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Matching a Nanosecond Pulse Source to a Streamer Corona Plasma Reactor With a DC Bias

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Abstract—Matching a pulse source to a plasma load is one of the main challenges to overcome to maximize the full potential of pulsed discharges for air purification applications. In this paper, we propose experiments that investigate the matching of a nanosecond pulse source to a corona plasma reactor that is aided by a high voltage on a tertiary electrode. The corona plasma reactor is a wire-cylinder reactor, as is commonly used in pulsed power plasmas. A tertiary electrode is situated on a dielectric layer against the cylinder of the reactor. On this tertiary electrode, we can apply a pulsed RF or dc voltage to provide an additional plasma and bias voltage in the corona plasma reactor.

The pulse source that energizes the main corona plasma is the nanosecond pulse source of Kumamoto University, Japan. In this paper, we show the results of experiments with a dc voltage on the tertiary electrode. We varied the amplitude of the pulsed voltage as well as the dc voltage and investigated their effect on the corona plasma with energy and ozone measurements. The results show that the matching to the reactor increases with increasing dc voltages. However, the matching effect decreases with higher repetition rates. Furthermore, ozone measurements confirmed that a better matching also results in a higher ozone production, but in a lower ozone production energy yield.

Index Terms—DC voltage, high voltage, nanosecond pulses, pulsed power supply.

I. INTRODUCTION

MATCHING a pulse source to a plasma load is one of the main challenges to overcome to maximize the full potential of pulsed discharges for air purification applications. Recent research has shown that plasmas generated by very short nanosecond high-voltage pulses are very efficient for a variety of applications [1]–[5]. Nonthermal plasma proves to be especially useful for air purification purposes [6], [7]. However, matching a pulse source to a corona plasma reactor is a challenge, especially when the pulse duration of the applied pulses becomes short (nanosecond with subnanosecond rise time). In this regime, a corona plasma reactor behaves as a transmission line and part of the applied high-voltage pulse will be reflected back to the source. Therefore, this part of the pulse energy is lost and will not contribute to the initial plasma process.

In our project, we will work with a corona plasma reactor in which we generate a streamer plasma with very short (<10 ns) high-voltage pulses for air purification [8]–[10]. It is therefore especially useful to investigate matching of a pulse source to a corona plasma reactor.

Previous studies into matching a nanosecond pulsed power source to a corona plasma reactor focused on changing a number of reactor and source parameters, such as reactor length, reactor configuration, pulse amplitude, pulse polarity, pulse duration, pulse rise time, pulse source output impedance, dc-bias voltage, and gas temperature [11]–[21]. The results show a number of good matching methods. Naturally, changing the output impedance of the pulse source to the plasma load works well [17], but this is not always practical. Changing the plasma load itself would often be a more flexible solution. Changing the plasma load by changing reactor parameters, such as length and electrode spacing, works well in some instances [19], [20]. Another practical method of providing matching is to change the plasma load by changing the parameters of the high-voltage pulse that generates the plasma. A short rise time and a high amplitude generate a low-impedance streamer plasma, which matches better to the source [15], [16], [20]. In some processes, the temperature of the gas is higher than room temperature, which can also lead to better matching [21]. Another good way to provide better matching is to superpose the pulse voltage on a dc bias [11]–[14], [20].

In this paper, we propose a new matching method by adding a tertiary electrode on a dielectric layer in the corona plasma reactor. On this tertiary electrode, we can apply a pulsed RF or dc voltage. The purpose of the pulsed and RF voltages is to generate a (surface) dielectric barrier discharge (S)DBD plasma on the tertiary electrode. This (S)DBD plasma can improve the matching of the pulse source to the corona plasma reactor in two ways.

First, the (S)DBD plasma can be generated at a high frequency to ensure that the background ionization of the gas in the corona plasma reactor is higher. A higher background ionization provides more free electrons for the streamers of the main plasma to propagate, and therefore, it changes the main plasma behavior [22].

Second, a secondary plasma on the surface of the outer wall of the corona plasma reactor virtually decreases the outer
Fig. 1. Sketch of the 5-ns pulse source with corona plasma reactor. For display purposes the length and thickness of various parts have been modified. The nanosecond pulse source is a triaxial Blumlein generator. The SF₆ spark gap switches the middle conductor of the Blumlein line to ground. This middle line is charged through the charging port with a charging circuit. When the spark gap switches, a pulse propagates toward the output of the pulse source. This pulse has the same amplitude as the charging voltage and a pulse duration that is determined by the length of the middle conductor.

The diameter of the reactor. This decreases the transmission line impedance $Z_r$ of the reactor

$$Z_r = \frac{1}{2\pi} \sqrt{\frac{\mu_r \mu_0}{\epsilon_r \epsilon_0}} \ln \frac{d_o}{d_i} \tag{1}$$

where $\mu_r$ and $\epsilon_r$ are the relative permeability and permittivity of the medium in the reactor, respectively, (both 1 for air), $\mu_0$ and $\epsilon_0$ are the permeability and permittivity of vacuum, respectively, and $d_o$ and $d_i$ are the outer and inner diameter of the reactor, respectively. A lower transmission line impedance improves the matching to the pulse source, because the transmission line impedance of a corona plasma reactor is almost always much higher than the output impedance of the source.

The purpose of a dc voltage on the tertiary electrode is to provide a dc bias to the pulse voltage, because a dc bias has proven to be a very effective way to match a pulse source to a corona plasma [11]–[14], [20]. It is a challenge to add a dc circuit to an existing nanosecond pulse generator circuit without deteriorating the rise time and other pulse properties of the nanosecond pulses [9], [23]. When the dc voltage is applied to the tertiary electrode in the corona plasma reactor, this issue is overcome.

In this paper, we focus on the experiments with a dc voltage on the tertiary electrode. We measure plasma energies to investigate if a better matching is provided by applying a dc voltage. Furthermore, we measure ozone production by the plasma to verify if a higher energy dissipation by the plasma also results in a higher plasma effectiveness.

In Section II, we present our experimental setup, followed by the results and discussion in Section III and the conclusion in Section IV.

II. EXPERIMENTAL SETUP

A. Nanosecond Pulse Source

The nanosecond pulse source we used for the experiments is described in [2] and [23]. It is a triaxial Blumlein configuration switched by a high-pressure SF₆ spark gap switch. A corona plasma reactor is connected directly to its output. Fig. 1 shows this setup.

The SF₆ spark gap is located on the left-hand side of the figure. It switches the middle conductor of the Blumlein line to ground. This middle line is charged through the charging port with a charging circuit that will be described in Section II-C. When the spark gap switches a pulse propagates toward the output of the pulse source. This pulse has the same amplitude as the charging voltage and a pulse duration that is determined by the length of the middle conductor (5 ns in our case).

At the output of the pulse source, a calibrated capacitive voltage divider and a Bergoz CT-F1.0 current transformer measure the output voltage and current, respectively. All waveforms were measured with a 2.5-GHz bandwidth oscilloscope (Tektronix DPO7254C, Tektronix Japan, Ltd) located in an Electromagnetic Interference shielded room. Fig. 2 shows a typical voltage, current and energy measurement. In Fig. 2(c), $E_{\text{pulse}}$ indicates the total energy dissipation in the plasma. This includes the energy deposited into the plasma not only by the initial pulse $E_{\text{1st pulse}}$ but also by the subsequent reflections of the pulse. These reflections are a result of imperfect matching of the pulse source to the plasma. The reflected pulse propagates back into the pulse source, where it will be reflected again to the corona reactor.

B. Corona Reactor With dc Bias

The nanosecond pulse source is connected to the corona plasma reactor, as shown in Fig. 1. Fig. 3 shows a cross section drawing of this corona plasma reactor. The corona plasma reactor is a wire-cylinder reactor to which we added a dielectric layer on the cylinder wall. This layer consists of ceramic (Al₂O₃). On top of this layer, we placed tertiary electrodes (copper strips) for the dc-bias voltage. In future experiments, we can also apply pulsed and RF voltages to these electrodes to generate a secondary (S)DBD plasma. The inner diameter of the cylinder electrode is 75 mm. The ceramic tube has a wall thickness of 5 mm and has an inner diameter of 65 mm. The length of the corona plasma reactor is 600 mm.

Fig. 4 shows the dc circuit that is used to connect to the tertiary electrodes. Resistor $R$ limits the charging current.
of buffer capacitor $C$ and also prevents any transients from the nanosecond pulse to damage the dc source. The buffer capacitor provides a stable dc voltage on the tertiary electrodes during plasma discharges. A P6015 voltage probe and a Bergoz CT-F0.5 current measure the associated voltage and current, respectively.

**C. Charging Circuit**

Fig. 5 shows the charging circuit of the nanosecond pulse source. The high-voltage capacitors $C_{HV}$ are charged in parallel by a 0–20-kV dc source with charging resistor $R_{ch}$. The voltage on the bottom capacitor is then reversed by thyratron switch $S$ and inductor $L_1$. As a result, twice the charging voltage is applied to the primary winding of pulse transformer $T$ and the high-voltage capacitors are discharged into the pulse forming line of the nanosecond pulse source. The Finemet core of the pulse transformer is premagnetized with an extra winding on the pulse transformer and a dc source with resistor $R_{LV}$. This allows for a bigger flux swing of the pulse transformer core without saturating.

**D. Ozone Measurements**

We used a UV/Vis spectrophotometer (V-550, JASCO Corporation, Japan) at the exhaust of the reactor for
Fig. 6. Energy measurements of the total dissipated plasma energy at positive pulse voltages at repetition rates of (a) 1 Hz, (b) 10 Hz, and (c) 100 Hz. $E_{\text{pulse}}$ is the total energy that is dissipated by the plasma, while $E_{\text{dc}}$ is the energy that is supplied by the high-voltage dc source. The figure shows that more energy is dissipated by the plasma when a higher dc bias is applied to the tertiary electrode at the cost of energy from the dc source. For higher repetition rates, this effect decreases.

Fig. 7. “Energy measurements of the total dissipated plasma energy at negative pulse voltages at repetition rates of (a) 1 Hz, (b) 10 Hz, and (c) 100 Hz. $E_{\text{pulse}}$ is the total energy that is dissipated by the plasma, while $E_{\text{dc}}$ is the energy that is supplied by the high-voltage dc source. The figure shows that more energy is dissipated by the plasma when a higher dc bias is applied to the tertiary electrode at the cost of energy from the dc source. For higher repetition rates, this effect decreases.

III. RESULTS AND DISCUSSION

A. Energy Measurements

In most corona plasmas with a dc bias, the dc bias is applied to the central electrode and added directly to the pulsed voltage [11]–[14], [20]. In doing so, the dc bias increases the applied electric field from the central electrode to the grounded wall in the reactor. In our case, we apply the dc bias to an electrode near the wall. Therefore, to increase the electric field in the corona reactor, we apply a positive dc voltage to the tertiary electrode when we have a negative pulse voltage and vice versa.

We measured the energy that the plasma dissipates for both negative and positive pulse voltages. Fig. 2 shows a

absorbance measurements for all ozone measurements in this paper. The ozone concentration was determined using

$$\log \frac{I_0}{I} = \frac{C_{\text{mol}} \cdot L^{-1}}{\epsilon d}$$

where $I$ and $I_0$ are the light intensity in the presence and absence of ozone, respectively, $C_{\text{mol}} \cdot L^{-1}$ is the ozone concentration (in mol $\cdot$ L$^{-1}$), $\epsilon$ is the molar extinction coefficient (in L $\cdot$ mol$^{-1}$ $\cdot$ cm$^{-1}$), and $d$ is the path length used in the measurements (in cm) [24]. We used $\epsilon = 3000$ L $\cdot$ mol$^{-1}$ $\cdot$ cm$^{-1}$ at a wavelength of 254 nm and $d = 1$ cm in our measurements.
Fig. 8. Energy measurements of the energy dissipated by the plasma during the first pulse (denoted by $E_{1\text{st pulse}}$) at positive pulse voltages at repetition rates of (a) 1 Hz, (b) 10 Hz and (c) 100 Hz. Comparing these results to Fig. 6 we see that the main energy increase in $E_{\text{pulse}}$ occurs during the first pulse. Again, the effect diminishes at higher repetition rates.

typical energy measurement. We differentiate between two energies. First, the total plasma energy $E_{\text{pulse}}$, which is the total dissipated power by the plasma due to the high-voltage pulse and its reflections, and second, $E_{1\text{st pulse}}$, which indicates only the plasma energy due to the first pulse. This last energy parameter is especially important because it indicates how well the pulse source matches to the corona reactor. Besides energy measurements in the nanosecond pulse source, we also measure the energy $E_{\text{dc}}$ that is supplied by the dc circuit.

From the first reflection of the high-voltage pulse onward, the gas in the corona reactor is highly ionized and therefore, any extra applied high voltage (due to the pulse reflections) will sustain or reignite the plasma [25]. Consequently, to make any statements about matching the pulse source to the corona reactor, $E_{1\text{st pulse}}$ gives the most information. For instance, in [9], we use a delay cable between the nanosecond pulse source and the load. Any pulse reflections will be reapplied to the load more than 200 ns later [26]. Therefore, the initial matching of the pulse source to the plasma load is the most important goal of this paper.

Figs. 6 and 7 show the results of the total energy measurements for positive and negative pulse voltages, respectively, at three different repetition rates of the pulse source $f_r$. The error bars indicate the standard deviation on each measurement. At 100-Hz repetition rate, arc discharges started to occur in some measurements. Therefore, we performed these measurements only up to 30 or 35 kV for those settings. We did all measurements with synthetic air (<5 ppm H$_2$O content) in the corona reactor with a flow of 1 L · min$^{-1}$.

From the results, we can conclude that applying a dc bias to the tertiary electrode increases the total plasma energy that is
dissipated by the nanosecond pulse, which indicates improved matching of the pulse source to the reactor. This effect becomes more pronounced when the dc voltage increases. However, for higher repetition rates, the matching effect of the dc bias reduces to where the plasma energies for different applied dc voltages are very similar. A possible explanation could be a shifting dominant source of background ionization. The background ionization of the gas in the corona plasma reactor will be increased if a dc corona plasma ignites at the wire electrode due to the applied dc bias. With this higher background ionization, the main plasma ignites more readily, resulting in a higher dissipated energy. For high-repetition rates, the background ionization of the gas is further increased, because there is more plasma. Therefore, any effect of a higher background ionization due to the dc bias becomes less pronounced.

The improved plasma energies at higher applied dc voltages are accompanied by an energy cost in the dc circuit. Especially for high dc voltages, $E_{dc}$ increases significantly.

Figs. 8 and 9 show the energy deposited by the first pulse for positive and negative pulse voltages, respectively. It is apparent that $E_{1st\, pulse}$ increases significantly when a dc bias is applied. When we compare Figs. 6 and 7 with Figs. 8 and 9, we can conclude that the main energy increases during the first pulse, which was the main goal of this paper. When more energy is dissipated in the first pulse, the pulse reflection to the pulse source is lower, which explains why the energy increase with an applied dc voltage is lower for $E_{pulse}$ than that for $E_{1st\, pulse}$. Now the energy increase in the main plasma (for the first pulse) is very similar to $E_{dc}$, even for higher dc voltages. Fig. 10 shows a good example of improved matching of the main pulse when a dc bias is applied.

### B. Ozone Measurements

We measured ozone production in the corona plasma reactor to investigate if any increased plasma energy due to an applied dc voltage also results in an increased ozone production. The gas in the corona plasma reactor was again synthetic air with a flow of 1 L · min$^{-1}$. Due to the low sensitivity setting of the ozone measuring system, we only measured ozone at a repetition rate of 100 Hz.

Figs. 11 and 12 show the results of the ozone measurements. From the results, we can conclude that the better matching of the pulse source also results in more ozone production, which is a good indicator that the plasma effectiveness also increases. The ozone production is slightly higher for negative pulsed operation, but the difference with positive pulse operation is very small.

With the energy results of Figs. 6(c) and 7(c) and the ozone results of Figs. 11 and 12, we can calculate the ozone yield of the plasma. This yield is shown in Figs. 13 and 14 for positive and negative pulse voltages, respectively. Figs. 13(a) and 14(a) show the yield if we considered only $E_{pulse}$. For positive pulse voltages, the yield increases with increased dc voltages. For negative pulse voltages, the yield with a dc voltage is below the yield without a dc voltage (except for $E_{dc} = 15$ kV). Figs. 13(b) and 14(b) show the ozone yield when the dc energy $E_{dc}$ is also included in the yield calculation. Now, all yield results are similar when a dc voltage is used.

The yield results show that a dc bias has almost no effect on the ozone yield at a repetition rate of 100 Hz. The results might be different at lower repetition rates. In addition, the ozone production is a cumulative effect of the plasma generated by the first pulse and all its reflections. Unfortunately, the ozone measurements are unable to distinguish between the ozone production during the first pulse and the ozone production during the reflections. Therefore, we have no information on what effect the increased matching for the first pulse has on the ozone production.

Another observation from the ozone yield results is that a negative corona plasma results in a higher ozone yield and that the ozone yield decreases for higher pulse voltages. This is consistent with for instance [1]. The ozone production is also on the high side for a corona plasma,
especially compared with the theoretical maximum of around 1200 g · kWh⁻¹, [27], [28], but consistent with previous studies with the nanosecond pulse generator [23]. This shows that very short pulses are efficient for ozone production. Other studies with corona plasma reactors report efficiencies in the range of 15–100 g · kWh⁻¹ [29]–[32].

IV. CONCLUSION

Matching a pulse source to a plasma load is one of the main challenges to overcome to maximize the full potential of pulsed discharges for air purification applications. In this paper, we proposed experiments that investigate the matching of a nanosecond pulse source to a corona plasma reactor that is aided by a high voltage on a tertiary electrode. The corona plasma reactor is a wire-cylinder reactor, as is commonly used in pulsed power plasmas. A tertiary electrode is situated on a dielectric layer against the cylinder of the reactor. On this tertiary electrode, we can apply pulsed RF or dc voltages to provide an additional plasma and bias voltage in the corona plasma reactor. The pulse source that energized the main corona plasma was the nanosecond pulse source of Kumamoto University, Japan. In this paper, we showed the results of experiments with a dc voltage on the tertiary electrode. We varied the amplitude of the pulsed voltage and the dc voltage and investigated their effect on the corona plasma with energy and ozone measurements. The results showed that the matching to the reactor increases with increasing dc voltages. However, the matching effect decreases with higher repetition rates. This effect could be attributed to the minimal effect of increased background ionization by the dc bias when compared with the increased background ionization due to the higher repetition rate. Furthermore, ozone measurements confirmed that a better matching also results in a higher ozone production. However, the ozone production energy yield is not influenced by an applied dc bias.

V. FUTURE WORK

Besides the experiment with the dc voltage on the tertiary electrode in the corona plasma reactor, of which we showed the results in this paper, we proposed two more experiments in the introduction: applying an RF source and a pulse source to the tertiary electrode. The main benefit of these experiments is that besides a bias voltage, now also a strong secondary (S)DBD plasma can be generated in the corona plasma reactor. This secondary plasma might aid the main plasma and provide better matching of the nanosecond pulse source to the corona reactor. We will show results of these experiments in future work.

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