Conference Paper

# Experimental Study of Dielectric Barrier Discharge Plasma Actuators for Active Flow Control

**Miguel André Barbosa Moreira, Frederico Miguel Freire Rodrigues, and José Carlos Páscoa Marques**

Universidade da Beira Interior

## Abstract

The objective of this study is to compare the effect of varying the material used as dielectric layer on the properties of the plasma actuators themselves. The experiments have shown that actuators with a PIB dielectric have a lower power consumption, can achieve higher velocities and have a better mechanical efficiency, but are more prone to failure due to breakdown of the dielectric. We verified that PIB rubber is a suitable material for DBD plasma actuators fabrication presenting several interesting features.

**Keywords:** Active flow control, Plasma actuators, Dielectric barrier discharge, Dielectric materials

Corresponding Author:
Miguel André Barbosa Moreira
miguel.andre.moreira@ubi.pt

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## 1. Introduction

Dielectric barrier discharge (DBD) plasma actuators are simple electronic devices with several applications in the field of active flow control. During the recent years, several studies have been conducted and the efficiency of these devices for a great diversity of applications have been shown [1-3]. A DBD plasma actuator is composed of two electrodes and a dielectric layer, as represented in Figure 1. One of the electrodes is exposed while the other one is covered by the dielectric layer. The exposed electrode is connected to an AC power supply capable of supplying a high voltage and high frequency signal while the covered electrode is grounded.

When the amplitude of this signal is high enough, the breakdown voltage is achieved, and the air ionizes in the area in which the electric field is bigger. The generated charged particles are accelerated by effect of the electric field, which transfers the movement to the adjacent air creating an ionic wind.

These devices have several advantages such as being totally electronic, low mass, low energy consumption, fast response time and overall easy-going [4-7], with their

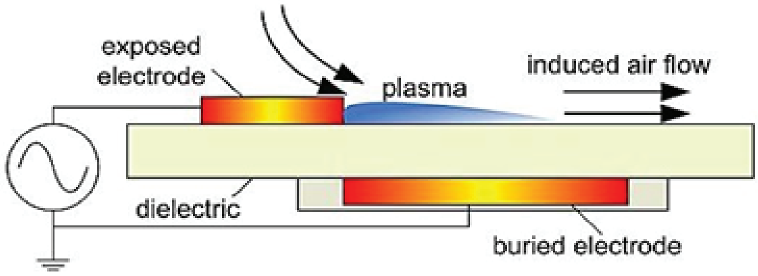



**Figure** 1: Schematics of a Dielectric Barrier Discharge plasma actuator

main applications being more industrial and aerodynamic oriented [8-10], also including boundary layer flow control [11-14] and separation control [15-18].

Dielectric barrier discharge devices were introduced as means of flow control during the 1990's by the works of Liu & Roth [19] and Roth et al. [20]. Since then, several studies have been performed in order to understand the physics behind their operation and also to evaluate their effectiveness for active flow control applications. Enloe et al. [21, 22] conducted very important studies in order to understand the mechanisms and responses of a single dielectric barrier discharge plasma actuator. On the other hand, the studies conducted by Hyun et al. [23], Sung et al. [24] and Post & Corke [25] are examples of studies in which plasma actuators were used for flow control. These studies showed that plasma actuators allow to modify the boundary layer and delay the flow separation. Further information about plasma actuators characteristics and studies related with their applicability, may be found in the reviews conducted by and Kotsonis [26] and Bernard & Moreau [27].

Although the efficiency of plasma actuators for active flow control has been already proved, these devices still present some drawbacks and need to be improved. The induced flow velocity is limited and after long time operation or when excessive levels of voltage are applied, these devices may fail. The dielectric layer influence the efficiency of the device and also its durability. Therefore it is important to study different dielectric materials in order to find materials that may improve the performance and durability of the device. Thus the purpose of this work is to compare the properties of two DBD plasma actuators with different materials used as dielectric layer, one using Kapton and another using Polyisobutylene, also known as "PIB" rubber. For that, an analysis about electrical parameters and induced velocity field was performed. All the experimental techniques are described with emphasis on those that can overcome the high electric field inherent to plasma generation.

# 2. Experimental Setup

## 2.1. Plasma actuators

The experimental setup includes different systems which allow to characterize the DBD plasma actuators in terms of electrical parameters and flow velocity.

The DBD plasma actuators themselves are composed of two electrodes, made of copper tape, which are mounted asymmetrically on either side of the dielectric with no gap between them.

The electrodes have the following dimensions: 10 mm width, 90 mm length and 80 μm thickness. The covered electrode has double the width of the exposed one to guarantee that the discharge extension is not limited by the end of the covered electrode.

The dielectric layer is constituted by several layers of Kapton or PIB tape, with 100 mm length and 50 mm width, which are layered to ensure a total thickness of 0.5 and 1mm.

The plasma actuator is powered by a PVM 500 power source, which can supply the plasma actuator with the high voltage and high frequency needed for the plasma to occur.

## 2.2. Electrical characterization setup

The electrical characterization setup is needed to measure the input signals applied to the plasma actuator and estimate electrical parameters such as: power consumption, charge, breakdown voltage, cold capacitance and effective capacitance.

The plasma actuator input signal is produced by a PVM 500 power supply and measured by a PicoScope model 5443A, a device normally used for diagnostics in the automotive industry which can turn a normal computer into an oscilloscope. The voltage and frequency of the signal were measured by a special probe named Secondary Ignition Pickup which can measure high voltage signals passing through a wire without disconnecting or stripping the wire. The sampling rate was 125MS/s, the vertical resolution of the measurement was 14bits and the uncertainty of the power measured is about 1%.

Since the signal presents high voltage levels, the current waveform cannot be measured by conventional equipment. To overcome this issue, two different methods were used in order to obtain the parameters: The electric current method and the electric charge method.

The electric current method was employed in order to estimate the current and voltage waveforms and the power consumption. In this method a resistor with known resistance $R$ is placed between the covered electrode and ground, and then the current is calculated from the voltage $Vr$ measured across the resistor using Ohm's law ($Ia = Vr/R$). The voltage across the resistor is now low enough to be measured by conventional instruments. The input voltage and current waveforms are recorded and the instantaneous power is given by the following equation:

$$P = v \times i \quad (1)$$

Where $v$ is the input voltage of the actuator, $i$ is the current and $P$ is the instantaneous power. The average power of $n$ periods ($T$) is obtained also through the voltage and current data, as described in the equation:

$$Pmed = \frac{1}{nT}\int_0^{nT} vi \quad (2)$$

In this case, a metal film resistor was used with 100 Ω of impedance with 1% of tolerance. The impedance of the resistor is relatively low compared with the impedance of the actuator so it won't affect the operation of the actuator.

In order to obtain the charge, the voltage breakdown and the capacitances of the actuator the electric charge method was used. In this method a capacitor is placed in series with the actuator between the covered electrode and ground. The capacitor should have a large value of capacitance comparatively to the capacitance of the actuator without plasma discharge.

The instantaneous charge of the capacitor is given by:

$$Q_m = C_m V_m \quad (3)$$

Where $C_m$ is the capacitor capacitance and $V_m$ is the voltage across the capacitor. The current through the capacitor is then given by:

$$i = C_m \frac{\partial V_m}{\partial t} \quad (4)$$

Once the capacitor is connected in series with the actuator, the current through the capacitor is equal to the current trough the actuator, so the instantaneous power dissipated by the actuator can be obtained by:

$$P = v \times i = v \times C_m \frac{\partial V_m}{\partial t} \quad (5)$$

The average power of n periods ($T$) is given by:

$$Pmed = \frac{1}{nT}\int_0^{nT} vC_m \frac{\partial V_m}{\partial t} \quad (6)$$

The instantaneous charge and the instantaneous actuator voltage plotted against each other generate a *Lissajous* curve. In this case a capacitor with 10 nF of capacitance and 10% of tolerance was used.

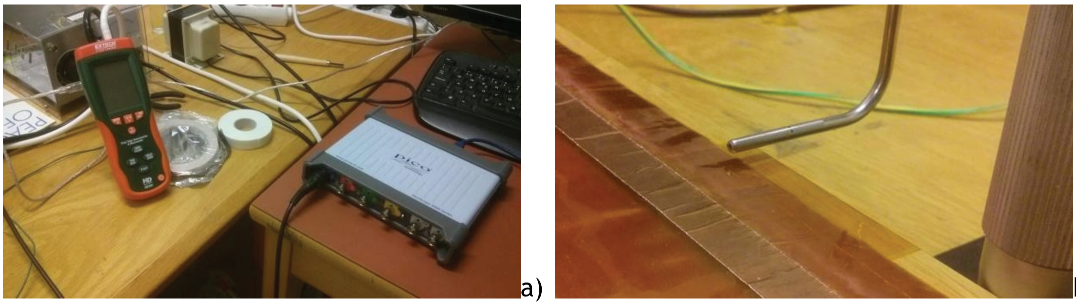
## 2.3. Flow velocity Setup

To measure the flow velocity of the plasma actuators a Pitot tube was used. This instrument allows to obtain the flow velocity and it is one of the most exact for this purpose. It has a circular section and is L shaped. To obtain the air flow velocity, the Pitot tube is placed on the opposite direction of the flow movement. The tip of the tube creates a stagnation point in the flow and, accordingly with Bernoulli's equation, the difference between the stagnation pressure and the static pressure allows to obtain the velocity, as describe by:

$$U = \sqrt{\frac{2(p_2 - p_1)}{\rho_{air}}} \tag{7}$$

Where $p_2$ is the stagnation pressure, $p_1$ is the static pressure and $\rho_{air}$ is the air density. Beyond the PVM500 power supply, the PicoScope model 5443A and the Secondary Ignition Pickup special probe, the Pitot tube was connected to a HD350 micro manometer which can make a certain number of readings depending on time. The final results consist on the average of 10 velocity samples, the velocity results present a standard error lower than +/-0.1m/s.

The Pitot tube was centred on the actuator's longitudinal plane, 1,5cm from the exposed electrode edge with variable height. The Pitot tube itself has a thickness of 3mm and, because of its circular shape, all the readings start at 1,5mm high instead of 0mm. Because of this limitation the velocities between 0 and 1.5mm cannot be measured.



a) b)

**Figure** 2: Experimental Setup a) From left to right: PVM500 power supply, HD350 micro manometer, Secondary Ignition Pickup special probe and PicoScope model 5443A b) Pitot tube in measurement position

# 3. Results

In the following subsections we are going to present the results obtained from plasma actuators with dielectric barriers made of Kapton and PIB.

Firstly, we are going to analyse their electrical parameters, including the power consumption and capacitances at different input voltage levels. After that, we are going to analyse the flow velocity induced by the DBD plasma actuator by using the Pitot tube method. By using the velocity profiles the mechanical power transferred by the actuator to the adjacent flow will be estimated and with that the mechanical efficiency will be analysed.

## 3.1. Electrical characterization

In order to obtain the voltage, current, power waveforms, and also the power consumption for different applied voltages, the electric current method was used.

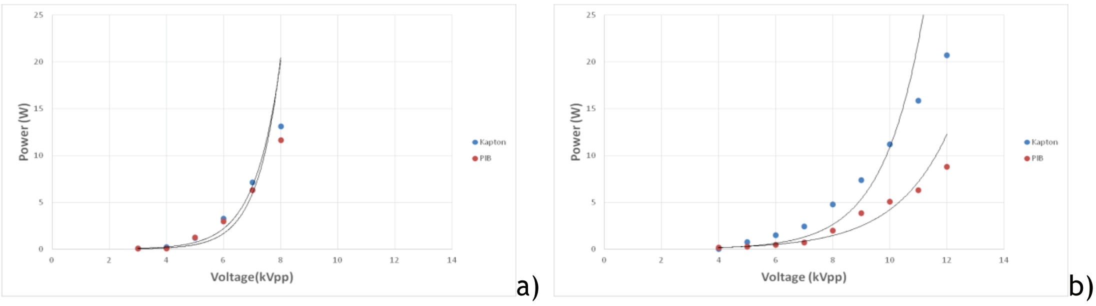



**Figure** 3: Average power consumption at different voltage levels and same frequency obtained from DBD plasma actuators made with Kapton and PIB a) 0.5 mm thickness b) 1 mm thickness

The average power consumed by the actuator at different applied voltage levels is shown above. The average power consumed presents an exponential evolution increasing with the growth of the applied voltage. The PIB plasma actuators have lower power consumption when compared to the Kapton ones. This behaviour was observed for 0.5 mm actuators and 1 mm actuators, but it is more evident in 1 mm actuators.

To obtain the evolution of the actuator charge during the ac voltage cycle the electric charge method was used. The *Lissajous* curves of each DBD plasma actuator were experimentally estimated and represented in Figure 3.

It is know that the area inside the curve is related with the electrical power consumed by the actuator. As we see in Figure 3, the area inside the *Lissajous* curves obtained for actuators with 0.5 mm thickness is bigger than the areas of the *Lissajous* curves obtained for actuators with 1mm thickness. Thus this results agree with the

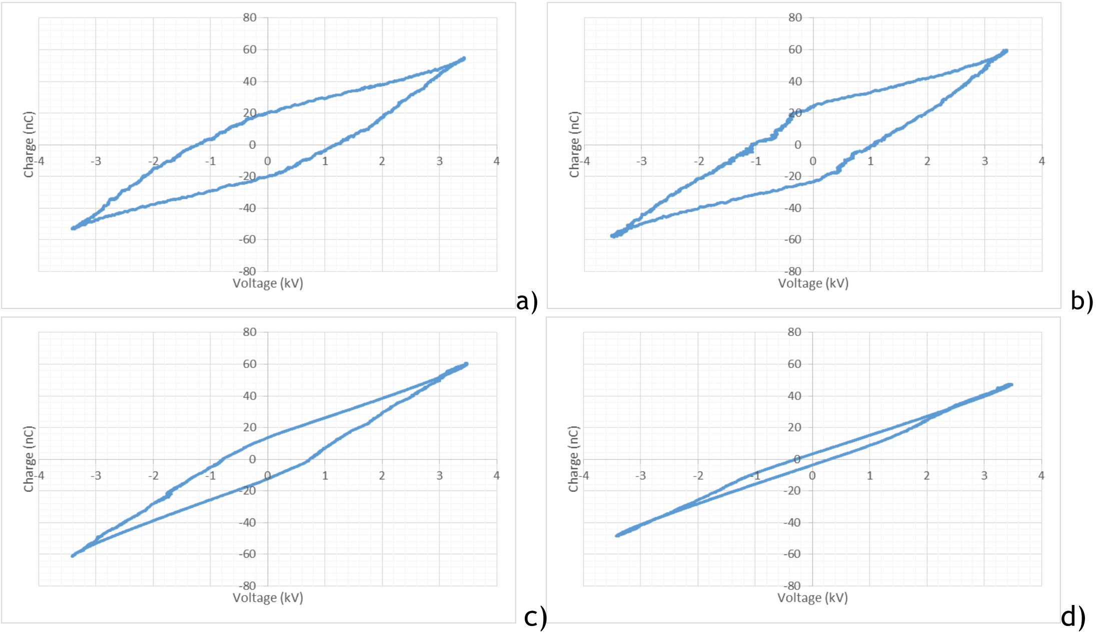



**Figure** 4: Lissajous curves obtained experimentally for 7 kVpp a) Kapton 0.5mm thickness b) PIB 0.5mm thickness c) Kapton 1mm thickness d) PIB 1mm thickness.

results obtained for power consumption since for 7kVpp, plasma actuators with 0.5 mm thickness presented higher power consumption than 1 mm thickness actuators. By the analysis of these figures, and as explained by Kriegseis et al. [28], the respective effective and cold capacitances were obtained. The results may be seen in table 1.

The cold capacitance of the device represents its capacitance when the actuator is off while the effective capacitance represents the capacitance of the device with the contribution of the plasma discharge. This is the reason why the cold capacitances obtained remain more or less constant and do not vary much with the applied voltage level. The same is not verified for the effective capacitance. In table 1 we see that when we increase the applied voltage, the effective capacitance also increases.

### 3.2. Flow velocity

In order to obtain the velocity profiles a Pitot tube was used. The induced flow velocity was obtained at different heights from the surface in which the actuator was applied. The results obtained are represented in Figure 4.

Figure 4 shows the velocity profiles extracted at different voltage levels. We can observe that the DBD plasma actuators made with PIB allow to obtain higher velocities when compared to Kapton. However, the 0.5mm PIB actuator could not withstand higher voltages for some time without breakdown of the dielectric, the 0.5mm kapton actuator

Table 1: Mechanical power and efficiency of DBD plasma actuators.

| Dielectric Material / Thickness | Applied Voltage (kVpp) | Ceff (pF) | Ccold (pF) |
|---|---|---|---|
| Kapton 0.5mm | 5 | 10.01 | 8.83 |
| | 6 | 19.73 | 9.40 |
| | 7 | 26.98 | 10.21 |
| | 8 | 36.78 | 10.22 |
| PIB 0.5mm | 5 | 19.06 | 9.16 |
| | 6 | 20.47 | 9.66 |
| | 7 | 28.43 | 10.85 |
| | 8 | 35.52 | 11.20 |
| Kapton 1mm | 8 | 26.21 | 14.18 |
| | 9 | 28.54 | 13.77 |
| | 10 | 29.80 | 13.74 |
| | 11 | 29.76 | 13.04 |
| | 12 | 35.17 | 12.94 |
| PIB 1mm | 8 | 16.37 | 12.15 |
| | 9 | 19.17 | 12.21 |
| | 10 | 20.45 | 11.98 |
| | 11 | 22.84 | 12.57 |
| | 12 | 22.18 | 12.60 |

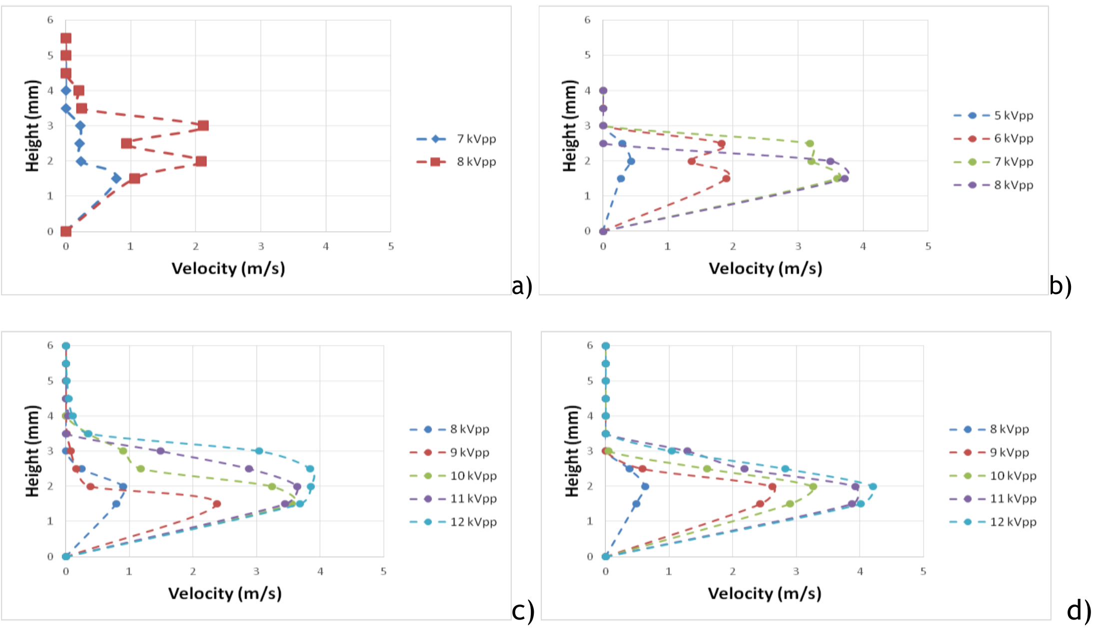



**Figure** 5: Velocity profiles at different voltage levels and same frequency obtained from DBD plasma actuators made with Kapton and PIB a) Kapton 0.5mm thickness b) PIB 0.5mm thickness c) Kapton 1mm thickness d) PIB 1mm thickness.

only has velocity profiles for 7kVpp and 8kVpp because its induced velocities at lower voltage levels are very low.

These results show that PIB rubber is a material that should be considered for plasma actuators fabrication because it allows to produce higher induced flow velocities when compared with Kapton actuators.

Because of the Pitot tube's diameter, the Pitot tube is he an intrusive element, the velocities cannot be measured directly at the plasma discharge of the actuators, therefore, these results are not going to be used in quantitative terms, but in qualitative terms instead, for a comparison between the cases studied.

The plasma originated is a low thermal plasma, this means that the heat transfer from the plasma actuators does not have any influence on the active flow control.

### 3.3. Mechanical efficiency analysis

To obtain the plasma actuators efficiency, the mechanical power was calculated as explained in Leger et al. [29] and Rodrigues et al. [30]. The mechanical power is the power delivered by the actuator to create the induced flow. By this method, it is considered that the power used to induce the flow corresponds to the balance of the kinetic energy density flow rate, expressed as:

$$Pm = \int_0^\infty \frac{1}{2}\rho u(Y)^3 l dY \tag{8}$$

Where $\rho$ is the air density, $u(Y)$ is the velocity profile and *l* the electrode length. From this it is possible to estimate the plasma actuator's efficiency:

$$\eta = \frac{Pm}{Pel} \tag{9}$$

The mechanical power and the efficiency were calculated for each plasma actuator. The results obtained are in table 2 below.

As it can be seen, the mechanical power is very small when compared to the electrical power delivered by the actuators. This is why the efficiencies are also small. The uncertainty for the mechanical power is related to the uncertainties of the electrical power and velocity results mentioned before.

Despite the fact that the obtained efficiencies are very low, these results are very similar to the results found in Pons et al. [31] in which the authors verified that the efficiencies of plasma actuators vary around 0.05%. These very small values suggest that most of the applied power is lost by heating, as it has been shown in other studies [1, 7]. As we can see, when the input voltage is increased the actuator's efficiency

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Table 2: Mechanical power and efficiency of DBD plasma actuators.

| Dielectric Material / Thickness | Applied Voltage (kVpp) | Electrical Power (W) | Mechanical Power (mW) | Efficiency (%) |
|---|---|---|---|---|
| Kapton 0.5mm | 7 | 7.11 | 0.0000124 | 0.0002 |
| | 8 | 13.01 | 0.0005038 | 0.0038 |
| PIB 0.5mm | 5 | 1.25 | 0.0000040 | 0.0003 |
| | 6 | 2.93 | 0.0001989 | 0.0068 |
| | 7 | 6.28 | 0.0011857 | 0.0189 |
| | 8 | 11.63 | 0.0019114 | 0.0164 |
| Kapton 1mm | 8 | 4.77 | 0.0000309 | 0.0006 |
| | 9 | 7.34 | 0.0003324 | 0.0045 |
| | 10 | 11.21 | 0.0020163 | 0.0180 |
| | 11 | 15.82 | 0.0028734 | 0.0182 |
| | 12 | 20.69 | 0.0047499 | 0.0230 |
| PIB 1mm | 8 | 1.99 | 0.0000099 | 0.0005 |
| | 9 | 3.85 | 0.0008070 | 0.0210 |
| | 10 | 5.05 | 0.0015613 | 0.0309 |
| | 11 | 6.28 | 0.0032467 | 0.0517 |
| | 12 | 8.79 | 0.0040237 | 0.0457 |

increase as well. This means that actuators that can operate at higher voltages will present better efficiencies. In our tests, the PIB actuator with 1mm thickness peaked at (12 *kV*) with the highest efficiency ($\eta$ = 0,0457%). When comparing the different efficiencies obtained from the same voltage levels, PIB actuators have a higher efficiency when compared to Kapton.

However, DBD plasma actuators are not used for their efficiency, but because of their capabilities and advantages as mentioned before in this study.

## 4. Conclusions

In the present study several DBD plasma actuators with different dielectrics were studied in terms of electrical characteristics and velocity profiles. Different experimental techniques were used and explained.

In the electrical characterization two different methods were used and explained: the electric current method and the electric charge method. These methods allowed us to obtain the power consumption, the instantaneous charge and the cold and effective capacitances.

The plasma actuator presents a similar electrical behaviour to a capacitor and the average power consumption presents an exponential evolution, increasing with the growth of the applied voltage. The PIB actuators presented lower power consumption than the Kapton actuators. Pitot tube measurements with the purpose of a qualitative comparison among the cases studied allowed to obtain the velocity profiles at different voltage levels. From these we concluded that PIB actuators allow to obtain higher velocities but are more prone to breakdown of the dielectric. The mechanical efficiency of the different actuators was estimated and, as expected, we verified that PIB rubber actuators present better mechanical efficiency. Therefore, we may conclude that PIB rubber is a suitable material for DBD plasma actuators fabrication which present several advantages when compared with Kapton.

## References

[1] Rodrigues F, Pascoa J, Trancossi M. Heat generation mechanisms of DBD plasma actuators. Exp Therm Fluid Sci 2018;90:55–65. doi:10.1016/j.expthermflusci.2017.09.005.

[2] Abdollahzadeh, M.; Rodrigues, F.; Pascoa, J. C.; Oliveira, P. J.: “Numerical design and analysis of a multi-DBD actuator configuration for the experimental testing of ACHEON nozzle model” Aerospace Science and Technology, Vol. 41 (2015), pp. 259-273.

[3] Rodrigues F, Mushyam A, Pascoa J, Trancossi M. A new plasma actuator configuration for improved efficiency: the stair-shaped dielectric barrier discharge actuator. J Phys D Appl Phys 2019;52:385201–385014.

[4] Rodrigues, F. F.; Pascoa, J. C.; Trancossi, M. Analysis of innovative plasma actuator geometries for boundary layer control. Proceedings of the ASME 2016 International Mechanical Engineering Congress & Exposition, Phoenix, Arizona, USA, Nov 2016.

[5] Kotsonis, M.; Veldhuis, L.: “Experimental Study on Dielectric Barrier Discharge Actuators Operating in Pulse Mode” Journal of Applied Physics, Vol. 108 (2010), pp. 1-9.

[6] Enloe, C. L.; McLaughlin, T. E.; Font, G. I.; Baughn, J. W.: “Parameterization of Temporal Structure in the Single-Dielectric-Barrier Aerodynamic Plasma Actuator” AIAA Journal, Vol. 44 n° 6 (2006), pp. 1127-1136.

[7] Rodrigues F, Pascoa J, Trancossi M. Experimental analysis of dielectric barrier discharge plasma actuators thermal characteristics under external flow influence. J Heat Transfer 2018;140:102801

[8] Corke, T. C.; Enloe, C. L.; Wilkinson, S. P.: "Dielectric Barrier Discharge Plasma Actuators for Flow Control" Annual Reviews of Fluid Mechanics, Vol. 42 (2010), pp. 505-529.

[9] Tirumala, R.; Bernard, N.; Moreau, E.; Fenot, M.; Lalizel, G.; Dorignac, E.: "Temperature characterization of dielectrc barrier discharge actuators: influence of electrical and geometric parameters" Journal of Physics D: Applied Physics, Vol. 47 n° 255203 (2014), pp. 12.

[10] Thomas, F.; Corke, T.; Iqbal, M.; Kozlov, A.; Schatzman, D.: "Optimization of Dielectric Barrier Discharge Plasma Actuators for Active Aerodynamic Flow Control" AIAA Journal, Vol. 47 n° 9 (2009), pp. 2167-2178.

[11] Schatzman, D. M.; Thomas, F. O.: "Turbulent Boundar-Layer Separation Control with Single Dielectric Barrier Discharge Plasma Actuators" AIAA Journal, Vol. 48 (2010), pp. 1620- 1634.

[12] Font, G. I.: "Boundary-Layer Control with Atmospheric Plasma Discharges" AIAA Journal, vol. 44 (2006), pp. 1572-1578.

[13] Porter, C. O.; McLaughlin, T. E.; Enloe, C. L.; Font, G. I.; Roney, J.; Baughn, J. W. Boundary Layer Control Using a DBD Plasma Actuator. AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 2007.

[14] Opaits, D. F.; Roupassov, D. V.; Starikovskaia, S. M.; Starikovskii, A. Y.; Zavialov, I. N.; Saddoughi, S. G. Plasma Control of Boundary Layer Using Low-Temperature Non-Equilibrium Plasma of Gas Discharge. AIAA Aerospace Sciences Meeting and Exhibit, Reno Nevada, 2005.

[15] Post, M.; Corke, T.: "Separation Control on High Angle of Attack Airfoil Using Plasma Actuators" AIAA Journal, Vol. 42 n° 11 (2004), pp. 2177-2184.

[16] Huang, J.; Corke, T. C.; Thomas, F. O.: "Plasma Actuators for Separation Control of Low- Pressure Turbine Blades" AIAA Journal, Vol. 44 (2006), pp. 51-57.

[17] Kelley, C.P.; Bowles, P.; Cooney, J.; He, C.; Corke, T. C.; Osborne, B.; Silkey, J.; Zehnle, J. High Mach Number Leading-edge Flow Separation Control Using AC DBD Plasma Actuators. Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Nashville, Tennessee, 2012.

[18] Poon, D. Separation Control using Plasma Actuators: Experimental Studies of Plasma Actuator Performance. University of Minnesota, 2011.

[19] Liu, C., Roth, J. Boundary layer control by a one atmosphere uniform glow discharge plasma layer. IEEE International Conference on Plasma Science, 1995.

[20] Roth, J. R., Sherman, D. M., Wilkinson, S. P. Boundary layer flow control with a one atmosphere uniform glow discharge surface plasma. 36th AIAA Aerospace Sciences Meeting and Exhibit, 1998.

[21] Enloe, C.; McLaughlin, T.; VanDynken, R.; Kachner, K.: "Mechanisms and Responses of a Single Dielectric Barrier Plasma Actuator: Geometric Effects" AIAA Journal, Vol. 42 n° 3 (2004), pp. 595-604.

[22] Enloe, C.; McLaughlin, T.; VanDynken, R.; Kachner, K.: "Mechanisms and Responses of a Single Dielectric Barrier Plasma Actuator: Plasma Morphology" AIAA Journal, Vol. 42 n° 3(2004), pp. 589-594.

[23] Hyun, K.; Chun, C.: "The Wake Flow Control Behind a Circular Cylinder Using Ion Wind", Experiments in Fluids, Vol. 35 (2003), pp. 541-552.

[24] Sung, Y.; Kim, W.; Mungal, M.; Cappelli, M.: "Aerodynamic Modification of Flow Over Bluff Objects by Plasma Actuation", Experiments in Fluids, Vol. 41 (2006), pp. 479-486.

[25] Post, M.; Corke, T.: "Separation Control on High Angle of Attack Airfoil Using Plasma Actuators", AIAA Journal, Vol. 42 n°.11 (2004), pp. 2177-2184.

[26] M. Kotsonis, "Diagnostics for characterisation of plasma actuators," Measurement Science and Technology, vol. 26, pp. 1-30, 2015.

[27] N. Bernard and E. Moreau, "Electrical and mechanical characteristics of surface ac dielectric barrier discharge plasma actuators applied to airflow control," Experiments in Fluids, vol. 55, pp. 1-43, 2014.

[28] J. Kriegseis, B. Moller, S. Grundmann, C. Tropea, "Capacitance and power consumption quantification of dielectric barrier discharge (DBD) plasma actuators", Journal of Electrostatics, vol. 69, issue 4, pp. 302-312, 2011

[29] Leger, L., Moreau, E., and Touchard, G., 2002. "Electro hydrodynamic airflow control along a flat plate by a dc surface corona discharge - velocity profile and wall pressure measurements". In 1st Flow Control Conference, pp. 1–11.

[30] Rodrigues, F. F.; Pascoa, J. C.; Trancossi, M. Experimental analysis of alternative dielectric materials for DBD plasma actuators. Proceedings of the ASME 2018 International Mechanical Engineering Congress & Exposition, Pittsburgh, Pensilvania, USA, Nov 2018.

[31] Pons, J., Moreau, E., and Touchard, G., 2005. "Asymmetric surface dielectric barrier discharge in air at atmospheric pressure: electrical properties and induced airflow