Investigation of nanosecond-pulsed dielectric barrier discharge actuators with powered electrodes of different exposures

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Abstract
Nanosecond-pulsed dielectric barrier discharge actuators with powered electrodes of different exposures were investigated numerically by using a newly proposed plasma kinetic model. The governing equations include the coupled continuity plasma discharge equation, drift-diffusion equation, electron energy equation, Poisson’s equation, and the Navier-Stokes equations. Powered electrodes of three different exposures were simulated to understand the effect of surface exposure on plasma discharge and surrounding flow field. Our study showed that the fully exposed powered electrode resulted in earlier reduced electric field breakdown and more intensive discharge characteristics than partially exposed and rounded-exposed ones. Our study also showed that the reduced electric field and heat release concentrated near the right upper tip of the powered electrode. The fully exposed electrode also led to stronger shock wave, higher heating temperature, and larger heated area.

Keywords: nanosecond-pulsed dielectric barrier discharge, plasma actuators, powered electrode, shock wave, flow field

(Some figures may appear in colour only in the online journal)

1. Introduction

Dielectric barrier discharges (DBD) have been used in various industrial applications, such as non-equilibrium magneto-hydrodynamic devices [1, 2], enhancing ignition and plasma-assisted combustion [3, 4], and flow-control actuators [5–7]. Extensive studies have been conducted to understand the fundamental mechanism and to improve DBD plasma actuator efficiency [8–10]. These studies have shown that the shape of electrodes can significantly affect the performance of DBD plasma actuators [11–13]. For example, serrated plasma actuators can induce streamwise and spanwise vortices in the shear layer [12, 14, 15], which enhance momentum-transfer across the boundary layer and hence increase DBD actuator efficiency [11, 12]. A serrated exposed electrode can also induce larger body force than a conventional trip configuration [16]. Previous studies have also shown that thrust produced by the DBD plasma actuator strongly depends on the thickness of the exposed electrode [17]: a 50% increase in body force was reported when a thin sheet was used as the exposed electrode [18].

DBD plasma actuators are promising for low-speed flow control, but their applicability to high-speed flow control is limited, because of the relatively low flow velocity they induce. It has been demonstrated that nanosecond-pulsed dielectric barrier discharges (NS-DBD) are able to induce flow reattachment at velocities up to a Mach number of 0.85 [6]. Unlike DBD plasma actuators that only transfer momentum to surrounding fluids, NS-DBD plasma actuators can also transfer thermal energy. The rapid heating over a short time...
period generates compression waves or even shock waves near the powered electrodes. Research has been conducted to improve the efficiency of NS-DBD plasma actuators by changing the dielectric thickness [19–21] or actuator geometry [7, 21, 22]. Moreau et al [7], for example, used a three-electrode configuration to increase the extension length up to the electrode gap, resulting in a 300% increase in the input energy from a current collected at the third electrode. Others [5, 20, 23] applied positive polarity pulses to investigate the effects of actuator parameters on the characteristics of gas heating generated in NS-DBD. Results from these studies suggested that dielectric thickness has little effect on the characteristics of gas heating generated in NS-DBD, and the new model was validated efficiently for complicated actuator geometries and problems in multiple fluids, but limited studies have been devoted to this subject. In our previous work [26], we proposed a simplified plasma kinetic model to investigate the mechanism of the plasma aerodynamic actuation driven by NS-DBD, and the new model was validated efficiently for the relative permittivity of vacuum space, $\varepsilon_0$, the electron temperature, $T_e$, the species number density, $n_j$, the corresponding flux, $R_j$, the local creation loss rate due to chemical reactions, $E$ the electric field, $q_j$ the corresponding species charge, the reactive rate coefficients are listed in table 1, of which the detailed explanation can be found in our previous work [26], in which the kinetic plasma model was simplified into one with seven species and nine reactions. The species include electron (e$^-$), electronically excited states of nitrogen (N$_2$(B$^3$I$^2$)), N$_2$(C$^3$I$^2$)), ions (N$_2^+$, O$_2^+$), and ground-state neutrals (N$_2$, O$_2$). The reaction mechanism includes electron impact reactions (1,2 and 6,7),

**Table 1. Reaction mechanism.** Number densities in m$^{-3}$, temperature $T$ in K, electron temperature $T_e$ in eV, one-body rates in s$^{-1}$, and two-body rates in m$^3$s$^{-1}$.

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>e$^-$ + N$_2$ $\rightarrow$ e$^-$ + e$^-$ + N$_2^+$</td>
<td>$4.1 \times 10^{-14} \exp(-18.7/T_e)$</td>
</tr>
<tr>
<td>2</td>
<td>e$^-$ + O$_2$ $\rightarrow$ e$^-$ + e$^-$ + O$_2^+$</td>
<td>$2.3 \times 10^{-15} T_e^{0.5} \exp(-12.79/T_e)$</td>
</tr>
<tr>
<td>3</td>
<td>N$_2$(C$^3$I$^2$) $\rightarrow$ N$_2$(B$^3$I$^2$)</td>
<td>$3 \times 10^6$</td>
</tr>
<tr>
<td>4</td>
<td>e$^-$ + N$_2^+$ $\rightarrow$ N$_2$</td>
<td>$2 \times 10^{-7} (300/T_e)^{0.5}$</td>
</tr>
<tr>
<td>5</td>
<td>e$^-$ + O$_2^+$ $\rightarrow$ O$_2$</td>
<td>$2 \times 10^{-7} (300/T_e)^{0.5}$</td>
</tr>
<tr>
<td>6</td>
<td>e$^-$ + N$_2$ $\rightarrow$ e$^-$ + N$_2$(B$^3$I$^2$)</td>
<td>$k_{excl}(\sigma)$</td>
</tr>
<tr>
<td>7</td>
<td>e$^-$ + N$_2$ $\rightarrow$ e$^-$ + N$_2$(C$^3$I$^2$)</td>
<td>$k_{excl}(\sigma)$</td>
</tr>
<tr>
<td>8</td>
<td>O$_2$ + N$_2^+$ $\rightarrow$ N$_2$ + O$_2^+$</td>
<td>$6.0 \times 10^{-11} (300/T_e)^{0.5}$</td>
</tr>
<tr>
<td>9</td>
<td>N$_2$(C$^3$I$^2$) + N$_2$ $\rightarrow$ N$_2$ + N$_2$(B$^3$I$^2$)</td>
<td>$1.0 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

The exposure of electrodes can affect the momentum and energy transfer to surrounding fluids, but limited studies have been devoted to this subject. In our previous work [26], we proposed a simplified plasma kinetic model to investigate the mechanism of the plasma aerodynamic actuation driven by NS-DBD, and the new model was validated efficiently for complicated actuator geometries and problems in multiple dimensions by comparing the results with experimental and numerical data. In this paper, we will investigate the effect of powered electrode exposure on NS-DBD plasma actuators. The rest of the paper is structured as follows: first, we present the physical model and numerical method. Then, we simulate NS-DBD actuators with three different exposed cases. We compare the discharge characteristics and responses of the induced flow field among these three actuators. Finally, we conclude the significance of the right edge and upper tip of the powered electrode on the performance of the fluid flow.

## 2. Governing equations and numerical method

The governing equations for plasma discharge shown below include the continuity equation for each species, drift-diffusion equation, and Poisson equation for electric field [27, 28],

$$\frac{\partial n_j}{\partial t} + \nabla \cdot \Gamma_j = \sum_i R_{ij} \tag{1}$$

$$\Gamma_j = \pm \mu_j n_j E - D_j \nabla n_j \tag{2}$$

$$\varepsilon_0 \varepsilon_r \nabla \cdot E = \sum_j q_j n_j \tag{3}$$

where, $n_j$ is the species number density, $\Gamma_j$ the corresponding flux, $R_{ij}$ the local creation loss rate due to chemical reactions, $E$ the electric field, $q_j$ the corresponding species charge, $\varepsilon_0$ the permittivity of vacuum space, $\varepsilon_r$ the relative permittivity of air, $\mu_j$ the electron mobility, and $D_j$ the electron diffusivity. The mobility and diffusion coefficient data for the neutral and ion species can be found in the literature [29–32]. The kinetic mechanism and corresponding reaction rate coefficients are listed in table 1, of which the detailed explanation can be found in our previous work [26], in which the kinetic plasma model was simplified into one with seven species and nine reactions. The species include electron (e$^-$), electronically excited states of nitrogen (N$_2$(B$^3$I$^2$)), N$_2$(C$^3$I$^2$)), ions (N$_2^+$, O$_2^+$), and ground-state neutrals (N$_2$, O$_2$). The reaction mechanism includes electron impact reactions (1,2 and 6,7),
electron-ion recombination reactions (4, 5), quenching reactions (3, 9) and charge-exchange reactions (8). Besides, the rates of reactions 6 and 7 ($k_{exch} = \tau$) can be found in [26].

The following electron energy equation was adopted to obtain the electron energy,

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma_e = -e \Gamma_e \cdot E - Q_e$$  \hspace{1cm} (4)

$$\Gamma_e = -\mu_e n_e E - D_e \nabla n_e$$  \hspace{1cm} (5)

where $n_e$ is the electron number density, which is the multiplier of the electron number density and the mean energy of the species of emitted electron, $\Gamma_e$ electron energy flux, $\mu_e$ the electron energy mobility, and $D_e$ the electron energy diffusion coefficient, and $Q_e$ is the energy loss of electrons due to elastic and inelastic collisions. The electron energy mobility and energy diffusivity are computed using Einstein’s relation for a Maxwellian electron energy distribution function $\mu_e = 5/3 \mu_e$ and $D_e = \mu_e T_e$.

NS-DBD plasma aerodynamic actuation transfers not only momentum but energy from plasma discharges to surrounding gas flow. The equations for the whole gas dynamics were based on the compressible Navier–Stokes equations including the continuity equation, momentum equation, and energy equation with source terms obtained from the discharge plasma:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$  \hspace{1cm} (6)

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u u + pI - \tau) = F$$  \hspace{1cm} (7)

$$\frac{\partial (\rho C_p T)}{\partial t} + \nabla \cdot [\rho u C_p T - k \nabla T] = Q$$  \hspace{1cm} (8)

where $\rho$ is the density, $p$ is the pressure, $\tau$ is the viscous shear stress tensor, $T$ is the temperature, $C_p$ describes the amount of heat energy required to produce a unit temperature change in a unit mass, and $k$ is the thermal conductivity. $F$ is the body force generated by the nanosecond plasma actuator given by $F = E \cdot j$, where $j$ is the space-charge density given by $j = \sum_i q_i n_i \cdot \nabla \cdot j E$ is the heat source term, $j$ is the current density $j = e(\Gamma_{NC} + \Gamma_{OE} - \Gamma_{E})$, and $\Phi$ is the viscous dissipation. Usually, compared to the gas heating released to the gas flow from the discharge process, the viscous dissipation of the NS-DBD plasma discharge has a negligible influence on the fluid field in such a short pulse discharge time and it was ignored during the simulation in the present model.

Figure 1 shows the procedures to solve the problem. The simulation starts from the plasma discharge model and ends with the induced fluid dynamic model. For computational efficiency, the calculations were carried out in two stages. The first stage encompassed the first 100 ns of the pulse discharge. For this stage, the discharge model and the fluid dynamic model were fully coupled. The plasma discharge model (equations (1)–(4)) calculates the averaged statistical properties of the plasma particles by solving the continuity (equation (1)) and drift-diffusion equations (equation (2)) using the Scharfetter–Gummel method [33] for flux calculation.
with an adaptive time step. The Poisson equation (equation (3)) for electric field was solved using the LU triangular matrix decomposition [27]. The space-charge density and current density from equations (1), (2), (4) and the electric potential from equation (3) were taken as power input to the flow dynamic model with Navier–Stokes equations (6)–(8), which were solved using the implicit, second-order upwind scheme [28, 34]. The temperature and velocity of the flow field affects the motion of the particles and the reaction rates in the discharge progress. Since the electric effects and particle motion become negligible after the input pulse dies away, in the second stage of the computations, only the fluid dynamic model was employed.

During the simulation, one set of unstructured mesh with about $10^4$ grid cells was adopted to couple the discharge model and fluid dynamic model. In order to capture the discharge features near the right edge and upper tip of the powered electrodes, the minimum value of the grid size was taken as $10^{-7}$ mm in the simulation. However, for computational efficiency, the time step for the discharge process is set at $10^{-11}$ s, while it was $10^{-7}$ s after discharge.

For each simulation, the initial number density ($n_j$) of the electron is about $10^{14}$ m$^{-3}$, the mole fraction of the neutral species is $1 \times 10^{-10}$, and the mole fraction for each ion species is set in a way that the space charge is zero under standard atmospheric pressure and temperature of 300 K. The initial time step is $10^{-13}$ s and the maximum time step is $10^{-9}$ s during the simulation.

Standard boundary conditions for the charged particles as well as the neutral particles described in [34] were employed: at the wall, the ion flux was set to zero and the ion temperature was the same as the wall temperature, where the ion velocity was set to satisfy the secondary emission with secondary electron emission coefficient 0.01 and the electron

![Figure 4](image1.png)

**Figure 4.** Diagram of the three NS-DBD plasma actuators. Case A has a rectangular powered electrode with only exposed upper surface; Case B has a rectangular powered electrode with three exposed surfaces; Case C has a round-cornered powered electrode with three exposed surfaces.

![Figure 5](image2.png)

**Figure 5.** Waveform of the pulsed voltage used in the simulation.

![Figure 6](image3.png)

**Figure 6.** Comparison of the reduced electric field at 40 ns (Left) and 80 ns (Right). First row: Case A; Second row: Case B; Third row: Case C.
temperature was set at 2 eV. At the far-fields, the normal
derivatives of the ion and electron flow to open boundaries
are set to zero. The surface-charge accumulation was deter-
mined by integrating
\[ \frac{\partial \rho_s}{\partial t} = n \cdot j_{ion} + n \cdot j_e, \]
where \( \rho_s \) is the surface-charge density, \( j_{ion} \) is the ion current density, and
\( j_e \) is the electron-ion density. The dielectric layer was
approximated to a uniform electric field \( E_d \), which is related to
the internal electric field at the surface through the relation
\[ -n \cdot (\varepsilon_0 \varepsilon_r E_d - \varepsilon_0 E) = \rho_s. \]
No-slip boundary conditions with a constant temperature wall were set for the hydrodynamics
model. The far-fields boundary conditions of Navier–Stokes
equations are set to be open boundaries.

3. Method validation

Plasma discharge and flow actuation on a typical asymmetric
NS-DBD plasma actuator were simulated under the condi-
tions described in [6] by solving the five-moment equations
for particle discharge and Navier–Stokes equations for flow
field in our previous work [26]. In this paper, under the same
conditions, the NS-DBD plasma actuation were carried out by
solving the drift-diffusion equations for particle discharge
using the simplified kinetic chemical model. As shown in
figure 2, the powered electrode, with three surfaces (top, left,
and right) exposed, is 0.0625 mm wide and 5 mm long. The

<table>
<thead>
<tr>
<th>Variables</th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td>The streamer where the electron density is higher than ( 1.4 \times 10^{18} \text{ m}^{-3} )</td>
<td>0.1 ( \times 0.05 )</td>
<td>0.2 ( \times 0.12 )</td>
<td>0.1 ( \times 0.07 )</td>
</tr>
<tr>
<td>The streamer where the power density is higher than ( 3 \times 10^{12} \text{ W/m}^3 )</td>
<td>0.05 ( \times 0.03 )</td>
<td>0.2 ( \times 0.06 )</td>
<td>0.1 ( \times 0.04 )</td>
</tr>
</tbody>
</table>

Figure 7. Distribution of electron density (Left) and power density (Right) for (a) Case A, (b) Case B, and (c) Case C.

Table 2. Comparison of the circumscribed rectangles of the discharge streamers at 40 ns.
powered and ground electrodes are separated by a fluorocarbon film with a thickness of 0.3 mm. The exposed electrode was powered by a single-pulsed high voltage with a peak amplitude of 12 kV. The waveform of the applied voltage is shown in figure 2. The pulse duration is 60 ns, and the pulse rising time is about 15 ns. A large computational domain of $20 \times 10.1$ mm$^2$ was used to avoid any effect from the outer boundary.

Energy released from the discharge leads to a rapid pressure growth in the adjacent gas layer, resulting in a series of cylindrical-shaped shock waves. The shock wave is formed at the moment of initial expansion and starts to move toward the surface. The computed wave front positions are compared with experimental results [6] in figure 3, showing a good agreement, with less than 5% difference. During discharge, the energy input is deposited along the surface above the grounded electrode in the dramatically changing electric field.

4. Results and discussion

To understand the effect of surface exposure of powered electrodes, we study three configurations of NS-DBD plasma actuators (shown in figure 4). In all three configurations, the powered and grounded electrodes are separated by a 0.0375 mm-thick dielectric. The grounded electrodes are rectangles of $5 \times 0.0625$ mm$^2$. In Case A, only the upper surface of the powered electrode is exposed (partially exposed electrode). The partially exposed electrode has the same dimensions as the grounded electrode. In Case B, three surfaces of the powered electrode are exposed (fully exposed electrode). The exposed electrode has the same geometry as the grounded electrode. In Case C, three surfaces of the powered electrode are exposed, but the exposed powered electrode has a round semi-circular corner with a 0.00375 mm diameter (rounded-exposed electrode). In all cases, the powered electrodes were driven by a single positive nanosecond-pulsed high voltage (shown in figure 5). The parameters are fixed in the three cases during the simulation. The single pulse has an amplitude of 6 kV, a rising time of 40 ns, and pulse duration of 80 ns. The half bandwidth of the pulse was about 40 ns.

4.1. Discharge characterization

Figure 6 compares the spatial distributions of the reduced electric field ($E/N_o$, $N_o$ is the density of the neutral gas) among the three cases at 40 and 80 ns, which correspond to the peak and end of the input voltage pulse (see figure 5), respectively. In figure 6, we used the same range scale in the three cases, and all the values greater than 450 Td are represented by the same color as that of 450 Td, so that the discharge domain can be resolved clearly. It is found that the streamers start from the region near the right upper tip of the powered electrodes. As the input signal increases, the streamers run right along the dielectric surface above the grounded electrodes and the discharge domain expands. Under the influence of the reduced electric field, the distributions of the species vibration temperature are similar to those of the reduced electric field for the three cases. Despite these common features, in figure 6, at the instant of peak input voltage (40 ns), the electric breakdown area in Case B is 0.1 mm longer and 0.05 mm higher than that created in Case A with the partially exposed electrode. The induced area in Case B is the largest with the strongest reduced electric field, while that in Case C is the second largest with the second strongest reduced electric field, and that in Case A is the smallest with the weakest electric field. At 80 ns, when the input signal decays to zero, the electric field decreases to zero in Case A, but is visible around the right edges of the powered electrodes in Cases B and C. The comparison demonstrates that the reduced electric field in Case B is stronger than Cases A and C, and the exposure effects of the powered electrode are
important to the transfer of momentum and energy into the surrounding air.

We further compare the contours of the electron density and power density at 40 ns in figure 7. In Case A with the partially exposed electrode, electrons are concentrated at the upper tip of the anode, where the values of the electron density and power density are the highest. In Cases B and C, electrons are concentrated near the right upper tip of the powered electrode throughout the discharge process primarily due to the influence of the electric field. As a result, the electron density forms a core discharge domain near the right upper tip of the powered electrode with higher density values. The streamers run right along the surface above the grounded electrode, accompanied by a reduction of the electron density.

Table 2 presents the comparison of the sizes of the circumscribed rectangle of the streamers of the three cases at

Figure 9. Evolution of pressure wave along a horizontal line \( y = 0.6 \) mm (left) and a vertical line \( x = 9 \) mm (right). (a) Case A, (b) Case B, and (c) Case C.
40 ns, respectively. For electron density, the area of the circumscribed rectangle in Case B is approximately four times bigger than that in Case A, and twice as big as in Case C. For power density distributions, the area of the circumscribed rectangle in Case B is seven times bigger than that in Case A, and three times bigger than that in Case C. This difference is primarily due to the higher reduced electric field for the exposed right edge and tip of the powered electrode.

Figure 8 compares temporal profiles of the electric body force and power density for the three exposed cases. Due to particle collisions that happened around the exposed electrodes (Cases B and C) in the high electric field, higher space-charge density and current density are generated. The temporal profiles of body force and powered density for Cases B and C are similar, as both are higher than those for Case A. From the numerical results, it can be concluded that the complete exposure electrodes can increase the induced energy-transfer performance and momentum-transfer compared with those induced by the partial exposure electrode.

4.2. Characterization of the induced flow

The three cases were simulated by coupling the plasma kinetic model with the Navier–Stokes equations to study the effect of actuators on surrounding neutral gas. In the flow control by NS-DBD plasma actuator, energy release leads to a pressure increase in the gas layer near the surface of the dielectric. Figure 9 shows the pressure waves along a horizontal line of $y = 0.6$ mm and a vertical line of $x = 9$ mm (immediately on the right edge of the powered electrode) within 6 $\mu$s. Right after the electric field breakdown, a strong pressure wave was generated at 0.1 $\mu$s. The wave strength decays as it propagates. Case B has the strongest pressure wave at 0.1 $\mu$s, while Case A has the weakest. Note that, at the same instant, the waveform in Case B is fatter than that in the other two Cases, which might be due to the higher reduced electric field in Case B. For all cases, the pressure wave expands with a velocity of 0.3 mm $\mu$s$^{-1}$ along both the $x$ and $y$ directions, giving rise to a shock of $M = 1.23$ near the surface.

In order to investigate the effects of the right upper tip and edge of the powered electrode on the induced flow, figure 10 presents the evolution of the pressure waves at 1, 3, and 5 $\mu$s after the discharge induced by Case A and Case B. In both cases, it is obvious that fast discharge thermalization merges into a single cylindrical compression wave centered on the right upper electrode tip. The compression waves decay into weak pressure waves as they propagate with time. However, the pressure generated in Case B propagates slightly faster than that induced in Case A, which is due to the more intensive wave in the Case B. The comparison of the results demonstrates that the exposure of the right upper tip and edge of the powered electrode significantly affects the propagation of the pressure waves.

Figure 11 shows the temperature distribution at 1 and 5 $\mu$s, which is generated by fast gas heating from the discharge. In all cases, the gas heating almost occurs near the right tip and edge of the powered electrode, where electrons concentrate under the high electric field with higher temperature values. During the short pulse discharge time, the energy deposited and released into the surrounding gas. Despite these common features, gas temperatures in Cases B and C are larger in the heated region and higher in temperature values than those in Case A, using the same temperature scale. This indicates that more effective heating was induced with the right edge and tip exposed. Furthermore, the highest temperature is observed near the tip of the powered electrodes in Case B. Comparing the temperature distribution at 5 $\mu$s between Case B and Case C, the gas heating area is larger in
Figure 11. Temperature distributions at 1 and 5 μs (a) Case A, (b) Case B and (c) Case C.

Figure 12. Temperature profiles at 3 μs (a) along a horizontal line $y = 0.503$ mm and (b) along a vertical line $x = 9.02$ mm.
Case B. The light difference verified the positive influence of the right upper tip on the performance of the gas heating.

Since similar temperatures are exhibited during the effective actuation period, respectively, profiles of temperature along horizontal line \( y = 0.503 \text{mm} \) and vertical line \( x = 9.02 \text{mm} \) at 3 \( \mu \text{s} \) are plotted in figure 12, and temperatures at other moments are similar. As shown in figure 12(a), along the horizontal line \( y = 0.503 \text{mm} \), temperature peaked near the right edge (about \( x = 9 \text{mm} \)) of powered electrodes, but immediately dropped when moving away from the tip. It can be seen that the temperature undergoes a drastic rise within the discharge time, which is due to the deposition of the electrons near the right upper tip of the powered electrode. At 3 \( \mu \text{s} \), the temperature reaches about 309, 430, and 405 K for Case A, Case B, and Case C, respectively. In figure 12(b), along the vertical line \( x = 9.02 \text{mm} \), the heating region ranges from \( y = 0.5 \text{mm} \) to around \( y = 0.56 \text{mm} \) with peak value about 309 K for Case A. For Case B, temperature heating distributes from \( y = 0.5 \text{mm} \) to around \( y = 0.6 \text{mm} \) with a temperature increase of 130 K. For Case C, temperature heating occurs from \( y = 0.5 \text{mm} \) to around \( y = 0.58 \text{mm} \), with a temperature increase of 115 K. These analytic data demonstrate that the temperature goes down to a value close to ambient temperature after discharge. It is obvious that higher gas heating and larger involved area was induced near the right edge and right upper tip of the powered electrode. Furthermore, the peak temperatures occur immediately near the right edge of the powered electrodes, and the temperature increases most rapidly in Case B, while that in Case C is the second fastest, and that in Case A is the slowest. The comparison results demonstrate that the gas heating temperature significantly depends on the exposure of the powered electrode.

5. Conclusions

The effects of the powered electrode exposure on air flow induced by three single NS-DBD plasma actuators were investigated in quiescent air at atmospheric pressure. Three exposed cases were studied using a reduced kinetic chemistry model. Discharge characteristics and induced flow features were compared. Our study showed the fully exposed case had earlier electric field breakdown, greater power energy input concentrated at the right edge and upper tip of the powered electrode, and had a longer duration and higher amplitudes than the partially exposed or rounded-exposed cases. Furthermore, the fully exposed electrode had higher heat release and stronger shock wave.

Acknowledgments

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