Applied Physics Letters

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Cite as: Appl. Phys. Lett. **92**, 071504 (2008); https://doi.org/10.1063/1.2885085
Submitted: 16 January 2008 . Accepted: 04 February 2008 . Published Online: 21 February 2008

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AIP Publishing

Cross-talk in multiple dielectric barrier discharge actuators

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(Received 16 January 2008; accepted 4 February 2008; published online 21 February 2008)

Phase locked particle image velocimetry (PIV) is used to study flow alteration by dielectric barrier discharge actuators mounted on a bluff body. Images from these PIV experiments confirm the importance of negative ions in the actuation process and demonstrate cross-talk interactions between adjacent actuators. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2885085]

Radio frequency (rf) dielectric barrier discharge (DBD) actuators have been studied for their potential use to control flows on aerodynamic surfaces for more than a decade.[1–9] The rf DBD actuator induces suction flows toward the surface, leading to the formation of the so-called wall jets. The typical rf DBD actuator consists of a buried and an exposed electrode pair separated by a dielectric material. The actuator produces a weakly ionized gas in the near-surface region and a persisting electric field between the electrodes which acts on ionized gas, causing it to flow. This induced flow was found to be capable of altering lift on airfoils,[7] reducing aerodynamic drag[1,8] and delaying flow separation.[2,9]

There have been numerous studies investigating the mechanism of rf DBD actuation. Conventional wisdom proposed in previous studies, based in part on early numerical studies, is that positive ions produced from nitrogen in the air play a central role in flow actuation.[10,11] However, very recent simulations[12] and experiments[13] suggest that negative ions (from oxygen) may be even more important than nitrogen ions in DBD actuation. In the experimental study on a single DBD actuator configuration,[13] it appears that flow suction occurs in the phase of the alternating current cycle when the polarity of the buried electrode is positive, indicating that the suction flow is induced by negative ions.

The current study, using a configuration of multiple closely spaced DBD actuators, further confirms the dominant role played by the negative ions. However, unlike in the single DBD case, we observe additional cross-talk phenomena in which the negative ions induce strong suction flow between adjacent actuator pairs. In the present study, this cross-talk is investigated by phase locked particle image velocimetry (PIV) techniques.[13]

Phase locked PIV is carried out by synchronizing the voltage phase of the rf power supply to the laser trigger. The power supply used here produces a burst of at most two rf cycles (9 kV peak to peak voltage, 20 mA peak current, and 1.25 kHz frequency) at a repetition rate of 260 Hz. Signals triggered by the bursts are adjusted to a specific phase utilizing a delay generator, which also triggers two consecutive 532 nm laser pulses separated by 120 μs.

A schematic of the bluff body used in this study is shown in Fig. 1(a). The bluff body is made by connecting a 20 $\times 20$ cm^2 flat plate to the tangent of a 57 mm radius ceramic half-cylinder where four DBD actuators (i.e., two actuator pairs) are mounted on the body surface equally spaced 25 mm apart. The actuator electrodes consist of 0.1 mm thick, 20 mm long, 5 mm wide copper strips. A buried and an exposed electrode pair of individual actuators are separated by a 520 μm thick glass fiber dielectric strip. A photograph of the rf DBD produced by the actuators is shown in Fig. 1(b). The discharges extend 3 mm from the exposed electrode toward the buried electrode in the streamwise direction.

The PIV images of the flow near the two actuators (E2 and E3) are shown in Fig. 2. To obtain the phase locked PIV images shown, 100 phase locked instantaneous PIV images are ensemble averaged. Figure 2(a) is the flow with the DBD turned off. Figure 2(b) corresponds to the discharge-actuated flow within the time interval of 50–170 μs from the start of the first rf cycle in the pulse (23°–77° into the first cycle, when the buried electrode is positive relative to the exposed electrode). Figure 2(c) corresponds to a time delay of 450–570 μs (203°–257° into the first cycle, with the buried electrode now negative relative to the exposed electrode). In these images, the direction of the free stream (0.5 m/s) is from bottom to top and the color bar, which varies from blue

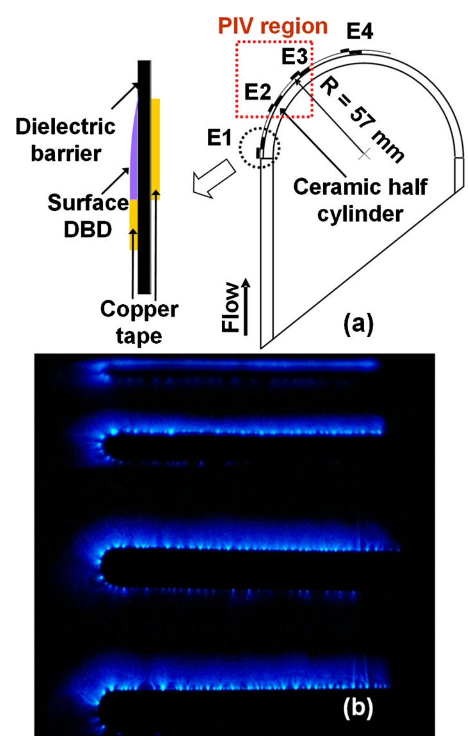

FIG. 1. (Color online) (a) Schematic of DBD actuator and bluff body and (b) rf DBD produced by the actuators viewed at 90° such that E1 is located at the bottom.

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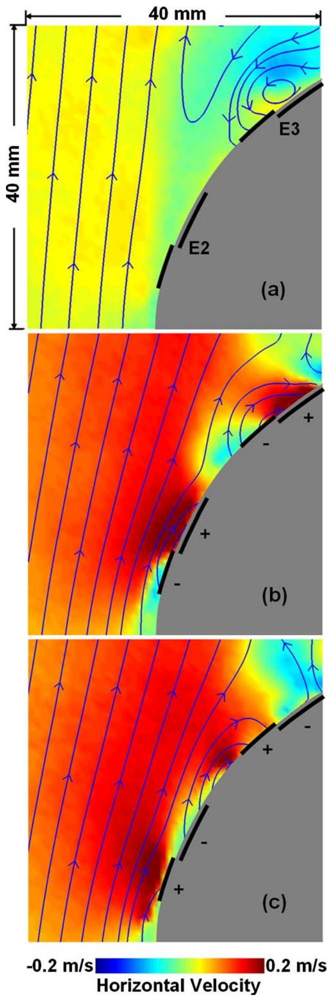

FIG. 2. (Color online) Ensemble averaged PIV images (a) in the absence of DBD actuation and (b) phase locked to 50–170 μs and (c) 450–570 μs in the presence of actuation.

to red (high velocity to the left and right respectively), represents the horizontal velocity component. The blue curves superimposed onto the PIV images represent pseudostreamlines. Locations of the electrodes are indicated by black strips on the body (which is shaded gray in the figure).

It is apparent from the PIV image in Fig. 2(a) that in the absence of DBD actuation, the freestream flow is separated from the surface under these flow conditions at a point near the vicinity of the electrode pair labeled E2. However, as seen in Figs. 2(b) and 2(c), when actuated, the DBD creates nonuniform suction flows that are always toward the positive electrodes, whether they are buried [Fig. 2(b)] or exposed [Fig. 2(c)]. This further confirms the significant role played by negative ions in DBD actuation. In contrast to our previous study of single electrode pair actuation,[13] we now find, with multiple actuator pairs, that significant suction flow is also observed when the exposed electrode is positively biased in the reverse stroke of the voltage swing. An examination of the flow by PIV during this phase of the rf cycle [Fig. 2(c)] reveals the surprising result that the suction flow is due to the interaction of the upstream buried electrode with the downstream exposed electrode. We believe that this cross-talk, i.e., the strong flow that is apparent at the exposed electrode of E3 during the reverse stroke, is caused by negative ion drift originating at the buried electrode of the upstream actuator, E2. The pseudostreamlines from the buried electrode of E2 toward the exposed electrode of E3 in Fig. 2(c) clearly highlight this observation.

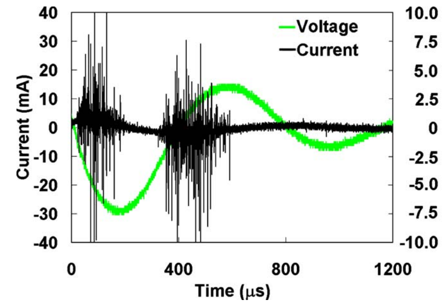

FIG. 3. (Color online) Voltage and current profiles of the DBD.

The discharge current and voltage waveforms, which also confirm the presence of cross-talk in the discharge cycles, are shown in Fig. 3. The voltage is measured at the exposed electrode, while the current measurements are taken at the buried electrodes. As seen in the figure, the strength of the current bursts generated during the forward voltage stroke (exposed electrode negatively biased) is comparable to the strength of those generated during the reverse voltage stroke. With only a single actuator activated, the current burst observed in the reverse stroke is small in comparison to that of the forward stroke.[13] In the absence of this detailed flow characterization, an examination of the current waveform alone might lead to the conclusion that the discharge cycle is nearly symmetric. However, the phase locked PIV images clearly reveal a complex flow interaction between actuators in a highly asymmetric discharge configuration.

In summary, this letter provides further evidence of the central role played by negative ions in DBD air flow actuation. The negative ions produced by the discharge induce a suction flow to the near-surface region and facilitate cross-talk interactions between adjacent actuators. These cross-talk interactions (between actuators that are separated by as much as 2.5 cm in our experiments) would require the drift of relatively long-lived negatively charged ions. Our previous study[13] determined that the strength of the negative-ion-induced suction flow is enhanced when the oxygen content in the flow is increased, suggesting that the negative ion responsible for flow actuation is a negatively charged form of oxygen (e.g., O_2^-). Future work will focus on identifying the dominant charged species in the flow and on understanding the detailed chemical mechanism responsible for their production.

This work is sponsored by the AFOSR/MURI Program-Experimental/Computational Studies of Combined-Cycle Propulsion: Physics and Transient Phenomena in Inlets and Scramjet Combustors, a joint effort of the University of Texas at Austin and Stanford University, with Julian Tishkoff as Technical Monitor.

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