The *Chlorella* killed by pulsed electrical discharge in liquid with two different reactors

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Abstract. The application of pulsed high-voltage discharge in liquid has attracted wide attention as an effective water treatment. In this paper, two different liquid high-voltage discharge systems were constructed with plate-hole-plate and needle-plate electrode structures, and the inactivation behaviors of *Chlorella* were studied in the two reactors. The results show that the killing rates of algae in both reactors all increased significantly with increasing discharge voltage and the killing rates were intensely related to discharge power, instantaneous power and single pulse input energy. Furthermore, the inactivation effect in needle-plate reactor was superior to that in plate-hole-plate reactor under the same experimental conditions.

1. Introduction
The indiscriminate discharge of ship ballast water and sediments is a serious threat to the marine environment, resulting in the spread of harmful aquatic organisms and pathogens [1, 2]. The high voltage pulse discharge has attracted wide attention as an effective treatment of ship ballast water.

Bing Sun et al. [3] studied the removal of organic compound (phenol) using pulsed-streamer corona discharge and the effects of various parameters on phenol removal efficiency. The results showed that the organic contaminants in aqueous solution could be destroyed effectively by the pulsed-streamer corona discharge and the removal of the organic compound (phenol) was greatly influenced by gas injection (bubbling). M. Sato et al. [4] investigated the decoloration of some dyes in aqueous solution by pulsed discharge plasma in water through the pinhole. They concluded that the decoloration occurs as a result of the attack of high-speed electron and radical reaction in the plasma. Bing Sun et al. [5] reported the inactivation effect of algae with pinhole pulsed discharge reactor. The results showed that the chlorophyll a in the treated algae solution decreased with the increase of peak voltage. Bing Sun et al. [6] also investigated the decoloration of Methyl Orange and the degradation mechanism with multi-needle reactor. G. M. El-Aragi et al [7] proposed the effect of hybrid gas-liquid electrical discharge on liquid foods (milk). Their results showed that the electric field, ultra-violet radiation, shock wave, ozone and free radicals destructed the microorganisms, and the hybrid discharge treatment was effective in the destruction of different types of bacteria. M. Sato et al. [8] studied the sterilization of microorganisms by high-voltage pulsed discharge in water. They found that the great advantage of sterilization by pulsed discharge in water is that feed liquid can be selectively

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sterilized, with little damage to any immobilized catalytic organism. Chih-Wei Chen [9] attempted the influence of pH on the inactivation of aquatic microorganism with gas-liquid pulsed electrical discharge using brush-plate type discharge reactor.

This paper investigated the inactivation of Chlorella with two different liquid discharge systems, and the effects of discharge power, instantaneous power and single pulse input energy on algae inactivation rates were compared with these two reactors.

2. Materials and methods
A plate-hole-plate reactor and a needle-plate reactor were used in this experiment. The schematic diagrams of the experimental apparatus were shown in figure 1 and figure 2. The plate-hole-plate reactor was made of two Plexiglas cylinders containing two 28 mm diameter stainless steel plate electrodes with thickness 3 mm and one 1 mm thick insulating board with a 1 mm hole in the center. The distance between the high voltage electrode and the insulation board was 7 mm, and the distance between the ground electrode and the insulating plate was 6 mm. The needle-plate reactor was made of a Plexiglas cylinder containing a hollow needle electrode with a diameter of 1 mm and a 28 mm diameter stainless steel plate electrode with thickness 3 mm. The volume and inner diameter of both two reactors were 40 mL and 32 mm, respectively. The electrode distances of the two reactors were both 14 mm. A pulsed power supply with a rotating spark-gap switch was used to generate high voltage pulses (0–60 kV, 0–300 Hz, 3 nF). In this experiment, the frequency of pulsed power supply was kept at 30 Hz.

![Figure 1. The plate-hole-plate reactor.](image1)

![Figure 2. The needle-plate reactor.](image2)

In each experiment, 200 mL of Chlorella solution with an initial concentration of $8 \times 10^5$ per L$^{-1}$ was circulated by a peristaltic pump at a flow rate of 53 mL min$^{-1}$. The electrical conductivity of the algae solution was 500 $\mu$S cm$^{-1}$. The viability of the algae remaining after discharge treatment was determined by re-culturing for five days. The number of Chlorella was counted by the optical microscope (OLYMPUS MA5201). The individual experiments were carried out by introducing air into the liquid in the reactor with the gas flow rate of 0.04 L min$^{-1}$.

In order to calculate the single pulse input energy of the reactor and discharge power, discharge voltage and current were measured by Digital Storage Oscilloscope (TDS 2024 B). The current and voltage waveforms of the discharge system were recorded by the current probe (Tektronix A 22) and voltage probe (Tektronix P6015), respectively.

3. Results and discussion

3.1. Comparison of discharge characters of plate-hole-plate reactor and needle-plate reactor
The discharge characteristic parameters of these two discharge reactors in table 1 and table 2. The
values of peak current, maximum instantaneous power and single pulse input energy of two reactors both increased with increasing discharge voltage. The energy efficiency of needle-plate reactor was superior to that of plate-to-plate reactor because of higher peak current, maximum instantaneous power and single pulse input energy under the same voltage.

Table 1. The input voltage, peak instantaneous power and total input energy of a single pulse into the different pulse peak voltages (plate-hole-plate reactor).

| Voltage (kV) | Peak current (A) | Maximum instantaneous power (MW) | Single pulse input energy (J) |
|-------------|------------------|---------------------------------|-----------------------------|
| 18          | 122              | 2.02                            | 0.54                        |
| 22          | 138              | 2.71                            | 0.82                        |
| 26          | 164              | 3.51                            | 1.08                        |
| 28          | 164              | 3.74                            | 1.29                        |
| 30          | 182              | 2.48                            | 1.43                        |

Table 2. The voltage, peak instantaneous power and total input energy of a single pulse into the different pulse peak voltages (needle-plate reactor).

| Peak voltage (kV) | Peak current (A) | Maximum instantaneous power (MW) | Single pulse input energy (J) |
|-------------------|------------------|---------------------------------|-----------------------------|
| 18                | 148              | 2.45                            | 0.59                        |
| 22                | 228              | 3.65                            | 1.01                        |
| 26                | 252              | 4.54                            | 1.27                        |
| 28                | 278              | 6.13                            | 1.40                        |
| 30                | 284              | 6.72                            | 1.50                        |

3.2. Effects of pulse peak voltage upon the inactivation of Chlorella sp.
During the experiment, the both reactors pulse peak voltage was set at 18, 22, 26, 28 and 30 kV, the pulse frequency was 30 Hz, the treatment time was 10 min, and the introducing air was 0.04 L min\(^{-1}\).

As shown in the figure 3, the viability of algae gradually decreased with increased pulse peak voltage by plate-hole-plate reactor. The maximum inactivation rate of algae nearly reached to 100% at pulsed voltage of 28 kV. The reason was probably that the pulse input power and the amount of high-energy electron generation increased in a single pulse with increased pulse peak voltage, which leading to more production of high-energy electrons, hydroxyl radicals, active oxygen, ozone and
other strong oxidants [10]. In addition, the intensity of ultraviolet radiation also increased when the pulse discharge voltage, further contributing to the activation of algae.

From figure 4, the variation of viability of algae affected by pulse discharge voltage in needle-plate reactor was similar to that in plate-hole-plate reactor. There was no re-growth of algae when the pulse peak voltages were higher than 26 kV in the needle-plate reactor, even if the treated algae were re-cultured for five days. That is to say, the inactivation rate of algae nearly reached to 100% at pulsed voltage of 26 kV. The inactivation rate of the *Chlorella* sp. in the needle-plate reactor is higher than that in plate-hole-plate reactor under the same voltage. This result also confirmed that energy efficiency of discharge reactor played a key role in inactivation of algae.

![Figure 4](image)

**Figure 4.** The effects of needle-plate reactor pulse peak voltage changes upon the inactivation of the *Chlorella* sp. after re-culturing for 120 hr (treatment time of 10 min, frequency of 30 Hz, introducing air).

### 3.3. Color changes of *Chlorella* sp. solution by pulse peak voltage

After discharge treatment, the algae solution was re-cultured for 120 hours. The color changes of *Chlorella* sp. solution with different pulse peak voltage in two reactors were shown in figure 5 and figure 6. The leftmost conical flask labeled “Sample” contains the solution without discharge treatment and other flasks labeled with various pulse peak voltages contain the solutions that have been discharged. The results showed that the color of the treated algae solution gradually became colorless with increased pulse discharge voltage, and the solution became nearly colorless at 28 kV in plate-hole-plate reactor and at 26 kV in needle-plate reactor, even if the treated algae solutions were re-cultured again for 5 days. It again proved that the maximum inactivation rates reached almost 100% in both reactors with discharge voltage higher than 28 kV, and the energy efficiency of needle-plate reactor was remarkable compared with plate-hole-plate reactor under the same experimental condition.

![Figure 5](image)

**Figure 5.** The photo of *Chlorella* sp. solutions re-cultured for 120 hours after plate-hole-plate reactor discharge treatment with the pulse frequency of 30 Hz and the treatment time of 10 min.
4. Conclusions

The conclusions can be obtained as follows.

(1) Compared with plate-hole-plate reactor, needle-plate reactor had higher current intensity and instantaneous power in the discharge process, and total single pulse input energy was also higher under the same discharge condition.

(2) The killing rate significantly increased with increasing voltage in both the discharge reactors.

(3) The killing rate of algae reached to 100 % at voltage of 28 kV in plate-hole-plate reactor and at voltage of 26 kV in needle-plate reactor, and the color of the treated algae solution was nearly colorless. Generally, the inactivation rates of *Chlorella sp.* by needle-plate reactor are higher than that by plate-hole-plate reactor.

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