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Original Article

Effects of electrode gap and electric current on chlorine generation of electrolyzed deep ocean water

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ABSTRACT

Electrolyzed water is a sustainable disinfectant, which can comply with food safety regulations and is environmental friendly. A two-factor central composite design was adopted for studying the effects of electrode gap and electric current on chlorine generation efficiency of electrolyzed deep ocean water. Deep ocean water was electrolyzed in a glass electrolyzing cell equipped with platinum-plated titanium anode and cathode in a constant-current operation mode. Results showed that current density, chlorine concentration, and electrolyte temperature increased with electric current, while electric efficiency decreased with electric current and electrode gap. An electrode gap of less than 11.7 mm, and a low electric current appeared to be a more energy efficient design and operation condition for the electrolysis system.

1. Introduction

Electrolyzed water is environmental friendly, has significant disinfection effects and can comply with food safety regulations [1]. Since most surface area of our earth is covered by seawater, it is reasonable to make sustainable applications of this resource. Electrolyzed seawater, owing to its significant disinfection effects, has been used in many anti-fouling systems [2,3], aquaculture and seafood processing. For example, Kasai et al. [4,5] studied disinfectant effects of electrolyzed seawater on viable bacteria in hatchery seawater using a batch and a continuous electrolytic system. They reported a 2–4 log reduction of viable bacteria after treatment with electrolyzed seawater containing 0.5–1.0 mg/L chlorine for 1 min. Watanabe and Yoshimizu [6] disinfected various utensils and equipments for aquaculture and reported a >3 log reduction of viable bacteria after being treated with electrolyzed seawater containing 0.5–1.5 mg/L chlorine for 30–120 min. Kasai and Yoshimizu [7] studied disinfection of seawater from fishing port by an electrolytic apparatus and found its useful applications to sanitation of fish holding tanks, port deck and fishing equipment. Kimura et al. [8] reared sea urchins for 2 days using electrolyzed seawater

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containing 0.76 mg/L chlorine and found that 90% of bacteria in sea-urchins' viscera were eliminated. Kasai et al. [9] used electrolyzed seawater, which contained 0.2 mg/L chlorine to depurate contaminated oysters and found that *Escherichia coli* in the oysters was reduced to below detection limits.

Although many applications of electrolyzed seawater had been reported in aquaculture and seafood processing, few applications were reported in agriculture or food processing industry probably owing to its sanitary concerns. Plankton and bacteria are abundant in seawater and certain coastal seawater had been highly polluted [10,11]. By contrast, deep ocean water (DOW) is the cold, salty seawater found deep below the surface of earth's oceans. DOW makes up about 90% of the ocean volume. DOW has low temperature, typically from 0 °C to 3 °C, and a salinity of about 35 psu [12]. Although surface seawater can be contaminated by pollution or civilization, the high-pressure and low-temperature deep ocean water has remained unpolluted for the past thousand years.

In order to develop electrolyzed seawater for food and agricultural applications, especially for postharvest cleaning and disinfection of ready-to-eat fresh produce, surface seawater, DOW and DOW concentration products were electrolyzed, and their properties as well as storage stability were investigated in our previous studies [13,14]. Another study showed that optimal choice for electrode gap and cell potential depends on target chlorine level of the electrolyzed DOW and a small electrode gap is preferred [15]. A two-factor central composite design was adopted for an investigation on optimal electrolysis time and electric potential for electrolyzing DOW. Results showed that optimal choice of electrolysis time depends on chloride level in DOW and cell potential adopted. High electric potential resulted in fast chlorine generation, but reduced electric efficiency owing to temperature rise at the same time [16]. Since constant electric-current mode of operation has never been done before, a two-factor central composite design is adopted for further investigating optimal electrode gap and electric current for electrolyzing deep ocean water in this study.

2. Methods

2.1. Seawater samples

The Taiwan Yes Deep Ocean Water Co., Ltd. (Hualien County, Taiwan) provided DOW samples used in this study. DOW was drawn at 662 m below the Pacific Ocean at −5.0 km off the coastline of the Hualien County in eastern Taiwan. Table 1 shows a comparison of major elements, some pollution indicators and physical/chemical properties of the DOW with those of surface seawater samples collected at the nearby areas. Despite containing similar major elements, DOW appeared to be colder and purer than surface seawater, which contained more nitrite as well as chlorophyll and were more alkalinous in its pH values.

2.2. Electrolysis

DOW samples, 1600 mL each, were electrolyzed for 2 h in a 2.0 L glass-beaker electrolyzing cell equipped with a pair of 50 mm long × 25 mm wide anode and cathode. The Anode and Cathode (Model SUR-303, Surchem C&S International Corp., Taipei City, Taiwan), which were titanium mesh electrode plated with 3.75 μm of platinum, were powered by a Rectifier (Model MC48-4D, Surchem C&S International Corp.). The electrodes were immersed in seawater at 60 mm beneath the liquid surface. A constant current mode of operation was adopted in this study. Electrode gap and electric current were maintained at designated levels during electrolysis (Table 2). The levels were chosen based on preliminary tests. Additional stirring was done with a 16 × 30 mm (diameter × length) Teflon spindle-shape magnetic stir bar powered by a Stirrer (Model PC-101, Corning Inc., Acton, MA, USA) at speed setting 1.2, which was approximately 200 rpm. Electrolysis parameters and electrolyte properties were monitored during the electrolysis process.

2.3. Analytical measurements

A total chlorine test kit (Model 16900; Hach Co., Loveland, CO, USA; Method 8209, which is based on iodometric method.) was used to measure total residual chlorine in the electrolyzed seawaters. The assay was verified periodically using a 100 ± 0.05 ppm chlorine standard solution (Orion Research Inc., Beverly, MA, USA). All measurements were conducted at 29 ± 1 °C.

2.4. Electrolysis efficiency

Current density was calculated by dividing the electric current by the effective surface area of anode. Electric efficiency, which represents energy efficiency of the system, was calculated by dividing the total chlorine produced by the electric energy consumed. Current efficiency was calculated from the percentage ratio of the total chlorine produced to the theoretical chlorine production based on the Faraday's laws of electrolysis [17].

2.5. Statistical design and analysis

A two-factor central composite design [18] was adopted for studying the effects of electrode gap and electric current on chlorine generation efficiency of electrolyzed DOW. The test ranges of electrode gap and electric current were 6.7–20.1 mm and 2.5–5.5 A, respectively (Table 2). Four center-points were replicated for the estimation of random errors. Experimental data were analyzed by the response surface regression test of the Statistical Analysis Systems (SAS 9.4, SAS Institute, Cary, NC, USA).

3. Results and discussion

Electrolyzed seawater, because of its significant disinfection effects and availability, has been used in many anti-fouling, aquaculture and seafood processing systems. However, reports on design of electrolysis systems were mostly patented and detailed information on their mechanism as well as effects on electrolysis efficiencies was very limited. Therefore, the objectives of this study are to collect information on

Table 1 – Comparison on major elements, some pollution indicative compositions, and properties of surface seawater and deep ocean water sampled in recent years.[a]

Category	Item	Surface seawater	Deep ocean water	Deep ocean water	Deep ocean water
Sampling	Year	2014	2014	2015	2016
	Depth (m)	50	662	662	662
Major element (mg/L or kg)	Chloride	19,060–19,860	18,840–19,510	18,200–19,600	17,900–19,300
	Sodium	11,320–11,500	11,380–11,430	11,000–11,800	9811–12,100
	Magnesium	1327–1330	1283–1320	1260–1490	1270–1430
	Calcium	400–441	400–432	403–437	393–427
	Potassium	400–414	390–421	396–415	376–443
Composition	Nitrite (μM)	0.08–0.11	<0.03	<0.02	<0.05
	Chlorophyll a (μg/L)	0.12–0.19	<0.03	<0.03	0.03–0.06
Property	Temperature (°C)	22.5–23.8	9.4–10.4	9.4–10.2	9.4–11.0
	pH	8.10–8.20	7.70–7.75	7.56–7.7	7.56–7.77
	Salinity (psu)	34.2–34.5	34.3–35.0	33.3–34.0	32.9–33.7

[a] Data provided by the Stone and Resource Industry R&D Center, 2014–2016 (Hualien County, Taiwan).

Table 2 – Levels of a two-factor central composite design for studying electrolyzing deep ocean water.

Level	Electrode gap (mm)	Electric current (A)
1	6.7	2.5
2	8.7	2.9
3	13.4	4.0
4	18.1	5.1
5	20.1	5.5

effects of electrode gap and electric current on chlorine generation efficiency of electrolyzed DOW, which is important in designing electrolysis systems and choosing operation conditions.

As shown in Fig. 1, current density was significantly affected by electric current but not electrode gap in the testing ranges. The smaller the electrode gap the closer the electrodes and the higher the electric potential should be. However, since the electric current passing through the system remained unchanged due to the constant current mode of operation chosen for this study, the electric potential was adjusted accordingly and automatically by the electrolysis system for maintaining constant currents. Therefore, current density was not affected by electrode gap in this study.

As shown in Fig. 2, chlorine concentration was significantly affected by electric current but not electrode gap also due to the constant current mode of operation chosen for this study. The amount of chlorine generation depends on the amount of electric current passing through the electrodes. Therefore, high electric current generated high chlorine concentration, but the chlorine level was not affected by electrode gap in this study.

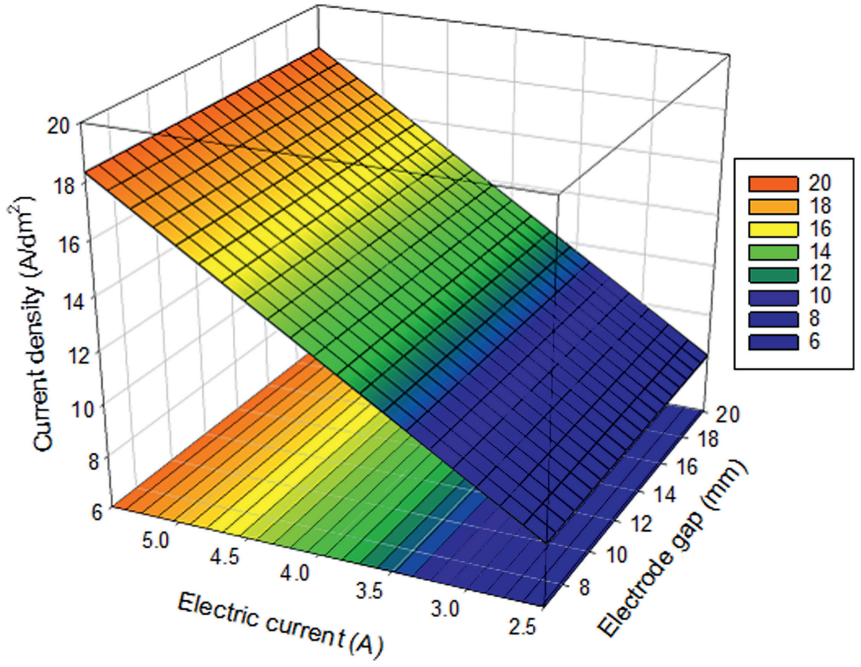

Fig. 1 – Response surface plot of current density with respect to electrode gap and electric current in electrolysis of deep ocean water.

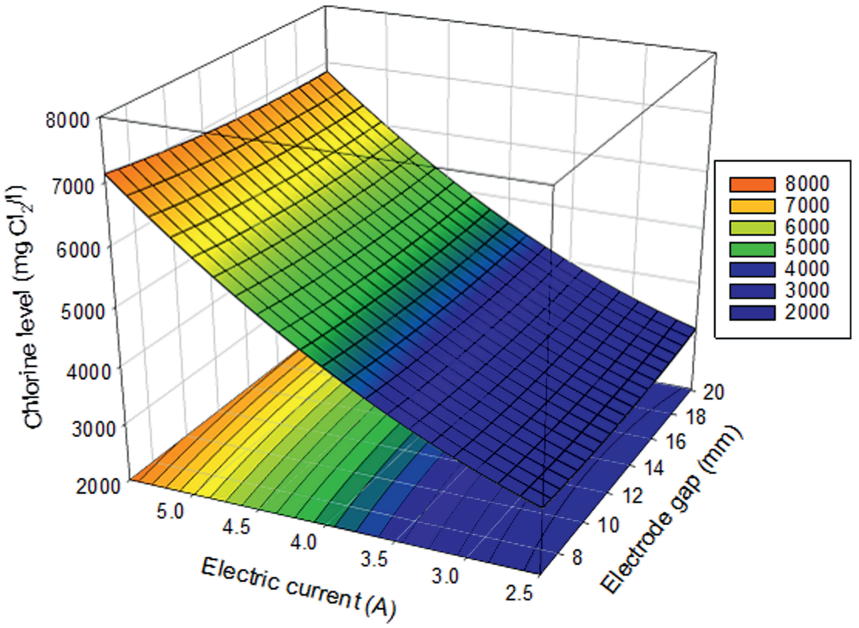

Fig. 2 – Response surface plot of chlorine concentration with respect to electrode gap and electric current in electrolysis of deep ocean water.

As shown in Fig. 3, electrolyte temperature increased with electric current and electrode gap in a quadratic from. As shown in our previous reports, electrolyte temperature increased during electrolysis process owing to continuous conversion of electrical energy to heat and heat dissipation at electrodes [13]. It is shown in this study that the higher the electric current passing through the electrodes the faster the chlorine generation and the higher the electrolyte temperature became (Figs. 1–3). High temperature increases chlorine evaporation rate.

As shown in Fig. 4, similar to electrolyte temperature, electric current and electrode gap affected electric efficiency of the system in a quadratic form. Overall effect of the increments of electric current and electrode gap was a significant decrement in energy efficiency of the system. As explained in Fig. 1, increment in electrode gap increased

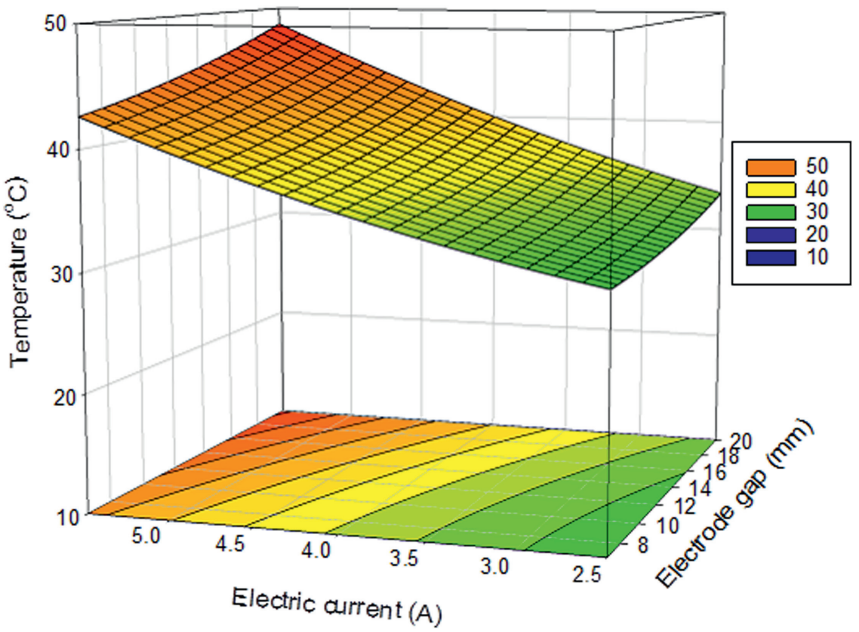

Fig. 3 – Response surface plot of electrolyte temperature with respect to electrode gap and electric current in electrolysis of deep ocean water.

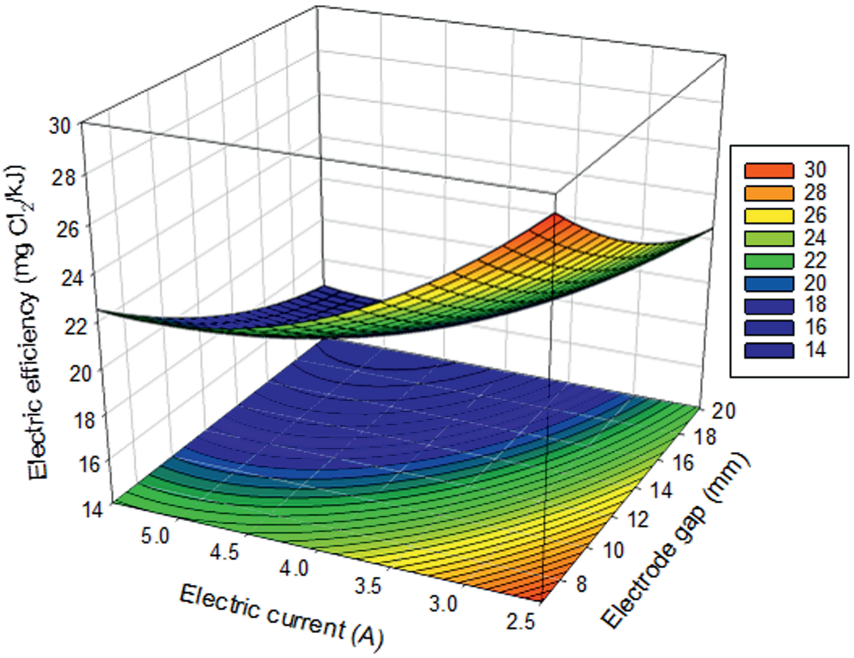

Fig. 4 – Response surface plot of electric efficiency with respect to electrode gap and electric current in electrolysis of deep ocean water.

electric potential of an electrolysis system running in a constant current mode. It's also been shown in our previous study that increment of electric potential reduced electric efficiency of an electrolysis system [15]. Therefore, the combined effect of increments in electric current and electrode gap resulted in a drastic decrement in electric efficiency of the system (Fig. 4). Comparing to a constant electric-potential mode of operation [15], a constant electric-current mode of operation has the advantages of more precise control on current density (Fig. 1) and chlorine concentration (Fig. 2), which were not affected by electrode gap. However, electric efficiency (Fig. 4) could be decreased, 17–29 vs. 0–47 mg-Cl_2/kJ, owing to more electricity needed for maintaining electric current in the system.

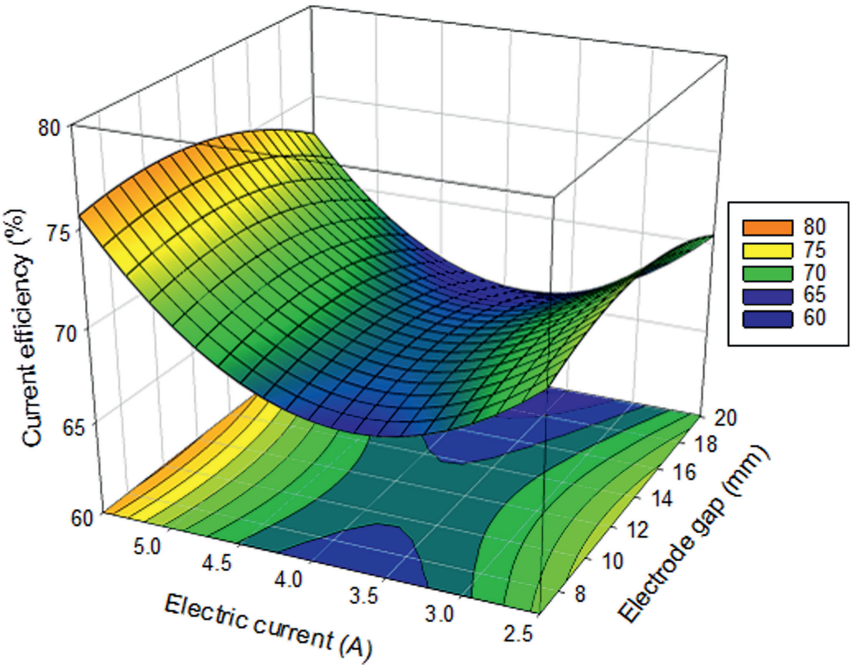

Fig. 5 – Response surface plot of current efficiency with respect to electrode gap and electric current in electrolysis of deep ocean water.

Current efficiency of the system fell in the range of 68–75% with an average of 71%.

As shown in Fig. 5, electric current and electrode gap affected current efficiency of the system in a saddle form. There was a minimum current efficiency at around 3.75 A of electric current in each electrode gap and a maximum current efficiency at around 11.8 mm of electrode gap in each electric current in the tested ranges. The antagonistic effects of increments in chlorine generation and chlorine evaporation at high electric current combined with the detrimental effects of high electric current and electrode gap on electric efficiency and resulted in an overall saddle form effects of electric current and electrode gap on the current efficiency.

In summary, electrolyzed DOW is more suitable for applications in postharvest cleaning and disinfection of ready-to-eat fresh produce owing to its better purity and stability. A constant current mode of electrolysis operation adopted in this study revealed that current density, chlorine concentration, and electrolyte temperature increased with electric current, while electric efficiency decreased with electric current and electrode gap or electric potential. Although current efficiency was high at high electric current, electric efficiency was low (Figs. 4 and 5). Therefore, a small electrode gap, which is less than 11.7 mm, and operating at a low electric current appeared to be a more energy efficient design and operation condition for the electrolysis system.

Conflicts of interest

All authors have no conflicts of interest to declare.

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