Discharge Enhancement Phenomenon and Streamer Control in Dielectric Barrier Discharge with Many Pores

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Abstract: The surface and volume discharge enhancement phenomena and streamer propagation direction control in catalytic pores are significant for the plasma catalytic degradation of pollutants. In this work, we use a two-dimensional particle-in-cell with Monte Carlo collisions model to explore the effect of lateral voltage on streamer enhancement and streamer propagation control for different driving voltages in pores of various shapes, sizes, and numbers. The driving voltage is applied to the top of the device, while the lateral voltages are applied at the left and right sides of the device. The surface and volume discharge enhancement phenomena become more significant and streamer propagation is more restricted within a narrow channel as the lateral voltage (with the same values on the left and right sides) increases from $-5 \text{kV}$ to $-30 \text{kV}$ for a fixed driving voltage of $-20 \text{kV}$. In this case, both the volume and surface discharges are intensive, leading to highly concentrated plasma species in a narrow channel. Moreover, the streamer propagates in a straight direction, from top to the bottom plate, with the lateral voltage added on both sides. The streamer propagation, however, deviates from the center and is directed to the right side when the lateral voltage is applied to the left. Our calculations also indicate that increasing the number or size of the pores enhances both the volume and surface discharges.

Keywords: plasma catalysis; dielectric barrier discharge; particle-in-cell/Monte Carlo collision; discharge enhancement; streamer control

1. Introduction

Due to the selectivity of catalytic materials and the high activity of plasma, plasma catalysis has been successfully applied to environmental protection activities. Plasma catalysis, an emerging branch of plasma processing, is thus attracting increasing attention [1–8]. In practice, two types of plasma catalysis exist according to the different positions of the catalyst: the single-stage type and the two-stage type [3]. In the single-stage type, the catalyst is placed inside the plasma discharging area, and two configurations exist: dielectric barrier discharge (DBD) [9–11] and corona discharge [1]. DBD is a kind of micro-discharge [12] in which the dielectric barriers are placed on the surface of the bare electrode. The filamentary mode [13] and Townsend mode [14] are two types of DBDs. Both can be operated at atmospheric pressure and generate non-equilibrium plasma [13]. The filamentary mode DBD can be treated as a streamer [15] and produces abundant plasma species without the need to heat the background gas remarkably.
DBD is used in many environmental protection and other applications, such as reduction of nitrogen oxides [2], abatement of volatile organic compounds (VOCs) [16–18], and so on [19]. Acetone, a VOC, is widely used as a solvent and paint thinner [20]. However, when using DBD to deal with pollution, toxic byproducts could be generated [21]. Adding a catalyst improves the effectiveness of pollution abatement [5]. Koo et al. [22] studied atmospheric pressure micro-discharge in porous ceramic to produce H$_2$ from an H$_2$O/SO$_2$ gas mixture. Although they did not use conventional electrocatalysts such as Pt, the reaction between H$_2$O and SO$_2$ was efficiently promoted, possibly due to non-thermal electrons. Adding packing materials may efficiently advance the selectivity of plasma catalysis [6] and generate the additional synergetic effect of plasma catalysts [23]. Hensel et al. studied the plasma catalyst system by adopting direct current [24,25] and alternating current (AC) [26] high-voltage power. They found that micro-discharge could be generated in porous dielectric materials such as alumina (Al$_2$O$_3$) and cordierite (2MgO·2Al$_2$O$_3$·5SiO$_2$). The pore size is one of the most critical parameters for atmospheric pressure micro-discharge. Stable and large-volume micro-discharges have been observed only for specific pore sizes such as 50 µm and 80 µm. The configuration chose in this work is similar to the experimental apparatus adopted by Hensel [24]. Moreover, Hensel [27] introduced two relatively new types of micro-discharges and found that applied voltage is also an important parameter. Above a certain voltage threshold, the discharge could propagate into the microporous ceramic foams from surface barrier discharge. By applying an AC voltage, Trinh et al. [28] proved experimentally that the combination of DBD plasma with annular porous multichannel monolithic ceramic-supported MnO$_2$ catalysts could effectively enhance the decomposition of acetone while producing byproducts such as CO, CO$_2$, HCHO, and CH$_3$CHO. Given that CH$_4$ is a powerful heat absorber and greenhouse gas, much research has been conducted on it. By combining dielectric barrier discharge and porous Ni/Al$_2$O$_3$ catalyst, Kameshima et al. [29] discovered a useful method for converting CH$_4$ into value-added products such as H$_2$ and CO.

Thus, experimental work has shed light on many electrical and optical properties of micro-discharge generation and propagation. Besides such experimental studies, many numerical simulations have been conducted to reveal the underlying mechanisms of micro-discharge [30–34]. Several methods could be used to study micro-discharge, including fluid and kinetics modeling as well as hybrid computational approaches. Most streamer dynamics are simulated by fluid models [35–38]. By adopting a fluid model of air at standard temperature and pressure, Luque et al. [35] simulated the propagation of double-headed (positive and negative) streamers in a homogeneous field of 50 kV cm$^{-1}$ emerging from needle electrodes with voltages of 10–20 kV. Zhang et al. [36] implemented a two-dimensional fluid model for various pore sizes to investigate the generation and propagation of plasma catalysis micro-discharge. Their calculations indicated that the plasma could propagate into catalyst pores in the µm range and affect the plasma catalytic process. Moreover, they studied the effect of the material dielectric constant [37] and pore shape [38] on plasma catalysis. They found that plasma is intensive for dielectric constants below 300 for a pore size of 100 µm [37], and tip-like structures could enhance the electric field greatly [38].

On the other hand, dynamic or hybrid models are also widely adopted to reveal information about the kinetic features of the discharge. Using a three-dimensional hybrid computational model, Li et al. [39] studied streamer discharges in N$_2$ and found that high-energy electrons were responsible for streamer propagation. The particle-in-cell [40]/Monte Carlo collision [41] model (PIC/MCC), a dynamic method, can efficiently simulate non-equilibrium state streamers. Zhang et al. [42] adopted a two-dimensional explicit PIC/MCC model to investigate micro-discharge in pore sizes in the micrometer and nanometer ranges. Streamers could propagate into pores, but it was difficult to differentiate between the volume and surface discharges in their work because the simulation area of the pores was too small. In our previous work [43], we also implemented a two-dimensional explicit PIC/MCC model to study surface and volume discharges in catalytic pores. We found that surface discharge is stronger than volume discharge. Zhang et al. [8,44] adopted a two-dimensional implicit PIC/MCC model to study plasma propagation in catalytic pores.
However, the effect of lateral voltages on streamer enhancement and streamer propagation control for different driving voltages in many pores of various shapes, sizes, and numbers has not been studied so far. Therefore, in this work, we use a two-dimensional explicit PIC/MCC model to investigate the effect of the lateral voltage on the properties of streamer formation and propagation in a DBD reactor containing numerous pores with smooth boundaries. Section 2 describes the simulation model. Section 3 presents the numerical results and discussion about the shape, size, numbers of the catalytic pores, the effects of the magnitude and direction of the applied voltage, and the effects of lateral voltage on the streamer enhancement phenomenon and streamer propagation control. Section 4 concludes this paper.

2. Simulation Model

2.1. Geometry and Physical Parameters

2.1.1. Geometry

Figure 1 displays the geometry of the DBD reactor used in this work. The simulated scale in the $x$ and $y$ directions is 2.0 mm and 1.65 mm, respectively. The yellow-colored area denotes the electrode. The blue and white-colored areas denote the dielectric material and discharge gap, respectively. The upper metal electrode ($x \in [0.0, 2.0]$ mm, $y \in [1.6, 1.65]$ mm) is powered by a voltage of $-8$ to $-32$ kV. The left metal electrode ($x \in [0.0, 0.05]$ mm, $y \in [0.3, 1.3]$ mm) and right metal electrode ($x \in [1.95, 2.0]$ mm, $y \in [0.3, 1.3]$ mm) are powered by voltages of $-5$ to $-60$ kV. The voltage of the bottom metal electrode ($y = 0$ mm) is 0 kV. After a rise time of 0.1 ns, the applied voltage remains unchanged during the simulation period. Two dielectric plates, each of thickness 0.3 mm, cover the bottom and top electrodes, and several vertical pores (0–16) exist in the bottom dielectric plate. The dielectric coefficient of each dielectric plate is $\varepsilon_r = 4$ (the representative material is SiO$_2$). The diameters and depths of these pores range from 0.0 to 0.1 mm and 0.0 to 0.2 mm, respectively. The pores and discharge gap ($x \in [0.0, 2.0]$ mm, $y \in [0.3, 1.3]$ mm) are filled with air (N$_2$:O$_2$ = 80%:20%) at atmospheric pressure. N$_2$ and O$_2$ at a temperature of 300 K are considered to be the background and are evenly set in the simulation area. Streamers are easily generated under such circumstances.

![Figure 1. Geometry used in the model.](image)

2.1.2. Grid and Streamer

We divide the simulation space into 50,000 uniform grids, 1000 × 500. Each grid measures 2.0 × 3.3 μm. Under the applied voltage driving, seed electrons set under the top dielectric plate ($x \in [0.9, 1.1]$ mm, $y \in [1.29, 1.30]$ mm) will spread down to the bottom dielectric plate and form streamers. The seed electrons are supplied by a current density of $10^5$ am$^{-2}$. Moreover, streamers formed from the seed electrons and propagating to the bottom dielectric plate give rise to electron and ion avalanches. Thus, we adopt a “particle merging algorithm” to merge the particles when
their number in a grid exceeds 10. Rationally, the use of numerical parameters and consideration of numerical convergence are crucial to avoid incorrect results. To obtain the Debye length $\lambda_D$ and electron frequency $\omega_{pe}$, it is important to use the correct time step and space step. These values were set to $10^{-14}$ s and $2.0 \times 3.3 \, \mu m$, respectively, in this work. As the results below show, we obtain the minimum Debye length and the maximum plasma frequency as approximately $10 \, \mu m$ and $3 \times 10^{13}$ rad/s, respectively, for a maximum electron density of $10^{21} \, m^{-3}$. Thus, to ensure numerical convergence, the selected space step and time step should be $\sim 2 \, \mu m$ and $10^{-14}$ s, respectively. Otherwise, if the grid width exceeds $3\lambda_D$, the PIC algorithm will become self-heating, leading to “fine grid instability”. In this work, self-heating is negligible as the grid width is not much larger than $\lambda_D$ [45,46].

2.2. VSim

VSim [47,48], a widely tested technical commercial software product, is used to solve the electrostatic (ES) and electromagnetic fields and study the movements of individual particles [49–52]. The following two basic processes must be conducted to study the movement of streamers:

1. We need to obtain the charge-current density distribution and electromagnetic field distribution in the streamers to compute the particle movement paths.
2. Then, by summing the mean of all the particle paths, we can track the overall movement of the streamers.

Two numerical methods could be used to deal with streamers: the fluid and dynamic approaches. The PIC/MCC model is the basic model of VSim, a very useful dynamic method. The PIC/MCC model is preferred for simulation of non-equilibrium state streamers whose electron velocity distribution is typically non-Maxwellian. Therefore, the VSim model, including the ES solver and particle moving algorithm, could be used to investigate low-temperature plasma at atmospheric pressure. This work used VSim version 9.1.

2.3. Particle-In-Cell Algorithm

Unlike the fluid method, whose electron velocity follows a Maxwellian distribution, the PIC algorithm is adopted to simulate individual dynamic behavior, and the speeds of the electrons and ions are self-consistent. As per the logic of this algorithm, “macro particles” are set to denote various real charged particles, and the space is divided into computational grids. The PIC algorithm defines the electromagnetic field on grid points, and we adopt a uniform Cartesian mesh in this work.

2.3.1. Particle Moving: The Newton Equations

Briefly, the calculation process for particle moving is called the “particle moving procedure.” The time needed for one moving is known as the “time step” ($\delta t$), and the particle moving process is conducted using the Newton equations, as follows:

\[
\begin{align*}
\mathbf{v}^{n+1} &= \mathbf{v}^n + \frac{q \mathbf{E}'}{m} \delta t, \\
\mathbf{x}^{n+1} &= \mathbf{x}^n + \mathbf{v}^n \delta t.
\end{align*}
\]

$n$ and $n + 1$ denote the $n$th and $n + 1$th time step, respectively. The time step defined in this work is $10^{-14}$ s. The stability of the PIC algorithm and the Courant-Friedrichs-Lewy (CFL) condition limit the value range of $\delta t$. The CFL condition is as follows:

\[
\frac{c \delta t}{\sqrt{\left(\frac{\delta x}{\delta y}\right)^2 + \left(\frac{\delta y}{\delta x}\right)^2}} < 1.
\]
2.3.2. Electric Field Solution: The Poisson Equation

In this work, we adopt the Poisson equation to solve the electric field. The Poisson equation is as follows:

\[-\nabla \cdot (\varepsilon \nabla \phi) = \rho_0.\]

To solve for electric potential in the Poisson equation, we adopt the Neumann boundary condition in the \(x\) direction and the Dirichlet boundary condition in the \(y\) direction. In this work, we define the PIC algorithm to solve the Poisson equation both in the discharge gap and the dielectric. However, we only need to solve the particle moving equation in the discharge gap given the dielectric barrier discharge properties. Moreover, should a charged particle arrive at the border or fall outside the simulation region, it will be absorbed, and a secondary electron will probably be emitted. The secondary electron emission coefficients for the dielectric surfaces of \(N_2^+\) and \(O_2^+\) are assumed to be the same as that of copper. In this work, we assume zero charge leak and zero electrical conductivity for the dielectric; specifically, we assume a perfect dielectric. The surface charge on the dielectric are calculated self-consistently by collecting all the charges deposited on it.

2.4. Reactions between Species: The Monte Carlo Collisions

This work considers several species: \(\text{e}^-, N_2^+, O_2^+, O_2^-, N_2, O_2, N_2^+\) and \(O_2^+\). “\(\ast\)” denotes the excitation states of both \(N_2\) and \(O_2\). We adopt the MCC method to deal with the reactions between the species. The reactions include electron-impact ionization, electron-impact excitation, elastic collision, and attachment, as seen in Table 1. The threshold energies data and cross sections are sourced from Ref. [53] and the LXCat database [54]. We consider molecules as the background and only trace the charged species.

Table 1. Electron-impact ionization, electron-impact excitation, elastic collision, and attachment reactions between species. The threshold energies data and cross sections are sourced from Ref. [53] and the LXCat database [54].

| Reaction | Threshold (eV) |
|----------|----------------|
| Electron-impact ionization |                     |
| \(e + O_2 \rightarrow e + O_2^+ + e\) | 12.06 |
| \(e + N_2 \rightarrow e + N_2^+ + e\) | 15.58 |
| Electron-impact excitation |                     |
| \(e + O_2 \rightarrow e + O_2^{a}\) | 0.98  |
| \(e + O_2 \rightarrow e + O_2^{b}\) | 1.63  |
| \(e + O_2 \rightarrow e + O^+O\) | 6.0   |
| \(e + O_2 \rightarrow e + O^{1D} + O^{1D}\) | 8.4  |
| \(e + O_2 \rightarrow e + O^{1D} + O^{1D}\) | 10.0 |
| \(e + N_2 \rightarrow e + N_2^{A}\) | 6.169 |
| \(e + N_2 \rightarrow e + N_2^{B}\) | 7.353 |
| \(e + N_2 \rightarrow e + N_2^{a}\) | 7.362 |
| \(e + N_2 \rightarrow e + N_2^{b}\) | 8.165 |
| \(e + N_2 \rightarrow e + N_2^{a}\) | 8.399 |
| \(e + N_2 \rightarrow e + N_2^{b}\) | 8.549 |
| \(e + N_2 \rightarrow e + N_2^{a}\) | 8.89  |
| \(e + N_2 \rightarrow e + N_2^{b}\) | 9.7537 |
| \(e + N_2 \rightarrow e + N_2^{c}\) | 11.032 |
| Elastic collision |                     |
| \(e + O_2 \rightarrow e + O_2\) |     |
| \(e + N_2 \rightarrow e + N_2\) |     |
| Attachment |                     |
| \(e + O_2 \rightarrow O_2^-\) |     |
3. Results and Discussion

In our previous works, we studied the filament discharge without pores [55] and with three pores [43]. We found that the surface discharge is enhanced on the surfaces of the catalyst pores compared with the micro-discharge inside the catalyst pores. However, the effect of a lateral voltage on the surface and volume discharge enhancement phenomena and the streamer propagation control for numerous pores of different shapes, sizes, and number were not considered. In this work, we investigate the effect law of these factors on the electron and ion densities, surface charge density, electric field, electron-impact ionization, and excitation rates in DBD with $\varepsilon_r = 4$ for both the top and bottom dielectric plates with pores. The effects of different dielectric constants are important. We have studied the effect of different dielectric constants of the dielectric barrier and found that streamers are difficult to propagate to the pores as the dielectric constants increasing from 2 to 100, which is similar to a published work [8]. Moreover, we cannot get any valuable information from it, so we did not put the results here.

3.1. Different Shapes of Catalytic Pores

Figures 2 and 3 display the electron density (m$^{-3}$) and surface charge density of N$_2^+$ (cm$^{-2}$) for different catalyst pore shapes at 0.3 ns. The size of the catalyst pore is 0.2 mm in the depth direction, while the diameter is different for different pore shapes. The voltage of the upper electrode ($y \in [1.60, 1.65]$ mm) is $-20$ kV, and the bottom electrode ($y = 0$ mm) is grounded. Before 0.3 ns, the streamer begins from the seed electron avalanches under the high driving voltage. The negative driving voltage drives the streamer to propagate from the upper plate to the lower plate, where a remarkable drift rate causes a new space-charge center at the streamer, thereby enlarging the streamer body [30,55]. Finally, the streamers propagate into the pores and produce plasma species inside the pores.

Some experiments have been operated to study porous dielectric discharge. Hensel et al. [24,25] reported stable discharge in porous dielectric material. As we know, it is difficult to experimentally measure discharge parameters such as electron and ion densities and reaction rates in detail. Thus, numerical simulations become indispensable in the study of porous dielectric discharge. It is worth mentioning that Zhang et al. [38] adopted a two-dimensional fluid model to study plasma properties for a steady glow discharge with one pore of different shapes. They found that the shape of the pore has a significant influence on electric field enhancement. Notably, tip-like structures could enhance the electric field significantly.

As shown in Figures 2 and 3, the surface discharge is stronger than the volume discharge, which is in line with our previous study [43]. Note in this model, no symmetrical or periodical condition is assumed, which will produce non-symmetrical results, similar to [56]. The reason is that in this case, the streamers start from random seed electrons. Applied voltages push seed electrons moving to the bottom dielectric plate. During the process, the velocity and direction of seed electrons movement are random. The maximum value of surface charge (N$_2^+$) density occurs at the position where the streamer head arrives at in all cases. The maximum value is occurring in the vicinity of the pores or inside them, since streamers are propagating around the pores. The surface discharge and electric field are enhanced there, pushing the electrons and ions into the pores and generating more intensive plasma species along the surface of the pores. For example, the maximum value is approximately $2.8 \times 10^{-3}$ cm$^{-2}$ occurring between the trapezoidal and triangle pores in f1 in Figure 3.

Note even with different shapes of pores, the electron density and surface charge density are similar from our simulations. The reason is that the pores are small enough to enhance the local field, and thus the shapes will not affect the results significantly. However, the numerical schemes adopted in VSim [47,48] will treat the elliptical pores more accurate, as the shape is smoother. In order to compare with our previous work [43] better and reduce the possible numerical errors, in the following works we will all adopt elliptical pores.
Figure 2. Electron densities ($m^{-3}$) of different catalyst pore shapes at 0.3 ns in DBD with $\epsilon_r = 4$ for both the top and bottom dielectric plates. The shapes of catalyst pores are ellipse and rectangle ($a_1,a_2$), ellipse and trapezoid ($b_1,b_2$), ellipse and triangle ($c_1,c_2$), rectangle and trapezoid ($d_1,d_2$), rectangle and triangle ($e_1,e_2$), trapezoid and triangle ($f_1,f_2$). The size of the catalyst pore is 0.2 mm in the depth direction. The voltage of the upper electrode ($y \in [1.60, 1.65]$ mm) is $-20$ kV, and the bottom electrode ($y = 0$ mm) is grounded.
3.2. Different Numbers of Catalytic Pores

As the number of pores increases, the surface discharge enhancement phenomenon becomes more significant. Figure 4 demonstrates the $N_2^+$ density (m$^{-3}$) for different catalyst pore numbers (0, 1, 2, 3, 4, 6, 8, 12, and 16) at 0.3 ns. The diameter and depth of the catalyst pore are 0.1 mm and 0.2 mm, respectively. The voltage of the upper electrode ($y \in [1.60, 1.65]$ mm) is $-20$ kV, and the bottom electrode ($y = 0$ mm) is grounded.

As the pore number increases from 0 to 16, more intensive surface and volume discharges occur in the pores. Thus, more reactive species are generated in the pores (such as electrons, $N_2^+$, $O_2^+$, and $O_2^-$), which are relevant for the active surface in plasma catalysis. To better understand this phenomenon, we present the density of $N_2^+$ for different catalyst pore numbers, as seen in Figure 4. Highly concentrated electrons and ions are generated in the catalyst pores, enhancing plasma catalysis and providing the advantages of highly efficient reactivity and selectivity [5,6]. Achieving such advantages would be challenging in porous catalyst experiments.
The maximum value of the $N_2^+$ density is $3.4 \times 10^{23}$ m$^{-3}$. As in our previous study [43], the maximum value appears on the surfaces of the pores. Abundant ions on the surface of the porous catalyst could improve the efficiency of plasma catalysis. One example is the elimination of 2-heptanone [57], a hazardous gaseous waste produced by anthropogenic activities. Ayrault et al. [57] selected 2-heptanone as the VOC [58,59] model molecule. Using a plasma catalytic device, which combines the highly efficient reactivity of plasma technology and the selectivity of catalysis, they improved the dissociation efficiency of 2-heptanone from less than 50% to 97%.

![Figure 4. $N_2^+$ density distributions (m$^{-3}$) with different catalyst pore numbers at 0.3 ns in DBD with $\varepsilon_r = 4$ for both the top and bottom dielectric plates. The numbers of catalyst pores are 0 (a), 1 (b), 2 (c), 3 (d), 4 (e), 6 (f), 8 (g), 12 (h), and 16 (i). The diameter and depth of the catalyst pore are 0.1 mm and 0.2 mm, respectively. The voltage of the upper electrode ($y \in [1.60, 1.65]$ mm) is $-20$ kV, and the bottom electrode ($y = 0$ mm) is grounded.](image)

### 3.3. Different Catalytic Pore Sizes

Figure 5 displays the $O_2^+$ densities (m$^{-3}$) of different catalyst pore sizes at 0.3 ns with 16 pores in the bottom plate. The sizes of the catalyst pore are $0.0 \times 0.0$ (a), $0.01 \times 0.02$ (b), $0.02 \times 0.04$ (c), $0.04 \times 0.08$ (d), $0.06 \times 0.12$ (e), and $0.08 \times 0.16$ mm (f). The voltage of the upper electrode ($y \in [1.60, 1.65]$ mm) is $-20$ kV, and the bottom electrode ($y = 0$ mm) is grounded.

Both volume discharge and surface discharge occur in the pores, which agrees with the predictions in Refs. [8,44]. The pore size increases from $0 \times 0$ mm to $0.08 \times 0.16$ mm, surface discharge becomes dominant, and the maximum value of the $O_2^+$ density is $1.3 \times 10^{23}$ m$^{-3}$, all of which agree with the predictions in Ref. [60]. These high-density ions could be used for improving the efficiency of the plasma catalysis process.
Figure 5. $O_2^+$ densities (m$^{-3}$) of different catalyst pore sizes at 0.3 ns in DBD with $\varepsilon_r = 4$ for both the top and bottom dielectric plates. The bottom dielectric plate has 16 pores. The sizes of the catalyst pores are $0.0 \times 0.0$ (a), $0.01 \times 0.02$ (b), $0.02 \times 0.04$ (c), $0.04 \times 0.08$ (d), $0.06 \times 0.12$ (e), and $0.08 \times 0.16$ mm (f). The voltage of the upper electrode ($y \in [1.60, 1.65]$ mm) is $-20$ kV, and the bottom electrode ($y = 0$ mm) is grounded.

3.4. Different Applications of Top Voltage

Figures 6 and 7 demonstrate the distributions of the electron-impact $O_2$ ionization rates (m$^{-3}$s$^{-1}$) and electric field distributions (Vm$^{-1}$) for different driving voltages applied at the top. The bottom plate has 16 pores. The diameter and depth of the catalyst pore are 0.1 mm and 0.2 mm, respectively. The voltage of the upper electrode ($y \in [1.60, 1.65]$ mm) varies from $-8$ kV to $-32$ kV, and the bottom electrode ($y = 0$ mm) is grounded.

At the top, the applied voltage first increases from $-8$ kV to $-32$ kV, and the surface discharge is dominant. Then, both the surface and volume discharges are enhanced with sufficiently large driving voltage. Similar to the prediction in Ref. [38], the electric field is significantly enhanced near tip-like structures. As shown in Figure 7, the maximum value of the electric field, $1.0 \times 10^8$ Vm$^{-1}$, appears at the bottom of the catalytic pores, consistent with our previous study [43]. As seen in Figure 6, the maximum value of the electron-impact $O_2$ ionization rate is $7.5 \times 10^{22}$ m$^{-3}$ s$^{-1}$. This value is as large as that in our previous work [43], $5.4 \times 10^{22}$ m$^{-3}$ s$^{-1}$. Compared with the case without pores [43,55], the presence of pores likely enhances the ionization rate in a restricted region, which could effectively accelerate the chemical reaction rate and increase the surface discharge in the catalyst pores. The active surface of the catalyst could result in a stronger electric field along the pore sidewalls. In turn, the stronger electric field could further enhance the surface discharge. The electric field on the surfaces of the pores is much higher than that within their interiors. Thus, surface streamers could
develop faster than volume streamers. However, when the external voltage is too large (over $-20 \text{kV}$), it is difficult to distinguish between surface discharge and volume discharge. Thus, this work adopted $-20 \text{kV}$ as the appropriate external voltage to study plasma catalysis properties.

Figure 6. Distributions of the electron-impact O$_2$ ionization rates (m$^{-3}$s$^{-1}$) for different voltages in DBD with $\varepsilon_r = 4$ for both the top and bottom dielectric plates. The bottom dielectric plate has 16 pores. The diameter and depth of the catalyst pore are 0.1 mm and 0.2 mm, respectively. The voltage of the upper electrode ($y \in [1.60, 1.65] \text{mm}$) varies from $-8 \text{kV}$ to $-32 \text{kV}$, and the bottom electrode ($y = 0 \text{mm}$) is grounded.

Figure 7. Electric field distributions (V/m) of different voltages for the same conditions as in Figure 6.
3.5. Effect of Lateral Voltage

Figure 8 demonstrates the distributions of the electron-impact $N_2$ excitation rates ($m^{-3}s^{-1}$) for different left and right lateral voltages. The bottom plate has 16 pores. The diameter and depth of the catalyst pore are 0.1 mm and 0.2 mm, respectively. The voltage of the upper electrode ($y \in [1.60, 1.65]$ mm) is $-20$ kV. The voltages of the left and right electrodes are varied from $-5$ to $-60$ kV. The bottom electrode ($y = 0$ mm) is grounded.

When lateral voltage is added to one side and its value increases from $-10$ to $-60$ kV, the direction of streamer propagation gradually biases to the other side. When the lateral voltage increases to $-60$ kV, the streamer does not even arrive at the bottom plate. However, irrespective of the change in the direction of the streamer, the surface discharge is always stronger than the volume discharge [43].

When lateral voltage is added to two sides and its value increases from $-5$ to $-30$ kV, the direction of streamer propagation is almost vertical. Moreover, the surface discharge and volume discharge are both enhanced. As the volume discharge increases sharply, it is quite difficult to differentiate between them. Notably, when the left and right voltages are $-30$ kV, the volume discharge is stronger than the surface discharge. As the lateral voltage restricts the streamer propagation in the vertical direction, the streamers cannot spread along the pore surface. The streamers propagate directly into the pores. Moreover, the lateral voltage is so powerful that the streamers propagate within a narrow propagation channel only, thus realizing streamer propagation control. When streamers arrive at the surfaces of the pores, surface ionization waves exert a weak effect in the transverse direction. The electrons and ions are rebounded back to the pores, which enhances volume discharge. Hence, our results reveal a stronger transfer of volume discharge than surface discharge in the catalyst pores.

The propagation direction of the streamer is controlled by intense lateral voltage and spread within a narrow propagation aisle. Volume discharge and surface discharge are concentrated and intensive.

Plasma catalysis is generating much interest, given the combined advantages of selectivity from catalysis and highly efficient reactivity from the plasma process [5,6]. This kind of configuration could generate abundant plasma species, enhance the efficiency of plasma catalysis, and improve the plasma catalysis process. There are various potential applications for such a configuration, such as significantly improving the conversion and energy efficiencies of the synthesis of materials [4] and the treatment of greenhouse gas [29]. Furthermore, with lateral voltage, the propagation of streamers can be controlled, and it may be used for gas switches [61] and other industrial applications such as oxidation of acetone [28].

In general, the size and numbers of catalytic pores, size of the applied top voltage, and magnitude and direction of the applied lateral voltage could affect the surface discharge and volume discharge enhancement phenomena as well as the propagation direction of streamers.

1. As the number of pores increases, the discharge enhancement phenomenon becomes increasingly distinct.
2. As the pore size increases from $0 \times 0$ mm to $0.08 \times 0.16$ mm, the surface and volume discharges are more easily distinguished.
3. As the top applied voltage increases from $-8$ to $-32$ kV, the surface and volume discharge enhancement phenomena become apparent.
4. When the top voltage is $-20$ kV, as the left and right voltages (of the same size) increase from $-5$ to $-30$ kV, streamer propagation is restricted within a narrow channel.

As the volume discharge and surface discharge are both concentrated and intensive in catalyst pores, they could generate abundant plasma species, enhance the efficiency of plasma catalysis, and improve the plasma catalysis degradation process of pollutants.
4. Conclusions

Using a two-dimensional PIC/MCC model, we investigate the effect of lateral voltages on the surface and volume discharge enhancement phenomena and streamer propagation control in DBD with numerous micro-sized pores of different shapes, sizes, and numbers. We obtain the optimum discharge enhancement and propagation direction of streamers for different magnitudes of applied top and lateral voltage. The PIC model is a two-dimensional explicit and ES arithmetic model, while the MCC model is adopted to deal with the reactions of electrons and ions. The background gas is air ($N_2:O_2 = 80\%:20\%$) under atmospheric pressure. The external voltages vary from $-5$ to $-60$ kV, and the electrodes are covered by SiO$_2$ with $\varepsilon_r = 4$.

Our calculations indicate that the magnitude and direction of the applied lateral voltage could affect the streamer enhancement phenomenon and control the streamer propagation direction, and both surface discharge and volume discharge are enhanced. The streamer propagation is strongly restricted within a narrow channel with sufficiently large lateral voltages of the same value added on both sides. Notably, when the left and right voltages are applied, the volume discharge is stronger than the surface discharge. The streamer propagates directly into the pores. The volume discharge and surface discharge are both intensive, generate highly concentrated plasma species, enhance the efficiency of plasma catalysis, and improve the plasma catalysis process.
Moreover, the size and number of catalytic pores, as well as the magnitude of the top driving voltage could affect the surface and volume discharge enhancement phenomena: (1) As the number of pores increases from 0 to 16, more intensive surface and volume discharges occur on the pore surfaces and within the pores, and the surface and volume discharge enhancement phenomena become significant due to the increase in volume for ionization collisions. (2) As the pore size increases from $0 \times 0$ mm to $0.08 \times 0.16$ mm, the surface discharge enhancement phenomena become more obvious. (3) As the top applied voltage increases from $-8$ to $-32$ kV, many plasma species are generated on the pore surface and inside the pores, thus enhancing both surface discharge and volume discharge. Our results predict the mechanisms of the surface discharge and volume discharge enhancement phenomena, which are of great significance for deeper understanding of plasma catalysis and enhancing the efficiency of this process.

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**Abbreviations**

The following abbreviations are used in this manuscript:

- **DBD** dielectric barrier discharge
- **PIC** particle-in-cell
- **MCC** Monte Carlo collision
- **VOC** volatile organic compound
- **AC** alternating current
- **ES** electrostatic
- **CFL** Courant-Friedrichs-Lewy

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