Evaluation of matching between a pulsed-power and corona discharge reactor containing different thickness of soil

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Abstract. Soil contamination by organic compounds has become an issue of concern around the world. Currently, non-thermal plasma, especially pulsed corona discharge, has received a great attention in environmental protection field. As a result, the matching between a pulsed-power and corona discharge reactor containing different thickness of soil was a significant aspect in optimizing the pulse corona discharge. In this paper, some methods have been adopted to achieve the matching, including choosing a suitable capacity, adjusting the frequency, providing a suitable soil thickness and comparing the energy and energy utilization efficiency. The details of the matching and optimization discussed were based upon the theories of streamer formation and experimental results as well. The results indicated that energy injected into the reactor increased with the pulse forming capacity and pulse frequency. There existed an optimal energy utilization efficiency with the change of soil thickness and pulse frequency under the pulse forming capacity of 100 pF. The SED at pulse voltage of 19 kV and pulse frequency of 70 Hz was achieved 0.11 J g⁻¹ soil at the soil thickness of 3 mm, which was only 0.064 J g⁻¹ soil at the soil thickness of 9 mm; meanwhile, with the increase of pulse frequency from 50 Hz to 90 Hz, the SED increased from 0.075 J g⁻¹ soil to 0.146 J g⁻¹ soil at 19 kV and soil thickness of 3 mm. This study is expected to provide reference for the matching between a pulsed-power and reactor containing different thickness of soil for producing corona discharge.

1. Introduction

Atmospheric corona discharge plasmas has been widely used in environmental pollution control including water purification and gas conversion [1, 2] and various material modification occasions [3, 4]. Besides the capability for contaminated water and exhaust gas treatment, corona discharge plasma has given rise to interest in the application of soil remediation [5, 6]. Under the right conditions, the plasma can be efficient: a large amount of the energy is utilized to initiate the desired chemical reactions. However, a part of energy is dissipated by the process of plasma generation and only little information that is about the mechanisms involved in generating the plasma in an efficient way can be found. To obtain high energy transfer efficiencies from pulsed-power into plasma generation, the

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matching between the power source and the corona plasma reactor is very important. Besides, the load impedance of reactor changes rapidly during the plasma generation [7] as the characteristic of plasma generation is transient. In a word, it’s difficult for corona plasma system to establish a criterion.

In recent years, many studies have been launched researching the factors that influence the pulsed corona characteristics [8-10]. However, due to slowness of systematic researches, the optimum conditions have not been fully studied. The matching between pulsed-power and the reactor containing different thickness of soil, which serves all pulsed energy, is vital to realize the optimum pulsed corona characteristics. And the detailed discussion on the matching realization and the roles it plays in forming the pulsed corona plasma has not been presented.

In this study, from the point of view of energy and energy utilization efficiency, we investigated the matching between pulse forming capacity and the reactor containing different soil thickness, and the relations between frequency of pulsed-power and energy input. The effect of soil thickness on energy utilization efficiency was also examined.

2. Experimental

2.1. Pulsed high voltage source and reactor

The pulsed high voltage source was shown in figure 1, which consisted of a high voltage positive direct current (DC) source, a storage capacity $C_e$, a pulse forming capacity $C_p$ and two rotary spark gap switches (RSG1, RSG2). Its principle was that the formed pulsed energy was injected into the reactor via rotary spark gap switch and transmission line after the forming capacity was discharged, and pulsed corona discharge was produced in the reactor at last. The pulsed high voltage source was with peak pulsed voltage in the range of 0-30 kV, repetition frequency of 0-150 Hz, pulse rise time of 30-100 ns, and pulse width of 200-1000 ns. The peak pulse voltage and current were measured with a Tektronix digital oscilloscope (TDS2012B, 100 MHz) equipped with a Tektronix P6015A high-voltage probe and a Tektronix A6021 current probe, and then the electric power was calculated through the integral of pulse voltage and current under time. Typical waveforms of the pulsed voltage and the discharge current were shown in figure 2.

![Figure 1. Schematic diagram of the experimental apparatus.](image)

The reactor was a cylinder containing a point-to-plate geometry electrode system. The high voltage electrodes were six stainless steel needles (Ø 2 mm) that distributed uniformly around a circle of 20 mm radius. The six stainless steel needles were sealed in a Plexiglas™ cylinder (80 mm inner diameter and 37 mm length), herein named as part (a) of the reactor. The ground electrode was made of aluminium, which was embedded into a quartz glass cylinder (80 mm inner diameter and 22 mm
length), herein named as part (b). The part (a) and part (b) were connected to form the reactor system. The distance of adjacent needle was 20 mm. The distance between the high voltage electrode and the ground electrode was 10 mm.

![Figure 2](image.png)

**Figure 2.** Typical waveforms of the pulsed voltage and the discharge current.

### 2.2. Experimental methods

In the present study, it achieved a relatively reasonable result by comparing four different forming capacities $C_P$ that has been used. And in another experiment, soil samples were spread on the ground electrode with a thickness that ranged from 1 mm to 9 mm. The maximum pulsed high voltage was 22 kV because of the limit of experiment condition.

$E_{\text{pulse}}$ ($E_P$) was the pulse energy delivered into the reactor and calculated by integration of the pulse voltage ($V_P$) times the discharge current ($I_{\text{cor}}$) over the pulse time [11]:

$$E_P = \int V_P I_{\text{cor}} dt$$  \hspace{1cm} (1)

In order to mutually compare the energy efficiency of different soil thickness, the specific energy density can be calculated by the following equation:

$$\text{SED} = \frac{E_P f}{m_{\text{soil}}}$$  \hspace{1cm} (2)

where SED was the specific energy density ($J \text{ g}^{-1}$), $f$ was the pulse frequency, $m_{\text{soil}}$ was the total mass of treated soil, and $t$ was the discharge time.

### 3. Result and discussion

#### 3.1. Effects of forming capacity on the energy

To investigate the effect of pulse forming capacity on the energy, it ranged from 50 pF to 200 pF and the frequency was fixed at 70 Hz. The energy input per discharge can be obtained by the integration of voltage and current measured at different pulse forming capacity. And variation of energy injected into the reactor with different pulse forming capacity was presented in figure 3. The energy that was injected into the reactor increased with the pulse forming capacity; however, the energy didn’t increase too much when the pulse forming capacity was changed from 100 pF to 150 pF, as shown in figure 3. It was related to the energy transfer efficiency since the voltage level after corona extinction increased with the pulse forming capacity, and the residual energy in the pulse forming capacity also increased with the pulse forming capacity. Therefore, poorer energy transfer efficiency was obtained when the pulse forming capacity was larger [12].
However, it was believed that a too low capacity was not desirable by reason of all the energy delivered to the reactor would be used only to charge the reactor, while accordingly corona discharge cannot develop. So it was important for the reactor to choose a reasonable capacity. In the present study, the whole system got a relative appropriate situation when the pulse forming capacity was 100 pF.

![Figure 3. Effect of pulse forming capacity on the energy under pulse frequency of 70 Hz.](image)

3.2. Effect of pulse frequency on the energy

Figure 4 showed the effect of pulse frequency on the energy. When the frequency was increased from 50 Hz to 110 Hz and the pulse forming capacity was fixed at 100 pF, it meant more energy was injected into the reactor at the same time. The energy delivered to the reactor can be divided into two parts: one delivered during the streamer propagation and the other delivered through the streamer channel after streamer propagation stops [9]. The energy delivered after streamer propagation was mainly used to sustain the low conductive streamer channel and to produce the secondary streamer, while the later part of the energy producing only slow electrons didn’t contribute to energy utilization. Consequently, the major part of the energy producing energetic electrons and radicals was delivered during the streamer propagation. However, with the increase of frequency, the wastage of pulsed-power would also raise.

![Figure 4. Effect of pulse frequency on the energy under the pulse forming capacity of 100 pF.](image)
Therefore, it was noted that the pulse frequency related to the energy and wastage should correspond to energy utilization efficiency during the discharge process.

3.3. Existence of soil on the energy and energy utilization

In non-thermal plasma process, the energy injected into the reactor increased with the pulse frequency which may benefit the matching between a pulsed-power and reactor containing different thickness of soil. The evolution of energy input obtained at different soil thickness with the increase of pulse frequency was presented in figure 5. With the increase of pulse frequency from 50 Hz to 90 Hz, energy that was delivered into reactor without soil enhanced from 0.59 W to 1.1 W at the pulse voltage of 19 kV; while the energy input increased from 0.9 W to 1.76 W at the same condition, except the soil thickness of 3 mm. This phenomenon suggested that energy input conducted at the soil thickness of 3 mm was more than the one without soil since the reduction of distance between high electrode and ground electrode. The effects of pulse frequency on specific energy density (SED) were performed at the soil thickness of 3 mm as shown in figure 6. And a certain range of maximal SED existed along with the change of pulse frequency, which was obtained at frequency of 90 Hz in the experiments. It was important to note that the increase of pulse frequency was reasonable at a certain extent, because proper increase of pulse frequency can improve the energy input but the wastage of pulsed-power also enhanced if the pulse frequency was raised too much.

3.4. Effect of soil thickness on the energy and energy utilization

The soil that was spread on the ground electrode with different thickness influenced the energy injected into the reactor and the SED. Increasing soil thickness could improve the energy delivered to reactor but the SED decreased at the same time. Hence, soil thickness was an important parameter to evaluate the matching between a pulsed-power and reactor. The effects of soil thickness on energy and SED under the pulse forming capacity of 100 pF were illustrated in figure 7 and figure 8, respectively. For example, when soil thickness increased from 3 mm to 9 mm, energy input enhanced from 1.36 W to 2.31 W at pulse voltage of 19 kV, while SED decreased from 0.114 J g\(^{-1}\)\(_{\text{soil}}\) to 0.064 J g\(^{-1}\)\(_{\text{soil}}\). The increase of soil thickness benefited energy input due to the reduction of distance between high voltage electrode and ground electrode, which meant the decrease of corona inception voltage and breakdown voltage at all other things being equal. However, with the increase of soil thickness, the volume of soil was also gained; correspondingly, the energy delivered to per gram was decreased. Based on these results, it could be deduced that selecting an appropriate soil thickness that could get a relatively high energy and energy utilization efficiency was important.
4. Conclusion
The matching between a pulsed-power and reactor containing different thickness of soil for producing corona discharge was studied. Under the studied conditions, increasing pulse forming capacity or pulse frequency resulted in higher energy input, due to the enhancement of energy in per unit time. The investigation of soil thickness in the matching between pulsed-power and reactor indicated that increase of soil thickness benefited the energy input during the discharge process. The change of soil thickness could also affect the SED, and there existed a maximal SED, as a result of the energy input and the volume of soil.

This study was a fundamental research effort, trying to offer an alternative solution for the matching between a pulsed-power and reactor containing different soil thickness. The performance was showed for the matching between a pulsed-power and reactor containing different soil thickness, demonstrating that optimizing the pulse forming capacity, pulse frequency and soil thickness for the matching was a reasonable solution.

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Figure 7. Effect of soil thickness on the energy under the pulse forming capacity of 100 pF.

Figure 8. Effect of soil thickness on the SED under the pulse forming capacity of 100 pF.