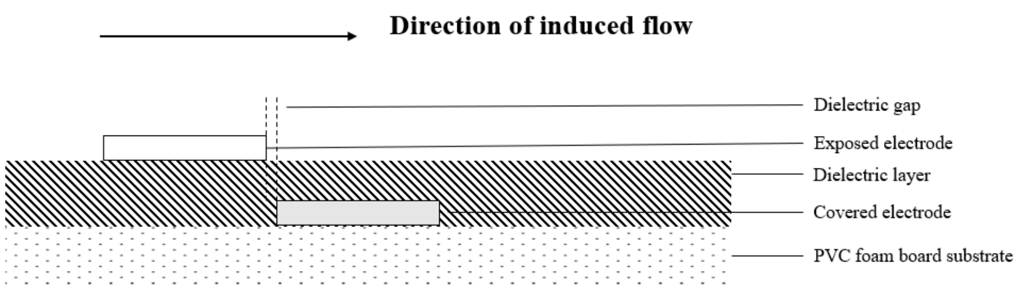

Figure 3.1 - Cross section of the actuator

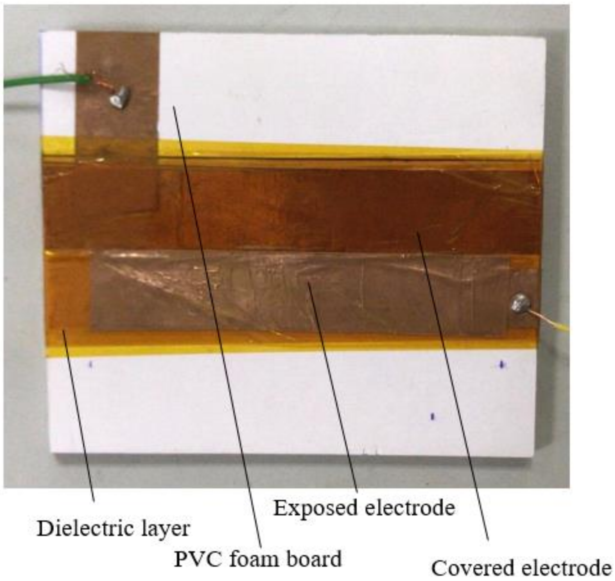

Figure 3.2 - Self-made actuator configuration

3.3 Electrical circuit

Figure 3.3 below shows the schematic diagram of the experimental setup. The actuator was powered by a transformer that acts as voltage regulator to step up the voltage to Kilovolts level.

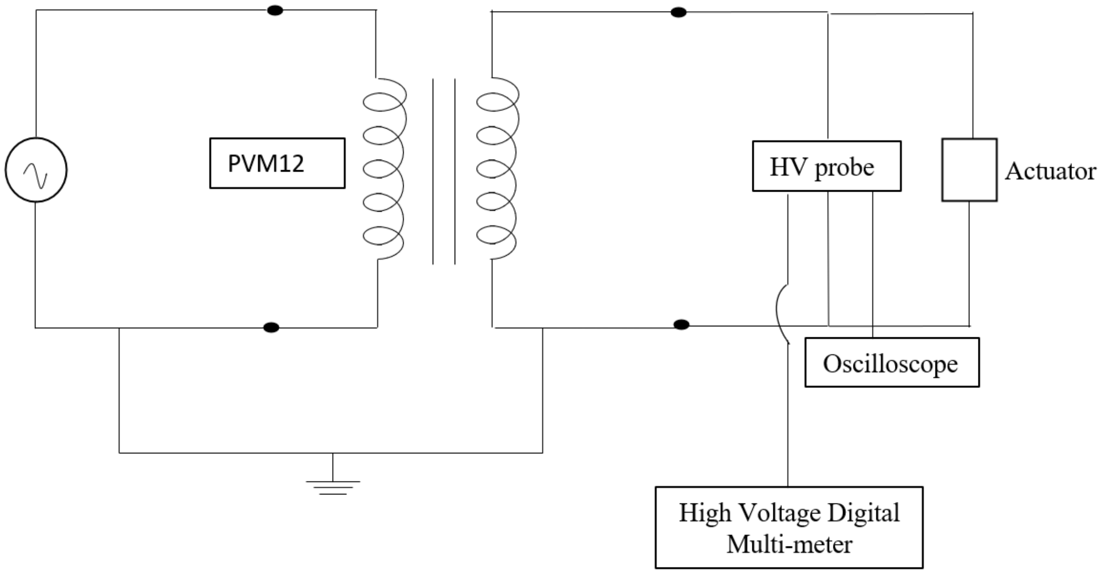

Figure 3.3 - Circuit diagram of the actuator electrical supply and measurement system

3.4 Power supply

The primary parts of the actuator driving circuitry consisting of a PVM12 . A PVM12 is a voltage regulator with output voltage range of 0-15KV and its frequency can be adjustable from 20k to 50kHz. The PVM12 served as the provider for continuously adjustable AC voltage. By modulating the amplitude of the AC waveform, this transformer is an effective and dependable technique of managing AC voltage from zero to line voltage. This transformer served as the actuator's power source and voltage regulator. Within the adjustment range, the voltage regulator's adjustable allows for stepless modification of the output voltage. The variable output of these transformer amplified the voltage to kilovolt levels.

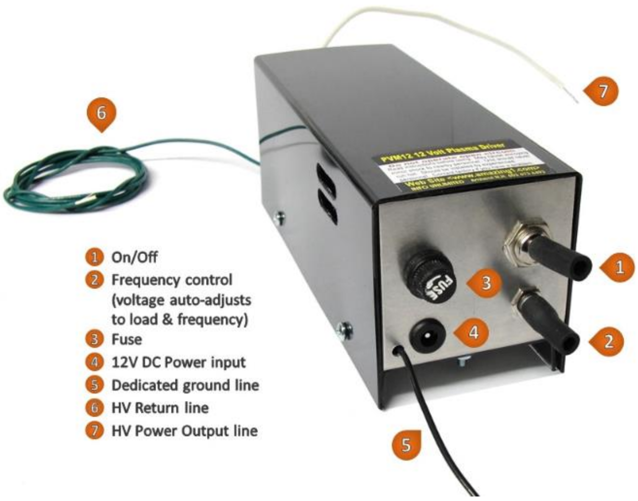

Figure 3.4 – PVM12 High voltage regulator

3.5 Electrical measurement

The experimental setup consists of the grounding circuit that was provided between the transformer and the actuator. In the event that there is a short circuit, the ground wire provides an alternative route for the electrical current to travel into the ground, so decreasing the threat of harm to any individuals who are working with the electricity in the nearby surroundings.

Figure 3.5 – The grounding circuit

The applied voltage to the actuator can be done by directly varying the variable auto transformer to a certain value. A Pintek HVP40 high voltage probe was used as the measuring tool to measure the applied voltage on the exposed electrode of the actuator so that the applied voltage can be set up to 0.353 KVrms and 0.900 KVrms . The Pintek HVP-40 is a high voltage probe designed for measuring voltages as high as 40kV DC or 28kV AC at 50/60Hz. With an input impedance of 1000 MΩ, the current flowing through the probe is only 40µA. The probe is aimed to allow measuring high voltages as safe as possible for the consumer. The high voltage probe was connected to a High Voltage Digital Multimeter Tester. The High Voltage Digital Multimeter Tester was used to capture the measurement of the voltage.

Figure 3.6 - A Pintek HVP40 high voltage probe

Figure 3.7 - A High Voltage Digital Multimeter Tester

3.6 Thrust measurement

The thrust measurement of the actuator was performed using a direct thrust measurement setup as shown in Figure 3.7. The direction of the plasma actuator is such that when an ac voltage is applied, the plasma-induced flow is directed upward (away from the balance), and the balance directly detects the reactive thrust force acting downward.

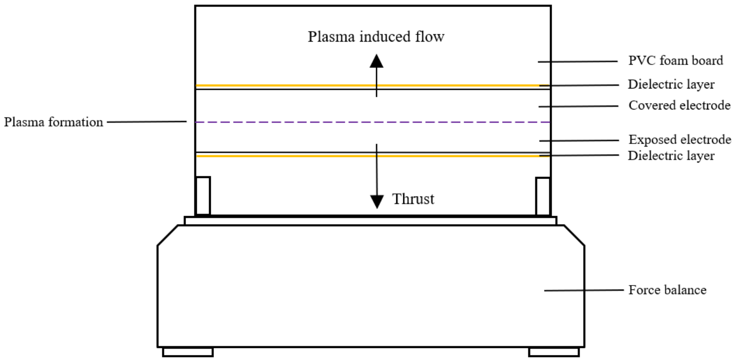

Figure 3.8 - Schematic of the thrust measurement setup

Figure 3.8 shows the completed experimental setup. The thrust measuring setup consists of the scale, the wiring for the actuator, the transformer, the HV probe and the high voltage digital multimeter were shown.

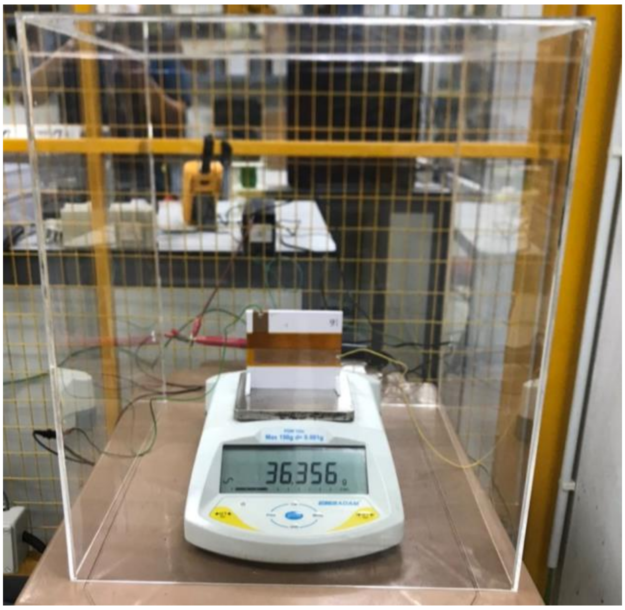

Figure 3.9 - Experimental setup components

The actuator thrust was measured using a high precision electronic force balance (PGW 153M high precision balances).This balance could measure up to 150 g with a resolution of 0.001 g. This results in a resolution of 10^{-6} N and a maximum measured force of 1.4715 N. The experimental test setup is housed in a Perspex box to reduce this noise on the thrust measurement and separate it from free-stream disturbances since the thrust measurement setup was so sensitive. Figure 3.9 displays the dimensions of the Perspex box.

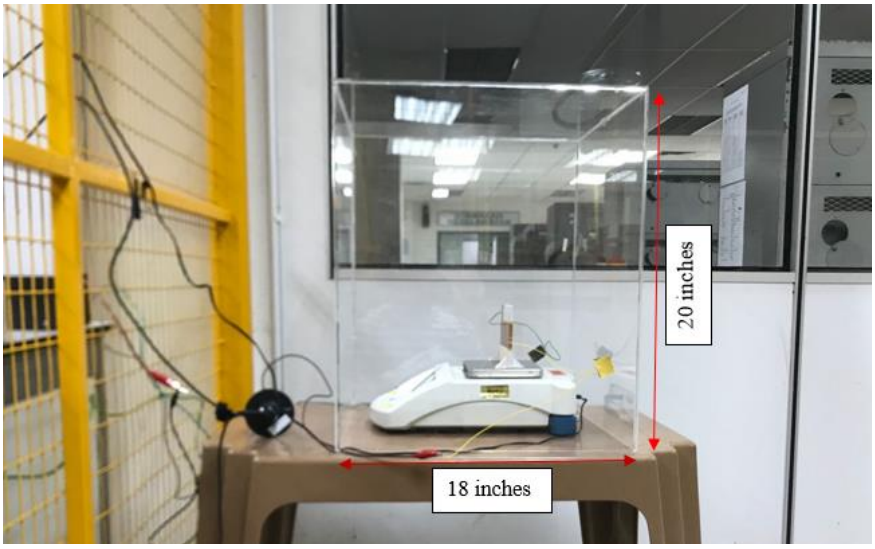

Figure 3.10 - The Perspex box and its dimension