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Effect of power parameters on micro-discharge induced by corona discharge

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Abstract

This research mainly describes the generation and diagnosis of plasma using a wire-plate discharge device driven by different power supplies, aimed at investigating the effect of driving source parameters on micro-discharge induced by a corona. The influence of parameters such as waveform, duty ratio and bias voltage on discharge characteristics was explored preliminarily. Experiment results show that the determination of volt-ampere characteristics under different driving source waveforms indicates that the application of square and pulse waveforms shows great advantages over that of sawtooth and sinusoidal waveforms. Similarly, the photo-thermal effects of the system were investigated by comparing the high-voltage electrode temperature and relative emission intensity of N_2 ($C^3\Pi_u \rightarrow B^3\Pi_g$, 0–0, 337 nm), where square and pulse waveforms also achieved better performance. But the pulse waveform had a slight advantage over the square waveform in terms of energy conversion. Further, investigations of the duty ratio and bias voltage applied on the pulse waveform were conducted, and the results indicate that the duty ratio could effectively improve the discharge power and thermal effect to a certain extent; however, the application of bias voltage on the pulse signal had little influence on the discharge power and thermal effect.

Keywords: photo-thermal effect, duty ratio, bias voltage, waveforms, micro-discharge

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

1. Introduction

Given the increasingly strict control of exhaust in the country, new requirements have been put forward to intensify terminal treatment technologies. Non-thermal plasma, a new technology for exhaust treatment, has the advantages of fast degradation and being convenient for real-time control in the process of purifying exhaust [1, 2], which give it great application foreground and technical optimization value. Thus more and more studies focus on promoting plasma generation to improve its application. With the aid of a three-electrode discharge reactor, Jiang *et al* systematically investigated the degradation efficiency and active species generation of volatile organic compounds (VOCs) during a sliding double-dielectric discharge driven by a unipolar pulse, a bipolar pulse and a coupled negative DC power supply [3, 4]. It was found that the sliding dielectric barrier discharge (DBD) not only produced a more uniformly distributed low-temperature plasma, but also had some advantages in the process of degrading VOCs. Besides, as an energy supply module, the driving sources played a critical role in enhancing the strength of the plasma. Wang [5] conducted an exploration of plasma generation and application using a coaxial DBD device driven by pulsed power and AC power, and higher energy efficiency and power deposition were achieved in the case of the pulsed power supply. Ma [6] made a comparison of discharge behavior between pulse-enhanced arcs and AC arcs. With the assistance of pulsed power, not only was the electron probe current enhanced by one to two times, but the electron emission was also strengthened. In our previous research, an investigation into improving plasma strength and activity by inducing micro-discharge in a porous insulating layer at low voltage during a corona was conducted and significant improvement was obtained [7]. Looking at existing researches

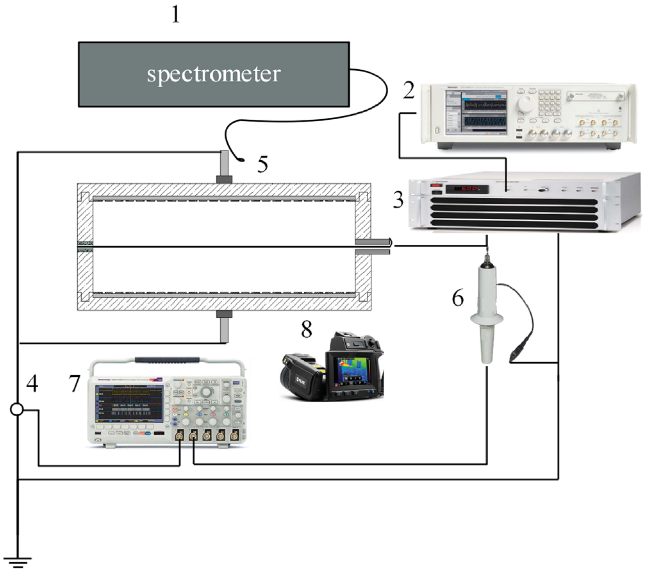

Figure 1. Schematic diagram of experimental setup: (1) spectrometer, (2) function generator, (3) power amplifier, (4) current probe, (5) wire-plate reactor, (6) high-voltage probe, (7) oscilloscope, and (8) infrared camera.

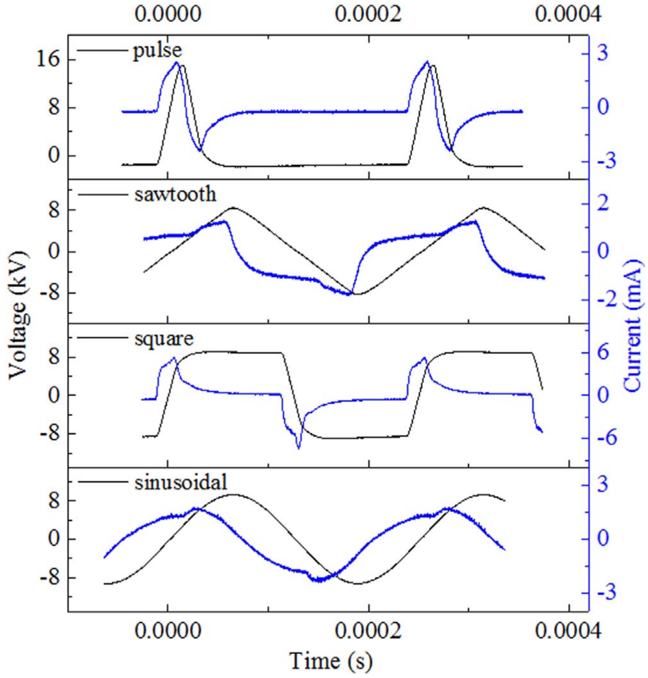

Figure 2. Voltage and current waveforms.

based on non-thermal plasma, the approaches for improving the application of plasma can be summarized as promoting plasma activity and strength using different methods [8–10]. However, there still exists a big space for optimization in enhancing the strength and activity of plasma.

In this paper, based on the micro-discharge induced by coronas in early research, the experiment focused on the influence of different power supplies on discharge. The effects of driving source parameters such as waveform, duty ratio, and bias voltage on discharge characteristics were investigated to illustrate the function rule of power supply on discharge, and thus to provide a theoretical basis for improving the efficiency of non-thermal plasma generation.

2. Experimental setup

The experiment system is shown in figure 1. In this experiment, a wire-plate discharge device with line-to-line spacing of 10 mm and line-to-plate spacing of 20 mm was employed; a tungsten wire with a diameter of 0.08 mm was selected as the high-voltage electrode, and a stainless steel plate was used as the low-voltage electrode with a size of $100 \times 60 \times 1\ mm^3$. Following previous research, a porous polytetrafluoroethylene layer with a thickness of 30 μm was deposited on the surface of the low-voltage electrode to meet the conditions for inducing surface micro-discharge. A function generator (AFG3152C) was used to generate and deliver various driving waveforms to a power amplifier (Matsusada AMPS20B20) with a magnification of 30 to provide external energy injection for the discharge device. A high-voltage probe (Tektronix 6015A) and a current probe (Pearson 2877) were used to measure the voltage and current during the discharge process.

To evaluate the photo-thermal effect during the discharge process, an infrared camera (FLIR T660) was mounted at a distance of 60 cm from the discharge device to capture a thermograph of the discharge. An emission spectrometer (Princeton Instruments sp-2750) with an optical fiber probe horizontally placed 3 cm away from the high-voltage wire electrode was employed to collect the emission spectral signals at 280–450 nm.

The discharge power of the system can be calculated according to the following formula:

$$P = f \cdot \int_0^T U(t) \cdot I(t) \mathrm{d}t$$

where f represents the repetition frequency, $U(t)$ is the instantaneous voltage, and $I(t)$ is the instantaneous current.

3. Results and discussion

3.1. Effect of signal waveforms on discharge characteristics

Figure 2 shows the voltage and current waveforms used in this study. The effects of waveforms on discharge were investigated by measuring volt-ampere characteristics and photo-thermal effect parameters during the discharge process to evaluate the energy injection of the discharge reactor. Figure 3 shows the volt-ampere characteristics of discharge with the application of a sinusoidal waveform, a square waveform (the duty ratio was 50%), a sawtooth waveform and a pulse waveform (the duty ratio was 8%). Comparing with the sawtooth and sinusoidal waveform, a better volt-

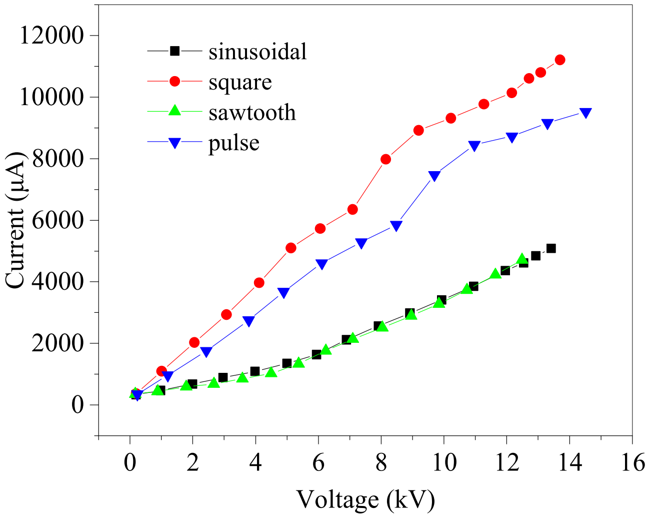

Figure 3. Effect of signal waveform on volt-ampere characteristic.

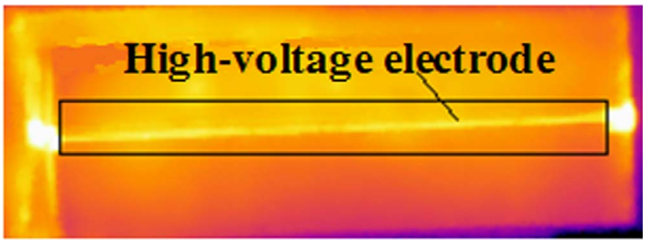

Figure 4. Heat energy distribution of the discharge space.

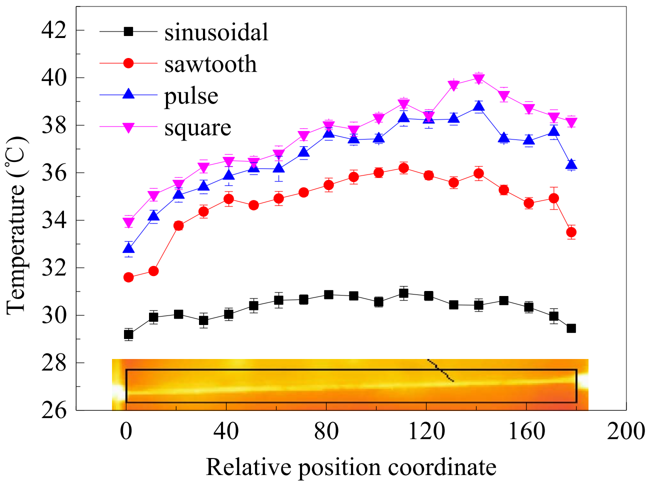

Figure 5. Effect of signal waveform on thermal effect.

ampere characteristic was obtained when the driving source was square or pulse waveform. When the applied voltage was 12 kV, the current was 10 140 μA, 8726 μA, 4712.5 μA and 4360 μA, corresponding to the square, pulse, sawtooth and sinusoidal signal waveforms. This shows the great advantage of the first two waveforms.

The effect of different waveforms on thermal effect was investigated preliminarily. Figure 4 shows the thermal distribution of the discharge space captured by the infrared camera under conditions of 12 kV applied voltage. We discovered that the heat produced during the discharge was mainly concentrated

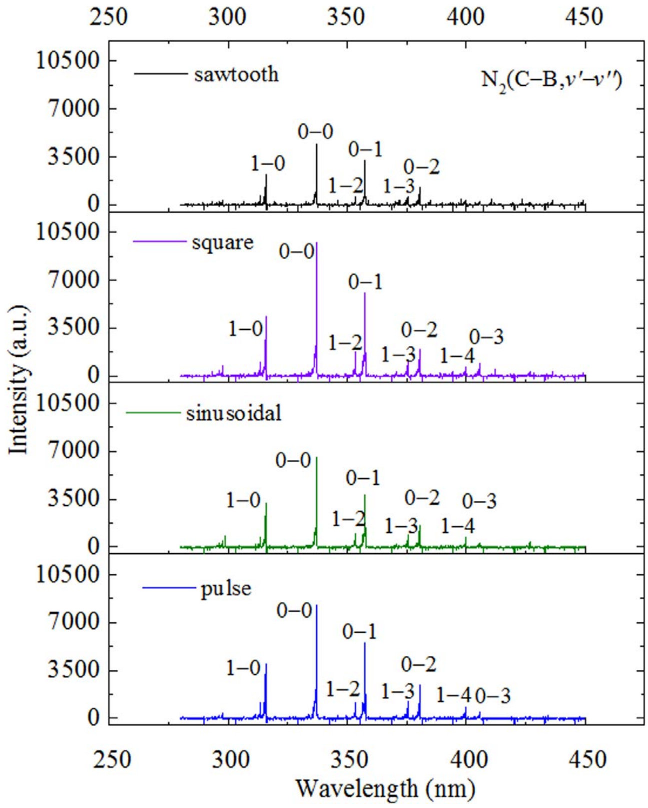

Figure 6. Effect of signal waveform on intensity of emission spectrum.

near the high-voltage electrode, so the experiment took the high-voltage electrode as the reference position to conduct further investigation into the influence of waveforms on thermal effect during the discharge process. Figure 5 shows the temperature measured on the high-voltage electrode when different waveforms were applied at the voltage of 12 kV; obviously, the temperature floated in a small range of 29 °C–40 °C. Similar to the volt-ampere characteristics, the temperature was relatively high when the input signals were square and pulse waveforms and relatively moderate when the signal was a sawtooth waveform, but the temperature of the electrode driven by a sinusoidal waveform was relatively low. At the voltage of 12 kV, the average temperatures on the electrode were 37.7 °C, 36.7 °C, 34.8 °C, and 30.3 °C, corresponding to square, pulse, sawtooth and sinusoidal waveforms, which intuitively reflect a better action of square and pulse waveforms on thermal effect.

Since the gas discharge was accompanied by heat and significant luminescence, in order to investigate the influence of different waveforms on discharge characteristics more comprehensively, the experiment first compared the optical emission spectra of plasma excited by different signal waveforms. As shown in figure 6, with applied voltage of 12 kV, the second positive band emission spectrum of N_2 ($C^3\Pi_u \rightarrow B^3\Pi_g$) [11] could be detected during the discharge, which was accounted for by a series of chemical reactions induced by the electron beam. Comparing the relative emission intensities of N_2 ($C^3\Pi_u \rightarrow B^3\Pi_g$, 0–0, 337 nm) to illustrate the photo-effect energized by different signal

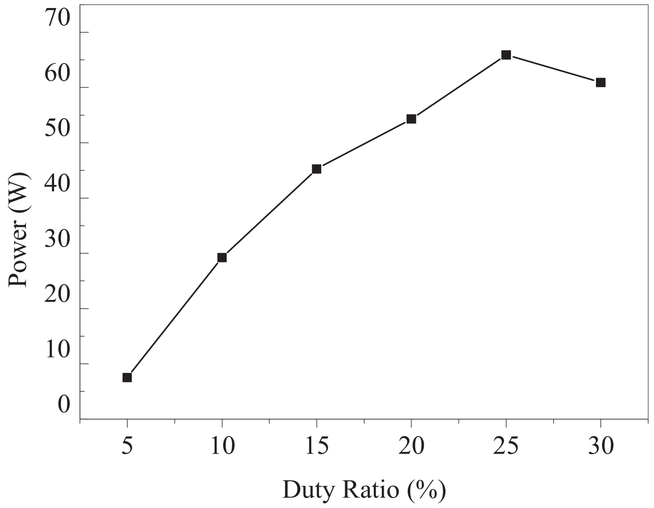

Figure 7. Effect of duty cycle on discharge power.

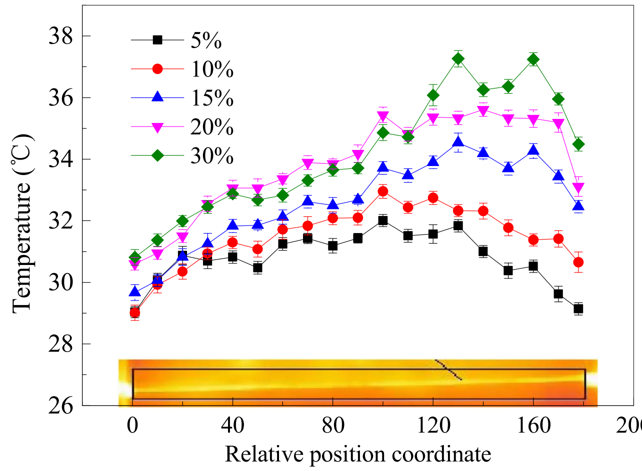

Figure 8. Effect of duty cycle on thermal effect.

waveforms, one could obviously discover that the relative emission intensities of N_2 ($C^3\Pi_u \rightarrow B^3\Pi_g$, 0–0, 337 nm) engendered by square waves and pulse waves were stronger than those produced by sinusoidal and sawtooth waveforms. The relative emission intensities of N_2 ($C^3\Pi_u \rightarrow B^3\Pi_g$, 0–0, 337 nm) corresponding to the different waveforms were in the following order: square > pulse > sawtooth > sinusoidal, with the relative intensity appearing as 10 844 a.u., 9604 a.u., 6026 a.u., 4384 a.u., respectively, thus corresponding to its function rule on volt-ampere characteristics and thermal effect.

Compared with sinusoidal and sawtooth waveforms, both square and pulse waveforms had the characteristics of a steeply rising edge and a short duty cycle [12, 13], which could instantaneously inject a large amount of energy into the discharge reactor, thereby inducing great power injection efficiency and photo-thermal energy [14]. However, considering the comparable photo-thermal effects engendered by the square waveform and pulse waveform under the same applied voltage, the higher power input made the energy conversion less efficient in the case of the square waveform. Therefore, the pulse waveform was selected for further research in this study.

Since the duty ratio and bias voltage might affect the generation efficiency of plasma driven by pulse waveforms to a certain extent [15, 16], this study focused on the effect of the duty ratio and bias voltage on discharge characteristics in the following experiment.

3.2. Effect of duty ratio on discharge characteristics

The experiment investigated the effect of the duty ratio on discharge characteristics. Figure 7 shows the change of discharge power with the duty ratio at a voltage of 13.5 kV and a frequency of 4 kHz. Within the range of duty ratios investigated, the discharge power of the system was obviously enhanced as the duty ratio increased, but the growth trend of power gradually slowed down with the increase of the duty ratio. At the duty ratio of 25%, a relatively better discharge power of 65.8 W was obtained, an increase of 58.4 W over that at a duty ratio set to 5%. Figure 8 shows the temperature of the high-voltage electrode under different duty ratios of 5%, 10%, 15%, 20% and 30%. The corresponding average temperatures measured on the electrode were 30.96 °C, 31.61 °C, 32.7 °C, 33.97 °C, and 34.26 °C. Similar to the variation of discharge power, the increase of the duty ratio efficiently promoted the thermal effect of the discharge. On the one hand, since the increase of the duty ratio could effectively lengthen the external electric field's action time, it could increase the discharge power of the system to some extent during the effective discharge period [17]. In addition, the increase of the duty ratio would enhance electron density and electron temperature, which could engender stronger ionization, hence increasing the thermal effect during discharge [18]. On the other hand, as the duty ratio increased, the energy input of the system simultaneously rose, but the discharge process was accompanied by energy loss. For a given discharge device, when the gas discharge excitation ionization reached saturation, excessive energy input would lead to an increase in energy loss, which in turn would reduce the energy utilization efficiency of the system.

3.3. Effect of bias voltage on discharge characteristics

In this experiment, we also studied the effect of bias voltage on discharge characteristics. The function generator provided bias voltage signals and then delivered them to the amplifier to magnify as applied bias voltage. Figure 9 shows the variation of discharge power with bias voltage at an applied voltage of 13.5 kV and a frequency of 4 kHz. During the course of the experiment, continuing to increase the positive applied bias voltage or to reduce the negative applied bias voltage outside the range of −135 V to 4050 V caused spark breakdown. Therefore, the range of bias voltages examined in this paper was the maximum range that the experimental device could withstand.

Within the bias voltage range explored, the changeable scale of positive bias voltage was greater than that of negative bias voltage, and the increase of the absolute value of the bias

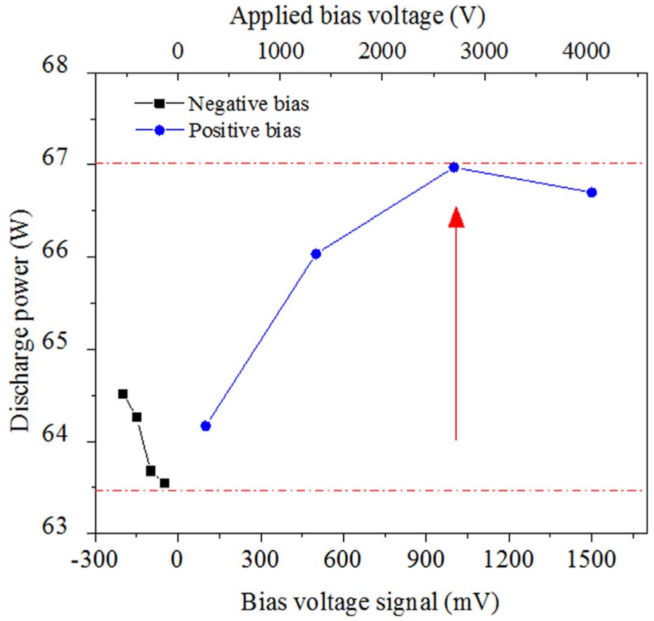

Figure 9. Effect of bias voltage on discharge power.

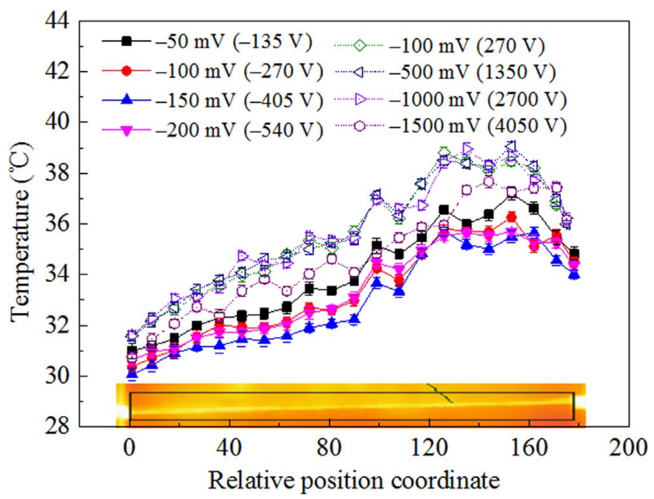

Figure 10. Effect of bias voltage on thermal effect.

Table 1. Average temperature of electrode under different bias voltages.

Bias voltage signal (mV)	Temperature (°C)
−200	34.1
−150	33.4
−100	33
−50	33.35
100	35.7
500	35.7
1000	35.7
1500	35.8

voltage would promote the discharge power of the system. However, the maximum increase induced by the variation of bias voltage was no greater than 4 W, which indicates just a slight impact on the discharge power. Similarly, figure 10 compares the temperature of the high-voltage electrode when different bias voltages were applied. With the variation of bias voltage, the average temperature of the electrode is shown in table 1. One could obviously find that the maximum and minimum temperatures were 33 °C and 35.8 °C, namely, the temperature variation range was less than 3 °C. This reaffirms the little effect of bias voltage on the thermal effect.

4. Conclusion

In conclusion, the comparison of volt-ampere characteristics, discharge power and photo-thermal effect not only enriches the theory of energy efficiency optimization during discharge, but also provides insight into the function rules of critical driving source parameters. Based on the research carried out in this study, the conclusions are as follows:

(1) Different waveforms had significant effect on the volt-ampere characteristics and photo-thermal effect of discharge. Specifically, compared with the application of sawtooth and sinusoidal waveforms, better volt-ampere characteristics and thermal effect were obtained when discharge was driven by square and pulse waveforms. Furthermore, the pulse waveform had a higher energy conversion efficiency than the square waveform.
(2) The increase of the duty ratio from 5% to 30% could significantly enhance the discharge power and the thermal effect of discharge. When the voltage was 13.5 kV and the frequency was 4 kHz, a relatively higher discharge power and temperature of the high-voltage electrode were observed (65.8 W and 33.97 °C respectively) when the duty ratio was set to 25%.
(3) The maximum adjustable range of bias voltages for the discharge device in this study was −135 V to 4050 V, and within the range investigated, the bias voltage had little influence on discharge characteristics.

Acknowledgments

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