Research on the energy efficiency of the multiphase nanosecond pulsed discharge system with TiO$_2$ photocatalysis

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Abstract. Energy efficiency of the system is always paid more attention in the research of the discharge plasma’s application technology. Based on the project of ballast water treatment technology by multiphase nanosecond pulse discharge cooperated with photocatalysis, the nozzles-plate electrode was adopted, system energy and energy efficiency were investigated with different discharge factors and compared when the nozzles were coated with the titanium dioxide (TiO$_2$) film or not. The results show that cooperating with the photocatalysis, pulsed discharge system power and energy efficiency were not significantly affected. Reactor power increases with the absolute value of the input high voltage and pulse repetition frequency and decreases with the distance between the nozzles and the plate. There are no obvious effects of the numbers of the nozzles and the air flow rate. Energy efficiency of the system increases with the absolute value of the input high voltage, firstly, then decreases. It changes inversely with the air flow rate. The energy efficiency of the system decreases with the pulsed repetition rate and the distance between the nozzles-plate. It was up to 25.7% with the input voltage of -30 kV, and the air flow rate of 80 mL/min, pulse repetition frequency of 50 Hz and 6 nozzles-plate distance of 0.5 cm.

1. Introduction

The commonly used treatment methods of ballast water include replacement method, filtration method, oxidation method, electrolysis method, high temperature heating method, ultraviolet light method, and a combination of several methods$^{[1-4]}$. The research group’s nanosecond negative pulse discharge simulated ballast water injected into the reactor through the multi-nozzle electrode. The glass medium pellets were filled between the multi-nozzle discharge electrode and the ground plate electrode. During the discharge, air was continuously blown into the ballast water, forming a gas, liquid, and solid three-phase pulse discharge system$^{[5]}$. In order to further improve the efficiency of ballast water treatment on this basis, TiO$_2$ is coated on the multi-nozzle discharge electrode, and the ultraviolet luminescence in the pulse discharge process is used to activate the TiO$_2$ photocatalyst to increase the number of active free radicals such as OH in the discharge process. This article aims to study the discharge characteristics, reactor energy, and energy injection efficiency of the cooperative reaction system under different discharge conditions, so as to provide a basis for further optimization of the reaction system.
2. Experimental device and method

The multi-nozzle-plate reactor designed and patented by the research group is shown in Fig 1 [6], the discharge electrode of the reactor has two structures: 6 nozzles and 12 nozzles, as shown in Fig 2.

![Multi-jet-plate discharge reactor installation diagram](image)

1-the hollow cylinder  2-insulation sleeve  3-upper tie plate  4-lower tie plate  5-cylinder wall  6-Water inlet (air outlet)  7-water outlet (air inlet)  8-nozzles electrode  9-Stainless steel circular plate  10-grounding electrode  11-support foot

**Fig 1 Multi-jet-plate discharge reactor installation diagram**

![Two kinds of nozzles electrode structure](image)

(a) 6 nozzles  (b) 12 nozzles

**Fig 2 Two kinds of nozzles electrode structure**

In this experiment, the reactor is equipped with 500 mL simulated ballast water solution and a glass ball with a diameter of 5 mm and a volume of 150 mL is filled into the simulated ballast water solution. The distance between the liquid surface and the ground plate is about 2 cm. The nozzle electrode 'distance between the bottom end and the earth pole plate is adjustable, and gas is introduced into the ballast water from the air inlet. The multi-nozzle discharge electrode was coated with TiO₂ by the pulling method, dried naturally, and then placed in a muffle furnace for baking at 200°C for 2 hours, and then cooled to room temperature.

The high voltage power supply used is PD-60 II bipolar high voltage pulse power supply (Institute of static electricity and special power supply, Dalian University of Technology), Energy storage capacitor 36 nF, 1.2 nF pulse forming capacitance, comparison of positive and negative pulse discharge experiments found that negative high voltage pulse discharge is more uniform and stable, and it is not easy to form spark discharge, negative high voltage pulse discharge was used in this experiment. A digital storage oscilloscope (Tektronix TDS 3014C), a high voltage probe (Tektronix P6015A), a current probe and an adapter (Tektronix TPC A300) are used to monitor the discharge voltage and current in the discharge process. SRC2100 high voltage tester is used to monitor the voltage U on the pulse forming capacitor. Typical discharge voltage , discharge waveform is shown in Fig 3.
Fig 3 The typical waveform of discharge voltage and Current

The input voltage is -30 kV, the pulse repetition frequency is 50 Hz, the air blowing rate is 80 mL/min, the distance between nozzles and the plate is 0.5 cm, 6 nozzles electrode is not coated with TiO2. As shown in Fig 3, the pulse width is about 50 ns, pulse peak voltage is -9.67 kV and the discharge peak current is -71 A.

The instantaneous injection energy power P(t) can be obtained: \( P(t) = u_i \times i_t \). u_i and i_t are the pulse discharge voltage and current respectively.

The instantaneous pulse power corresponding to Fig 3 is drawn by Origin software, as shown in Fig 4. Among them, the maximum instantaneous power is about 310 kW.

Fig 4 The diagram of instantaneous power pulse

3. Experimental research and analysis

3.1 Energy efficiency calculation method

Input discharge the energy of the reaction system can be divided into energy system input to pulse energy storage capacitor energy \( E_e \), from a pulse forming capacitance of single pulse energy of \( E_c \) and eventually the energy injected into the reactor \( E_p \), the corresponding calculation formula such as (1)-(3) shown in [7].

\[
E_e = \frac{1}{2} C_e U_e^2 \quad (1)
\]

\[
E_c = \frac{1}{2} C_p U^2 \quad (2)
\]

\[
E_p = \int u(t) \times i(t) dt \quad (3)
\]

The \( C_e \) for the energy storage capacitor, the \( C_p \) for pulse forming capacitance, \( U_e, U \) were added to the \( C_e \) and the voltage value on the \( C_p \).

Corresponding to the above three parts of energy, energy efficiency can be divided into the power conversion efficiency \( \eta_1 \), injection efficiency \( \eta_2 \) and power efficiency \( \eta_3 \). The \( \eta_1 \) representative from ac 220 V or 380 V input to the energy efficiency of pulse high voltage test system, as shown in formula (4). Injection efficiency \( \eta_2 \) on behalf of the energy efficiency of injected into the reactor from the experiment system, as shown in formula (5); Power supply always \( \eta_3 \) on behalf of the efficient use of energy efficiency and the ratio of the power consumption of energy, as shown in formula (6):

\[
\eta_1 = \frac{E_e}{E_{in}} \quad (4)
\]
\[ \eta_2 = \frac{E_p}{E_c} \]  
\[ \eta_3 = \frac{E_{out}}{E_{in}} = \frac{E_p f}{E_{in}} \]  

The energy \( E_{in} \) represents the energy obtained from the mains 220 V or 380 V. For single-phase power, it is the product of the effective value of voltage and current. For three-phase power, the phase factor should be considered. \( E_{out} \) is the output energy injected into the reactor by the power supply, and its value is the product of the energy \( E_p \) injected into the reactor by a single pulse and the pulse frequency \([8]\).

3.2 The influence of different experimental parameters on energy and its injection efficiency

3.2.1 The influence of input voltage on energy and injection efficiency

During the experiment, the discharge pulse frequency was 50Hz, the distance from the nozzle to the plate was 0.5cm, the air blowing rate was 80mL/min, the discharge electrode structure was 6 nozzles without titanium dioxide coating, the treated water sample was 500mL simulated ballast water, and the addition volume was 150mL, the glass ball with a diameter of 5mm, the discharge time is 20min, and the input voltage is -24kV, -26kV, -28kV, -30kV, -32kV. The influence of the input voltage on energy and injection efficiency is shown in Fig 5 and Fig 6 respectively.

![Fig 5 The energy of different input voltage](image)

![Fig 6 The injection efficiency of different input voltage](image)

It can be seen from Figure 7 that as the absolute value of the input voltage increases, both \( E_c \) and \( E_p \) keep increasing, but the overall growth rate of \( E_p \) becomes slower relative to the growth rate of \( E_c \). As the absolute value of the input voltage increases, the absolute value of the voltage \( U \) on the forming capacitor also increases, and the pulse forming capacitor capacity \( C_p \) is fixed, so \( E_c \) is also increasing; As the absolute value of the input voltage increase, the energy produced by the power supply continues to increase, making the internal matching relationship of the entire experimental device is better. High-temperature and high-pressure plasma channels are generated in the reactor, the energy is continuously strengthened, the amplitudes of the voltage \( u(t) \) and current \( i(t) \) injected into the reactor are also increasing, \( E_p \) is also increasing, which is consistent with the relationship between injected energy and input voltage when Gu Yi shan \([9]\) studied mostly plate gas-liquid mixed high-pressure pulse discharge reactors.
It can be seen from Figure 8 that with the gradual increase of the absolute value of the input voltage, the injection efficiency first increases and then decreases. When the peak voltage is -30kV, an inflection point occurs, that is, when the peak voltage is -30kV, the injection efficiency is the maximum. Its value is approximately 25.7%. With the increase of the absolute value of the input voltage, the single pulse energy $E_p$ keeps increasing, however, the growth rate becomes slower than the growth rate of $E_c$, so the injection efficiency first slowly increases and then decreases. It shows that during the discharge process, as the absolute value of the input voltage increases, the increased capacitance energy is more consumed in other areas, rather than in the process of multi-phase nanosecond negative pulse discharge to simulate ballast water.

3.2.2 The effect of blowing rate on energy and injection efficiency

During the experiment, the discharge pulse frequency was 50Hz, the input voltage was -30kV, the distance from the nozzle to the plate was 0.5cm, the discharge electrode structure was 6 nozzles and there was no titanium dioxide coating, the treated water sample was 500mL simulated ballast water, the addition volume was 150mL, the diameter was The 5mm glass ball, the discharge time is 20min, the air blast rate is 20mL/min, 40mL/min, 60mL/min, 80mL/min, and the influence of the blast rate on energy and injection efficiency is shown in Fig 7 and Fig 8, respectively.

![Fig 7 The energy of different blow rate](image)

![Fig 8 The injection efficiency of different blow rate](image)

It can be seen from Fig 7 that with the increase of the blast rate, the values of $E_c$ and $E_p$ fluctuate up and down, and remain basically unchanged. The blowing rate has no obvious influence on the matching of the entire device, so the value of $E_p$ will fluctuate up and down in a small range. It can be seen from Figure 8 that with the increase of the blasting rate, the energy injection efficiency first decreases and then increases. When the blasting rate is 80mL/min, the energy injection efficiency is the highest, with a value of 22.0%. so, under the same conditions, we can know that the blowing rate has little effect on the energy of the pulse forming capacitor and the energy injected into the reactor. Considering the energy injection efficiency plus the blowing rate, the multiphase nanosecond pulse discharge cooperates with the titanium dioxide discharge. To deal with the influence of the process of simulating ballast water, a set of conditions with the highest energy efficiency can be selected for experimentation.

3.2.3 The influence of the number of nozzles on energy and injection efficiency

In the experiment, the discharge pulse frequency is 50Hz, the distance between the nozzle and the plate is 0.5cm, the air blowing rate is 80mL/min, the water sample is 500mL, adding capacity is 150mL, 5mm diameter glass ball, discharge time 20min, pulse peak voltage-30kV, discharge electrode
without titanium dioxide coating, discharge electrode structure is 6 nozzles, 12 nozzles, the energy and injection efficiency of the two nozzle numbers are shown in the Table 1.

**Table 1** The energy and injection efficiency of two kinds of discharge electrode structure

| Number of nozzles | 6   | 12  |
|-------------------|-----|-----|
| \( U / kV \)      | -11.65 | -11.61 |
| \( Ec/J \)        | 0.0814 | 0.0809 |
| \( Ep/J \)        | 0.0224 | 0.0226 |
| Energy efficiency/\( \% \) | 27.5 | 28.0 |

It can be seen from Table 1 that under the same conditions, the \( Ec \) energy and \( Ep \) energy of the 12 nozzles remain basically unchanged. Reason is that it is compared with the 6 nozzles, the effective nozzles of the 12 nozzles are 6 nozzles in the lower layer, and the 6 nozzles on the upper layer of the 12 nozzles are exposed in the air and the 6 nozzles are far away from the plate electrode. Therefore, when processing 500mL simulated ballast water, the 12 nozzles are not all effective. Later, multiphase nanosecond negative pulses will be used in conjunction with titanium dioxide to process simulated ballast. When using water, you only need to select the 6-nozzle discharge electrode.

### 3.2.4 The effect of pulse frequency on energy and injection efficiency

The pulse peak voltage is -30 kV, 6 nozzles and no titanium dioxide coating, \( Ec, Ep \) and \( \eta_2 \) when the pulse frequency varies from 30 Hz to 70 Hz are shown in Fig 9 and Fig 10.

![Fig 9 The energy of different pulse frequency](image)

![Fig 10 The injection efficiency of different pulse frequency](image)

It can be seen from Fig. 9 that both \( Ec \) and \( Ep \) increase with the increase of the pulse repetition frequency. It can be seen from Figure 11 that \( \eta_2 \) shows a slight downward trend as the pulse repetition frequency increases.

### 3.2.5 The influence of the distance from nozzle to plate on energy and injection efficiency

When the pulse peak voltage is 30 kV, the pulse repetition frequency is 70 Hz, the \( Ec, Ep \) and \( \eta_2 \) of the 6 nozzle discharge electrode, and the distance between the nozzle and the plate is 0.5cm–1.5cm are shown in Fig 11 and Fig 12.
It can be seen from Fig 11 and Fig 12 that as the distance between the discharge nozzle electrode and the ground plate continues to increase, $E_c$ remains basically unchanged, while $E$ shows a downward trend. $\eta$ also shows a downward trend. It is also consistent with the conclusion of Gu Yishan \cite{9} in the study of the plate gas-liquid mixed high-voltage pulsed discharge reactor.

Under the premise of the same input voltage and other experimental conditions, the energy input to the reactor $E_c$ remains unchanged, about 0.075 J, and as the distance between the discharge nozzle electrode and the ground plate electrode increases, the average field strength between the nozzle and the plate decreases, and the discharge current decreases, resulting in a gradual decrease of the effective discharge energy $E_p$ from 0.017 J to 0.015 J, as a result, the energy efficiency of injection has gradually decreased by about 3%.

### 3.2.6 The influence of electrode TiO$_2$ before and after coating on system energy and injection efficiency

The pulse peak voltage is -30 kV, the pulse repetition frequency is 50 Hz, whether the 6-nozzle discharge electrode is coated with TiO$_2$ on the energy $E_c$, $E_p$, and $\eta$ of the experimental system are shown in Table 2.

| Nozzle situation | not exist | exist |
|------------------|-----------|-------|
| $U$/kV           | -11.51    | -11.49|
| $E_c$/J          | 0.0795    | 0.0792|
| $E_p$/J          | 0.01651   | 0.01616|
| $\eta$/%         | 20.8      | 20.4  |

It can be seen from Table 2 that under the same conditions of other experimental factors, the $E_c$ and $E_p$ of whether the discharge electrode is coated with TiO$_2$ are roughly the same, and the energy injection efficiency $\eta$ is also similar in the two cases.

It can be concluded that compared with the multiphase nanosecond pulse discharge technology, the energy and injection efficiency of the system are roughly equivalent to that of the multiphase nanosecond pulse discharge and the TiO$_2$ photocatalytic synergistic technology. The synergy of these will generate more active free radicals such as OH in the discharge reaction space, which is beneficial to improve the water treatment effect.
4. Conclusion

The system energy and energy efficiency of the multi-phase nanosecond pulse discharge reactor coated with TiO$_2$ photocatalysis film were investigated. Multi-nozzle-plate discharge electrode was adopted under different discharge conditions. Based on the experiments, the conclusions were drawn as follows:

The energy injected into the reactor increases with the absolute value of the input voltage, but the energy efficiency first increases and then decreases. The energy efficiency can reach up to 25.7%. The effect of the air blowing rate on the system energy is slight, but the energy efficiency first decreases and then increases. When the air blowing rate is 80 mL/min, the injection energy efficiency is the largest, about 22.0%. The system energy and energy efficiency are higher with 12 discharge nozzles, comparing to 6 nozzles. The system energy increases and the energy efficiency decreases with the pulse repetition frequency. When the pulse frequency is 30Hz, the energy injection efficiency is the largest, which is 22.5%. The reactor energy and the energy efficiency decreases with the distance between the discharge nozzle electrode and the ground plate. When the distance between the nozzle and the plate is 0.5 cm, the energy efficiency is the highest, which is 22.8%. The energy and energy efficiency of the reactor coated with TiO$_2$ film decrease slightly.

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