19th Australasian Fluid Mechanics Conference
Melbourne, Australia
8-11 December 2014

Studies on the Configurations of Nanosecond DBD Pulse Plasma Actuators

Y.D. Cui, Z.J. Zhao, Y. Bouremel, J. Li, J.G. Zheng, F.G. Hu and B.C. Khoo

Temasek Laboratories, National University of Singapore, S117411, Singapore

Abstract

A conventional straight dielectric barrier discharge (DBD) actuator and a comb-shape DBD actuator driven by a high voltage nanosecond pulse were experimentally studied. The electric characteristics of the actuators were measured using a high voltage probe and a current shunt. The shock wave generated by the pulsed plasma was captured using a phase-locked Schlieren imaging technique. Different from the straight DBD actuator, the comb-shape DBD actuator shows a distinct formation of shock wave. These shock waves are generated from the plasma occurred only at the tips of the actuator. This implies that the layouts of the DBD actuators affect the electric potential between the exposed and covered electrodes, leading to various formations of shock wave. Thus different configurations of the nanosecond DBD actuators need to be considered when they are used for different applications in flow control.

Introduction

Recently, much attention has been devoted to the nanosecond dielectric barrier discharge (ns-DBD) plasma actuators as they demonstrated superior flow separation control capability at higher speed regimes as compared to AC-DBD actuators [1, 4, 5, 7-9]. This type of actuator usually has similar configurations as the AC-DBD device, driven by high-voltage repetitive pulses with rise time from a few to tens of nanoseconds. It has been generally agreed that the main control mechanism of the ns-DBD plasma actuator is through Joule heating [2, 4, and 9]. This Joule heating causes steep gradients in pressure and temperature inside the heated gas volume. As a result, moving shock waves, also named as micro shock waves [11], are generated. The very recent experimental and numerical studies in quiescent air [12, 13] further revealed that the shock wave is basically a kind of blast wave. It is observed that the pressure wave generated by the low pulse voltage is an acoustic wave. At high voltage, the shock can be fairly strong in terms of the induced fluid velocity (of up to hundreds m/s) and the overpressure (of up to tens of kPas) shortly after its initiation but decays very fast during the first few microseconds. The shock induced perturbations (overpressure and induced velocity) are restricted to a narrow region behind the shock front, lasting for a few microseconds only, showing extremely localized effects in space and transient effects in time. All these findings are based on the conventional DBD layout, i.e., straight exposed and buried electrodes are asymmetrically separated by a dielectric barrier, which results in a semi-cylindrical kind of shock wave structures. As the working mechanism for the nanosecond pulsed plasma actuators is fundamentally different from the AC-DBD actuators, the layout may not necessarily follow the conventional DBD layout. Various configurations may produce different shock wave structures leading to different interactions with the external flow. This is motivated us to explore the behaviours of various configurations of the ns-DBD pulsed plasma actuators.

Experiment Facilities and Techniques

NS-DBD Plasma Actuator

The construction of ns-DBD plasma actuator in this study is similar to those found in other AC-DBD plasma actuator studies. It comprises two electrodes (copper foil with a thickness of 66μm) mounted on both sides of a dielectric layer. This dielectric layer is made of several layers adhesive Kapton films (Kapton 500FN131), and each Kapton layer is 127μm thick. A typical actuator's layout (baseline, Case 1) is shown in figure 1, with $L = 80mm$, $w_1 = 8mm$, $w_2 = 15mm$, and thickness of $t = 0.67mm$ including 4 layers of Kapton and glue. The gap between the two electrodes is about 0-0.1mm. The nanosecond pulse to drive the ns-DBD plasma actuator was achieved by means of a nanosecond pulse generator (NPG-18/3500). This generator produces high-voltage pulses with the peak voltage from 12kV to 20kV at matched 75 Ohm load, the pulse rise time about 4 ns, the repetition rate of up to 3.5 kHz and the energy of up to 30mJ/pulse. Note that the peak voltage, current and the associated energy are strongly load-dependent. The applied voltage and current were measured using a high voltage probe (Tektronix P6015A) and a current shunt probe (Megaimpulse CS-10/500), respectively. In order to apply this probe to measure a pulse with nanosecond rise times, a calibration was conducted using a square wave (30Vp-p) with rise time ≤ 10 ns and with duration of 100 ns (generated from Digital delay generator Model DG645) following the manual of Tektronix P6015A.

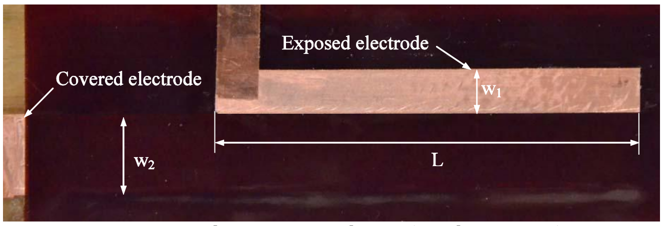

Figure 1. Typical DBD actuator layout (Baseline, Case 1).

Schlieren Observation

Schlieren technique was used to capture the evolution of the shock wave generated by the actuator. The Schlieren system mainly consists of two chromatic lenses (1m focal length), a Nanonolite flash lamp (25mJ/pulse, duration of 23ns) and a camera (PCO 1600). A Nikkor lens of 105mm was used, thereby giving rise to the spatial resolution of the image of about 0.081mm/pixel. To precisely synchronize the ns-pulse generator with other instruments, a digital delay with an accuracy of 5ps (DG645 Digital Delay Generator) was used to provide the trigger signals with predetermined time delays. The reference time $t = 0$ is defined as the moment when the discharge voltage reaches its peak value.

Results

Figure 2 shows the measured voltage, current traces and the corresponding calculated instantaneous power for Case 1. The peak voltage is about 30kV with the duration time of about 25ns and rising time of about 17ns. The peak current is about 120A, the peak power about 3200kW and the gross energy deposited about 22 mJ.

Typical formation of plasma for this case is shown in figure 3, with long time exposure. The picture was taken with the repetition rate of the pulsed plasma generator at 100Hz and with the camera exposure time of ½ seconds. From the observation of the pulsed plasma using ICCD camera [2, 8 and 9], the plasma lasts only tens of nanoseconds after the discharge. Thus the typical camera could not obtain a clear picture of the plasma formation. On the other hand, a long-time exposure picture still exhibits the instantaneous behaviour of the pulse plasma formation, i.e. plasma streamers. This indicates that the repeated high voltage pulse generates a certain pattern of plasma streamers rather than a random pattern that would form a uniform distribution of plasma under long time exposure conditions. This behaviour is favourable for studying the phenomena related to the pulse plasma using phase-locked technique since the generation of pulse plasma is very repeatable. Figure 3 shows that the plasma is composed of many streamers distributed along the edge of the exposed electrode toward the encapsulated electrode.

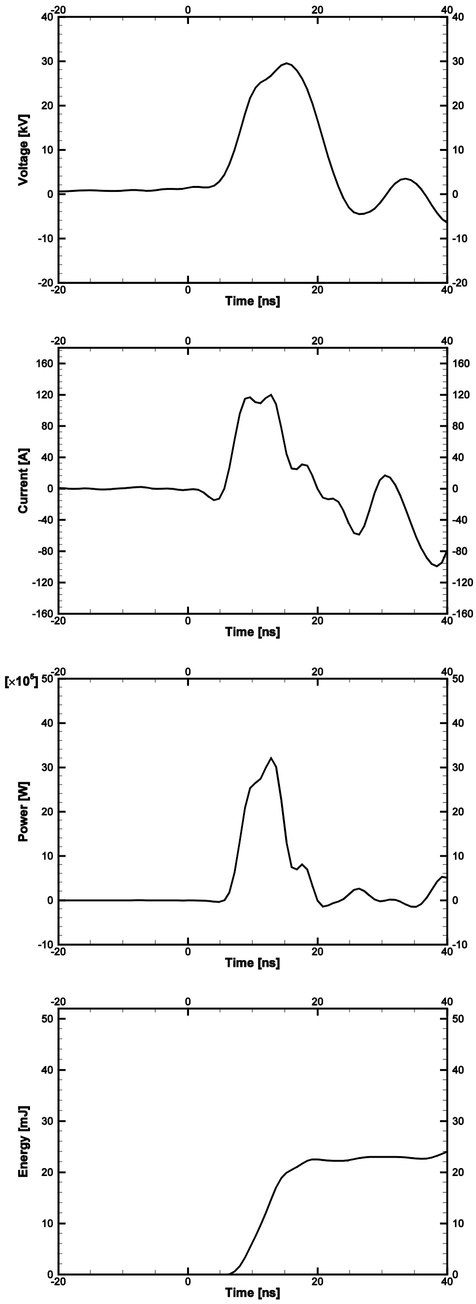

Figure 2. Electrical aspect of pulse discharge for Case 1 with low pass frequency of 500MHz.

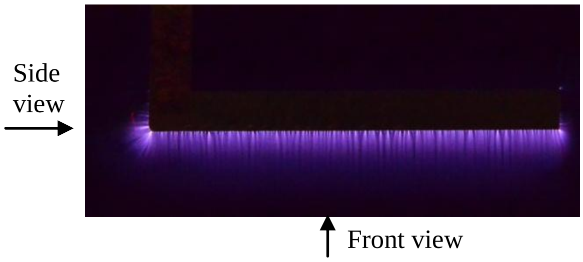

Figure 3. Plasma formation with repetition rate of 100Hz.

Figure 4 shows typical Schlieren images of the side view for four sequent time delays after discharge. Since the duration of the Schlieren source light is sufficiently short (23ns), the captured Schlieren images can be considered to be frozen. It can be seen clearly from the side view that the shock wave front consists of two distinct parts: a semispherical shock front with its center at the anode-cathode alignment point and a planar shock front which is parallel to the actuator surface with its end facing to the tips of the plasma streamers. These shock wave structures are in general the same as those observed by others [8, 9 and 12].

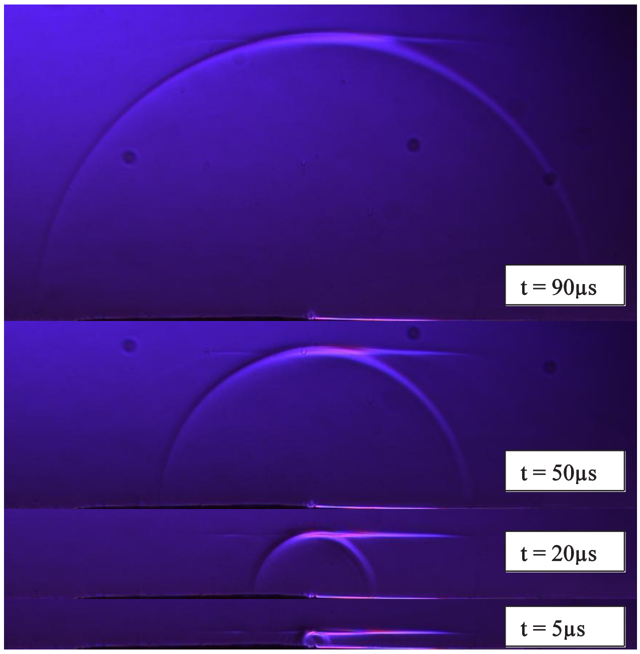

Figure 4. Phase-locked Schlieren images of the shock wave generated by the nanosecond pulse discharge (side view) with a straight DBD actuator.

Now we consider a comb-shape DBD actuator (Case 2) as shown in figure 5. All dimensions are the same as Case 1 except that there are 13 wires with diameter of 0.7mm diameter and length of 4mm between the exposed and covered electrodes. We expect that the wire tips have higher electric potential leading to the generation of the shock waves.

Figure 5. Comb-shape DBD actuator layout (Case 2).

The formation of plasma for this case is shown in figure 6, with long time exposure. It is clearly shown that the plasma streamers come out only from the tips of the wire. The measured voltage, current traces and the corresponding calculated instantaneous power and energy for Case 2 are shown in figure 7. The peak voltage is about 30kV similar to Case 1, while the measured current has some oscillations, which are not clear what causes these oscillations. The calculated peak gross energy is about 20 mJ.

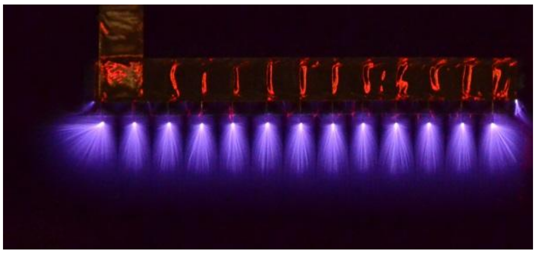

Figure 6. Plasma formation with repetition rate of 100Hz.

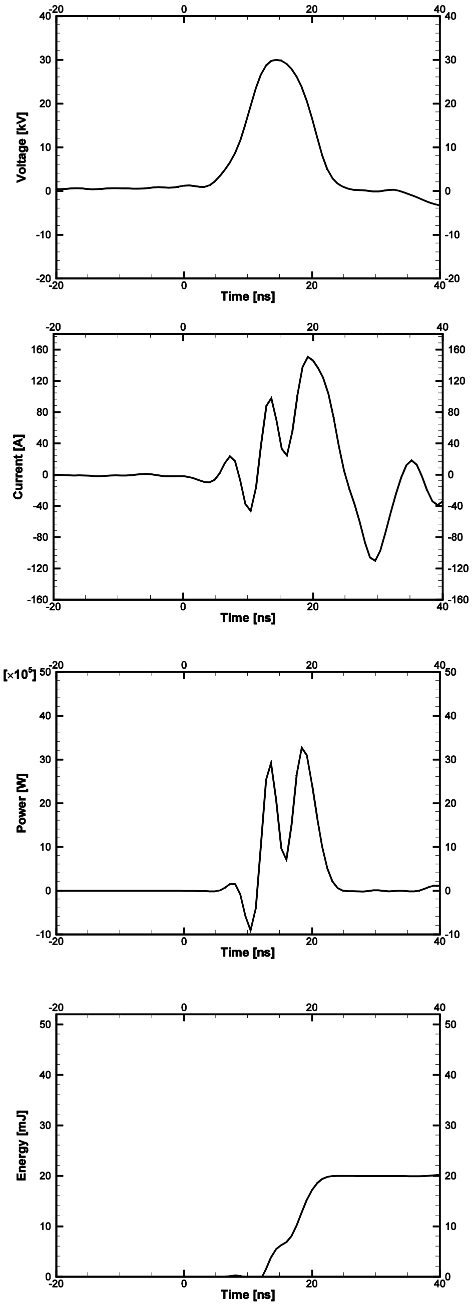

Figure 7. Electrical aspect of pulse discharge for Case 2 with low pass frequency of 500MHz.

Figure 8 shows typical Schlieren images of the side view for Case 2, which are very similar to Case 1. Figure 9 shows the front view for four sequent time delays after discharge. At t = 5μs, discrete shocks corresponding to individual tip of the actuator are evident. These shock waves merged gradually with the time. For the straight DBD actuators like Case 1, there are numerous semi-cylindrical shock wave fronts from numerous plasma filaments (see figure 9 in [12]), which are superimposed to form a straight shock wave front and propagate downstream. As for Case 2, the arrangement of the comb-shape actuator forces the plasma occurs at the tips of the actuators, forming the discrete shock waves at earlier stage after the discharge. This implies that the layouts of the DBD actuators affect the electric potential between the exposed and covered electrodes, leading to various formations of the plasma. The formations of plasma further determine how the shock waves are generated and interact with the external flow.

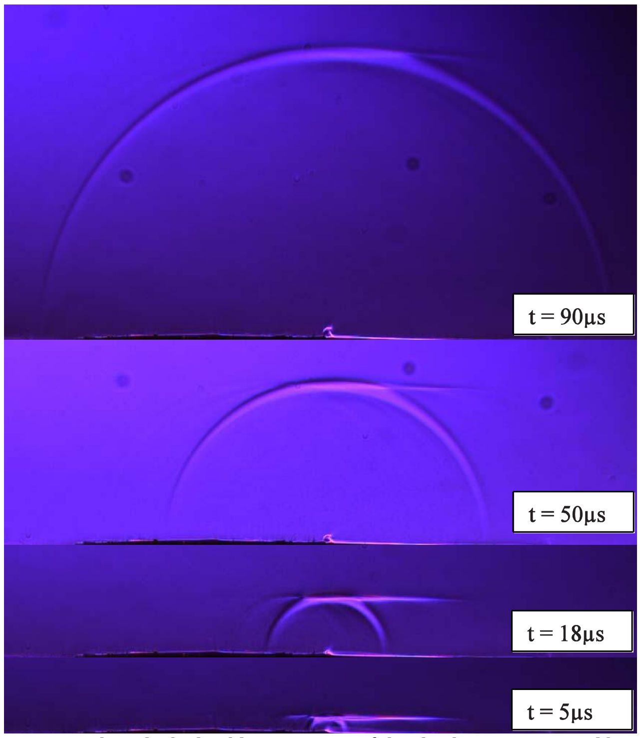

Figure 8. Phase-locked Schlieren images of the shock wave generated by the nanosecond pulse discharge (side view) with a comb-shape actuator.

Figure 9. Phase-locked Schlieren images of the shock wave generated by the nanosecond pulse discharge (front view) with a comb-shape actuator.

Another important issue is the load (impedance) of the DBD actuator, which affects greatly the performance of the actuator [3, 6]. For the pulse generator, it has optimal designed load. For example, the pulse generator used in this study has optimal output with 75 Ohm load. Following the method used in reference [6], we can roughly estimate the impendence of the actuators. For Case 1, the actuator's capacitance was measured experimentally using a Fluke LCR meter (LCR-916) and found to be about C = 7pF. The impedance of the actuator can be found from the expression $Z = 1/(U_pC)$, where U_p is the electric propagation speed in the dielectric barrier, defined as $Up = \frac{c}{\sqrt{\varepsilon}}$. (c is the speed of light and ε is the dielectric constant, for Kapton, ε is about 3.9). Thus the impedance estimated is about 940 Ohm. For this case, the impedance is far away from the cable impedance, which may lead to poor performance of the actuator. The load of the DBD actuator is affected by many parameters, such as the length and width of the electrodes, the thickness of the dielectric materials and the layout of the exposed and covered electrodes. By choosing the proper layout, dimensions and dielectric constant, the actuator could be designed in a way to match the cable impedance to improve the actuator's performance [3, 6].

Conclusions

As the working mechanism for the nanosecond pulsed plasma actuators is fundamentally different from the AC-DBD actuators, the layout may not necessarily follow the conventional AC-DBD layout. In present study, a conventional straight dielectric barrier discharge (DBD) actuator and a comb-shape DBD actuator driven by a high voltage nanosecond pulse were experimentally studied. Different from the straight DBD actuator, the comb-shape DBD actuator shows a distinct formation of shock wave. These shock waves are generated from the plasma occurred only at the tips of the actuator. This implies that the layouts of the DBD actuators affect the electric potential between the exposed and covered electrodes, leading to various formations of shock wave. Various configurations may produce different shock wave structures leading to different interactions with the external flow. For proper use of the nanosecond pulsed plasma DBD actuators, different configurations (layouts) of the actuators for various applications in flow control needed to be considered.

Acknowledgments

The authors gratefully acknowledge the financial support of the research project by the National University of Singapore. We thank Dr. Marco Debiasi of Temasek Laboratories for his support. We wish to express our gratitude to Mr. Bernard Lee Beng Teck and for the kind assistance rendered in the preparation of the experiments.

References

[1] Adamovich, I., Little, J., Nishihara, M., Takashima, K. and Samimy, M., "Nanosecond Pulse Surface Discharges for High Speed Flow Control," *6th Flow Control Conference*, No. 2012-3137, 2012.

[2] Benard, N., Zouzou, N., Claverie, A. Sotton, J. and Moreau, E., "Optical Visualization and Electrical Characterization of Fast-Rising Pulsed Dielectric Barrier Discharge for Airflow Control Applications," *J. Appl. Phys*, Vol. **111**, 033303, 2012).

[3] Dawson, R. and Little, J., "Characterization of nanosecond pulse driven dielectric barrier discharge plasma actuators for aerodynamic flow control," *J. Appl. Phys*, Vol. **113**, 103302, 2013.

[4] Little, J., Takashima, K., Nishihara, M., Adamovich, I., and Samimy, M., "Separation control with nanosecond-pulse-driven dielectric barrier discharge plasma actuators," *AIAA Journal*, Vol. **50**, no. 2, 2012, pp. 350-365.

[5] Nishihara, M., D. Gaitonde, D., and Adamovich, I., "Effect of Nanosecond Pulse Discharges on Oblique Shock and Shock Wave - Boundary Layer Interaction," *AIAA 2013-461*, 2013.

[6] Opaits, D.F., Shneider, M.N., and R. B. Miles, R.B., "Electrodynamic effects in nanosecond-pulse-sustained long dielectric-barrier-discharge plasma actuators," *Appl. Phys. Lett.* Vol. **94**, 061503, 2009.

[7] Rethmel, C., Little, J., Takashima, K., Sinha, A., Adamovich, I. and Samimy, M., "High lift airfoil leading edge separation control with nanosecond pulse driven DBD plasma actuators," *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, No. 2011-487, 2011.

[8] Roupassov, D., Nikipelov, A., Nudnova, M., and Starikovskii, A., "Flow Separation Control by Plasma Actuator with Nanosecond Pulsed-Periodic Discharge," *AIAA Journal*, Vol. **47**, No. 1, 2009, pp. 168–185.

[9] Starikovskii, A.Y., Nikipelov, A.A., Nudnova, M. M. and Roupassov, D.V., "SDBD Plasma Actuator with Nanosecond Pulse-Periodic Discharge," *Plasma Sources Science Technology*, Vol. **18**, 034015, 2009.

[10] Takashima (Udagawa), K., Zuzeek, Y., Lempert, W.R. and Adamovich, I., "Characterization of A Surface Dielectric Barrier Discharge Plasma Sustained by Repetitive Nanosecond Pulses", *Plasma Sources Science and Technology*, Vol. **20**, 055009, 2011.

[11] Unfer, T. and Boeuf, J.P., "Modelling of A Nanosecond Surface Discharge Actuator" *J. Phys. D: Appl. Phys*, Vol. **42**, 194017, 2009.

[12] Zhao, Z.J., Li, J., Zheng, J.G., Cui, Y.D., and Khoo, B.C., "Study of shock and induced flow dynamics by pulsed nanosecond DBD plasma actuators," *AIAA SciTech 2014, National Harbor*, Maryland, US, 13-17 January, 2014. AIAA- 0402.

[13] Zheng, J.G., Zhao, Z.J., Li, J., Cui, Y.D., and Khoo, B.C., "Numerical simulation of nanosecond pulsed dielectric barrier discharge actuator in a quiescent flow," *Physics of Fluids*, Vol. **26**, 036102, 2014.