Characterization of a surface dielectric barrier discharge plasma sustained by repetitive nanosecond pulses

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Abstract

The paper discusses experimental characterization of a surface dielectric barrier discharge plasma sustained by repetitive, high-voltage, nanosecond duration pulses. The discharge pulse energy is controlled primarily by the pulse peak voltage and scales approximately linearly with the length of the electrodes. Images of the plasma generated during the discharge pulse, taken by a nanosecond gate ICCD camera, show that the plasma remains fairly uniform in the initial phase of the discharge and becomes filamentary at a later stage. The temperature rise in the discharge, operated in both continuous mode and in burst mode, is inferred from UV/visible emission spectra. Phase-locked schlieren images are used to measure the speed of the compression waves generated by the nanosecond pulse discharge and the density gradient in the wave. The density gradient is inferred from the schlieren images using absolute calibration by a pair of wedged windows. The results demonstrate that discharge filaments generate compression waves with higher amplitude and higher speed compared with waves produced in a diffuse discharge. The density gradient in the compression waves is compared with numerical modeling of propagating compression waves produced by short-pulse localized heating, and shows satisfactory agreement between the model and the experimental results.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Plasmas generated in surface dielectric barrier discharge (DBD) flow actuators have been extensively studied over the last decade (see [1, 2] and references therein). Typically, DBD plasma actuators are driven by high-voltage, sine wave ac waveforms, with frequencies ranging from a few kHz to a few tens of kHz. In some cases, a dc bias or a series of short (nanosecond duration) pulses are added to the ac waveform to improve the actuator performance [3]. The dominant mechanism of neutral species flow acceleration by a surface DBD plasma, i.e. flow entrainment by ions accelerated in a space charge region of the plasma (electrohydrodynamic, or EHD flow acceleration), appears to be well understood [1, 2]. Compared with the Coulomb force interaction, the effect of Joule heating in surface DBD actuators driven by ac voltage waveforms appears insignificant.

One of the most critical issues for surface DBD plasma flow control technology is maintaining the actuator performance and achieving flow control authority at high flow velocities. The main limitation on the use of EHD acceleration for high-speed flow control is sustaining a high ion density, \(n_i\), in the space charge region of the electric discharge. For the EHD effect to be significant, the ratio of the Coulomb force work to the flow kinetic energy (the EHD interaction parameter) should be of the order of unity [4]. For electron/ion number densities achieved in atmospheric pressure surface discharges, \(n_i \sim 10^{10} - 10^{12} \text{ cm}^{-3}\), significant EHD effect on the flow can be achieved at free stream flow velocities of \(u_\infty \sim 1 - 10 \text{ m s}^{-1}\). Further ion density increase in the glow discharge plasma is severely limited by ionization instability development. As a result, the use of EHD acceleration for high-speed flow control, at flow velocities of a few hundred m s\(^{-1}\), is problematic. However, recent experiments on high-speed
airfoil flow control using DBD plasma actuators powered by a series of high-voltage, nanosecond duration pulses demonstrate flow reattachment at much higher velocities, up to $M = 0.85$ [5]. In [5], it was suggested that in this case the dominant effect of the plasma on the flow is caused by rapid localized heat generation in the actuator. Indeed, shock waves generated in quiescent air by localized heating in the discharge were detected in [5].

If confirmed, this mechanism would be consistent with the high-speed flow control mechanism used in repetitively pulsed localized arc filament plasma actuators (LAFPAs) [6–11]. The main idea of this approach is to force the flow with a high-amplitude, high-bandwidth perturbation, at a frequency approaching one of the flow instability frequencies, thereby triggering their subsequent growth in the flow. Previous studies of flow control using LAFPAs in atmospheric pressure jet flows ($M = 0.9–2.0$) [6–11] demonstrated significant localized heating and repetitive shock wave formation by the plasma, large-scale coherent structure generation, and mixing enhancement. This effect was achieved at a low actuator power, of the order of $\sim 10$ W per actuator, at forcing frequencies near the jet column (preferred mode) instability frequency. Also, our recent studies of high-speed flow control over an airfoil, using DBD plasma actuators powered by nanosecond pulse DBD plasma actuators have been detected in our recent experiments in a Mach 5 flow [13]. This suggests that the mechanisms of flow control for both types of actuators may be fairly similar.

The objective of this work is to characterize the plasma of a surface DBD plasma actuator driven by repetitive, high-voltage, nanosecond duration pulses and operating in quiescent air. In particular, measurements of temperature rise in the plasma, detecting compression waves generated in ambient air by localized heat release, and quantifying the compression wave strength, are the critical technical issues. This work is closely related to a recent study of airfoil flow separation control using surface DBD actuators powered by repetitive nanosecond pulses [12]. In particular, the same custom-designed nanosecond pulse plasma generator was used in both series of experiments.

2. Experimental setup and diagnostics

A schematic of the DBD plasma actuator used in this work is shown in figure 1. The actuator consists of an exposed high-voltage electrode 6.35 mm wide and a buried grounded electrode 12.7 mm wide, separated by three layers of 25.4 mm wide Kapton tape, each layer 0.1 mm thick. Both electrodes are made of adhesive copper tape 0.1 mm thick. There is no overlap between the two electrodes, as shown in figure 1. The actuator geometry is essentially the same as in [12]. The GFRP channel was used to mount variable length surface DBD actuators (up to 150 cm long) to measure energy coupled to the plasma versus actuator length. For ICCD plasma imaging, schlieren imaging, and plasma temperature measurements by emission spectroscopy, the actuator was mounted on the Nylon cylinder and its length was fixed at 30 cm. The cylinder model was chosen to simplify the schlieren diagnostics alignment and to resolve the region near the actuator surface. During some of the present experiments, a floating electrode with a sharp point, also made of an adhesive copper tape, was placed on the top of the Kapton tape with the point located 2 mm away from the high-voltage electrode, as shown in figure 1. This was done to stabilize a discharge filament in which the temperature was measured by emission spectroscopy. For emission spectroscopy and calibrated schlieren measurement, an additional Kapton layer

Figure 1. Schematic of a nanosecond pulse DBD plasma actuator, with a photograph showing a floating tip electrode.
was added, bringing the total thickness of the dielectric barrier in the actuator to approximately 0.4 mm.

The repetitive nanosecond pulse voltage waveform of a surface DBD discharge was generated by a high-voltage pulsed power supply, custom designed and built at Ohio State University. The power supply generates high-voltage pulses (peak voltage up to 20 kV, pulse duration 50–100 ns FWHM), with a pulse repetition rate of up to 10 kHz (in burst mode) or up to 2 kHz (in continuous mode). Both the peak voltage and the pulse energy coupled to the load are strongly load-dependent. Pulse voltage and pulse current are measured at the load using a Tektronix P6015 high-voltage probe, a custom-made current shunt probe, and Tektronix TDS2024 oscilloscope, as shown in figure 1. The current probe consists of five radially arranged resistors connected in parallel, with a total resistance of 0.2 Ω. The current probe impedance is set at 50 Ω by adding a 49.8 Ω resistor. The stray phase shift between the high-voltage probe signal and the current probe signal is determined by reducing to zero the integral of the product of voltage probe signal and the current probe signal is determined by reducing to zero the integral of the product of voltage and current, under the conditions when the pulse voltage is a few hundred volts and does not cause breakdown between the actuator electrodes. The estimated upper bound uncertainty in the measured coupled pulse energy is 2%.

To detect compression waves (shock waves) generated by the nanosecond pulse discharge in the DBD actuator, a custom-built phase-locked schlieren system was used, shown schematically in figure 2. The light source used was a 5 W green light-emitting diode (LED). The schlieren images were acquired by a Thorlab DCC1545 CMOS camera. To discriminate stray UV/visible emission from the plasma, a green dichroic filter was placed in front of the camera, as shown in figure 2. The LED pulse duration was set at 300 ns, and it was operated at the same pulse repetition rate as that of the nanosecond pulse discharge in the DBD actuator. The LED drive circuit was synchronized with the pulsed plasma generator with a certain delay time, and phase-locked schlieren images were accumulated over several hundred discharge pulses. The pulsed plasma generator jitter was approximately 50–100 ns, with the overall timing uncertainty of ±200 ns (shock front position uncertainty of 0.07 mm).

The schlieren signal, \( I_{\text{Sch}} \), is proportional to the relative density gradient integrated over the depth of field, as follows:

\[
I_{\text{Sch}} \propto \int_{-a/2}^{a/2} \frac{1}{\rho_0} \left( \frac{\partial \rho}{\partial x} \right) \, dz = \int_{-a/2}^{a/2} \frac{\partial \rho}{\rho_0} \, dz \quad (1)
\]

where \( n_0 \) and \( \rho_0 \) are the index of refraction and the density of air at 273 K and 1 atm, \( n_{\text{air}} \) is the index of refraction in the region of interest, \( a \approx 4 \) cm is the depth of field, and \( \partial \rho_{\text{air}}/\partial x \) is the density gradient averaged over the depth of field. To infer the average density gradient from the schlieren signal intensity, the schlieren system is calibrated using a pair of wedged BK-7 glass windows, as shown in figure 3. The wedged surfaces of the windows are set parallel to each other, such that for the baseline window orientation the transmitted schlieren beam is parallel to the incident beam. The distance between the non-wedged surfaces is set to be equal to the depth of field, \( a = 4 \) cm. When window \( W_2 \) is rotated, the transmitted beam is refracted, and the beam focal point at the plane of the knife edge follows a circle with a diameter of approximately 120 mm (i.e. much greater than the diameter of the focused beam, \( < 1 \) mm). Therefore, if the rotation angle, \( \omega \), is small, it can be assumed that the focal point moves across the knife edge in a straight line, along the \( x \)-axis for the window orientation shown in figure 3. Thus, the wedged window rotation changes the schlieren signal intensity. It can be shown that the relative density gradient, averaged along the field of view, is related to the window rotation angle as follows:

\[
f = \frac{1}{\rho_0} \frac{\partial \rho_{\text{air}}}{\partial x} = \left( \frac{n_{\text{glass}} - n_0}{n_0 - 1} \right) \tan \theta \frac{a}{2} \sin \omega, \quad (2)
\]

where \( n_{\text{glass}} \) is the index of refraction of the window, \( \theta = 2^\circ \) is the wedge angle, and \( \omega \) is the rotation angle.

To obtain the density gradient across the shock wave, the value of \( f \) inferred from the schlieren signal intensity was
multiplied by the ratio of the depth of field, \( a \), and the optical path along the shock, \( s \)

\[
\frac{\partial \rho\text{\_shock}}{\partial x} = \frac{a}{s} \approx \frac{a}{(8R\delta)^{1/2}}, \quad (3)
\]

where \( R \) is the radius of a cylindrical shock wave and \( \delta \approx 0.1 \text{ mm} \) is the apparent shock thickness in the phase-locked schlieren image.

Images of the nanosecond pulse plasma during the high-voltage pulse and after the pulse were taken using an Andor ICCD camera with a UV lens. The time-averaged temperature in the plasma was inferred from the nitrogen second positive system spectra \( N_2(C^3\Pi \rightarrow B^3\Pi) \), \( (0,0) \) and \( (0,2) \) bands, taken using an OMA system with an Acton SP-300i spectrometer, 2400 lines \( \text{mm}^{-1} \) grating, and a Princeton Instruments PI-MAX gated ICCD camera.

3. Results and discussion

Figure 4 shows time traces of pulse voltage, current, instantaneous power and time integral of the instantaneous power (i.e. energy coupled to the actuator) measured in a DBD actuator 148 cm long. The pulse repetition rate was fixed at 10 Hz. Increasing the actuator length resulted in a peak voltage reduction, from 16 kV for a 30 cm long actuator to 11 kV for a 148 cm long actuator. This is caused by the actuator capacitance increasing as its length is increased, \( C_{\text{load}} \sim 10^2 - 10^3 \text{ pF m}^{-1} \). Note that varying the actuator length also changes the voltage pulse rise time, controlled by the inductance and the capacitance of the plasma generator, the actuator, and the cables. In this work, the shortest voltage pulse rise/fall time is approximately 40 ns, which corresponds to a knee frequency of \(~12 \text{ MHz}\) and the wavelength of \(~24 \text{ m}\). Therefore, under the present conditions, the nanosecond pulse DBD load can be considered as a lumped parameter circuit, because the actuator length is much shorter than a quarter of the wavelength.

Figure 5 plots coupled pulse energy per unit length, in \( \text{mJ cm}^{-1} \), defined as the integral of the instantaneous power 300 ns after the beginning of the discharge pulse, for different actuator lengths and peak voltages. During these measurements, the actuator length, initially 148 cm, was gradually reduced to 15 cm, to exclude the effect of small differences in geometry between different actuators. It can be seen that the coupled energy per unit length is basically controlled by the peak voltage and is nearly independent of the actuator length and the voltage rise time, which varied in the range from 40 to 100 ns for the conditions of figure 5. Figure 5 also plots coupled pulse energy for negative polarity pulses, produced by a different pulsed plasma generator of the same design. Note that coupled pulse energies for the same peak voltage and different polarities are noticeably different. This effect may be attributed to the difference in charge build-up characteristics for different pulse polarities \[3\], but it may well be due to difference in the residual inductance of the two plasma generators. Figure 6 plots coupled pulse energy in a 44 cm long actuator under steady-state conditions (measured after approximately 10 min of continuous operation of the
Figure 7. Photographs of repetitive nanosecond pulse discharges. (a) 150 cm long actuator, positive polarity pulses, 1 kHz pulse repetition rate; (b) 30 cm long actuator, positive polarity pulses, 100 Hz and 4 kHz pulse repetition rates; (c) 30 cm long actuator, negative polarity pulses, 100 Hz and 4 kHz pulse repetition rates.

Figure 8. ICCD images of a positive polarity pulse discharge in a DBD actuator, shown together with the current pulse waveform. The ICCD camera gate time is 2 ns, the pulse repetition rate is 1 Hz.

plasma generator) versus pulse repetition rate. It can be seen that increasing the pulse repetition rate from 10 Hz to 1 kHz results in a coupled pulse energy increase by more than 50%, from 8.9 mJ to 14.8 mJ.

Figure 7(a) shows a photograph of a repetitive nanosecond pulse discharge in a DBD actuator 148 cm long, taken with a digital camera with a 0.8 s exposure. Figures 7(b) and (c) illustrate the effect of pulse repetition rate on discharge uniformity. The camera exposure time was varied with pulse repetition rate to keep the number of discharge pulses during the exposure approximately the same. It can be seen that the discharge becomes filamentary as the pulse repetition rate is increased. This effect becomes even more apparent for negative polarity pulses, shown in figure 7(c). At a pulse repetition rate of 100 Hz, the negative polarity discharge appears diffuse and nearly uniform. However, as the repetition rate is increased above 1 kHz, multiple large-scale filaments begin to form.

Figure 8 shows a series of ICCD images of a positive polarity nanosecond pulse discharge in the DBD actuator mounted on a cylinder model, at the pulse repetition rate of 1 Hz. In the images shown in figure 8, the camera gate
is 2 ns. In the present experiments, the jitter between the discharge pulse and the camera gate is within 1 ns. In figure 8, the discharge images are shown together with the current waveform, indicating the moment in time when they are taken. The discharge emission, initially observed near the high-voltage electrode (at the top of the ICCD images), propagates along the dielectric surface toward the grounded electrode (at the bottom of the images). The propagating emission front corresponds to the positive polarity current (i.e. current directed from the high-voltage to the grounded electrode). The emission wave appears to have two distinct ‘fronts’. In this phase, the discharge appears rather uniform, although some structure can still be identified. Since the current in this phase remains positive, positive charge builds up on the dielectric surface.

After the current switches direction (approximately at \( t = 70 \) ns in figure 8), the luminous wave propagating from the high-voltage electrode is observed again (at \( t = 80–130 \) ns). Since the current now has negative polarity, the positive charge build-up on the dielectric is reduced. The discharge filaments near the high-voltage electrode are constricted and become diffuse on the dielectric side. The filamentary structure of the discharge is also apparent from photographs (e.g. see figure 7) and visual observations.

Figure 9 shows ICCD images of the negative polarity discharge, under the same conditions as in figure 8. Qualitatively, the discharge emission behavior is similar to that of the positive polarity pulse. Initially, the emission propagates from the high-voltage electrode over the dielectric covering the grounded electrode. During this phase, negative charge accumulates on the dielectric surface. When the current polarity changes to positive (approximately at \( t = 70 \) ns in figure 9), the charge stored on the dielectric surface flows back to the high-voltage electrode, and the emission wave propagates over the dielectric surface again. Although the negative polarity discharge appears somewhat more uniform than the positive polarity discharge shown in figure 8, constricting filaments near the high-voltage electrode are still apparent (see figure 9). Basically, plasma filamentation is observed when the electric charge accumulated on the dielectric surface is removed, independent of the pulse polarity. Further ICCD images demonstrate that location, shape and intensity of individual filaments are fairly random, although some of the filaments have a tendency to form at nearly the same locations. However, even these relatively reproducible filaments shift pulse-to-pulse considerably, over distances exceeding their thickness (~0.1 mm).

Rotational temperature in the discharge was inferred from the nitrogen second positive band system \( \text{N}_2(C^3\Pi_u \rightarrow B^3\Pi_g) \), using a synthetic spectrum code [14]. For this, the ICCD camera exposure time was set to 1 \( \mu \)s to capture emission from a single discharge pulse. During these measurements, the discharge was operated in burst mode, with 50 pulses in a burst at 10 kHz pulse repetition rate and 10 Hz burst repetition rate. To take emission spectra from a filament stabilized by a sharp tip floating electrode (see section 2), the filament emission was selected using collimation optics and a slit. Figure 10 compares experimental emission spectra (vibrational band (0,0)) with best fit synthetic spectra. The experimental spectra in figure 10(a) were obtained from relatively diffuse plasma, without the floating tip electrode. The synthetic spectra providing the best fit to the experimental spectra from pulses #1 and #50 in the burst give rotational temperatures of \( T = 380 \pm 50 \) K and \( T = 450 \pm 50 \) K, respectively. The experimental spectra in figure 10(b) were obtained from a filament stabilized using a sharp tip floating electrode. In this case, temperatures inferred from the synthetic spectra are significantly higher, \( T = 550 \pm 70 \) K for pulse #1 and \( T = 650 \pm 90 \) K for pulse
the density gradient in the positive y-direction (i.e. up) and to the second derivative of the density along the horizontal (x) axis, because a pinhole light source is used instead of a slit source. Since the wave generated by the discharge pulse is propagating upward, lower intensity indicates compression and higher intensity indicates expansion. It can be seen that the wave in figure 11 consists of a compression wave and an expansion wave following it. To monitor the wave propagation, a series of schlieren images have been taken for delay times after the pulse ranging from 1 \( \mu s \) to 50 \( \mu s \), with 1 \( \mu s \) intervals. Figure 11 shows just three of these images, with 10 \( \mu s \) intervals.

Figure 12 shows phase-locked schlieren images taken under the same conditions but from a different direction, perpendicular to the cylinder model axis (x-axis in figure 11). In figure 12, the model is on the bottom of the images. Phase-locked schlieren images in figure 12 show a nearly plane wave front propagating along the vertical axis, as well as multiple circular waves. In figure 12, higher signal intensity indicates compression and lower intensity indicates expansion. It can be seen that the wave front near the actuator surface appears to have multiple ‘ripples’ created by individual circular waves, coalescing into a superposition wave with an apparently plane front. It is likely that the line-of-sight averaging of these individual waves creates a ‘circular’ wave front apparent in the schlieren images of figure 11. It was observed that the individual circular wave pattern correlates well with the discharge emission intensity pattern. As discussed above, heating in the discharge filaments occurs on the time scale of \( \sim 200 \) ns. This is comparable to the acoustic time scale, \( \tau_{\text{acoustic}} \sim d/a \sim 300\) ns, where \( d \sim 0.1 \) mm is the apparent filament diameter in the ICCD camera images and \( a \sim 300 \) m s\(^{-1}\) is the speed of sound. Therefore, such rapid localized heating is likely to produce strong compression waves.

Figure 13(a) shows a phase-locked schlieren image taken using a sharp point floating tip electrode in a positive polarity discharge, again looking in the direction perpendicular to the cylinder model axis (x-axis in figure 11). The electrode tip is located near the center of the image. It can be seen that a circular compression wave is generated near the electrode tip. This wave propagates more rapidly than the plane wave generated by diffuse plasma, and its intensity on the schlieren image is higher. In figure 13(b), showing a schlieren image from the negative polarity discharge, both bright plasma emission from a strong filament (compare with figure 7) and a circular compression wave originated from the filament can be detected. Again, the localized compression wave propagates significantly more rapidly compared with the plane compression wave, and its intensity is higher.

Figure 14(a) plots the compression wave front position above the cylinder model surface versus time delay between the nanosecond discharge pulse and the schlieren light source pulse. The two data sets shown are for the positive polarity discharge, with and without the floating tip electrode. The data in figure 14(a) are obtained from phase-locked schlieren images such as shown in figures 12 and 13. Symbol size in figure 14(a) indicates the uncertainty in the shock front location.

### Figure 10.
Nitrogen second positive emission spectra (vibrational band (0,0)) from a DBD actuator, (a) without a sharp tip floating electrode, (b) with a sharp tip electrode. Spectra were taken with the pulser operating in burst mode, at a pulse repetition rate of 10 kHz, burst repetition rate of 10 Hz, with 50 pulses in the burst.

#50 in the burst, although the fit to experimental spectra is not as good as in diffuse plasma. Since the discharge emission is observed only during the current pulse (e.g. see figures 8 and 9), temperature rise during a pulse occurs over a period of less than \( \sim 200 \) ns. Kinetic mechanisms of rapid energy thermalization (\( \sim 1 \) \( \mu \)s time scale at atmospheric pressure) in pulsed discharges in air at high reduced electric field (\( E/N \sim 10^{-2} \)–\( 10^{-3} \) Td, 1 Td = \( 10^{-13} \) V cm\(^2\)) are discussed in [15–18]. Kinetic modeling calculations suggest that the dominant processes contributing to rapid energy thermalization include quenching of excited electronic states of \( \text{N}_2 \) molecules and O atoms (at \( E/N < 400 \) Td) [15, 17, 18], as well as ion–molecule reactions, electron–ion and ion–ion recombination (at \( E/N \sim 10^{-3} \) Td) [16, 17].

Figure 11 shows phase-locked schlieren images of a Mach wave generated by a nanosecond pulse DBD actuator in quiescent air, for three different time delays between the discharge pulse and the schlieren light source (LED) pulse. Both the discharge pulse and the schlieren light pulse repetition rates are 1 kHz. These images are taken using a DBD actuator mounted on a cylinder model, looking in the direction parallel to the cylinder axis (z-axis in figure 11). The surface of the DBD actuator, mounted on the model, is curved in the images. In figure 11, the image intensity is proportional to

\[ \text{Intensity} = \text{exp}( - \frac{d}{L} ) \]

where \( d \) is the distance from the model axis, \( L \) is the laser beam length, and \( 1/m \) is the range of intensity detected by the laser source. It is likely that the line-of-sight averaging of these individual waves creates a ‘circular’ wave front apparent in the schlieren images of figure 11. It was observed that the individual circular wave pattern correlates well with the discharge emission intensity pattern. As discussed above, heating in the discharge filaments occurs on the time scale of \( \sim 200 \) ns. This is comparable to the acoustic time scale, \( \tau_{\text{acoustic}} \sim d/a \sim 300\) ns, where \( d \sim 0.1 \) mm is the apparent filament diameter in the ICCD camera images and \( a \sim 300 \) m s\(^{-1}\) is the speed of sound. Therefore, such rapid localized heating is likely to produce strong compression waves.

Figure 13(a) shows a phase-locked schlieren image taken using a sharp point floating tip electrode in a positive polarity discharge, again looking in the direction perpendicular to the cylinder model axis (x-axis in figure 11). The electrode tip is located near the center of the image. It can be seen that a circular compression wave is generated near the electrode tip. This wave propagates more rapidly than the plane wave generated by diffuse plasma, and its intensity on the schlieren image is higher. In figure 13(b), showing a schlieren image from the negative polarity discharge, both bright plasma emission from a strong filament (compare with figure 7) and a circular compression wave originated from the filament can be detected. Again, the localized compression wave propagates significantly more rapidly compared with the plane compression wave, and its intensity is higher.

Figure 14(a) plots the compression wave front position above the cylinder model surface versus time delay between the nanosecond discharge pulse and the schlieren light source pulse. The two data sets shown are for the positive polarity discharge, with and without the floating tip electrode. The data in figure 14(a) are obtained from phase-locked schlieren images such as shown in figures 12 and 13. Symbol size in figure 14(a) indicates the uncertainty in the shock front location.
Figure 11. Phase-locked schlieren images of a compression wave generated by a nanosecond pulse discharge for several time delays after the discharge pulse, 5 \( \mu \)s to 25 \( \mu \)s. Positive polarity pulses, discharge pulse repetition rate 1 kHz, camera exposure time 156 ms (images are averaged over 156 discharge pulses). Images taken from a direction parallel to the cylinder axis.

Figure 12. Phase-locked schlieren images of a compression wave generated by a nanosecond pulse discharge for several time delays after the discharge pulse, 5 to 25 \( \mu \)s. Positive polarity pulse, pulse repetition rate 2 kHz, camera exposure time 214 ms (images are averaged over 428 discharge pulses). Images taken from a direction perpendicular to the cylinder axis.

Figure 13. Close-up view of compression waves produced by a discharge filament stabilized by a sharp floating tip electrode. (a) Positive polarity pulses; (b) negative polarity pulses. Pulse repetition rate 2 kHz. Camera exposure time 214 ms (images are averaged over 428 discharge pulses). Images taken from a direction perpendicular to the cylinder axis.

Figure 14 also plots a \( M = 1 \) sound wave trajectory at \( T = 285 \) K (\( u = 338 \) m s\(^{-1} \)) as a straight line. One can see that several millimeters away from the actuator surface, the speed of compression waves generated by the pulsed discharge (i.e. the trajectory slope) becomes close to Mach 1. However, the compression wave trajectories near the actuator surface are shifted up (especially the one with the floating tip electrode), indicating propagation at a speed higher than the speed of sound.

The density gradient in the compression waves produced by the nanosecond pulse discharge was inferred from the schlieren signal intensity using wedged window calibration, as discussed in section 2. Figure 15 plots the density gradient in the wave, normalized by the ambient air density, versus time delay after the discharge pulse for two different sets of conditions, positive polarity pulses with and without a floating tip electrode. From figure 15, it is clear that the compression wave amplitude is considerably enhanced using the sharp tip electrode. However, the density gradient in the compression wave generated in a discharge with a strong filament, stabilized by a floating tip electrode, decays rapidly with the distance from the actuator surface. In the discharge without a floating tip, the density gradient, although significantly lower near the origin, decays more slowly with distance.
The pulse, compared with modeling calculations.

Figure 15. Normalized density gradient in compression waves generated by the nanosecond pulse discharge versus delay time after the pulse, compared with modeling calculations.

The compression wave density gradient inferred from the calibrated schlieren images was compared with the density gradient predicted by numerical modeling of propagating compression waves produced by short-pulse localized heating. For this, we used a one-dimensional compressible Navier-Stokes flow model developed in our previous work [7]. Using this model, density gradient across a compression wave generated in atmospheric pressure air by an isolated filament 0.1 mm in diameter, heated over a 100 ns period to a centerline temperature of $T = 650$ K ($\Delta T \approx 350$ K) and $T = 380$ K ($\Delta T \approx 80$ K), was modeled in cylindrical and spherical geometries. These filament temperatures were chosen based on the emission spectroscopy temperature measurements (see figure 10).

The results, plotted in figure 15, show that the density gradient predicted in a spherical geometry compression wave with the initial filament temperature of $T = 650$ K agrees well with the measurements in a discharge with a floating tip electrode. On the other hand, density gradient predicted in a cylindrical geometry wave with the initial filament temperature of $T = 380$ K is in satisfactory agreement with the data obtained in a discharge without a floating tip electrode. Qualitatively, this result is expected. Indeed, since the size of the filament stabilized by a floating tip electrode is $\sim 1$ mm $\times$ $\sim 0.1$ mm (based on ICCD camera images), the compression wave produced by the filament becomes a nearly spherical wave at distances exceeding $\sim 1$ mm from the actuator surface. On the other hand, the wave generated by a more diffuse discharge without a floating tip electrode propagates as a nearly cylindrical wave, as shown in figure 11, and decays significantly more slowly.

4. Summary

This work discusses experimental characterization of a surface dielectric barrier discharge (DBD) plasma sustained by repetitive, high-voltage, nanosecond duration pulses. Current, voltage, instantaneous power, and coupled pulse energy in the surface DBD actuator powered by high-voltage nanosecond pulses have been measured for different pulse peak voltages, pulse repetition rates, and actuator lengths. The results demonstrate that pulse energy per unit length is controlled primarily by the pulse peak voltage and is not affected by the actuator length. The results also show that the actuator can be scaled to a length of at least 1.5 m. Images of the plasma generated during the nanosecond pulse discharge development were taken by a nanosecond gate ICCD camera. The results show that the plasma remains fairly uniform in the initial phase of discharge development and becomes filamentary at a later stage. Although the negative polarity nanosecond pulse discharge generates a uniform plasma at low pulse repetition rates ($\sim 100$ Hz), it becomes strongly filamentary as the pulse repetition rate is increased beyond $\sim 1$ kHz.

The temperature rise in the discharge with a floating tip electrode, inferred from UV/visible emission spectra, is $\Delta T = 250 \pm 70$ K after the first pulse in a 50-pulse burst at a 10 kHz pulse repetition rate, and $\Delta T = 350 \pm 90$ K after pulse #50 in the burst. The temperature rise in more diffuse plasma without a floating tip under the same conditions is $\Delta T = 80 \pm 50$ K after the first pulse and $\Delta T = 150 \pm 50$ K after pulse #50 in the burst. Based on the ICCD images of the plasma, the estimated time scale for temperature rise during the pulse does not exceed $\sim 300$ ns.

Phase-locked schlieren images were used to measure the speed of compression waves generated by the nanosecond pulse discharge and the density gradient in the wave. The density gradient was inferred from the phased-locked schlieren images using absolute calibration by a pair of wedged mirrors. The results demonstrate that discharge filaments generate compression waves with higher amplitude and higher speed compared with those produced in a diffuse discharge. The density gradients in these compression waves were compared with numerical modeling of propagating compression waves produced by short-pulse localized heating. The results of the calculations are in satisfactory agreement with the
experimental data. Strong compression wave generation in surface DBD actuators powered by nanosecond discharge pulses at high repetition rates may be used for exciting instabilities in air flow, and potentially for high-speed flow control.

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