Available online at www.sciencedirect.com
ScienceDirect
Journal of Environmental Sciences 2010, 22(2) 204–210
JOURNAL OF ENVIRONMENTAL SCIENCES
ISSN 1001-0742
CN 11-2629/X
www.jesc.ac.cn

Electrochemical disinfection using the gas diffusion electrode system

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Received 04 May 2009; revised 25 May 2009; accepted 06 July 2009

Abstract

A study on the electrochemical disinfection with H_2O_2 generated at the gas diffusion electrode (GDE) from active carbon/polytetrafluoroethylene was performed in a non-membrane cell. The effects of Pt load and the pore-forming agent content in GDE, and operating conditions were investigated. The experimental results showed that nearly all bacterial cultures inoculated in the secondary effluent from wastewater treatment plant could be inactivated within 30 min at a current density of 10 mA/cm^2. The disinfection improved with increasing Pt load. Addition of the pore-forming agent NH_4HCO_3 improved the disinfection, while a drop in the pH value resulted in a rapid rise of germicidal efficacy and the disinfection time was shortened with increasing oxygen flow rate. Adsorption was proved to be ineffective in destroying bacteria, while germicidal efficacy increased with current density. The acceleration rate was different, it initially increased with current density. Then decreased, and finally reached a maximum at a current density of 6.7 mA/cm^2. The disinfection also improved with decreasing total bacterial count. The germicidal efficacy in the cathode compartment was approximately the same as in the anode compartment, indicating that the contribution of direct oxidation and the indirect treatment of bacterial cultures by hydroxyl radical was similar to the oxidative indirect effect of the generated H_2O_2.

Key words: gas diffusion electrode; cathode; oxygen reduction; electrochemical disinfection; mechanism analysis
DOI: 10.1016/S1001-0742(09)60094-2

Introduction

Disinfection, the process of killing or rendering pathogenic organisms inert, is a commonly used process in water supply and wastewater treatment and represents the last barrier against pathogen microorganisms. Its effectiveness is, therefore, a crucial point for public health and environmental protection. Conventional techniques of water disinfection are frequently inconvenient. Chlorinating generates hazardous and carcinogenic byproducts (Jolley et al., 1982). Ozone and ultraviolet light are efficient and produce harmless derivatives, but they are more expensive (Miller and Valentine, 1995); moreover, ultraviolet light has no long-lasting effect.

Research into alternative oxidants was carried out to identify inexpensive techniques, with long-lasting effect, producing harmless byproducts. Such a process could be based on hydrogen peroxide produced by electrolysis. Hydrogen peroxide is a meta-stable molecule with high redox potential (1.77 V). Its oxidizing properties result from a direct molecular action, but, mostly, from free radicals formed by catalysis. The current efficiency of electroperoxidation was generally lower than for other electrochemical processes. However, electroperoxidation does have many advantages, such as producing no carcinogenic byproducts (Jolley et al., 1982). Disinfecting by electroperoxidation combines the direct effect of electrolysis with the indirect oxidative effect of hydrogen peroxide, which allows for a reduction in the operation cost. The electrosynthesis of H_2O_2 is also of interest because of the costs and risks associated with transportation, storing, and handling of concentrated hydrogen peroxide.

The last two decades have witnessed an intense investigation into the electrosynthesis of hydrogen peroxide, and several publications have demonstrated that *in situ* electrogenerated H_2O_2 may also be used successfully for the treatment of aqueous effluents containing organic pollutants. Graphite flat plates (Do and Chen, 1993, 1994) and three-dimensional electrodes made from reticulated vitreous carbon (RVC) (De Leon and Pletcher, 1995; Alvarez-Gallegos and Pletcher, 1998, 1999) and carbon-based electrodes (Brillas et al., 1995, 1997; Harrington and Pletcher, 1999; Shen et al., 2005) have all been used to reduce oxygen to hydrogen peroxide. The use of oxygen diffusion cathodes, where O_2 was reduced to H_2O_2 and ·OH with the presence of Fe^{2+} to treat aniline (Brillas et al., 1995, 1997, 1998; Brillas and Casado, 2002), 4-chloroaniline (Brillas et al., 1995) and 2,4-D (Brillas et al., 2000) aqueous solution has achieved good treatment results. Additionally, Shen et al. (2005) used a porous gas diffusion electrode (GDE) to reduce oxygen to hydrogen peroxide that is capable of oxidizing Acid Red B in the cathodic chamber.

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Nevertheless, oxygen diffusion cathodes did not find wide application in water treatment as they can only reduce oxygen dissolved in water to H_2O_2 with a low yield. GDEs accelerate oxygen reduction and thus have been introduced to provide a larger reaction area and favorable conditions for gas diffusion processes (Zhou and Poorten, 1995). When oxygen diffuses through the porous gas diffusion layer (GDL), it is reduced to H_2O_2 with a high yield. Hydrogen peroxide formation rate on oxygen-fed graphite/PTFE may be greatly improved by the presence of an organic redox catalyst or noble metals incorporated into the active carbon mass. For example, when 2-ethylanthraquinone is used as a catalyst, it has been shown to improve the H_2O_2 formation rate and reduce the overpotential for oxygen reduction (Forti et al., 2007).

This article reports on an investigation of the electrochemical disinfection with the H_2O_2 generated at the modified O_2-fed active carbon/PTFE electrode, and in which the catalyst and pore-forming agent were incorporated into the active carbon mass. The catalyst chosen for the modification was Pt and the pore-forming agent was NH_4HCO_3. Effects were investigated relative to Pt load W_{Pt} and pore-forming agent content $W_{NH_4HCO_3}$ in gas diffusion electrode, solution pH, oxygen flow rate, salt content, current density, and total bacterial count in the raw water. The disinfection mechanism was investigated as well.

1 Materials and methods

1.1 Reagent and instruments

Active carbon powder with a diameter of 200 nm (Shanghai Hainuo Carbon Co., Ltd., China), PTFE suspension (60%), and Pt/C catalyst with 40% W_{Pt} (Shanghai Hesen Electric Co., Ltd., China) were used to fabricate GDE. The rest reagents applied in the experiments were analytical grade materials.

A homemade electrolytic cell with a volume of 1 L made from 0.5 cm thick acrylic glass, a constant current DC power supply (Wuxi Qiaobo Power Supply Co., Ltd., China), and a gas flow meter at 5 L/min (Dawn Instrument Co., Ltd., China) were used to perform batch disinfection experiments.

1.2 Fabrication of gas diffusion electrode

A Pt/C GDE was fabricated and used as a cathode fed with oxygen to produce H_2O_2. For the fabrication of the Pt/C GDEs, a homogeneous suspension was prepared by mixing and stirring the active carbon, the Pt/C catalyst, and the pore-forming agent NH_4HCO_3, with an appropriate amount of PTFE suspension and ethanol as solvent, in an ultrasonic bath at room temperature for 30 min. The mixing ratio of ethanol/active carbon/PTFE was 12/10/5 by weight, the mixing ratio of catalyst/active carbon (W_{Pt}) was < 5‰ by weight, and the mixing ratio of NH_4HCO_3/active carbon ($W_{NH_4HCO_3}$) was < 70% by weight. The mixture was dried at 80°C for at least 2 hr until a uniform paste was obtained.

The paste was hot-pressed at 95°C for 2 min under 10 MPa to produce a diffusion layer with a thickness of about 0.5 mm. The diffusion layer was then spread uniformly over a piece of stainless steel cloth with a thickness of 0.5 mm and hot-pressed at 95°C for 2 min under 15 MPa to form a GDE.

The prepared GDE was soaked in fresh acetone for 24 hrs, was then flushed repeatedly with distilled water and dried (Yu et al., 2006). The GDEs with the pore-forming agent were soaked in boiling deionized water for 30 min afterwards (Zhu et al., 2006).

1.3 Electrolysis

1.3.1 Batch experiments

Deionized water was applied to conducting batch disinfection experiments. Na_2SO_4 (2%–10%, *W/W*) was added as an electrolyte, and bacterial cultures inoculated in the secondary effluent from Shanghai Quyang Waste Water Treatment Plant (China) were then added. The total bacterial count in the prepared solution was set at 10^4 and 10^6 CFU/mL, respectively. The experimental setup consisted of an oxygen cylinder, an oxygen flow meter, an electrolytic cell, and a constant current DC power supply. The homemade active carbon/PTFE GDE, 5 cm × 6 cm in size, was used as the cathode to reduce oxygen to H_2O_2, and the graphite plate electrode, 5 cm × 6 cm in size, was used as the anode. The rectangular anode was 5 mm thick and the rectangular cathode was located with a spacing of 10 mm in the middle part of the electrolytic cell. The effective area of both the anode and cathode immerged in the water was 5 cm × 4 cm. One oxygenation header was equipped at both sides to ensure equal distribution of oxygen in the electrolytic cell.

The working current between the two electrode plates was adjusted by regulating the DC power supply. A 900-mL of the solution prepared for the disinfection was added to the electrolytic cell and adjusted to the appropriate pH with 0.1 mol/L H_2SO_4 or 0.1 mol/L NaOH before electrolysis. After 30 min, 1 mL of the solution was sampled with a sterile pipette. Subsequently, the oxygen flow rate Q_{O_2} was regulated with the gas flow meter, and the solution was electrolyzed for 30 min. During the electrolysis, 1 mL of solution was sampled every five minutes. Colony count was performed after the electrochemical disinfection.

Germicidal efficacy was used to evaluate bactericidal effect. The calculating formula of germicidal efficacy η is shown below:

$$\eta = \frac{N_0 - N}{N_0} \times 100\% \quad (1)$$

where, N_0 and N are the number of viable bacterial cultures in colony-forming units before and after the disinfection.

1.3.2 Mechanism study

Electrolysis for investigating the disinfection mechanism was conducted in an electrolytic cell separated into two compartments by a permeable cellulose acetate membrane (Fig. 1). Each compartment was 5 cm × 5 cm × 10 cm in size. A graphite plate (6 cm × 4.8 cm) was

used as the anode and a fabricated GDE with different compositions (6 cm × 4.8 cm) was used as the cathode.

The prepared solution with bacterial cultures was electrolyzed with the current under control at 0.1 and 0.2 A. Sampling and bacterial colony count was performed according to the procedures specified in Section 1.3.1, for both the anolyte and catholyte.

1.4 Analytical methods

1.4.1 Measurements of H_2O_2 concentration

The solution of 4% Na_2SO_4 was electrolyzed for 30 min, with the current under control at 0.1 A. The H_2O_2 concentration was then determined by titration with potassium permanganate, with 25 mL of the electrolyzed solution titrated with a $KMnO_4$ solution of 2 mmol/L (Lei et al., 2005).

1.4.2 Measurements of total bacterial count

Total bacterial count was measured by the plate count method after being cultured at 37°C for 24 hr in a homoeothermic incubator.

2 Results and discussion

2.1 Effects of GDE structure on the disinfection

2.1.1 Effect of Pt load (W_{Pt})

The effect of W_{Pt} on disinfection is shown in Fig. 2. These results show that the disinfection improved with increasing Pt load W_{Pt}, but the germicidal efficacy at 3‰ W_{Pt} was equivalent to that at 4‰ W_{Pt}. The electrocatalysts with high activity and stable performances, without significant degradation over time, are of utmost importance for GDEs (Kiros et al., 2006). The results showed that Pt increased the current efficiency of H_2O_2 generation. When the reaction occurred at the catalyst/reaction gas/aqueous solution interface, however, only the Pt located on the surface may become the active site of the electrode reaction (Shen et al., 2003). Further increases of W_{Pt} in GDE, therefore, did not accelerate the electrode reactions. A 3‰ W_{Pt}, therefore, is the most cost-effective dosage of the catalyst. Some of the following disinfection experiments were performed using the GDE with 3‰ W_{Pt} as the cathode, the Pt surface mass load (ρ_{Pt}) of which was calculated to be 0.16 mg/cm^2.

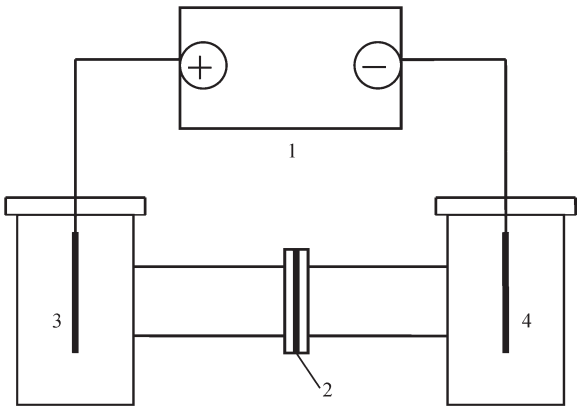

Fig. 1 Electrolytic cell for investigating the disinfection mechanism. (1) stabilized current supply; (2) diaphragm; (3) graphite plate; (4) GDE.

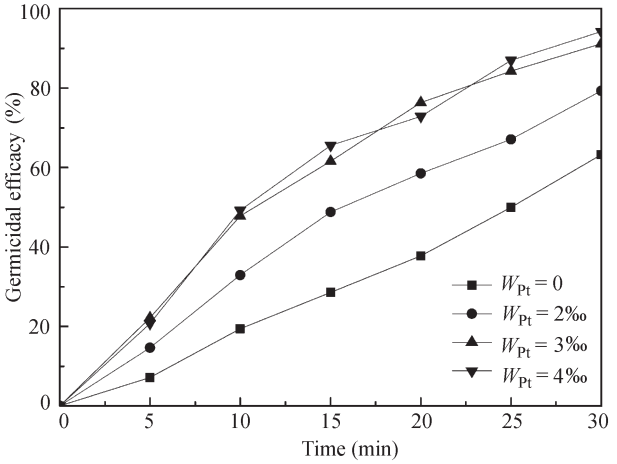

Fig. 2 Effect of Pt load (W_{Pt}). Total bacterial count in the raw water: 10^4 CFU/mL; Na_2SO_4 solution content ($W_{Na_2SO_4}$): 4%; oxygen flow rate (Q_{O_2}): 0.5 L/min.

2.1.2 Effect of pore-forming agent content ($W_{NH_4HCO_3}$)

The major functions of gas diffusion layers are the distribution of reactants to the active sites of electrode (pore size as well as porosity distribution), and the management of water supplied or generated. Hence, the necessary properties of gas diffusion layers are efficient gas diffusion with suitable water and air permeability, appropriate electrical conductivity, high mechanical integrity, and enhanced oxidative stability (Kannan et al., 2006). On the one hand, with increasing pore-forming agent content, gas diffusion layers (GDLs) become porous to allow for distribution of the gases to unexposed areas of the flow channel and for the electrode area to be utilized completely. On the other hand, however, poor electrical conductivity of these GDLs can affect the transportation of electrons from the electrode to the current collector. This decrease in the average porosity causes a reduction in oxygen consumption so that less H_2O_2 is generated during the electrolysis.

The effect of the pore-forming agent content on the disinfection is shown in Fig. 3. From these results, it can be seen that the addition of the pore-forming agent improved the disinfection. The germicidal efficacy did not exceed 90% after 30 min of electrolysis when using the pore-forming agent free GDE as the cathode. Under the same conditions, however, the germicidal efficacy reached 97.33% using the GDE with 30% $W_{NH_4HCO_3}$ for disinfection. Further addition of the pore-forming agent shortened the disinfection in time, thus reducing the need for equipment investment. The germicidal efficacy reached 93.67% after merely 20 min of electrolysis using the GDE with 70% $W_{NH_4HCO_3}$ as the cathode, and was 91.72% after 25 min of electrolysis when using the GDE with 40% $W_{NH_4HCO_3}$.

The total bacterial count in secondary effluent from wastewater treatment plants usually amounts to about 10^4 CFU/mL. Under these circumstances the microbiological discharge standard of 100 CFU/mL can be achieved after 30 min of electrolysis, or less using the GDE with the pore-forming agent as the cathode.

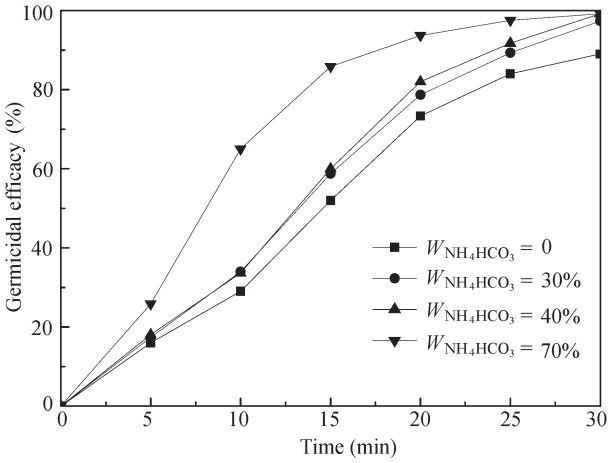

Fig. 3 Effect of pore-forming agent content ($W_{NH_4HCO_3}$). Total bacterial count in the raw water: 104 CFU/mL; $W_{Na_2SO_4}$: 4%; Q_{O_2}: 0.5 L/min.

2.2 Effect of operating conditions on the disinfection

2.2.1 Effect of pH

The effect of pH on the disinfection is shown in Fig. 4. A drop in pH value resulted in a rapid rise of the germicidal efficacy. This appeared to be primarily due to a shift in the oxygen reduction equilibrium in a positive direction, thus accelerating the formation of H_2O_2. In addition, H_2O_2 was easily decomposed to highly oxidative hydroxyl at acidic pH. The oxidizing ability of H_2O_2 was weak under alkaline conditions, thus the germicidal efficacy was lower at pH 8.

2.2.2 Effect of oxygen flow rate (Q_{O_2})

The effect of the oxygen flow rate on the disinfection is shown in Fig. 5. These results show that continuous oxygenation improved the electrochemical disinfection; however, the germicidal efficacy tended to form a plateau at Q_{O_2} of 1.25 L/min after 15 min of electrolysis. This phenomenon was particularly noticeable using the GDE with the pore-forming agent as the cathode. This appeared to be primarily because more H_2O_2 was generated during the electrolysis. The analytical results showed that after 30 min of electrolysis, 14.2756 mg H_2O_2 was generated in 1 L 4% Na_2SO_4 solution at a current of 0.1 A and Q_{O_2} of 0.5 L/min

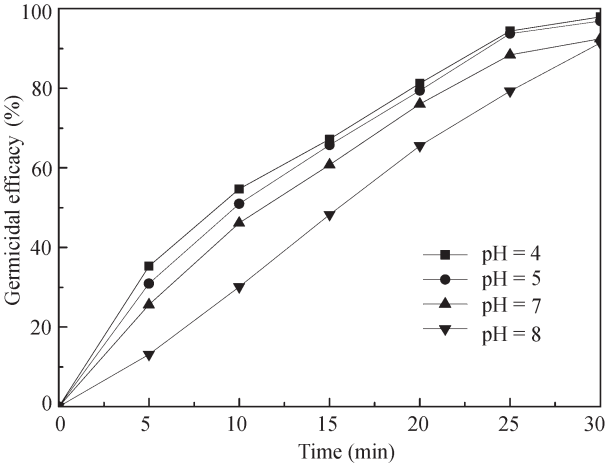

Fig. 4 Effect of pH. GDE with 3‰ W_{Pt} was used as cathode; total bacterial count in the raw water: 10^4 CFU/mL; $W_{Na_2SO_4}$: 4%; Q_{O_2}: 0.5 L/min.

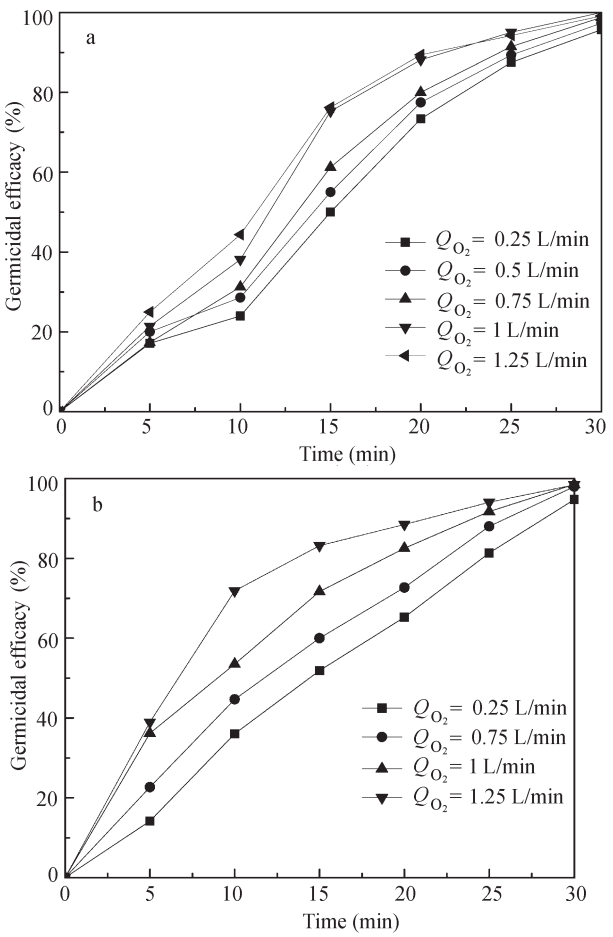

Fig. 5 Effect of oxygen flow rate (Q_{O_2}). Total bacterial count in the raw water: 10^4 CFU/mL; (a) GDE with 3‰W_{Pt} used as cathode; (b) GDE with 30% $W_{NH_4HCO_3}$ used as cathode. $W_{Na_2SO_4}$: 4%; Q_{O_2}: 0.5 L/min.

using the GDE with 30% $W_{NH_4HCO_3}$ as the cathode. Under the similar conditions, 12.5478 mg H_2O_2 was generated using the GDE with 3‰ W_{Pt} as the cathode. The dissolved oxygen tended gradually towards saturation after 20 min of oxygenation, which might hinder the further generation of H_2O_2. The disinfection was shortened in time with an increase in Q_{O_2}. For example, at Q_{O_2} of 0.25 L/min the germicidal efficacy was 95.71% after 30 min of electrolysis using the GDE with 3‰ W_{Pt} (Fig. 5a), while, under the similar conditions, it reached 97.33% at Q_{O_2} of 0.5 L/min. The germicidal efficacy reached 95% after merely 25 min of electrolysis when Q_{O_2} was increased to 1 L/min and 1.25 L/min. The germicidal efficacy at Q_{O_2} of 0.25 L/min was compared with Q_{O_2} of 0.5 L/min and 0.75 L/min. The results showed that the increasing margin remained unchanged after 10 min of electrolysis, indicating that the increase in Q_{O_2} within limits had little influence on the generation of H_2O_2 and the succeeding disinfection. This was the same as reported in previous literature (Qiang et al., 2002). When Q_{O_2} was 1.25 L/min, the germicidal efficacy first increased rapidly until it reached 76.25% after 15 min of electrolysis. Oxygen dissolved rapidly in the water and a large number of oxygen molecules were adsorbed to the surface of GDE and reduced with the formation of H_2O_2, thus accelerating the disinfection. On the one hand, high oxygen flow rates caused an increase

in the solution's resistance and energy consumption of the disinfection, which increased the operating costs of this disinfection process. On the other hand, treatment time was reduced reasonably at high oxygen flow rates, which lead to a reduction in equipment investment.

GDEs were prepared from the active carbon with an immense surface area. It was proposed that, instead of being destroyed by the generated H_2O_2 and other oxidants, a part of bacterial culture might be simply adsorbed by the GDEs. Similar experiments were performed with no electrical current and using this system to investigate the contribution of adsorption to the disinfection. As shown in Fig. 6, no distinct regularity in the change of germicidal efficacy was observed with increasing Q_{O_2}. Furthermore, the germicidal efficacy was less than 10% at all times and the disinfection was not improved over time. In other words, adsorption had no influence upon the bacteria. This phenomenon, therefore, was supposed to be caused by errors in the experimental data.

2.2.3 Effect of salt content

The effect of salt content on the disinfection is shown in Fig. 7. From these results, it can be seen that the germicidal efficacy showed a relatively smooth change with increasing salt content and reached over 95% after 30 mins of electrolysis. According to Faraday's law of electrolysis, the reduced amount of oxygen is proportionate to the electricity flowing past the solution during the electrolysis. An equal amount of H_2O_2 should be generated after the same electricity is passed through the solutions, and the germicidal efficacy should, therefore, be approximately the same. The energy consumption, however, reduced significantly with increasing salt content in the solution. The experimental results showed that energy consumption for the disinfection reduced by about 50%, when the salt content increased from 2% to 10%. This process is, therefore, more suitable for disinfecting salt water.

2.2.4 Effect of current density

The effect of current density on the disinfection is shown in Fig. 8. These results show that germicidal efficacy increased with current (I). The acceleration rate was different however. Firstly, it increased with the current, then decreased, and finally reached a maximum at I = 0.2 A. The reduction of O_2 to H_2O_2 is a two-electron transfer process. Electrode polarization, however, increased with current density and, subsequently, the generated H_2O_2 was oxidized to H_2O, thus reducing H_2O_2 in amount and current efficiency. It is feasible to have current controlled at 0.2 A (the corresponding current density is 6.7 mA/cm^2).

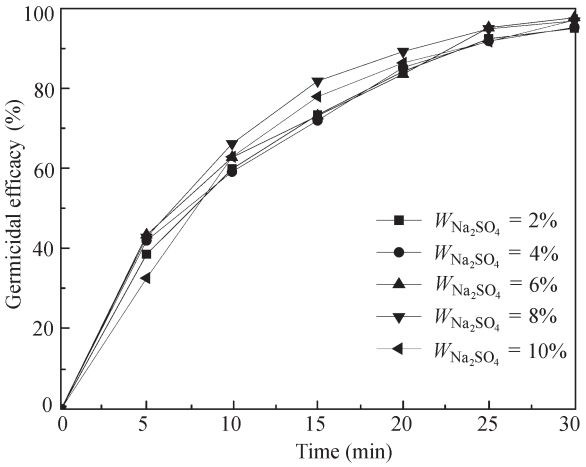

Fig. 7 Effect of salt content. GDE with 3‰ W_{Pt} was used as cathode; total bacterial count in the raw water: 10^4 CFU/mL; Q_{O_2}: 0.5 L/min.

2.2.5 Effect of total bacterial count

The effect of total bacterial count on the disinfection is shown in Fig. 9. These results show that the germicidal efficacy decreased with total bacterial count. After 30 min of electrolysis, germicidal efficacy was about 98% when total bacterial count in raw water was 10^4 CFU/mL using the GDE with 3‰ W_{Pt} as the cathode. Under similar conditions, the germicidal efficacy was merely 88% at total bacterial count of 10^6 CFU/mL.

2.3 Mechanism study

To study the disinfection mechanism, electrolysis of the prepared solution containing bacterial cultures was conducted in a diaphragm electrolytic cell. As shown in

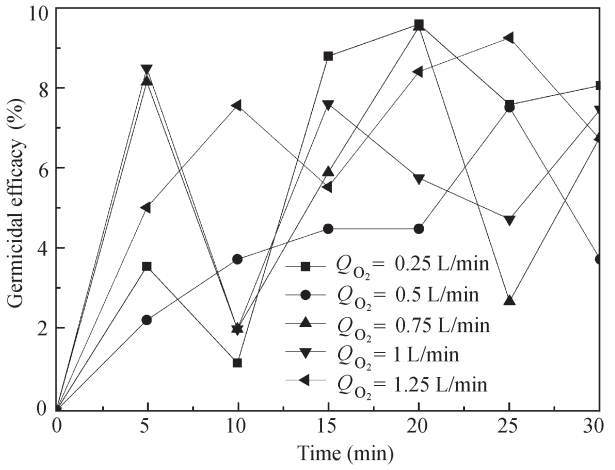

Fig. 6 Effect of oxygen flow rate without current being switched on. GDE with 3‰ W_{Pt} was used as cathode; total bacterial count in the raw water: 10^4 CFU/mL; $W_{Na_2SO_4}$: 4%.

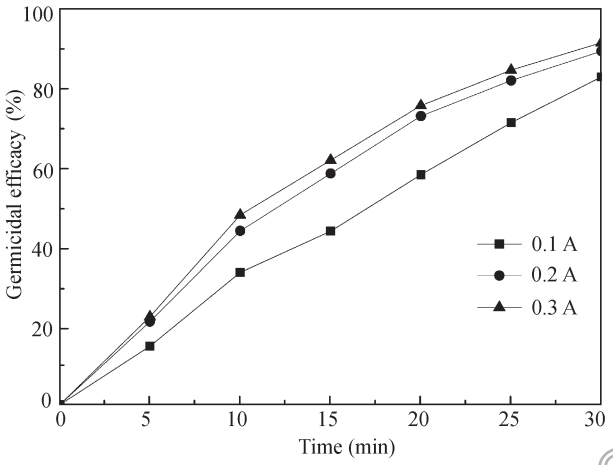

Fig. 8 Effect of current density. GDE with 3‰ W_{Pt} was used as cathode; total bacterial count in the raw water: 10^6 CFU/mL; $W_{Na_2SO_4}$: 4%; Q_{O_2}: 0.5 L/min.

Fig. 10, while the germicidal efficacy increased in both the anode and cathode compartments, the growth rate was different. The germicidal efficacy increased rapidly due to the direct oxidation and generation of hydroxyl radicals at the beginning of electrolysis, and then reached a plateau in the anode compartment. In the cathode compartment, the germicidal efficacy increased comparatively slowly; however, similar to the anode compartment, it grew at a relatively high rate at the beginning of electrolysis. This phenomenon was particularly significant at higher current density due to the generation of more H_2O_2. After 30 min of electrolysis, the germicidal efficacy in the cathode compartment was approximately the same as in the anode compartment. This indicated that the contribution of direct oxidation and the indirect treatment of bacterial cultures by the hydroxyl radical were similar to the indirect oxidative effect of the generated H_2O_2. Compared to the GDE with 3‰ W_{Pt}, the germicidal efficacy grew more rapidly in the cathode compartment using the GDE with 40% $W_{NH_4HCO_3}$ as the cathode. This was due to the generation of more H_2O_2. The analytical results showed that 30 min after electrolysis, 14.9692 mg H_2O_2 was generated in 1 L 4% Na_2SO_4 solution at a current of 0.1 A and an oxygen flow rate of 0.5 L/min using the GDE with 40% $W_{NH_4HCO_3}$ as the cathode.

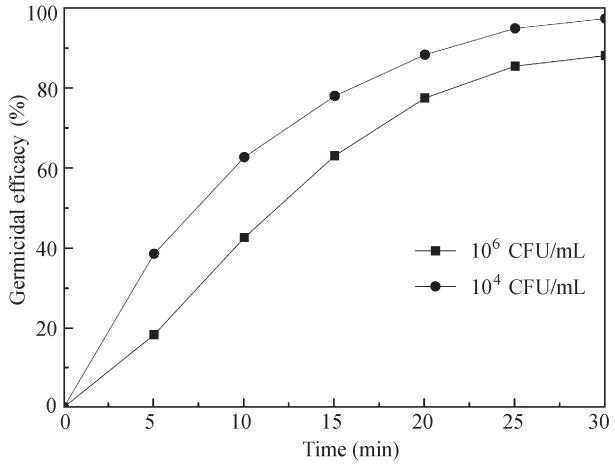

Fig. 9 Effect of total bacterial count. GDE with 3‰ W_{Pt} was used as the cathode; $W_{Na_2SO_4}$: 4%; Q_{O_2}: 0.5 L/min.

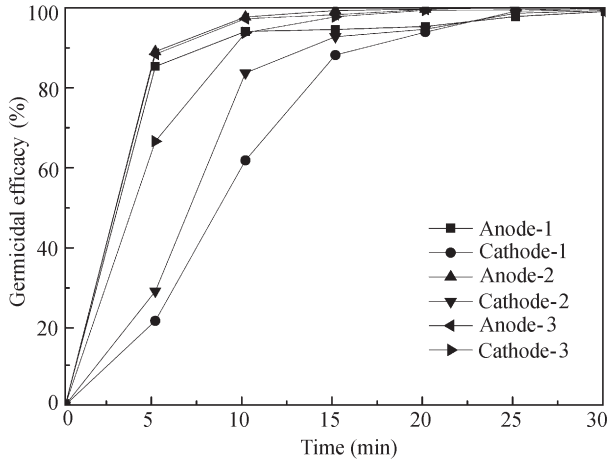

Fig. 10 Germicidal efficacy vs. time plots both in the anode and cathode compartments. Total bacterial count in the raw water: 10^4 CFU/mL; $W_{Na_2SO_4}$: 4%; Q_{O_2}: 0.5 L/min. (1) GDE with 3‰ W_{Pt} was used as the cathode, I = 0.1 A; (2) GDE with 3‰ W_{Pt} was used as the cathode, I = 0.2 A; (3) GDE with 40% $W_{NH_4HCO_3}$ was used as the cathode, I = 0.2 A.

3 Conclusions

The effects of Pt load W_{Pt} and the pore-forming agent content ($W_{NH_4HCO_3}$) in GDE, operating conditions such as pH value, oxygen flow rate (Q_{O_2}), salt content, current density and total bacterial count in the raw water on the disinfection were investigated, respectively. Additionally, the disinfection mechanism was studied.

The results showed that nearly all bacterial cultures inoculated from the secondary effluent from wastewater treatment plant could be inactivated within 30 min at a current density of 10 mA/cm^2. The disinfection improved with increasing Pt load W_{Pt}, but the germicidal efficacy at 3‰ W_{Pt} was equivalent to that at 4‰ W_{Pt}. The addition of the pore-forming agent improved the disinfection, while a drop in the pH value resulted in a rapid rise in germicidal efficacy and an increase in oxygen flow rate shortened the disinfection in time. When the total bacterial count measured 10^4 CFU/mL in raw water, germicidal efficacy reached 99.17% after 30 min of electrolysis using the GDE with 70% $W_{NH_4HCO_3}$ as the cathode.

The disinfection was shortened in time with increasing oxygen flow rate. On the one hand, the resistance of the solution and energy consumption of the disinfection increased at high oxygen flow rates, which increased the operating costs of this GDE disinfection process. On the other hand, treatment time was reduced reasonably at high oxygen flow rates, which leads to a reduction in equipment investment. The results also showed that adsorption had no influence upon bacteria.

The increase in salt content resulted in a reduction in energy consumption for the disinfection. This system, therefore, is more suitable for water with high concentrations of salt. Germicidal efficacy increased with current density. The acceleration rate was different, however. Firstly, it increased with the current density, then decreased, and then finally reached a maximum at a current density of 6.7 mA/cm^2. Therefore, it is feasible to have electric current density controlled at 6.7 mA/cm^2. The disinfection improved with decreasing total bacterial count in the raw water.

The mechanism study showed that the direct oxidation and the formation of the free radicals at the anode initially played a greater role, after which the indirect oxidative effect of the generated H_2O_2 at the GDE enhanced rapidly with the reaction. After 30 min of electrolysis, the germicidal efficacy in the anode compartment was approximately the same as in the cathode compartment, which indicates that their contribution was similar at that moment in time.

Acknowledgments

This work was primarily supported by the National Natural Science Foundation of China (No. 20777053).

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