A Wire-Plate Type Nonthermal Plasma Reactor Utilizing a Slit Dielectric Barrier and a Third Electrode

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Abstract—The effects of the third electrode on the discharge and ozone generation characteristics of a wire-plate type nonthermal plasma reactor, with a slit dielectric barrier, have been investigated. When a third electrode is installed just above the slit of the slit dielectric barrier, where an intense surface corona discharge occurred, it is found that a significantly-increased ozone can be obtained, especially from a negative corona discharge. This, however, reveals that the third electrode can activate the corona discharges, not only on the wire but also on the slit of the slit barrier of the plasma reactor. As a result, a stainless-steel wire and an insulator-wrap wire, which are used as the third electrodes, have significantly influenced both the corona discharge on the corona wire and the surface charges on the slit barrier. As a result, much higher amounts of output ozone can be obtained.

Keywords—Nonthermal plasma reactor, Third electrode, Slit dielectric barrier, Corona discharge, Ozone generation.

I. INTRODUCTION

Air pollution is the most significant environmental problem facing the world today. Non-thermal discharge plasma techniques offer an innovative approach as a cost-effective solution of these problems [1-4]. Several non-thermal discharge plasma techniques have been proposed for the removal of NOx, SOx, VOCs, and CFCs from pollutant-gases [5]. These include the production of non-thermal discharge plasma using a pulsed corona discharge [5, 6], a silent or dielectric barrier discharge [7], a surface discharge [8], an electron beam [5, 9], and a corona discharge in a ferroelectric pellet packed-bed [5, 10, 11]. The effective removal of NOx, SOx, and VOCs from pollutant gases, however, requires the generation of an intense corona discharge in the processing region of the plasma reactor [5]. Consequently, most of the electrical energy, which is fed into the reactor, has to produce energetic electrons instead of heating ambient gases and ions in the processing space [5, 12]. The removal of pollutant gases can be stimulated by an electrophysicochemical reaction. This electrophysical reaction originates from energetic electrons [9], where the electrochemical reaction is mainly caused by the ozone and radicals which are produced from corona discharge in a non-thermal discharge plasma reactor [5, 6]. Effective ozone generation is the key technology in making nonthermal plasma reactors practical and effective in the removal of pollutant gases [5, 6, 13].

A wire-plate type plasma reactor, with a slit barrier, has been reported as being an effective nonthermal plasma reactor because it produces a vast amount of ozone [14, 15]. When a DC high voltage is applied to the corona electrode of the wire-plate type plasma reactor with a slit barrier, which is installed on the ground plate electrode, the surface of the slit barrier becomes corona-charged, and a strong electric field is formed between the corona-charged surface and ground electrode, through the slit of the barrier. Thus, the slit and the surface of the barrier are covered with intense corona discharges. Due to the back current flowing from the slit discharge area toward the corona wire in the wire-plate air gap space, the efficiency of the produced ozone decrease.

In this paper, the effects of the third electrode on the discharge and ozone generation characteristics of a wire-plate type nonthermal plasma reactor, with a slit barrier, have been investigated experimentally. This paper will report on the corona discharges, the current-voltage and ozone generation characteristics of the plasma reactor, with and without the third electrode. Parametric studies regarding the resistance and the airgap distance of the third electrode have been conducted, and their characteristics have been compared and analyzed.

II. EXPERIMENTAL SETUP

A schematic diagram of the experimental setup is shown in Fig. 1. The setup consists of a wire-plate type non-thermal plasma reactor (PR) placed in cylindrical chamber, a high-voltage DC power supply (HV), an O2 gas feeder (OB) with a flowmeter (FM), an ozone monitor (OM), and current and voltage measurement sets (HP, DVM, SO). The configuration of the reactor is a typical wire-plate type electrode system consisting of a corona-wire electrode (CW) and a grounded plate electrode (PE). A slit mica sheet barrier (SB) is glued on the ground electrode (PE). A third electrode (TE) is installed above the slit of the mica barrier. For different third resistance ($R_3$) levels ranged between $R_3=1k\Omega$ and $R_3=\infty\Omega$, the third electrode was grounded (G) or no connected (NC, floating, $R_3=\infty\Omega$) with the ground, as shown in Fig. 1.
Fig. 1. The schematic diagram of the experimental setup.

(a) close-up configuration of the proposed plasma reactor

(b) side-view of the proposed plasma reactor

Fig. 2. The configuration of the proposed plasma reactor with a slit barrier and a third electrode.

Fig. 3. Current-voltage characteristics of the three types of plasma reactors (teflon-wrapped wire third electrode, \( h = 1.5 \) mm, \( R_3 = \infty \Omega \)).

III. RESULTS AND DISCUSSION

Fig. 3 shows the measured current-voltage (I-V) characteristics, for the three types of plasma reactors, the wire-plate type without SB and TE (WP), the wire-plate type with SB and without TE (WB), and the wire-plate type with SB and TE (WT). The corona characteristics of the WP exhibited a very slow increase and an eventual breakdown as the applied voltage increased.
increased above 21.0 kV and 24.8 kV for the positive and negative coronas, respectively. The I-V characteristics of the WB and the WT were significantly different from those of the WP. In particular, the corona current increased more rapidly with an increase in the applied voltage, reaching peak corona currents of up to 1.38 mA and 1.34 mA at voltages of about 14.4 kV and 14.7 kV, respectively, for the negative and positive coronas of the WB, and to 1.39 mA and 1.45 mA at voltages of about 14.7 kV and 15.5 kV, respectively, for the negative and positive coronas of the WT, both increases were caused by discharges of the slit barrier.

**Fig. 4.** Ozone generation characteristics of the three types of plasma reactors (teflon-wrapped wire third electrode, h=1.5 mm, \( R_3 = \infty \Omega \)).

**Fig. 4** shows the output ozone generation characteristics, as a function of the applied DC high voltage, for the three types of plasma reactors; the WP, WB and WT. As plots show, the generation of ozone is initiated at the corona onset voltage and it increases with an increase in the applied voltage, until a maximum value is reached near the breakdown voltage. Table 1, shows the detailed data of Fig. 4, higher amounts of output ozone were obtained from the plasma reactors, with maximum values of 1,244 ppm and 1,130 ppm from the WB and 1,364 ppm and 1,414 ppm from the WT, as compared with 318 ppm and 741 ppm from the WP, for the positive and the negative coronas, respectively.

![Breakdown](image)

**Table 1.** A comparison of the characteristics of the three types of plasma reactors.

<table>
<thead>
<tr>
<th>Reactor Types</th>
<th>Vam [kV]</th>
<th>Icm [mA]</th>
<th>O₃m [ppm]</th>
<th>O₃m/O₃WP [-]</th>
<th>P [W]</th>
<th>Pm/PWP [-]</th>
<th>Y [ppm/W]</th>
<th>Ym/YWP [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Positive corona</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP</td>
<td>21.0</td>
<td>0.27</td>
<td>318</td>
<td>1.00</td>
<td>5.67</td>
<td>1.00</td>
<td>56.09</td>
<td>1.000</td>
</tr>
<tr>
<td>WP+SB</td>
<td>14.4</td>
<td>1.38</td>
<td>1,244</td>
<td>3.91</td>
<td>19.87</td>
<td>3.51</td>
<td>62.60</td>
<td>1.116</td>
</tr>
<tr>
<td>WP+SB+TE</td>
<td>15.7</td>
<td>1.39</td>
<td>1,244</td>
<td>4.29</td>
<td>20.43</td>
<td>3.60</td>
<td>66.76</td>
<td>1.190</td>
</tr>
<tr>
<td><strong>Negative corona</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP+SB</td>
<td>14.7</td>
<td>1.34</td>
<td>1,130</td>
<td>1.52</td>
<td>19.70</td>
<td>1.53</td>
<td>57.37</td>
<td>0.998</td>
</tr>
<tr>
<td>WP+SB+TE</td>
<td>15.5</td>
<td>1.45</td>
<td>1,414</td>
<td>1.91</td>
<td>22.48</td>
<td>1.74</td>
<td>62.91</td>
<td>1.095</td>
</tr>
</tbody>
</table>

**Fig. 5.** The schematic diagram and corona discharge mechanism of the wire-plate plasma reactor with a slit barrier.

The discharge mechanism on the surface and slit of the WB type, as shown in Fig. 5 (a), would be considered as follows [14, 15]. When a HV is applied to a corona wire (CW) and a plate electrode (PE) with a dielectric slit barrier (SB), a corona discharge takes place on the CW. The ions produced from the corona discharge near the CW will migrate to the SB, and attach to it, as

\[ Q_O = \int I dt \]

where

- \( Q_O \), \( I \), and \( t \) are the stored charge, the mean corona current, and the corona-exposed time.
- Most migrated ions attach and store themselves to the surface of the SB, as shown in Fig. 5 (b), and they act as a space charge. This is due to a very long relaxation time (\( \tau = \rho \varepsilon_0 \varepsilon = 155 \mu s \), where \( \rho = 3.5 \Omega \cdot \text{cm}, \varepsilon_0 = 5.0 \)) of the mica sheet SB. A little leakage charge, \( Q_L = Q_O \exp(-t/\tau) \), however, will leak from the surface of the SB without any corona discharge occurring. The surface charge \( Q_S = Q_O - Q_L \) on upper-side surface of the SB, will increase with increases in \( I \) and \( t \).
If a space charge is stored on the upper-side surface of the SB, an opposite charge of the same amount (-QS) will be induced on the bottom-side surface. A space-charge-induced voltage, $V_S = \frac{Q_S}{C_S}$, will appear between the upper-side and bottom-side surfaces of the SB, where $C_S$ is the capacitance of the SB. If the charges increase, the space-charge-induced field at slit $E_S$ will increase. If $E_S$ exceeds the breakdown strength of the air, $E_B$, $E_S \geq E_B$, there would be a discharge, along the shortened path $L$, through the slits of the SB. This discharge follows the barrier surfaces, and converges at the slits, where intense corona discharges occur, as shown in Fig. 6.

![Corona discharge on wire and slit barrier](image)

(a) positive corona discharge

(b) negative corona discharge

Fig. 6. Photographs of the corona discharges on the wire and slit barrier of the WB type plasma reactor.

This means that this type of a plasma reactor generates a corona discharge twice, once from the CW and again from the SB surface and slits [14-15].

The intense corona discharges that dominate in the slits of the barrier, as shown in Fig. 6, would produce many ions, which migrate from the slit toward the corona electrode. These, however, increase current consumption and decrease ozone output. If a third electrode is installed just above the slit, the third electrode would perform two actions; a field enhancing action and an ion-reducing action. The field enhancing action, weakly enhancing the field on the discharge wire, would be caused by the shielding the barrier effect of the slit barrier on the plate to the corona wire. From the slit, the ions, having an opposite polarity to the discharge wire, would migrate to the discharge wire as a backward current [16]. The third electrode, installed just on the slit and connected to the ground electrode, can absorb back-current ions, effectively. The grounded third electrode would collect ions [$I_3 = (+I_C) + (-I_B)$] from the corona wire (+$I_C$) and the slit (-$I_B$), and this concurrently determines the potential of the third electrode ($V_3 = R_3 I_3$). These actions and the potential of the third electrode might control corona discharges, not only on the slit, but also on the corona wire. These effects are shown in Fig. 4 and Table 1, as the increased amount of the output and yield of ozone.

There is a space potential in the air-gap space of a wire-plate [17], where a high voltage is applied on a corona wire. The space potential at a given space-place is determined by the distance ($h$) from the ground electrode. A third resistance, $R_3$, which connects from the third electrode and ground, also effects to the space potential in the air-gap space. The smaller values of $h$ and $R_3$ give lower potential values, while larger values of $h$ and $R_3$ form higher potential values. The floated third electrode, having space potential ($V_3$) of $h$ point, would collect the backward-ions from the slit. Then the potential of the floated third electrode become decreased, this makes to collect ions from the corona wire. These actions will be repeated. Then the potential of the floated third electrode would be saturated to a certain value, by associating with the space potential of $h$ point. These actions and the potential might also influence corona discharges, on the slit and the corona wire. These effects would be shown in Fig. 4 and Table 1.
current and ozone generation. Fig. 9 shows that there is an optimum distance ($h=1.0\text{mm}$) between the third electrode and substrate for which the intenser corona discharge and the larger output ozone were generated.

Figs. 10 and 11 show the I-V and ozone generation characteristics of the WP, WB and WT for different grounded third resistance ($R_3$) levels, 1kΩ, 20MΩ and ∞Ω (NC in Fig. 1), at a fixed distance, $h=1.0\text{mm}$, and for the third electrode of the stainless-steel wire and the teflon-wrapt wire. As shown in Figs. 10 and 11, $R_3$ also significantly influences corona discharge and ozone generation, as shown in Table 2.

Table 1, 2 show the comparisons for the three types of plasma reactors, the WP, WB and WT, for positive and negative corona discharges, respectively. For the wire-plate type (WP), the maximum output ozone concentration levels were only 318ppm and 741ppm for the positive and negative coronas, respectively. For the wire-plate type with a slit barrier (WB), the maximum output ozone concentration levels increased to 1,244ppm and 1,130ppm for the positive and negative coronas, respectively. For the WB with the third
electrode (WT), the maximum output ozone concentration amounts increased significantly to 1,437 ppm and 1,948 ppm, for the third electrode of the stainless-steel wire and the teflon-wrapt wire respectively, for the negative corona at \( R_3 = 20 \, \Omega \). On the other hand, it shows a little change for the positive corona case. Especially for the negative corona discharges, the output ozone concentration levels of the WT, at optimized \( h \) and \( R_3 \), were 1.27 and 1.72 times, and, the maximum output ozone yields of the WT were 1.33 and 1.51 times, higher than those of the WB, for the stainless-steel type and the teflon-wrapt type of the third electrode, respectively.

### Table 2

<table>
<thead>
<tr>
<th>Reactor Types &amp; Experimental Conditions</th>
<th>( V_{\text{am}} ) [kV]</th>
<th>( I_{\text{cm}} ) [mA]</th>
<th>( O_3 ) [ppm]</th>
<th>( O_3/O_{\text{WB}} ) [-]</th>
<th>( P ) [W]</th>
<th>( P_{\text{WT}}/P_{\text{WB}} ) [-]</th>
<th>( Y ) [ppm/W]</th>
<th>( Y_{\text{WT}}/Y_{\text{WB}} ) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive Corona (WB+SB)</td>
<td>14.4</td>
<td>1.38</td>
<td>1,244</td>
<td>1.00</td>
<td>19.87</td>
<td>1.000</td>
<td>62.60</td>
<td>1.000</td>
</tr>
<tr>
<td>( R_3 = 1 , \Omega )</td>
<td>13.6</td>
<td>1.42</td>
<td>1,163</td>
<td>0.93</td>
<td>19.31</td>
<td>0.972</td>
<td>60.22</td>
<td>0.962</td>
</tr>
<tr>
<td>( R_3 = 20 , \Omega )</td>
<td>14.9</td>
<td>1.20</td>
<td>1,251</td>
<td>1.01</td>
<td>17.88</td>
<td>0.900</td>
<td>69.97</td>
<td>1.118</td>
</tr>
<tr>
<td>( R_3 = \infty , \Omega )</td>
<td>15.4</td>
<td>1.16</td>
<td>1,183</td>
<td>0.95</td>
<td>17.86</td>
<td>0.899</td>
<td>66.22</td>
<td>1.058</td>
</tr>
<tr>
<td>Positive Corona (WB+TE)</td>
<td>14.7</td>
<td>1.53</td>
<td>1,130</td>
<td>0.91</td>
<td>22.49</td>
<td>1.132</td>
<td>50.24</td>
<td>0.803</td>
</tr>
<tr>
<td>( R_3 = 1 , \Omega )</td>
<td>14.7</td>
<td>1.53</td>
<td>1,130</td>
<td>0.91</td>
<td>22.49</td>
<td>1.132</td>
<td>50.24</td>
<td>0.803</td>
</tr>
<tr>
<td>( R_3 = 20 , \Omega )</td>
<td>15.1</td>
<td>1.39</td>
<td>1,209</td>
<td>0.97</td>
<td>20.99</td>
<td>1.056</td>
<td>57.60</td>
<td>0.920</td>
</tr>
<tr>
<td>( R_3 = \infty , \Omega )</td>
<td>15.2</td>
<td>1.52</td>
<td>1,212</td>
<td>0.97</td>
<td>23.10</td>
<td>1.163</td>
<td>52.46</td>
<td>0.838</td>
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<tr>
<td>Negative Corona (WB+SB)</td>
<td>14.7</td>
<td>1.34</td>
<td>1,130</td>
<td>1.00</td>
<td>19.70</td>
<td>1.000</td>
<td>57.37</td>
<td>1.000</td>
</tr>
<tr>
<td>( R_3 = 1 , \Omega )</td>
<td>13.4</td>
<td>1.34</td>
<td>1,114</td>
<td>0.98</td>
<td>17.96</td>
<td>0.912</td>
<td>62.04</td>
<td>1.081</td>
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<tr>
<td>( R_3 = 20 , \Omega )</td>
<td>14.2</td>
<td>1.33</td>
<td>1,437</td>
<td>1.27</td>
<td>18.89</td>
<td>0.959</td>
<td>76.09</td>
<td>1.326</td>
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<tr>
<td>( R_3 = \infty , \Omega )</td>
<td>15.1</td>
<td>1.20</td>
<td>1,260</td>
<td>1.12</td>
<td>18.12</td>
<td>0.920</td>
<td>69.54</td>
<td>1.212</td>
</tr>
<tr>
<td>Negative Corona (WB+TE)</td>
<td>14.4</td>
<td>1.47</td>
<td>1,685</td>
<td>1.49</td>
<td>21.17</td>
<td>1.075</td>
<td>79.60</td>
<td>1.388</td>
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<tr>
<td>( R_3 = 1 , \Omega )</td>
<td>14.7</td>
<td>1.62</td>
<td>1,948</td>
<td>1.72</td>
<td>23.81</td>
<td>1.209</td>
<td>81.80</td>
<td>1.426</td>
</tr>
<tr>
<td>( R_3 = \infty , \Omega )</td>
<td>14.4</td>
<td>1.05</td>
<td>1,313</td>
<td>1.16</td>
<td>15.12</td>
<td>0.768</td>
<td>86.84</td>
<td>1.514</td>
</tr>
</tbody>
</table>

The reason for this is shown in Fig. 6, which shows that there is a dominantly intense corona discharge that occurs from the corona wire for the negative case, while a relatively weak slit discharge can be seen from the slit barrier. In this experiment, the third electrode was set just above the slit of the barrier, as a result, it might have a significant influence on the corona discharges of the slit, more so than that of the upper corona wire. The corona discharge on the slit would be enhanced tremendously by the actions of the third electrode and become intensified, as shown as in Fig. 12, thus...
producing additional ozone effectively, and concurrently elevated the yield of ozone.

This result is attributable to the intense corona discharges which occurred at the slits and surfaces of the barrier. Such discharges can be stimulated by the actions of the third electrode. From the results, the wire-plate type plasma reactor, with a slit barrier on the plate and a third electrode on the slit, may be of use as an effective plasma reactor that can remove pollutants.

IV. CONCLUSION

A new wire-plate type of discharge plasma reactor, utilizing a mica slit barrier and a third electrode, has been investigated. The effect of the third electrode on corona discharges was examined, and the following conclusions have been made:

From the observed results, the third electrode of a wire-plate type plasma reactor with a slit barrier can activate corona discharges of the slits. Then, it would control fields, forms an intensified corona discharge, and produces a higher amount of output ozone.

A stainless-steel wire and an insulator-wrap wire, which are used as the third electrode, have significant influence on the corona discharges of the corona wire and the slits. As a result, higher output ozone levels, 1,437ppm and 1948ppm, can be obtained at the optimum conditions. These amounts are 1.27 and 1.72 times higher than those without a third electrode, especially for negative corona discharges. And this type of plasma reactor, with a slit barrier and a third electrode, may be effective in removing pollutant gases.

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