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An investigation into the effect of electric field on the performance of Dielectric Barrier Discharge plasma actuators

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A R T I C L E I N F O

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The influence of the inter-electrode electric field of a single Dielectric Barrier Discharge (DBD) actuator on the performance of the device was investigated. The electric field of the actuator was manipulated through the variation of the angle between the electrodes of the actuators. Response forces generated by the plasma actuators were used as performance indicators for these devices. These forces were measured directly utilizing a highly sensitive balance scale. It was verified that depending on the orientation of the variation of the angle between the electrodes, the performance of the actuator may be decreased or increased when compared to a DBD on a flat dielectric plate more commonly investigated in literature. The manner in which the ionic wind flows over the actuators was also explored in the effort to elucidate the influence of the variation of the angle between the electrodes on the response force generated by the device. Results demonstrated that the response forces generated by the actuators may be improved by up to 50% compared to the actuator configuration on a flat dielectric plate commonly investigated. These results indicate the potential available to advance plasma technology by physically manipulating these devices to increase the performances of the actuators.

1. Introduction

Dielectric Barrier Discharge (DBD) plasma actuators are devices commonly utilized to generate non-thermal plasma discharge under atmospheric conditions. The application of active airflow control using plasma actuators has been conventionally investigated for the purposes of boundary layer control [1–3], flow separation control [4,5], and stall control on an airfoil [6–8]. DBD actuators consist of two electrodes separated by a dielectric layer; with one electrode exposed to airflow and the other encapsulated by an insulation material. These electrodes are designated as the exposed electrode and the encapsulated electrode respectively.

Plasma discharge is generated between the electrodes when an electric field of sufficient strength to sustain electron–ion pairs in the gas is established (Fig. 1a). When a high AC voltage is applied to the exposed electrode, a plasma discharge is formed over the surface of the dielectric between the exposed electrode and the encapsulated electrode (Fig. 1b). The generation of the plasma discharge in the vicinity of the electric field causes the charged particles to accelerate towards their respective electrodes. Collisions between these accelerating charged particles and the neutral air particles result in momentum being transferred to the ambient air.

It is well understood that the plasma discharge is distinctly different in the two AC half cycles [9]. The difference in the characteristics of the plasma discharge in each of the half cycles may be elucidated with the source of electrons during the ionization stage. During the negative half cycle, electrons originate from the exposed electrode which easily releases electrons. These electrons are then accelerated towards the encapsulated electrode, impinging on the dielectric surface in the process and subsequently become the source of electrons during the positive half cycle. As these electrons do not readily come off the dielectric layer, an asymmetrical momentum coupling is observed to occur during both half cycles with the neutral air particles. Details concerning the mechanism behind DBD actuators have been widely investigated [10–14] however the actual mechanism behind the physics of the plasma discharge is still under debate.

In quiescent air conditions, activating the DBD actuator induces ambient gas to be drawn in towards the surface of the actuator and accelerated downstream in a direction parallel to the actuator (Fig. 1b). This plasma induced airflow is termed ionic wind in literature. The generation of plasma discharge that accelerates the ambient gas causes a response force to be experienced by the plasma actuator itself (Fig. 2). This net force experienced by the actuator is attributed to the asymmetrical nature of the plasma discharge generated by the device during each of the AC half cycles. These response forces, although small, are readily measurable as a means of determining the performance of the actuators investigated [15,16].

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Nomenclature

A	area of plates in parallel	ε	permittivity of material between plates
C	capacitance	ε_o	permittivity of space
d	distance between the two plates	ϕ	capacitance angle
$\mathbf{E}$	electric field strength	θ	electrode angle
$\mathbf{F}$	force vector		
k	dielectric constant	*Subscripts*	
l	length of plates	$\Vert$	parallel
t	thickness of plates	a	air
V	voltage difference between the two plates	d	dielectric
w	width of plates		

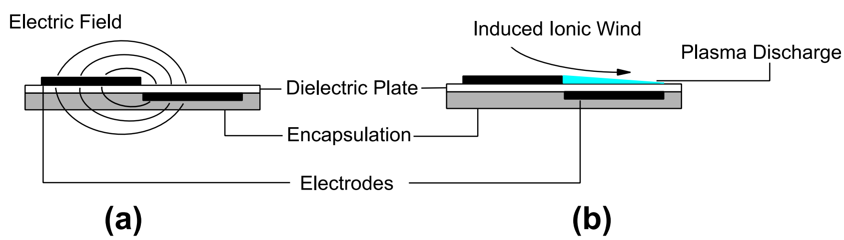

Fig. 1. Schematics of: (a) electric field and (b) plasma discharge.

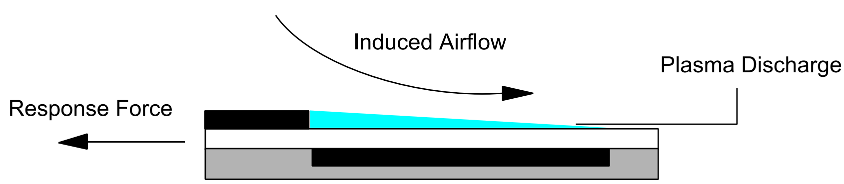

Fig. 2. Response force and induced airflow of plasma actuator.

Research on plasma actuators have been predominantly focused towards optimization through parametric investigations. Studies have demonstrated that the ionic wind velocities increase with frequency, power and voltage [14,17]. Previous works have also indicated that the ionic wind velocity is significantly influenced by geometrical parameters such as electrode gap, electrode orientation, dielectric thickness and dielectric material [10,12,14,17]. These works were undertaken to increase the velocities of the electric wind generated in order to improve the performance of plasma actuators.

Recent works have also been aimed at increasing the response forces generated by these devices as a means of improving the performance of the plasma actuators. Studies by Baughn et al. (2006) and Porter et al. (2007) demonstrated that the forces generated by the actuators were proportional to the frequency within the range of a few kHz [15,16]. In 2008, Abe et al. observed that response forces generated could be improved up to 50% by replacing thin sheet electrodes with mesh-type electrodes [18]. Works by Hoskinson and Hershkowitz (2010) demonstrated that modifying the geometry of the exposed electrode from the conventional rectangular electrode to a thin cylindrical electrode can improve the response force by 2–5 times [19]. Actuator effectiveness in terms of forces generated was also found to improve with increasing applied voltage [20].

Methods to improve the response forces of plasma actuators conventionally explored involve the modification of the geometry of the electrodes, material of the dielectric plates and electrical parameters. Contrary to conventional methodologies, a potential to improve response forces exists through the manipulation of the inter-electrode electric field of plasma actuators. It has been established that the plasma discharge propagates in the direction of the regions with increasing electric field gradients and induces a wall jet in the flow direction along the surface of the plasma actuator thereby adding momentum to the boundary layer of the fluid [21]. The inter-electrode electric field therefore governs the flow of the induced ionic wind whereby the velocity of the induced ionic wind can be changed through the interaction between the electric field and the space charge [22]. The presence of high space charge in the fluid is generally associated with the presence of strong electric field gradients and ionization waves. As such, the space charge on the ionization wave front under the influence of the strong electric field would result in significant acceleration of the fluid in the region of the electric field. Consequently, the interaction between the space charge and the electric field, together with the effective momentum transfer between the charged and neutral particles, collectively generates the flux acceleration of the fluid as a whole [22].

The inter-electrode electric field interactions therefore significantly impact the coupling of the response forces into the actuators [23]. The strength of the electric field and subsequently the response forces generated may be manipulated through modifications in the spatial orientation of the electrodes. Improvement in the electric field strength may be realised through the variation of the angle between the electrodes of the plasma actuators. This study is therefore aimed at investigating the effect of varying the angle between the electrodes of a single DBD actuator on the response forces generated. It is demonstrated that the variation of angles between electrodes was capable of improving the response forces generated when