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Original Article

# Effects of electrode gap and electric potential 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 environmentally friendly. A two-factor central composite design was adopted for studying the effects of electrode gap and electric potential 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. Results showed high electric efficiency at a low cell potential, and a high current density and high chlorine concentration at a high cell potential and low electrode gap. Current efficiency of the system was not significantly affected by electrode gap and electric potential. A small electrode gap reduced the required cell potential and resulted in high energy efficiency. The optimal choice of electrode gap and cell potential depends on the chlorine level of the electrolyzed deep ocean water to be produced, and a small electrode gap is preferred.



## 1. Introduction

Electrolyzed water is environmentally 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 antifouling 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 minute. Watanabe and Yoshimizu [6] disinfected various utensils and equipment 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 minutes. Kasai and Yoshimizu [7] studied disinfection

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of seawater from fishing port by an electrolytic apparatus and found its useful applications to sanitization of fish-holding tanks, port deck, and fishing equipment. Kimura et al [8] reared sea urchins for 2 days using electrolyzed seawater 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 the 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 due 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 a 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 DOW 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]. In this study, for the purposes of designing better electrolysis systems and developing optimal processing conditions, a two-factor central composite design is adopted for investigating optimal electrode gap and electric potential for electrolyzing DOW.

## 2. Methods

### 2.1. Seawater samples

DOW samples used in this study were provided by the Taiwan Yes Deep Ocean Water Co., Ltd (Hualien County, Taiwan). 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 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 hours 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 Internation Corp., Taipei City, Taiwan), which were titanium mesh electrodes plated with 3.75 μm of platinum, were powered by a rectifier (Model MC48-4D; Surchem C&S Internation Corp.). A constant potential mode of operation was adopted in this study. The electrodes were immersed in seawater at 60 mm beneath the surface. Electrode gap and cell potential were maintained at designated levels during electrolysis (Table 2). Additional stirring was done with a 16 × 30 $mm^2$ (diameter × length) Teflon spindle-shaped magnetic stirring bar powered by a stirrer (Model PC-101; Corning Inc., Acton, MA, USA) at speed setting 1.2, which was ~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 the 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 the anode. Current efficiency was calculated from the percentage ratio of the total chlorine production to the theoretical chlorine production based on the Faraday's laws of electrolysis [15]. Electric efficiency, which represents energy efficiency of the system, was calculated by

**Table 1 – Comparison of major elements, some pollution indicative compositions, and properties of surface seawater and deep ocean water samples.[a]**

| Category | Item | Surface seawater | Deep ocean water |
|---|---|---|---|
| Major element (mg/L or kg) | Chloride | 19,060–19,860 | 18,840–19510 |
| | Sodium | 11,320–11,500 | 11,380–11,430 |
| | Magnesium | 1327–1330 | 1283–1320 |
| | Calcium | 400–441 | 400–432 |
| | Potassium | 400–414 | 390–421 |
| Composition | Nitrite (μM) | 0.08–0.11 | <0.03 |
| | Chlorophyll a (μg/L) | 0.12–0.19 | <0.03 |
| Property | Temperature (°C) | 22.5–23.8 | 9.4–10.4 |
| | pH | 8.10–8.20 | 7.70–7.75 |
| | Salinity (psu) | 34.2–34.5 | 34.3–35.0 |

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

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

| Level | Electrode gap (mm) | Cell potential (V) |
|---|---|---|
| 1 | 6.7 | 6.00 |
| 2 | 8.7 | 6.59 |
| 3 | 13.4 | 8.00 |
| 4 | 18.1 | 9.41 |
| 5 | 20.1 | 10.0 |

dividing the total chlorine produced by the electric energy consumed.

### 2.5. *Statistical design and analysis*

A two-factor central composite design [16] was adopted for studying the effects of electrode gap and electric potential on chlorine generation efficiency of electrolyzed DOW. The test ranges of electrode gap and electric potential were 6.7–20.1 mm and 6.00–10.0 V, 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

As reviewed in the Introduction section of this paper, electrolyzed seawater, because of its significant disinfection effects and availability, has been used in many antifouling, 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 effects of electrode gap and electric potential on chlorine generation efficiency of electrolyzed DOW, which is important in designing electrolysis systems and choosing operation conditions.

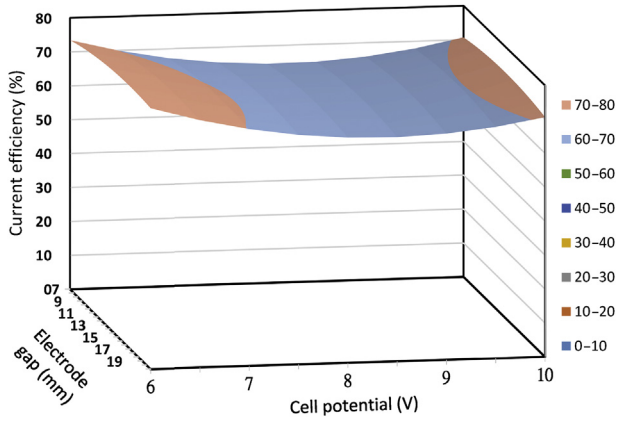


**Figure 1 – Response surface plot of current efficiency with respect to electrode gap and electric potential in electrolysis of deep ocean water.**

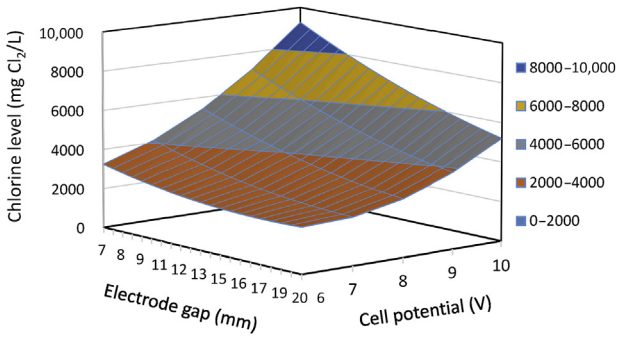


**Figure 2 – Response surface plot of chlorine concentration with respect to electrode gap and electric potential in electrolysis of deep ocean water.**

As shown in Figure 1, current efficiency of the system was lower in the middle level (8.0 V) of the cell potential, but the difference was not statistically significant ($p < 0.05$). The additional stirring appeared to be effective in mixing electrolyte during electrolysis, which reduced the effects of electrode gap and cell potential on current efficiency in the testing ranges. Current efficiency of the system fell in the range of 65–82% with an average of 69%.

As shown in Figure 2, chlorine concentration was significantly affected by electrode gap and electric potential. The smaller the electrode gap and the higher the cell potential, the higher the chlorine concentration. As shown in Figure 3, current density was significantly affected by electrode gap and electric potential as well. The closer the electrodes and the higher the electric potential, the more the electric current passing through the system and the more the chlorine generation.

Energy efficiency or electric efficiency of the system was significantly affected by cell potential, while electrode gap had a minor effect (Figure 4). As indicated in Figure 1, current efficiency of the system was not significantly affected by the electrode gap of the system. Therefore, the size of the electrode gap in the testing ranges did not affect energy efficiency. However, a high electric potential led to chlorine generation at a faster speed, but resulted in low energy efficiency (Figures 2 and 4).

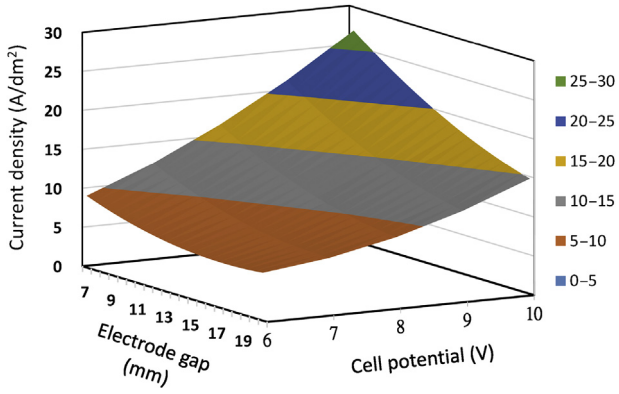


**Figure 3 – Response surface plot of current density with respect to electrode gap and electric potential in electrolysis of deep ocean water.**

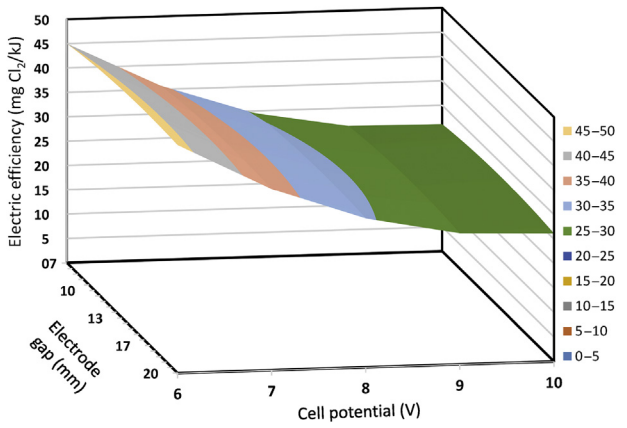


**Figure 4 – Response surface plot of electric efficiency with respect to electrode gap and electric potential in electrolysis of deep ocean water.**

As shown in our previous reports, electrolyte temperature increased steadily during the electrolysis process owing to continuous conversion of electrical energy to heat and heat dissipation at electrodes [13]. We also reported that chlorine concentration positively correlated with oxidation–reduction potential and temperature, while oxidation–reduction potential negatively correlated with electric conductivity and electrolyte pH, which decreased because of conversions of inorganic ions of high electric conductivity, such as chloride, to compounds of low electric conductivity, low pH, and high oxidation–reduction potential, such as chlorine, hypochlorite, etc. [14]. In this study, it is shown that the smaller the electrode gap and the higher the cell potential, the higher the current density passing through electrodes and the faster the chlorine generation (Figures 3 and 4). This resulted in a reduction of energy efficiency of the system because the higher the electrolyte temperature, the faster the chlorine loss during evaporation.

In conclusion, 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 reduction in electrode gap increased current density and chlorine concentration without affecting energy efficiency. An increase in electric potential increased current density and chlorine concentration, but reduced energy efficiency of the electrolysis system. Therefore, the optimal choice of electrode gap and cell potential depends on the chlorine level of the electrolyzed DOW to be produced, and a small electrode gap is preferred. A small electrode gap reduces the required cell potential for producing electrolyzed DOW with the same chlorine level and results in high energy efficiency of the system. This principle is applicable to all electrolysis systems, including those used for electrolysis of surface seawater and DOW concentration products.

## Conflicts of interest

All authors have no conflicts of interest to declare.

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