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Efficiency optimization for plasma actuator in atmospheric air

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ABSTRACT

This work is an experimental study for plasma actuators to get a maximum efficiency at the best operating conditions using several variables such as different electrodes materials, horizontal distances between the effective and ground electrodes, also two type of dielectric materials used like Poly methyl methacrylate (PMMA) and high density polyethylene (HDPE). The discharge plasma was produced by AC power supply source of 8 KHz frequency and applied voltages (3, 5, 7, 9) kV. The results show that, the efficiency have maximum value, up to 0.25, when the dielectric is PMMA, copper electrodes, applied voltage of 7kV, and 1mm dielectric thickness. It's clear there was distinction efficiency up to 0.20 using aluminum electrodes of 2mm thickness for PMMA dielectric and 5kV as applied voltage. Also, most likely the efficiency decrease with the increasing horizontal distance between the two electrodes.

INTRODUCTION

Plasma actuator have a wide usage based on a single dielectric barrier discharge (SDBD) mechanism. It has desirable features for use in air at atmospheric pressures. The aerodynamic benefits of the induced body force from these actuators were first publicized in the mid of 1990s. Roth et al. was among the first to utilize the DBD actuator to manipulate the boundary layer on a flat plate over a range of free stream velocities (R. Durscher *et al* (2011).

The dielectric barrier discharge (DBD) plasma actuator consists of two electrodes separated by dielectric material. The active electrode is exposed while the other is covered by the dielectric. To operate the actuator, a high voltage AC signal is applied on the active electrode. This causes a plasma discharge to form over the surface of the dielectric between the exposed and covered electrodes. The discharge causes an ionic wind to flow across the actuator. In still air, the actuator induces a flow that draws air toward the surface of the actuator, and accelerates this air downstream in a direction tangential to the dielectric. This is the result of collisional momentum transfer from the ions and electrons in the plasma with the neutral fluid molecules surrounding them. It is clear that the actuator itself forms and accelerates the plasma; the reaction force on the actuator is small but readily measured (J. W. Ferry, (2010).

The produced plasma and the cathode electrodes has role to provide current continuity at this interface. The current in the boundary region consists of two components: the conduction current (Ic) and displacement current (I_D) hence the displacement current is equal zero in DC fields, and the remaining conduction current which was consists of electron and ion components (D. E. Ashpis *et al* (2012). For AC fields, the contribution of the displacement current to the total current increases where applied voltage increase's, when the operating conditions (applied field, electrode cross section area, static Pressure, and frequency) are such that the current density in the boundary region near the cathode is independent of the flow current in the circuit, the discharge is called a glow discharge (T. Corke *et al* (2009). The initiation of the ionization occurs when the potential

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difference between the electrodes exceeds a minimum threshold (D. Orlov,(2006). A set of methods used for calculate of current that passing through insulating material, such electric charge method or shunt resistance method or Rogowski coil. The most widely used capacitance method or shunt resistance methods (Wagner, H.-E *et al.* (2003).

One of the most relevant topics for future applications of plasma actuators is the efficiency of the force production. In this work, we have focused on aspects such as applied voltage, dielectric materials, electrodes materials, and electrodes distance and their arrangement to achieve optimized efficiency.

MATERIALS AND METHOD

As mention previously, the dielectric barrier discharge (DBD) plasma actuator consists of two electrodes separated by dielectric material. Poly methyl methacrylate (PMMA) is an acrylic material with a dielectric strength of 25 MV/m and good uniformity. The dielectric strength and uniformity prevent discharge plasma between the electrodes, making PMMA an effective and reliable dielectric material for the plasma discharge (Justin C. Zito *et al.* (2010).

The plasma actuator arrangement within the global experimental setup for this work is shown in figure (1); the active electrode supplied with AC voltage which give enough energy to plasma generation in air.

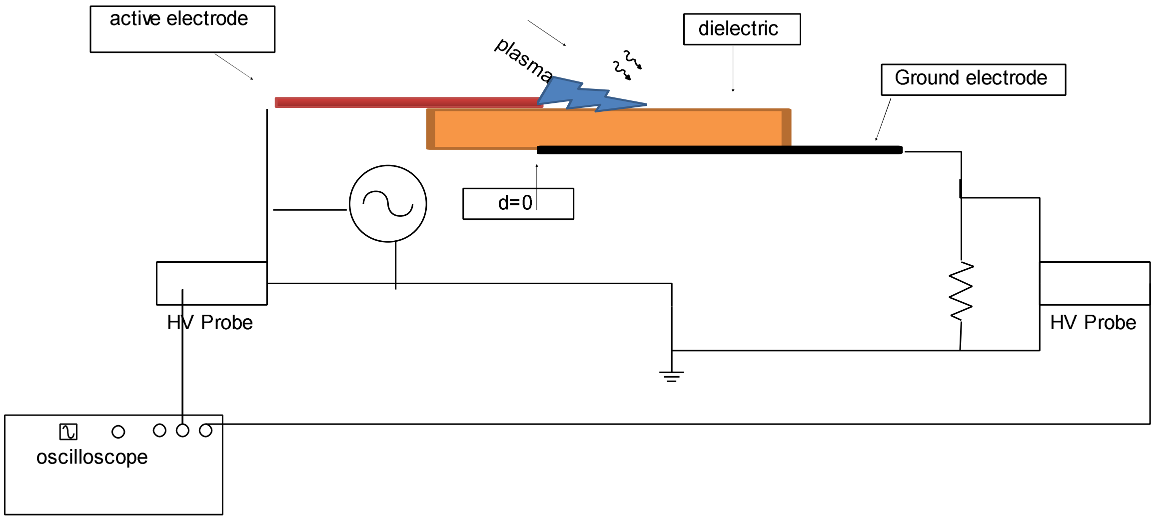


Fig. 1: Single dielectric barrier discharge plasma actuator setup.

The practical experience is made up of AC high-voltage device, the dielectric polymer material is placed between the two electrodes, area of dielectric (3 ×3) cm^2 with (1-5) mm as thickness. The active electrode length) 1cm) , width (1cm) and (1 mm) thickness, also, the grounded electrode length is) 2cm) , (1cm) width and (1 mm) thickness. The ground electrode was connected to a shunt resistance of 10MΩ, then grounded to earth.

Two High voltage probe was used, Attention ratio (1000:1) volt, AC (PD-28)[SEW-made in Taiwan] with two digital multimeters and TWINTEX digital Oscilloscope, TSO 1202, 200MHz, 1GSa/s connected with high voltage probe for actuator electrodes.

The voltage in an AC circuit is representing in equation (Boylestad,(2010):

$$V = v_m \sin(wt \pm \varphi) \tag{1}$$

Hence, v_m is maximum voltage, φ is phase angle.

The electrical consumed power (input power) of plasma actuator is calculate from the relation (Boylestad,(2010):

$$Pav = \frac{1}{T}\int_0^T I(t).V(t)dt \tag{2}$$

$$P_{av} = \frac{V^2}{|Z|}\cos(\varphi) \tag{3}$$

$$P_{av} = I^2|Z|\cos(\varphi) = VI\cos(\varphi) \tag{4}$$

Hence cos φ is power factor representing cosine of angel between voltage and current in AC circuits. The power dissipated by the resistor at any instant of time can be found by simply substituting the time, In resistance state , $\varphi = 0$, The average real power (output power) in the equation (3) becomes :

$$P_{av} = \frac{V^2}{|Z|} \quad (5)$$

The actuator efficiency is the efficiency of transforming the electrical energy to mechanical energy which can be calculated as the ratio between the output and input powers of the actuator circuit. In order, to consider the actuator performance with reference to the supply conditions related to the momentum transfer mechanism, the efficiency η is defined as the ratio between the produced power P_{out} and the consumed power P_{in}. (Boylestad (2010):

$$\eta = P_{out.} / P_{in.} \quad (6)$$

RESULT AND DISCUSSION

In this section, we will view and discuss the results that were obtained from experiments. The results will show the effects of the applied voltages, the electrodes and dielectric materials and the horizontal and vertical (dielectric thickness) distances between the two electrodes on efficiency of the actuator.

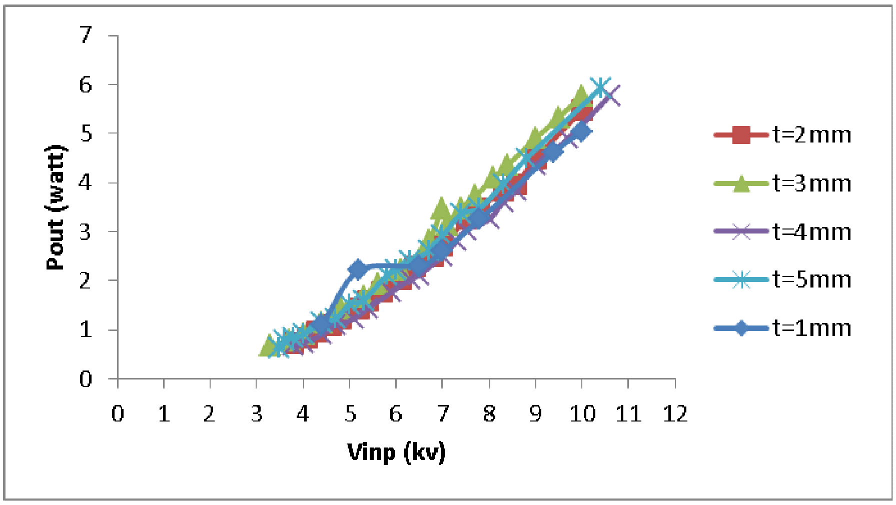
Two materials of polymer are used, as a dielectric between the electrodes, in current experiments, poly methyl methacrylate (PMMA) and high density polyethylene HDPE to optimize the actuator efficiency. That was done in a set of varied operating parameters such as applied voltages (3-9) kV of 8kH frequency), electrodes materials type (Copper and Aluminum), and dielectric materials thickness (1-5mm). Also the horizontal distance (0-8) mm between the two electrodes.

1. The Actuator output power:

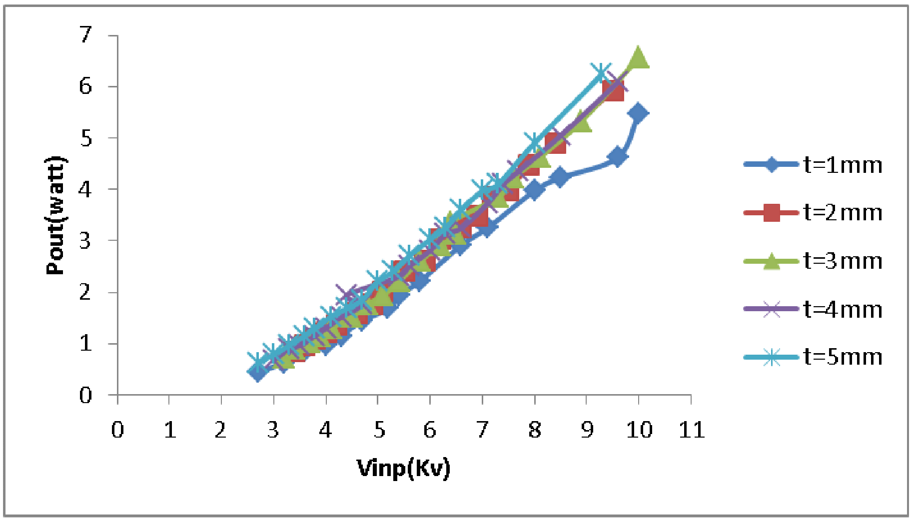
The out power of the plasma actuator is an important parameter because it indicates the final efficiency of the actuator. So that, it was calculated, for the plasma actuator in this work, using equation (5), where the shunt resistance is 10 MΩ among a range of applied voltage from 2.7 to 11 kV as shown in figure (2).

Figure (2a) shows the behavior of the out power as a function of the applied voltage when the electrodes is copper and the dielectric is high density polyethylene in different thicknesses (1-5)mm. It appears, approximately, linear increasing for the power with the increasing of applied voltage and small decreasing with the dielectric thickness increasing. That is because the effect of the electric field and the capacitance of the arrangement that were affected by the applied voltage and the vertical distance between the electrodes (dialectic thickness).

Figure (2b) shows the results for experiment at same above conditions except that when the dielectric material is the poly methyl methacrylate. It shows, in general, same behavior as in (2a), but the power is greater, which makes the (PMMA) material better than HDPE. That is because electric field behaver inside dielectric material, and its effect on chemical bonds is higher.



(a)



(b)

Fig. 2: The plasma actuator out power as a function of the applied voltage for different dielectric thicknesses when the dielectric materials are, a) HDEP, b) PMMA.

For comparison purpose, the out power was calculated; using equation (5), for cooper and aluminum electrodes and same dielectric material is PMMA as shown in figure (3). The figure show clearly that the out power of the plasma actuator greater when the when the electrodes material is copper than that of aluminum along all the rage of allied voltages.

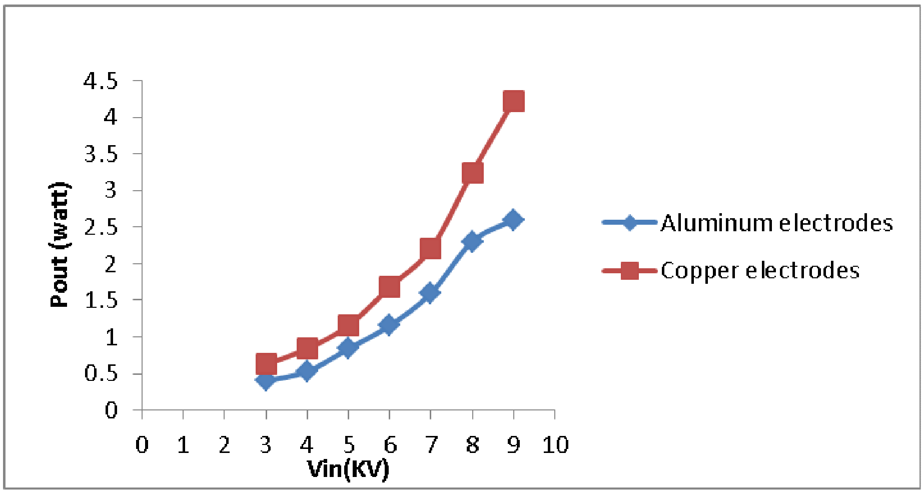


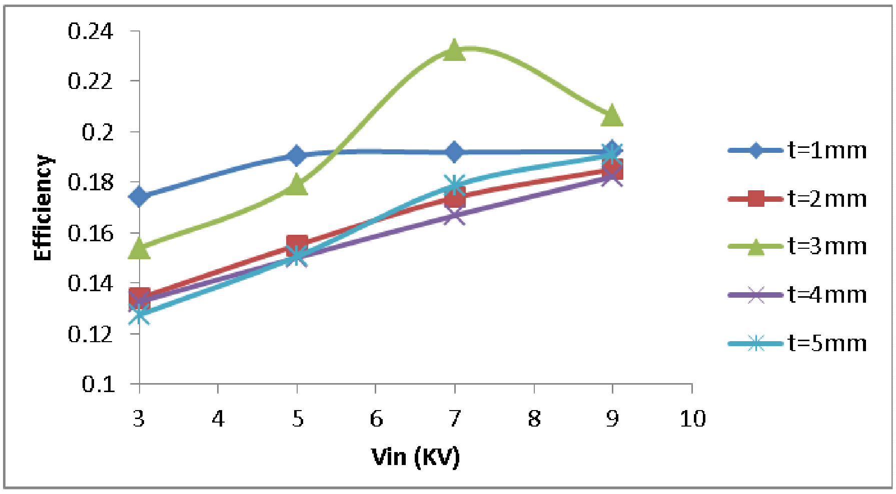
Fig. 3: The plasma actuator out power as a function of the applied voltage when the electrodes material is Copper and Aluminum, and the dielectric material is PMMA.

2.The Actuator Efficiency:

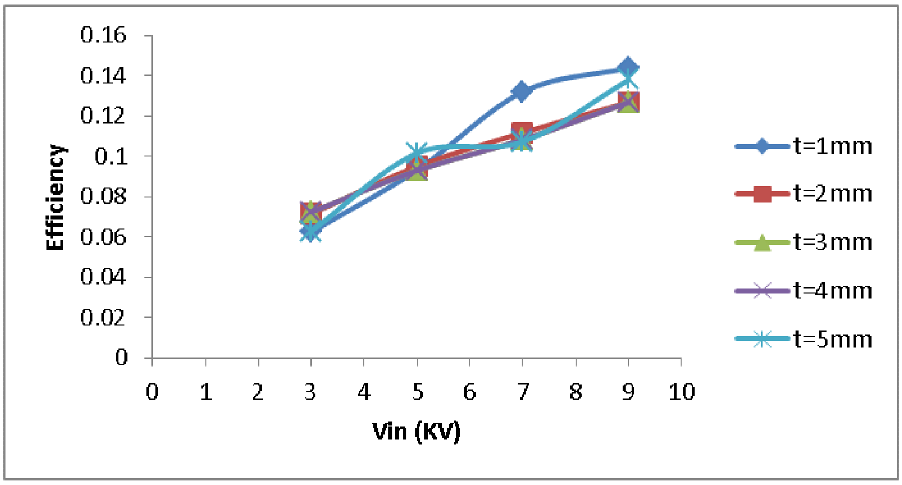
The criteria for good plasma actuator is its ability to transform the applied power to mechanical power; in other word its efficiency to transform the applied electric power to out power. The operating parameter of the actuator affects the efficiency. In this section, we will view the effect of some of these parameters on the actuator efficiency, such the dielectric thickness (i.e. the vertical distance between the two electrodes) and the horizontal distance the two electrodes. To give a full explanation, that was done at a range of applied voltages, different electrodes and dielectric materials.

3. The Dielectric Thickness Effect:

The actuator efficiency was calculated, using equation (6) for different dielectric thicknesses when the electrodes are copper and aluminum and dielectric materials are HPED and PMMA. Figure (4) shows the actuator efficiency as a function of the applied voltage when the dielectric is HDPE. It shows in (4a), copper electrodes, that the efficiency increases with the increasing of applied voltage for all dielectric thickness (1-5) mm, also it was denoted that the maximum efficiency, up to 0.23, occurs at the thickness of 3mm and 7 kV applied voltage in PMMA actuator. That is because higher stability as shown to getting resonance frequency at these values and output power is maximum as shown in figure (2-a). Approximately , same behavior appears in figure (4b) when the electrodes are aluminum, but all the values of the efficiency are less than that for the case of copper electrodes.



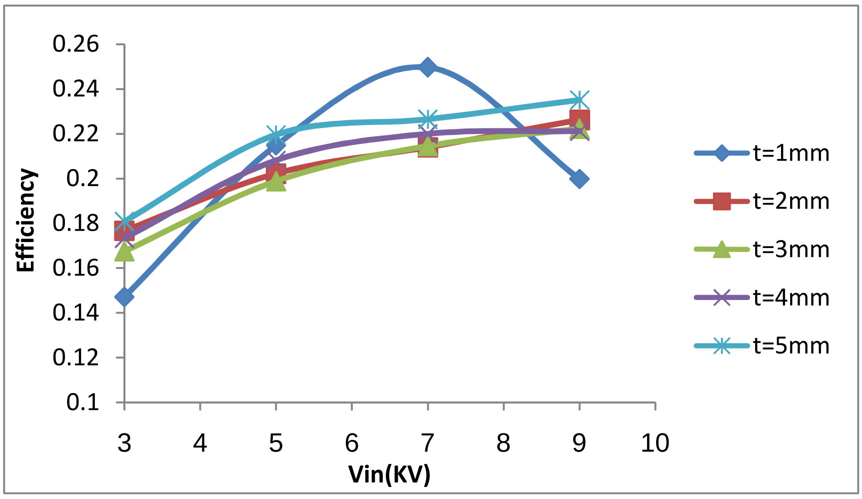
(a)



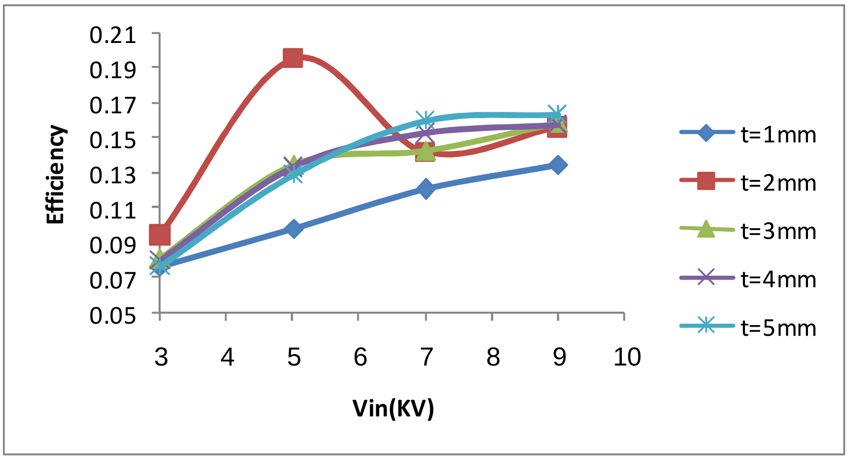
(b)

Fig. 4: The plasma actuator Efficiency as a function of applied voltage, for different dielectric thicknesses, when the dielectric is HDPE and the electrodes materials are a) Copper, and (b)Aluminum.

Under same conditions, except the dielectric is PMMA, another experiment was developed and the results, in figure (5), show approximately same general behavior but the efficiency values are greater and the maximum up to 0.25 when the electrode material is copper, the applied voltage 7 kV, and the dielectric thickness is 1mm. also is important to note the efficiency in general increases with the increasing of the dielectric thickness in high applied voltage.

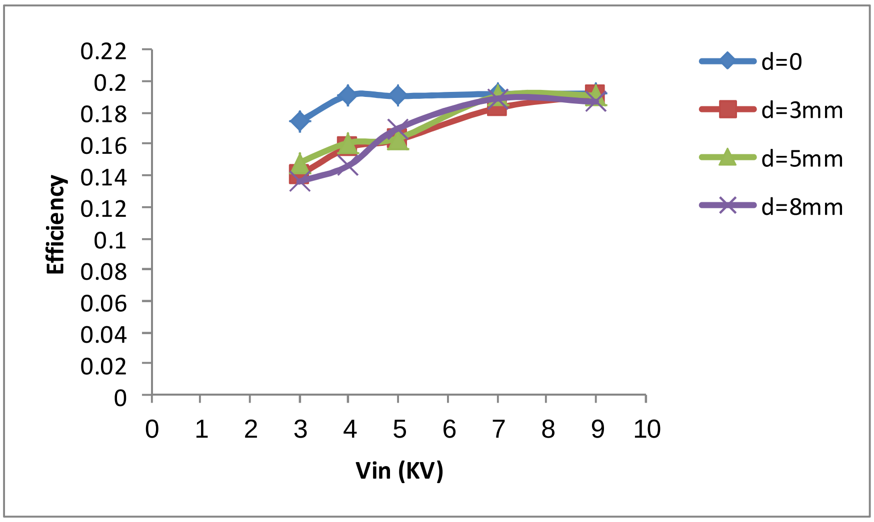


(a)

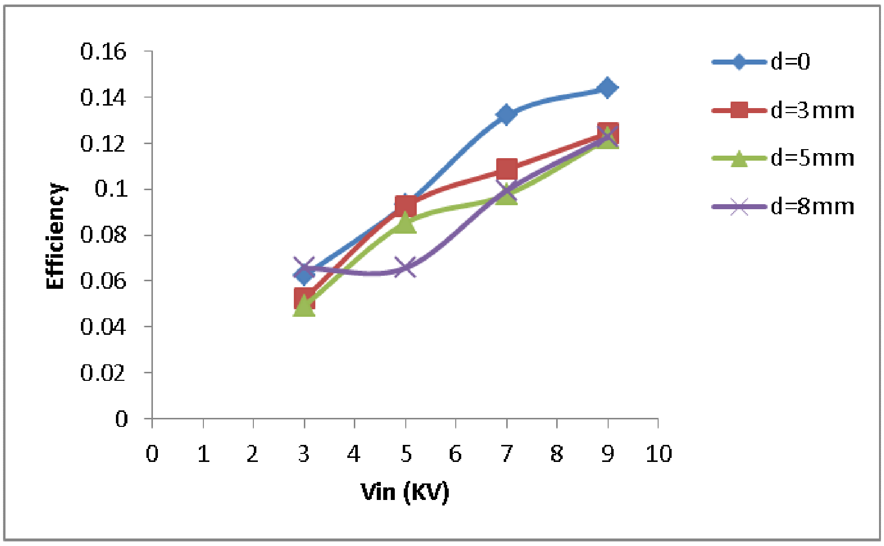


(b)

Fig. 5: The plasma actuator Efficiency as a function of applied voltage, for different dielectric thicknesses, when the dielectric is PMMA and the electrodes materials are a) Copper, and b) Aluminum.

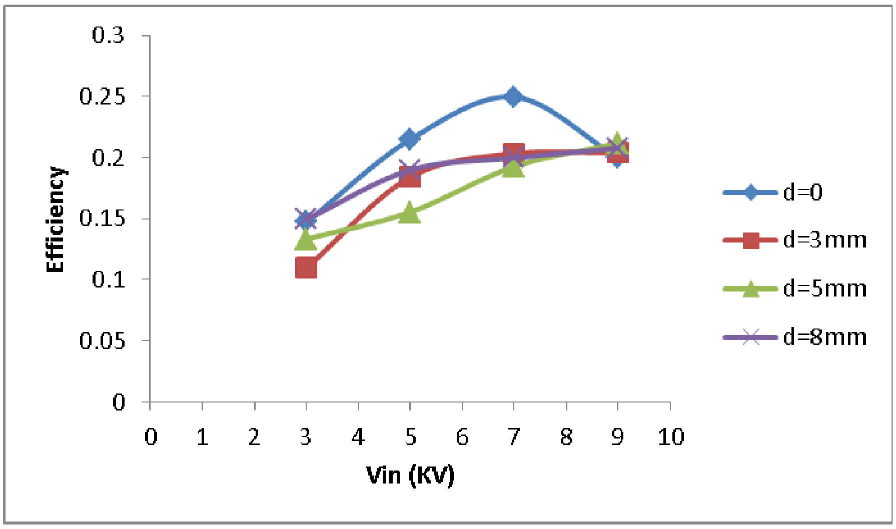


(a)

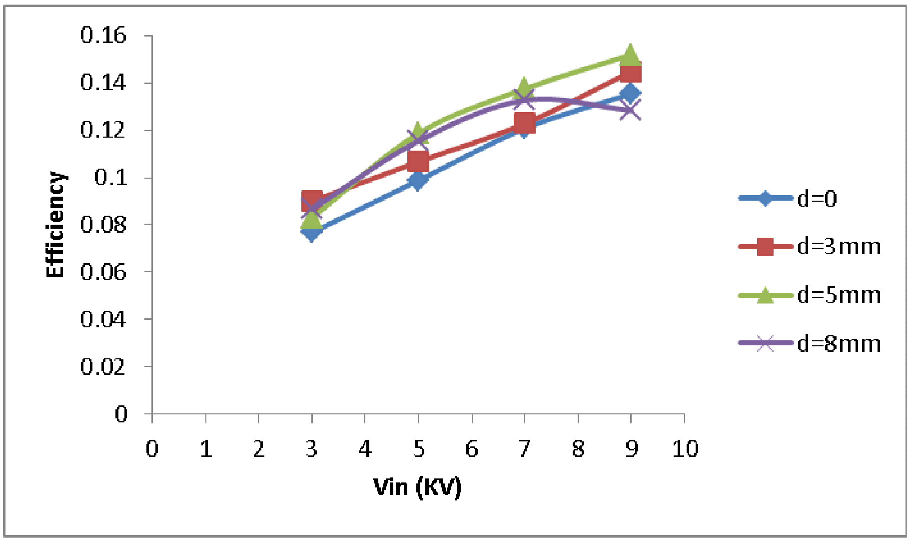


(b)

Fig. 6: The plasma actuator Efficiency as a function of applied voltage, for different horizontal distances, when the dielectric is HDPE and the electrodes materials are a) Copper, and b) aluminum.



(a)



(b)

Fig. 7: The plasma actuator Efficiency as a function of applied voltage, for different horizontal distances, when the dielectric is PMMA and the electrodes materials are a) Copper, and b) Aluminum.

4. The Horizontal Distance Effect:

In same procedure, as previously, the efficiency was calculated for different horizontal distances between the two electrodes. The results show unstable behavior in the efficiency with the increasing of the horizontal distance and applied voltage. But one can indicate that, the efficiency values became near at the higher applied voltages for all distances. Also, and as always in previous, the efficiency is greater when the cathode is copper and when the dielectric is PMMA as in figure (6) and (7).

Conclusions:

From the above results, one can conclude that, the plasma actuator efficiency can be controlled by some operating conditions. This study indicates that the copper is better cathode material than aluminum and PMMA better than HPED as dielectric for better efficiency. Also the zero horizontal distance and 3mm dielectric thickness are approximately the better.

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