A non-equal gap distance dielectric barrier discharge: Between cone-shape and cylinder-shape electrodes

Shaohui Jin | Zhiyu Li | Yubin Xian | Lanlan Nie | Xinpei Lu

State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, Hubei, China

Abstract
A non-equal gap distance dielectric barrier discharge (DBD) between cone-shape and a cylinder-shaped electrodes is reported. The DBD is driven by a nanosecond voltage pulse. When the pulse frequency is 500 Hz or lower, ladder-shape plasma with multiple plasma layers is generated within the gap, with a distance increasing from 1 to 7 mm. According to high-speed photographs of the plasma captured by an intensified charge-coupled camera detector camera, the ladder-shaped plasma is formed owing to propagation of ring-shaped plasma from the region of the short-gap distance to the region of long-gap distance with regular variations in its propagation speed. The propagation speed drops to zero and lasts for about 20–30 ns at the region of each plasma layer, which results in bright plasma layers. The electric field of the plasma layer at the region of the different gap distance is evaluated according to the optical emission intensity ratio \( R_{391/394} \) of \( \text{N}_2^+ \) at 391 nm and \( \text{N}_2 \) at 394 nm. The obtained electric field drops from 8.1 to 6.4 kV/mm when the plasma is propagated from regions of gap distance of 2–5 mm. When the pulse frequency is increased to 1 kHz or higher, the discharge changes into a filamentary mode and the multiple-layer plasma disappears.

1 | INTRODUCTION

Non-thermal plasma has been studied for a variety of industrial applications such as ozone generation, waste gas treatment, pollutant degradation, the generation of ultraviolet or vacuum ultraviolet radiation, biological sterilisation, material processing and surface treatment (modification, deposition, etching, etc.) [1–5]. Non-thermal plasma can be produced by many kinds of discharge [6–10]. Dielectric barrier discharge (DBD) is one of the most widely used methods for generating non-thermal plasma under atmospheric pressure. Most DBDs appear to be filamentary. Because of the memory effect [11], discharge filaments in different discharge cycles tend to be generated at the same position, which is undesirable for applications such as surface treatment [10] and thin film deposition [12]. Therefore, much effort has been made to obtain homogeneous DBD. However, when air is used as the working gas, according to all reported studies, the discharge always appears filamentary when the air gap is larger than 4 mm and the gas pressure is at 1 atm pressure.

The discharge characteristics of DBD are determined by the electrode configuration, working gas, and applied voltage. For air discharge at 1 atm pressure, the working gas is no longer an adjustable parameter. Regarding the electrode configuration, in general, DBD can be classified into two categories: volume DBD and surface DBD. For all volume DBD reported, including both planar configuration volume DBD and cylindrical or coaxial volume DBD, the gap distance between the two electrodes is always a constant. For the applied voltage, generally speaking, when air DBD is excited by AC voltage source, a series of microdischarges will appear near the positive and negative peaks of applied voltage. Both unipolar and bipolar voltage pulses have also been used to generate air DBD [13]. Pulse excitation can generate homogeneous air plasma when the air gap distance is shorter than 4 mm [14–18]. In particular, a nanosecond pulse voltage power supply has been widely used to drive DBD [19–22]. High overvoltage breakdown is achieved when nanosecond pulse voltage with a fast rising time is used, which is capable of generating homogeneous air plasma when the air gap distance is shorter than 4 mm [23–27]. The rising time of the power supply is the time required for the pulse to rise from 10% to 90% of the amplitude. Regarding the effect of the frequency of the applied voltage, increasing the frequency tends to lead to the discharge transition from the homogeneous to the filamentous discharge...
mode. This is suspected to be because of the diffusion of ions, which have longer diffusion time at a low frequency [11].

On the other hand, achieving homogeneous plasma treatment does not necessarily require homogeneous plasma. If the plasma appears to have a certain regular pattern, homogeneous plasma treatment could also be achieved by scanning the object to be treated.

Nanosecond pulse voltage is used to drive a non-equal gap distance DBD plasma. The plasma is generated between cone-shaped and cylinder-shaped electrodes. Ladder-shaped plasma with multiple plasma layers is generated between two electrodes with a gap distance increasing from 1 to 7 mm. Homogeneous or regular plasma can be obtained in larger gaps, and greater processing space can be obtained, which expands the scope of DBD application.

2 | EXPERIMENT SETUP

The schematic of the experimental setup is shown in Figure 1. The high-voltage electrode is made of cone-shaped stainless steel with an up-and-down radius of 40 and 52 mm and a height of 70 mm. The ground electrode is made of a quartz tube filled with saline. The wall thickness of the quartz tube is 2 mm. The dielectric constant of the quartz tube is 5. The conductivity of saline used as the grounded electrode is 20 μs/cm. The gap between the cone-shaped stainless-steel electrode and the quartz tube is filled with surrounding air. The relative humidity of the air used for the experiment is 40%–60%. The minimum and maximum gap distance between the stainless-steel electrode and the quartz tube is 1 and 7 mm, respectively.

The high-voltage electrode is connected to a nanosecond pulsed DC power supply (APG-1500-30-P; Eagle Harbour Technologies). The pulsed DC power supply is able to deliver a voltage with an amplitude of up to 30 kV, pulse width from 50 ns to DC, and pulse frequency of up to 2 kHz. The voltage and current of the discharge are measured by a voltage probe (Tektronix P6015A) and current probe (Tektronix P6016), respectively, and are recorded with an oscilloscope (Tektronix TDS 3034B). Photographs

![Figure 2](image2.png) **Figure 2** Horizontal view of plasma at different frequencies. Amplitude of applied voltage: 20 kV; pulse width: 300 ns. Exposure time of camera: 0.1 s

![Figure 3](image3.png) **Figure 3** Vertical view of plasma at different frequencies. Amplitude of the applied voltage: 20 kV; pulse width: 300 ns. Exposure time of camera: 0.1 s

![Figure 1](image1.png) **Figure 1** (a) Schematic of experimental setup: x is the length of the air gap, (b) photograph of plasma device
of the DBD in different modes are captured by a digital camera (Canon D7000) with an exposure time of 0.1 s. Photographs from both the horizontal and vertical directions are captured. An intensified charge-coupled camera detector (ICCD) is employed to capture the dynamics photographs of the DBD. A half-metre spectrometer (Acton SpectraHub 2500i; Princeton Instruments) is used to measure the spatial resolved optical emission spectrum (OES) of the plasma. According to the obtained OES, the spatial resolved electric field and vibrational temperature of the plasma are obtained.

3 | EXPERIMENT RESULTS

3.1 | Ladder- and chaos-shaped plasma

Figures 2 and 3 show photographs of the plasma captured from horizontal and vertical directions for different pulse frequencies. The amplitude of the applied voltage is adjusted to 20 kV and the pulse width is adjusted to 300 ns. The plasma has a ladder shape when the pulse frequency is 500 Hz or lower, and it is in the chaos mode when the pulse frequency is 1 kHz or higher. Moreover, when the pulse width is adjust to 300 ns, the height of

---

**Figure 4** High-speed photographs of plasma captured by intensified charge-coupled camera detector (ICCD). Amplitude of applied voltage: 20 kV; pulse width: 300 ns; pulse frequency: 300 Hz. Exposure time of ICCD camera: 3 ns
the plasma is the highest and the number of steps of the ladder-shaped plasma is the largest. Further increasing the pulse width will not increase the height of the plasma. When the pulse frequency is set to 300 Hz, the plasma striation is clear and the plasma of each layer is homogeneous. The height of the plasma can reach 5 cm, whereas the maximum air gap distance reaches 5 mm and the plasma is always homogeneous. When the pulse frequency is increased to 500 Hz, the discharge at the place where the air gap is large becomes unstable at first. The top two layers of the plasma have an undulated shape. With a further increase in pulse frequency to 1 kHz, the discharge takes on a chaos filamentary mode.

To understand how the striation and chaos modes are formed, an ICCD is used to capture high-speed photographs of the DBD. As shown in Figure 4, the plasma is ignited layer by layer from the place of the relatively small air gap distance to the place of the relatively large air gap distance with a certain delay time. In addition, plasma produced by the discharge is homogeneous in each layer, which indicates that plasma produced at each position in each layer is of the same nature, compared with filamentous discharge, which is different at each position and cannot be stabilised at a fixed position. However, upon a closer look at the photographs, it is found that the plasma is actually propagating from the bottom to the top rather than jumping from layer to the next layer. Its propagation speed varies periodically with time. To show details for how the plasma propagates, the position of the plasma versus time is plotted in Figure 5 and the corresponding voltage and current waveforms are shown in Figure 6. The position of the plasma in several consecutive photographs is the same, expressed as the shape of the platform in Figure 5. It shows that the plasma does not propagate at a constant speed; there are several platforms corresponding to bright layers of plasma captured by the regular camera. This means that the plasma actually stops propagating for 20–30 ns at the position of each layer, which is why they are bright. During this time, the dielectric is charged until the voltage across the gas gap is unable to sustain the discharge. Then, it propagates again to a new position where such processes repeat.

According to Figure 6, the current waveform contains several peaks. The time each peak appears corresponds to the time of the discharge of each plasma layer. Origin9 is used to integrate each peak of the current waveform. The total movement charges in each layer of the discharge are shown in Table 1.

To see how the chaos mode of the plasma is formed, high-speed photographs of plasma for a pulse frequency of 1 kHz are captured as shown in Figure 7. The corresponding current and voltage waveforms are shown in Figure 8. The plasma also propagates from the region of the relatively small air gap to the region of the relatively large air gap, but it appears with many filaments rather than a regular bright plasma layer. According to the waveforms of current, it has only one peak, and the peak value decreases slowly.

![Figure 5](image1.png)

**FIGURE 5** Relationship of position of plasma versus time

![Figure 6](image2.png)

**FIGURE 6** Current and voltage waveforms for pulse frequency of 300 Hz

| Number | A | B | C | D | E |
|--------|---|---|---|---|---|
| Q (x10^{-7} C) | 2.15 | 1.45 | 1.40 | 1.38 | 1.32 |

*Note: Useful for discussion later.*

### 3.2 Characteristics of plasma with different layers

As pointed out earlier, for the case of low-frequency discharge, the plasma appears to have a ladder shape with multiple layers. On the other hand, because of the natural unequal gap distance of the configuration, the actual gap distance of each layer is different; thus, the plasma characteristics might also be different, although they look similar according to photographs captured by a regular camera. In the next, first, the optical emission of the plasma for the bottom layer (x = 2 mm) and top layer (x = 5 mm) is measured. As shown in Figure 9, in general, the optical emission intensity of the spectrum for the
Spectral lines of $N_2$ and $N_2^+$ at $x = 2$ mm is significantly higher than that at $x = 5$ mm. Both have no measurable spectral lines between 500 and 800 nm.

Second, the OES of an $N_2$ second positive system between 368 and 384 nm is used to evaluate the vibrational temperature of the plasma. According to the measured spectrum and the simulated spectrum with a given rotational and vibrational temperature, the rotational and vibrational temperature is obtained when the best fit is achieved (Figure 10). The rotational and vibrational temperature of the plasma is 300 and 3600 K, respectively, at $x = 2$ mm, whereas at $x = 5$ mm, it is 300 and 3350 K, respectively. Thus, the gas temperature of the plasma at both positions is close to room temperature and the vibrational temperature of the plasma has a slight difference between the positions.

Third, for plasma with different layers, the gap distance is different, so the electric field of the plasma might be different, too. In the next, the ratio of the intensities of the second positive system of $N_2$ and the first negative system of $N_2^+$ is used to evaluate the electric field \[28, 29\]. For $N_2$, emission at 394 nm is selected, whereas for $N_2^+$, emission at 391 nm is selected \[30–34\]. Thus, we use the optical emission intensity ratio $R_{391/394}$ of $N_2^+$ at 391 nm and $N_2$.
at 394 nm to evaluate the electric field. In Gangwar et al. [28] and Ran et al. [30], non-self-sustained discharge was excited in a parallel-plane gap using the radiation of a pulsed laser. Results of theoretical calculations of that ratio as a function of reduced field strength $E/N$, where $E$ is the field strength and $N$ is the gas number density, are presented by the known electric field. It is used to derive empirical formulae for relationships between intensity ratios and reduced field strength $E/N$:

$$R_{391/394} \left( \frac{E}{N}, N_0 \right) = 46 \exp \left( -89 \left( \frac{E}{N} \right)^{-0.5} \right) \quad (1)$$

where $N_0$, the gas number density at atmospheric pressure, is known (Figure 11). $R_{391/394} = 0.15$ at position $x = 5$ mm and $R_{391/394} = 0.26$ at position $x = 2$ mm, which correspond to an electric field of 6.4 and 8.1 kV/mm, respectively.

**Figure 9** Optical emission spectra of dielectric barrier discharge at positions of air gap: (a) $x = 2$ mm, (b) $x = 5$ mm

**Figure 10** Experimental and simulated spectra of plasma from the $N_2$ second positive system between 368 and 384 nm at positions, $x$ is the length of the air gap: (a) $x = 2$ mm, (b) $x = 5$ mm

**Figure 11** Spectra of $N_2^+$ (391 nm) and $N_2$ (394 mm) emission with different positions. $R_{391/394}$ represents the electric field strength. $x$ is the length of the air gap.
4 | DISCUSSION

DBD generated in a constant gap distance with two discharge modes (i.e., homogeneous and filamentary) has been reported by many researchers. A DBD plasma is generated in a non-equal gap distance between a cone-shaped stainless-steel electrode and a quartz tube filled with saline as ground electrode. The plasma has a ladder shape with multiple homogeneous layers under specific electrical parameters. Adjusting the amplitude of the applied voltage and pulse width changes only the total height of the plasma: that is, the number of plasma layers. However, increasing the pulse frequency results in a change in the discharge mode. For a pulse frequency 500 Hz or lower, plasma takes on a multiple homogeneous layer mode. Increasing the pulse frequency to 1 kHz or higher, chaos filamentary plasma appears.

The reason why discharge changes from homogeneous to chaos filamentary mode when the frequency increases might be because of the shorter diffusion time of ions in the discharge channel for the case of higher frequency; the discharge channel is narrower, and the discharge transfers to filamentary mode at high frequency [35].

In the next, the forming of the ladder-shaped discharge is discussed. Many different capacitors connected in parallel with a variable current source are used to simulate the air gap. Each capacitor represents a layer of discharge. The dielectric layer is simulated by a capacitor. The two parts are connected in series, as shown in Figure 12. According to the equivalent circuit, the height of each plasma layer that is related to the equivalent capacitance of the air gap can be calculated according to the measured voltage and current at different times. The related equations are:

\[ C_g = \frac{2\pi \varepsilon_d L}{\ln(R_2/R_1)} \]  
\[ C_d = \frac{2\pi \varepsilon_d L}{\ln(R_3/R_2)} \]  
\[ I_g = \left(1 + \frac{C_g}{C_d}\right) I_1 - C_d \frac{dU_g}{dt} \]  
\[ U_g = \left(\frac{C_d}{C_d + C_g}\right) U_1 - \frac{1}{C_d + C_g} \int_{t_1}^{t_2} I_g(t) dt \]

where \( C_g \) and \( C_d \) are the equivalent capacitances of the air gap and dielectric, respectively. \( L \) is the height of each plasma layer. Although the height of the plasma layer according to the photographs of the plasma is about 1 mm, the actual height, \( L \), of the charge deposited on the dielectric could be much larger. This is true according to the evaluation presented later. \( R_1 \) represents the radius of the discharge position of each layer of the cone-shaped stainless steel. \( R_2 \) is the inner diameter of the quartz tube. \( R_3 \) is the outer diameter of the quartz tube. \( \varepsilon_d \) and

![Figure 12](image)

(b) Parameters, in which \( L \) is the height of each plasma layer

\( \varepsilon_d \) are the dielectric constants of the air gap and quartz, respectively. \( U_1 \) is the external applied voltage; \( U_d \) is the voltage across the dielectric; \( U_g \) is the voltage over the air gap; \( I_1 \) is the total external current; \( I_g \) is the discharge current through the air gap; and \( I_c \) is the displacement current in the air gap.

Based on the current waveform and the high-speed photographs of the plasma, each current peak corresponds to a layer discharge. For each layer, the discharge starts at time \( t_1 \) and ends at \( t_2 \). At the end of each layer discharge, voltage across the air gap cannot sustain the discharge, but it must be still larger than zero because the voltage is still increasing; therefore:

\[ U_g = \frac{C_d}{C_g + C_d} U_1 - \frac{1}{C_d + C_g} \int_{t_1}^{t_2} I_g(t) dt > 0 \]

According to the measured voltage and current waveforms, using Equations (2)-(6), the minimum height of each plasma layer is calculated as shown in Table 2.
TABLE 2  Minimum height $L$ of each plasma layer

| Number | A   | B  | C  | D  | E  |
|--------|-----|----|----|----|----|
| $L$ (mm) | 5.72 | 5.085 | 4.51 | 4.23 | 3.8 |

The obtained $L$ is close to the distance between each plasma layer. On the other hand, according to the photographs of the plasma, the height of the bright region of each layer is only about 1 mm, which is much smaller than the calculated $L$. This means that the actual area of the charge deposited on the dielectric surface is much larger than that of the bright region, which means that the dark region between two nearby plasma layers is deposited with charges.

5  CONCLUSION

A non-equal gap distance DBD between a cone-shaped stainless-steel electrode and quartz tube filled with saline is reported. The plasma has a ladder shape with multiple homogeneous layers when the pulse frequency is 500 Hz or lower. The discharge is still diffused even at a region with an air gap distance of 5 mm. When the pulse frequency is 1 kHz or higher, the plasma takes on a chaos filamentary mode and homogeneous layers disappear.

According to the high-speed photographs of the plasma, multiple homogeneous plasma layers form owing to the propagation of the ring-shaped plasma from the region of the short gap distance to the region of the long gap distance with regular variations in propagation speed. The propagation speed drops to zero and lasts about 20–30 ns at the region of each plasma layer while the dielectric is charged, resulting in bright plasma layers.

Finally, the electric field of the plasma layer at the region of the different gap distance is evaluated according to the optical emission intensity ratio $R_{391/394}$ of $N_2^+$ at 391 nm and $N_2$ at 394 nm. The obtained $R_{391/394}$ is 0.26 at the region of a gap distance of 2 mm, and it drops to 0.15 at the region of a gap distance of 5 mm, corresponding to the electric field drop from 8.1 to 6.4 kV/mm when the plasma propagates from regions of a gap distance of 2–5 mm.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China (Grant nos. 51625701 and 51977096).

ORCID

Xinpei Lu  https://orcid.org/0000-0003-0676-9585

REFERENCES

1. Fridman, A., Chirokov, A., Gutsol, A.: Non-thermal atmospheric pressure discharges. J. Phys. D Appl. Phys. 38(2), R1–R24 (2005)
2. Ostrnikov, K.K., Cvetican, U., Murphy, A.B.: Plasma nanoscience: setting directions, tackling grand challenges. J. Phys. D Appl. Phys. 44(17), 174001–174029 (2011)
3. Keidar, M., Shashurnit, A.: System and method for mass production of graphene platelets in arc plasma. (2016)
4. Naidis, G.V., et al.: Dynamics and structure of nonthermal atmospheric-pressure air plasma jets: experiment and simulation. IEEE Trans. Plasma Sci. 44(12), 3249–3253 (2016)
5. Cvetican, U.: Interaction of non-equilibrium oxygen plasma with sintered graphite. Appl. Surf. Sci. 269(15), 33–36 (2013)
6. Laroussi, M., Graves, D.B., Keidar, M.: Effects of low temperature plasmas on proteins. IEEE Trans. Radiat. Plasma Med. Sci. 2(3), 229–234 (2018)
7. Zhen, Y., et al.: Thermal characterisation of dielectric barrier discharge plasma actuation driven by radio frequency voltage at low pressure. High Voltage. 3(2), 154–160 (2018)
8. Park, S., et al.: The creation of electric wind due to the electro-hydrodynamie force. Nat. Commun. 9(1), 371 (2018)
9. Cheng, Z., Wang, R., Ping, Y.: Atmospheric-pressure pulsed discharges and plasmatic mechanism, characteristics and applications. High Voltage. 3(1), 14–20 (2018)
10. Zhao, Z., Li, J.: Repetitively pulsed gas discharges: memory effect and discharge mode transition. High Voltage. 5(5), 569–582 (2020)
11. Lu, X., Ostrnikov, K.K.: Guided ionization waves: the physics of repeatability. Appl. Phys. Rev. 5(3), 031102 (2018)
12. Vallade, J., et al.: Effect of glow DBD modulation on gas and thin film chemical composition: case of Ar/SiH$_4$/NH$_3$ mixture. J. Phys. D Appl. Phys. 47(22), 224006–224015 (2014)
13. Julian, K., Daniela, C., Slobodan, M.: Phase-resolved optical emission spectroscopy of a transient plasma created by a low-pressure dielectric barrier discharge jet. Plasma Sources Sci. Technol. 27(10), 105003 (2018)
14. Kratzer, J., et al.:Behaviour of selenium hydride in heated quartz tube and dielectric barrier discharge atomisers. Anal. Chim. Acta. 1028, 11–21 (2018)
15. Alexei, N., et al.: Diffuse discharges in SF$_6$ and mixtures of SF$_6$ with H$_2$ formed by nanosecond voltage pulses in non-uniform electric field. High Voltage. 3(4), 316–322 (2018)
16. Khacef, A., Cormier, J.M.: Pulsed sub-microsecond dielectric barrier discharge treatment of simulated glass manufacturing industry flue gas: removal of SO$_2$ and NO$_x$. J. Phys. D Appl. Phys. 39(6), 1078 (2006)
17. Kettlitz, M., et al.: Effect of a high-voltage mesh electrode on the volume and surface characteristics of pulsed dielectric barrier discharges. J. Appl. Phys. 128(23), 233502 (2020)
18. Walsh, J.L., Kong, M.G.: 10 ns pulsed atmospheric air plasma for uniform treatment of polymeric surfaces. Appl. Phys. Lett. 91(25), 251504 (2007)
19. Babavea, N.Y., Naidis, G.V.: Modelling of streamer dynamics in atmospheric-pressure air: influence of rise time of applied voltage pulse on streamer parameters. IEEE Trans. Plasma Sci. 44(6), 899–902 (2016)
20. Grauerwald, J., et al.: Characterisation of a simple non-thermal atmospheric pressure plasma source for biomedical research applications. Contrib. Plasma Phys. 55(4), 337–346 (2015)
21. Naidis, G.V.: Modelling of streamer propagation in atmospheric-pressure helium plasma jets. J. Phys. D Appl. Phys. 43(40), 402001 (2010)
22. Li, X., et al.: Detection of trace heavy metals using atmospheric pressure glow discharge by optical emission spectra. High Voltage. 4(3), 228–233 (2019)
23. Tao, S., et al.: Surface modification of polyimide films using unipolar nanosecond-pulse DBD in atmospheric air. Appl. Surf. Sci. 256(12), 3888–3894 (2010)
24. Rai, S.K., Pal, U.N., Dhakar, A.: A compact nanosecond pulse generator for DBD tube characterisation. Rev. Sci. Instrum. 89(3), 033505 (2018)
25. Zhang, C., et al.: Uniform of unipolar nanosecond pulse DBD in atmospheric air. Trans. China Electrotech. Soc. 25(1), 30–36 (2010)
26. Xu, J., et al.: Formation of hydrophobic coating on PMMA surface using unipolar nanosecond-pulse DBD in atmospheric air. J. Electroct. 71(3), 435–439 (2013)
27. Sainct, F.P., et al.: Determination of the electron temperature in plane-to-plane He dielectric barrier discharges at atmospheric pressure. Plasma Sources Sci. Technol. 25(1), 015011 (2016)
29. Paris, P., et al.: Measurement of intensity ratio of nitrogen bands as a function of field strength. J. Phys. D Appl. Phys. 37(8), 1179 (2004)
30. Ran, J., et al.: Effect of dielectric surface morphology on dielectric barrier discharge mode in air at atmospheric pressure. IEEE Trans. Plasma Sci. 49(1), 214–218 (2020)
31. Paris, P., et al.: Intensity ratio of spectral bands of nitrogen as a measure of electric field strength in plasmas. J. Phys. D Appl. Phys. 38(21), 3894–3899 (2005)
32. Yuan, G., et al.: Highly efficient conversion of methane using microsecond and nanosecond pulsed spark discharges. Appl. Energy. 226(15), 534–545 (2018)
33. Naidis, G.V., Babaeva, N.Y.: Electric field distributions along helium plasma jets. High Voltage. 5(6), 650–653 (2020)
34. Shao, T., et al.: An experimental investigation of repetitive nanosecond-pulse breakdown in air. J. Phys. D Appl. Phys. 39(10), 2192–2197 (2006)
35. Liu, S., Neiger, M.: Electrical modelling of homogeneous dielectric barrier discharges under an arbitrary excitation voltage. J. Phys. D Appl. Phys. 36(24), 3144–3150 (2003)

How to cite this article: Jin, S., et al.: A non-equal gap distance dielectric barrier discharge: Between coneshape and cylinder-shape electrodes. High Voltage. 1–9 (2021). https://doi.org/10.1049/hve2.12126