

# Discharge Characteristics of DBD with Contact Electrodes at Atmospheric Pressure in Quiescent Air



Jin Haosheng, Liu Shiyun, Liang Hengrui, Shi Yaqin, Mei Danhua, and Fang Zhi

**Abstract** Dielectric barrier discharge (DBD) has been widely concerned due to its stability and non-corrosive electrode structure. In this study, a mesh-like DBD reactor with wire-to-wire cross-contact electrodes is proposed. Coated high-voltage electrodes with dielectric barriers in directed contact with the ground electrodes facilitate the generation of a wide range of non-thermal plasma at lower voltages. The performance of the designed plasma reactor has been investigated in terms of its electrical, optical, thermal properties and ozone generation capabilities. It is shown that the discharge first occurs in the gap at the contact point, which produces initial electrons and then diffuses into the surrounding air gap, leading to the formation of a certain discharge region. Increasing the magnitude of the applied voltage and the number of contact points increases the discharge intensity, discharge power, emission intensity of active particles and ozone concentration. Decreasing the mesh size  $d$  favors ozone formation, and the highest ozone yield of 240 ppm can be achieved with a mesh size  $d$  of 4 mm.

**Keywords** Dielectric barrier discharges · Wire-to-wire cross electrode · Discharge characteristics · Ozone generation

## 1 Introduction

Non-thermal plasma has received increased attention as a promising technology for versatile applications in environmental, material, food and biological fields [1–5]. For better industrial application performance large area plasma are required [6]. Dielectric barrier discharges (DBDs), also regarded as silent discharges or barrier

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J. Haosheng · L. Shiyun (✉) · L. Hengrui · S. Yaqin · M. Danhua · F. Zhi  
School of Electrical Engineering and Control Science, Nanjing Tech University, Nanjing 211816, China  
e-mail: [shiyunliulisza@163.com](mailto:shiyunliulisza@163.com)

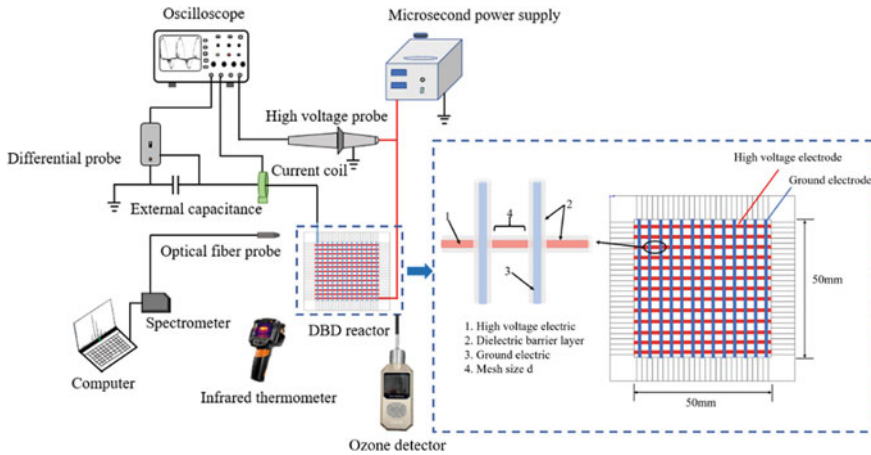
L. Shiyun  
School of Electrical Engineering Southeast University, Nanjing 210096, China

discharge attract growing interest in different applications since it offers high electron density and a large volume stable discharge in atmospheric pressure [1, 7]. The application performance of DBD strongly depends on the discharge characteristics, which can be easily tuned by the electrodes arrangement. There are a number of existing configurations of DBD, including volume discharge (coaxial cylindrical and parallel plate discharge), surface discharge and coplanar discharge [8]. Compared with the conventional volumetric DBDs, surface discharge shows more potential since it offers more available treatment space over the plasma zone, which allows some active species (e.g.,  $O_3$ ) to accumulate without destructing by the plasma channels [1, 9]. However, typical surface DBD plasma sources are limited by relatively high energy consumption for large areas.

Glow discharge is characterized by stable, low temperature and large-volume, while its difficult to avoid the transition from glow to arc and sustenance of a large-volume plasma discharge mode [10]. The proper arrangement of DBDs could generate a diffuse plasma, which has the advantage of large-area production of glow discharge and the dielectric material used in the DBDs avoid the discharge transition from glow to arc [11]. Mesh electrodes have been employed to obtain the diffused DBD in various gas conditions [12]. In this study, a mesh-like DBD reactor with wire-to-wire contact electrodes is developed to generate more widespread plasma discharges with relatively low energy consumption and high activity. The discharge characteristics are evaluated in terms of the applied voltage and mesh size. Furthermore, an ozone monitor is used to investigate the capability of the designed reactor for ozone generation.

## 2 Experimental Setup

Figure 1 shows the structure of the plasma reactor and the corresponding diagnostic system for discharge characteristics. The discharge apparatus consists of several wire-to-wire cross-contact electrodes forming a mesh-like structure with dimensions of  $50\text{ mm} \times 50\text{ mm}$ . The electrodes have an outer diameter of 1.4 mm and consist of a 1.1 mm diameter copper rod and a 0.15 mm thickness dielectric material PTFE. The mesh size  $d$  is set to 4, 8 and 12 mm, respectively. The developed mesh-like plasma reactor is connected to a laboratory homemade microsecond pulse power supply with a maximum peak voltage of 20 kV and a pulse repetition frequency in the range of 0–5 kHz. The applied voltage is measured by a high voltage probe (Tektronix P615A) while the discharge current is recorded by a current monitor (Pearson 4100). An external capacitor (10 nF) is inserted between the induction electrode and grounded point, through a differential voltage probe (Pintech N1070A) to obtain the charge generated in the discharge process. All the electrical signals are saved by a four-channel digital oscilloscope (Tektronix TDS2014B). The discharge images are captured by a Canon EOS6D digital camera with an exposure time of 1/4 and an ISO of 25,600. The emission spectrum of the plasma discharge is measured using the Ocean Optics HR4000CG spectrometer with a resolution of 0.75 nm.



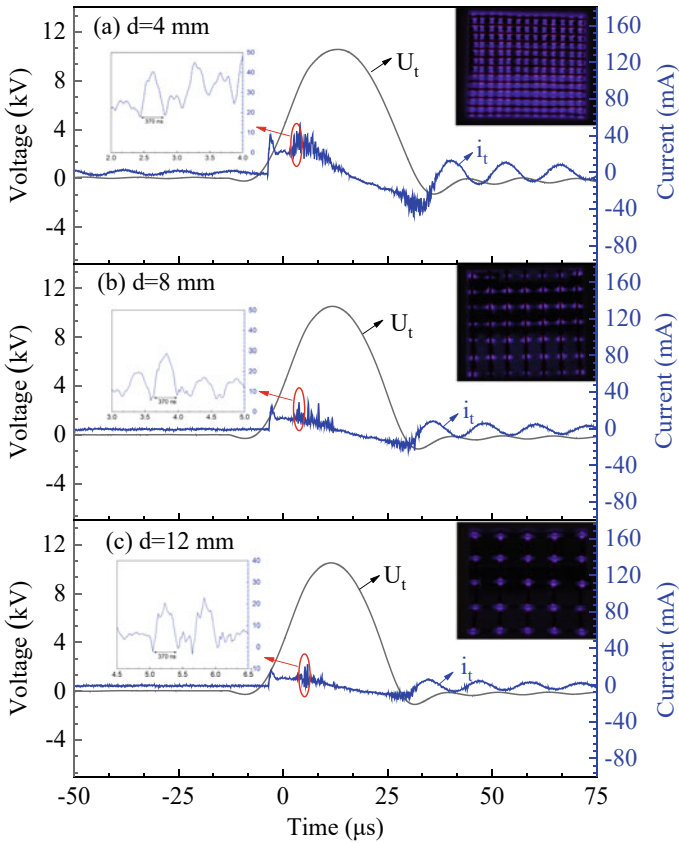
**Fig. 1** The experimental setup of the wire-to-wire cross contact electrode configuration

Moreover, the surface temperature of the reactor during the discharge is collected by an infrared thermometer (FOTRIC 325 Pro).

### 3 Results and Discussion

#### 3.1 Electrical Characteristics of Discharge

Figure 2 shows the typical voltage and current waveforms and discharge image of the wire-to-wire cross contact electrodes with different mesh size ( $d$ ), where  $U_t$  and  $i_t$  are the applied voltage and the total current, respectively. As demonstrated in Fig. 2, the rising and falling edges of the pulse voltage contain multiple current pulses that oscillate with a period of about 370 ns. During the discharge process, when the applied voltage across the electrodes reaches a certain value, the breakdown field strength is formed in the externally applied electric  $E_a$  and leads to the formation of the discharge. Under the effect of  $E_a$  the charged particles would do directional movement in the discharge space while the electrons accumulate on the surface of the dielectric material at the high electrode, eventually forming an electric field  $E_c$  with an opposite direction of the  $E_a$ . When the difference between the external applied electric field  $E_a$  and the strengths of  $E_c$  is less than the strength of breakdown field, the discharge terminate. Once the difference between the  $E_a$  and  $E_c$  exceeds the breakdown field again, the discharge could occurs again [13]. At the rising and falling edges of the pulse voltage, the strength of the external electric field  $E_a$  increases monotonically with time and the several discharges can be observed during this stage, so that the discharge current appears as many short pulses. Literatures also reported similar results [11].



**Fig. 2** Typical discharge waveforms and images of the mesh structure electrode with different mesh size  $d$  (applied voltage: 10 kV, frequency: 1.5 kHz)

It is worthy to note that the initial discharge voltage of the proposed electrodes almost at the same level regardless the changes in the mesh size  $d$ . However, the amplitude and number of the discharge current pulse remarkably reduced with the increases of mesh size  $d$ . This phenomenon might be attributed to the changes of the number of contact points, which is significantly reduced from 169 to 25 when the mesh size  $d$  increases from 4 to 12 mm. Each contact point would occurs discharge and contributes to the discharge current during the discharge process, therefore the magnitude of the discharge current pulse increased with the decreases in mesh size  $d$ . As can be seen from the discharge images that the discharge is occurred at each single contact point and gradually expands to the surrounding space, resulting in a three-dimensional discharge space with a shape of cube. Compared to a large mesh size  $d$ , the discharge can be developed to the full surface of the proposed reactor with a narrow mesh size  $d$ . At a same time, the discharge density and intensity are significantly weaker when the mesh size  $d$  is increased, which matches perfectly with

the discharge current waveform. This result suggests that decreasing the mesh size  $d$  can generate the non-thermal plasma discharges in a large area with good stability and discharge strength.

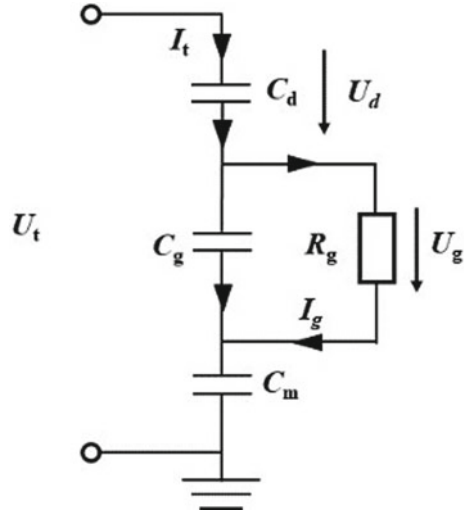
For more detailed analysis, an equivalent circuit of the wire-to-wire cross contact electrodes is established to evaluate its physical properties such as power consumption and transferred charge. Based on previous studies, the discharge process of a DBD can be simulated by an RC circuit as shown in Fig. 3, where  $C_d$ ,  $C_g$  and  $C_m$  represent the equivalent capacitance of the dielectric layers, the capacitance of the air gap and the measured capacitance, respectively.  $R_g$  stands an equivalent resistance of the discharge path [14]. Therefore, for the proposed electrodes, the applied voltage  $U_t$  consists of the voltage across the dielectric barrier and the voltage across the air gap, similarly the measured current  $I_t$  can be divided into the displacement current  $I_d$  and the conduction current  $I_g$ . Through the above voltage and current, the instantaneous values of total power ( $P_t$ ), power deposited on the dielectric layer ( $P_d$ ) and the air gap also noted as discharge power ( $P_g$ ) and the corresponding average values could be determined ( $\overline{P_t}$ ,  $\overline{P_g}$ ,  $\overline{P_d}$ ). The energy efficiency ( $\eta$ ) of the mesh-like cross electrode DBD reactor is determined by the ratio of the average discharge power and the average total power, as described by Eq. 1. The detailed descriptions of the calculation procedure of the above-mentioned parameter can be found in our previous studies [15–17]. The transferred charge ( $Q_{\text{trans}}$ ) in the single pulse of applied voltage is calculated by integrating the instantaneous conduction current over the duration of the discharge pulse (see Eq. 2).

$$\eta = \frac{\overline{P_g}}{\overline{P_t}} \times 100\% \quad (1)$$

$$Q_{\text{trans}} = \int_0^{t=T} I_g(t) dt \quad (2)$$

Figure 4 shows the variations in the power consumption and transferred charge of the proposed DBD reactor with various mesh size  $d$ . It is clear that narrow the mesh size  $d$  significantly enhanced the discharge intensity, the average discharge power almost quadrupled when the mesh size  $d$  changes from 12 to 4 mm (from 0.6 W to 2.3 W). Similarly, decreasing the mesh size  $d$  results in an exponential growth of the transferred charge. For a mesh-like structure reactor with a fixed reactor size, decreasing the mesh size  $d$  would increase the number of contact points and form more discharge points, leading to intense discharge current pulses and favoring an increase in discharge power and transferred charge. The voltage on the dielectric layer is proportional to the capacitance of the dielectric layer, which depends on the contact point. Increasing the number of contact points leads to an increase in capacitance since two dielectric layers are involved, resulting in an enhancement of the voltage across the dielectric layer and therefore more power deposited on the

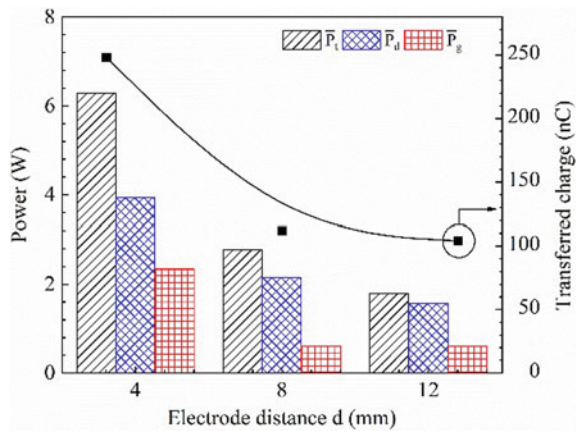
**Fig. 3** The equivalent circuit of the proposed DBD reactor



dielectric layer. As a result, the average power deposited on the dielectric layer rises from 1.6 W to 3.9 W for mesh sizes ranging from 12 to 4 mm.

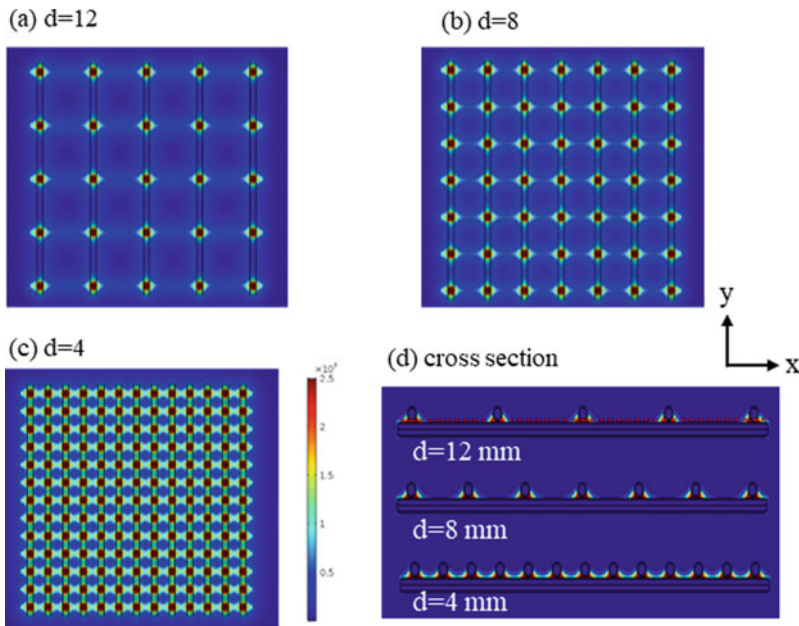
To further analyze the effect of the mesh size on the discharge characteristics, the spatial electric field distribution is analyzed by using the COMSOL simulation software. Figure 5 shows the spatial distribution of the electric field at the applied voltage of 10 kV for the proposed reactor with different mesh sizes. Obviously, the strongest electric field is located at the contact point with a value of  $2.5 \times 10^7$  V/m, which decreases exponentially with increasing horizontal distance  $X$  from the contact point. It is interesting to note that the mesh size  $d$  has no appreciable effect on the maximum strength of the electric field, it only affects the number of discharge points. The discharge first occurs at the contact point and generates initial

**Fig. 4** The variation of power consumption and transferred charge at with different mesh size



electrons, which then diffuse into the gas space, resulting in a cubic 3D discharge space. Figure 6 presents the variation of strength of electric field along the horizontal axis in order to further characterize the electric field distribution with different mesh size  $d$ . It is observed that decreasing the mesh size  $d$  from 12 to 4 mm, the value of lowest electric field is continuously increased from 25 to around 80 kV/cm, while the maximal strength of electric field is almost same, indicating that decreasing the mesh size is favored to stable the variation of electric field. Moreover, as the mesh size decreases, leading to an increase in the number of contact points, the interaction of the electric field between any two adjacent points is strengthened, thus facilitating the development of discharges.

Figure 7 presents the power consumption, transferred charge and discharge images of a mesh-like cross contact electrode DBD reactor with a mesh size of 4 mm at different applied voltages with a frequency of 1.5 kHz. It is clear that the energy consumption of the DBD reactor increases with the applied voltage. Specifically, the value of  $\overline{P_g}$  and  $\overline{P_t}$  are in the range of 1.0–5.6 W and 2.2–8.6 W, respectively when the applied voltage varies from 7 to 11 kV. Both energy efficiency and energy consumption tend to increase with the applied voltage. The transferred charge increases almost linearly with the applied voltage, reaching a maximum value of 302 nC at the applied voltage of 11 kV. Similar conclusions have been reported in previously work [15, 16]. The applied voltage shows a considerable effect on the discharge properties, especially for the discharge area and intensity. As can be seen from Fig. 7c, the



**Fig. 5** Spatial distribution of the electric field for the mesh-like structure DBD reactor with different mesh size

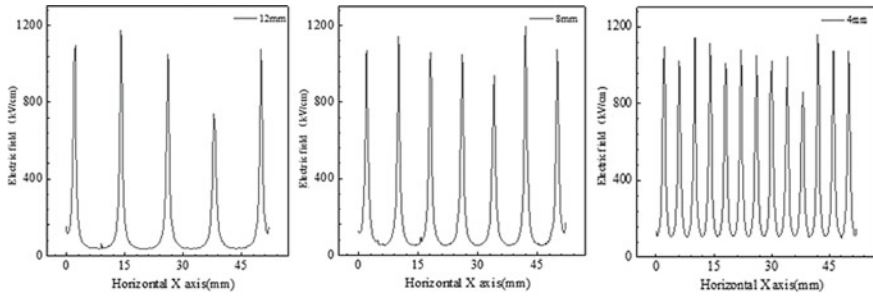


Fig. 6 The variation of electric field along the horizontal distance X with different mesh size

discharge only occurred at the contact point when the applied voltage at a lower level. Increasing the magnitude of the applied voltage expands the discharge into the surrounding space, leading to a wider discharge, which can be attributed to an increase in the discharge power, resulting in a large discharge area and high discharge intensity.

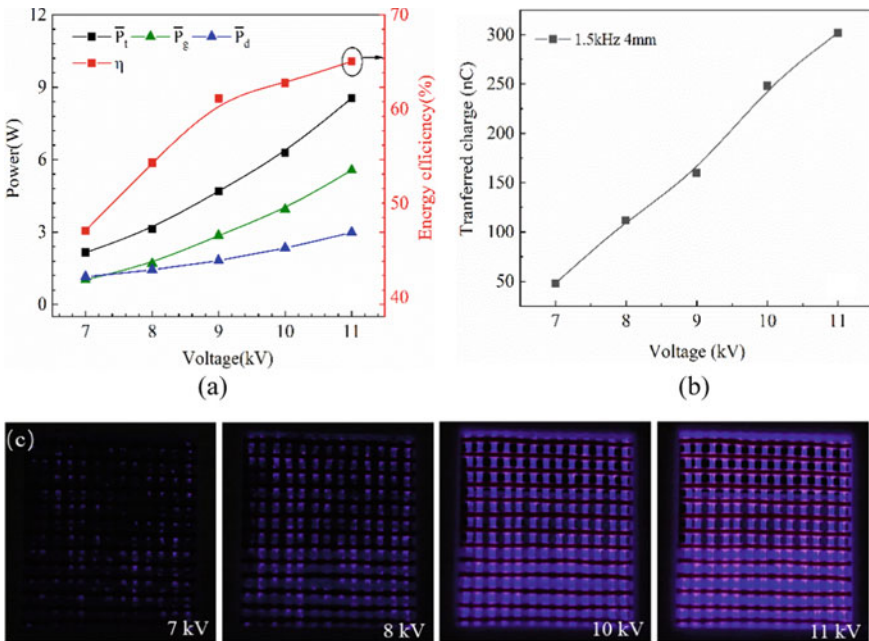
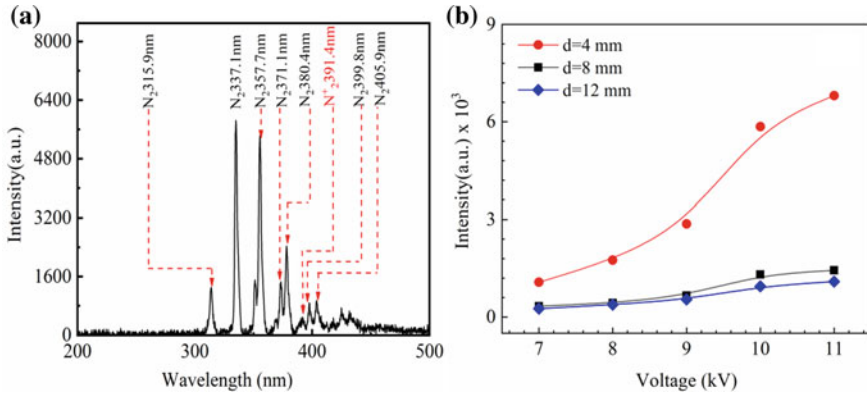


Fig. 7 The effect of applied voltage on a power consumption, b transferred charge and c discharge images





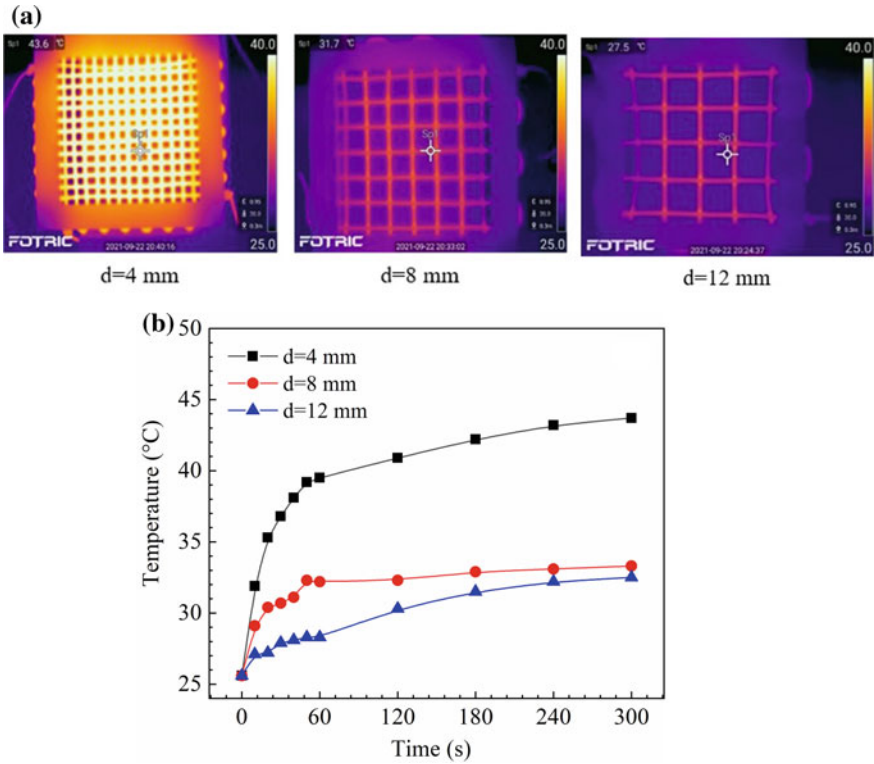
**Fig. 8** **a** Typical emission spectra in range of 250–500 and **b** the influence of applied voltage on the emission intensity at 337.1 nm

### 3.2 Optical Emission Spectrum Diagnosis

The typical optical emission spectra (OES) of the proposed DBD reactor with mesh size  $d$  of 4 mm in the wavelength range of 250–500 nm is shown in Fig. 8 under the operation condition of applied voltage 10 kV and pulse repetition frequency 1.5 kHz. It is clearly that the spectral dominated by various vibrational transition bands in  $N_2(C^3 \Pi_u - B^3 \Pi_g)$  second positive system and the first negative system band of  $N_2^+(B^2 \Sigma_u^+ - X^2 \Sigma_g^+)$ , which correspond to the excitation energy of 6.17 eV and 11.03 eV, respectively [18]. This result confirms that the proposed reactor can generate abundant energetic electrons to excite the working gas and generate a variety of reactive species. The emission intensity of the excited state of nitrogen at 337.1 nm is the strongest, therefore its evolution at different applied voltages is also obtained to investigate its effect. From Fig. 7b, the emission intensity gradually rises with the increased applied voltage regardless of the mesh size  $d$  and lower the mesh size  $d$  contributes to obtain a higher emission intensity at the same applied voltage. The reason for this phenomenon is that the discharge power becomes stronger with the narrow mesh size  $d$ , whereas the value of discharge power is proportional to the applied voltage. Thus, increasing the applied voltage or decreasing the mesh size  $d$  favors the formation of more active species.

### 3.3 Operation Temperature

Figure 9 shows the temperature profile and the variation of the surface temperature of the mesh-liked structure DBD reactor as a function of operation time. The discharge conditions are selected with the stable and intense discharge, which are more preferred to the practical operation conditions (applied voltage 10 kV, frequency



**Fig. 9** **a** The temperature profiles and **b** the variations of surface temperature of the proposed DBD reactors as a function of operation time

1.5 kHz). The surface temperature of the reactor suddenly climbs in the first 60 s and gradually increases with the operation time regardless of the mesh size  $d$ . Moreover, decreasing the mesh size  $d$  significantly enhances the surface temperature of the reactor and the highest temperature of the mesh size  $d$  follows the order of 4 mm > 8 mm > 12 mm. This agrees with the properties of the power consumption given in Fig. 4, which shows that the narrowest electrode distance has the largest total power.

### 3.4 Ozone Concentration

The mesh-like DBD reactor is capable of generating a widespread non-thermal plasma, therefore, it has great potential for many applications such as indoor purification, waste gas treatment, bleaching and air sterilization. Ozone shows positive effects in applications since its strong oxidizing capability and non-residual pollution property [19]. Hereby, the capability of the proposed DBD reactor for ozone generation is evaluated by using the ozone monitor (Pulitong, PLT3000-O3, China).

**Fig. 10** The effect of applied voltage on ozone concentration

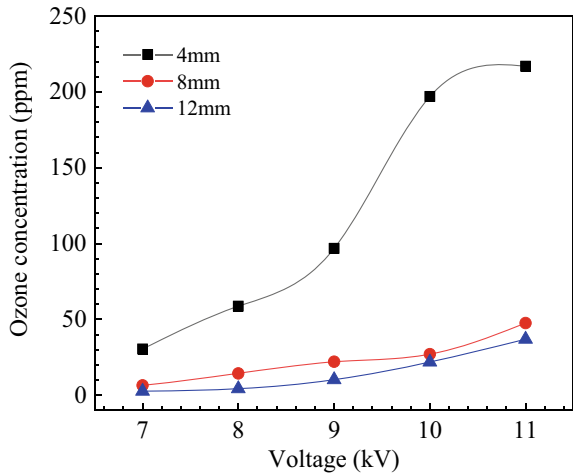


Figure 10 shows the influence of the applied voltage and the mesh size  $d$  on ozone concentration. Evidently, increasing the applied voltage is found to increase the ozone concentration. Ozone could be generation through the reaction between atomic and molecular oxygen based on the basic mechanism [20]. In air environment, increasing the applied voltage would deliver more energy into the reactor to trigger the reaction of oxygen dissociation, leading to the formation of atomic oxygen  $O$ . Therefore, a higher applied voltage is favorable to the formation of  $O$  and an increase of ozone concentration can be achieved (R1–R2). Xie et al. reported a similar result that the improvement of applied voltage favors the yield of ozone [21]. Notably, the ozone concentration decrease with the increase of the mesh size  $d$  and the ozone concentration of these electrodes follows the order  $4\text{ mm} > 8\text{ mm} > 12\text{ mm}$ . This phenomenon can be attributed to the lower discharge power when the mesh size  $d$  varies from 4 to 12 mm. The maximum ozone concentration of 240 ppm is reached at the applied voltage of 11 kV and the frequency of 1.5 kHz.



## 4 Conclusion

In this paper, a mesh-like DBD reactor with wire-to-wire cross contact electrode is proposed. The discharge characteristics of the proposed reactor in air are evaluated in terms of different applied voltages and mesh sizes. Increasing the applied voltage

could significantly enhance the discharge power, discharge area and transfer charge, leading to an increase in the discharge intensity and the emission intensity of the active species. Based on the analysis of the spatial electric field distribution, the highest electric field is generated at the contact point and decreasing the mesh size  $d$  is preferred to stabilize the electric field variability. The temperature of the reactor during discharge is inversely proportional to the mesh size  $d$ , indicating the large values of the mesh size  $d$  correspond to lower reactor temperatures. The maximum ozone yield of 240 ppm could be achieved with the applied voltage of 10 kV, the frequency of 1.5 kHz and the mesh size  $d$  of 4 mm.

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