



## Electrochemical disinfection of simulated ballast water on conductive diamond electrodes



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### HIGHLIGHTS

- Ballast water treatment deals with invasive species elimination.
- Electrochemical disinfection is an easy to apply process on-board.
- Modeling of chlorine generation during electrochemical disinfection was performed.
- Both bacteria (*E. coli*) and higher organisms (*A. salina*) were tested as model microorganisms.

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### ABSTRACT

In this work, the electrochemical disinfection with conductive diamond electrodes was studied to treat simulated ballast water. *Artemia salina* was used as indicator organism and *Escherichia coli* as indicator bacterium. The influence of salinity (3 and 30 g/L NaCl simulating brackish and ballast water, respectively), current density (up to 1273 A/m<sup>2</sup>) and operation mode (batch and single-pass) on inactivation and total residual chlorine production rates was investigated. An increase in salinity and current density generally had a beneficial effect on both rates. *A. salina* in ballast water was completely inactivated after 45 min of batch treatment at 255 A/m<sup>2</sup> (corresponding to about 200 mg/L of produced chlorine) and this increased to 60 min in brackish water. *A. salina*, whose inactivation follows first order kinetics, was found to be more resistant to electrochemical disinfection than *E. coli*. The complete inactivation of *E. coli* was achieved in less than 5 min of batch operation at 127 A/m<sup>2</sup>, whereas the concentration of produced chlorine was less than 20 mg/L. Operation in single-pass mode was less effective for *A. salina* because it did not suffer mechanical stress, whereas *E. coli* inactivation occurred at low current densities and irrespective of the salinity due to both direct oxidation on the surface of conductive diamond anode and chemical reactions with chlorine species and/or reactive oxygen species.

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## 1. Introduction

Ballast water is defined as the water carried by ships to ensure stability, trim and structural integrity. If a ship is empty of cargo, it will fill with ballast water whereas if it loads cargo, the ballast water will be discharged. The International Maritime Organization (IMO) estimates that at least 7000 different species are being carried in ships' ballast tanks around the world [1]. These marine species are microorganisms, phytoplankton, zooplankton, etc. and most of them do not survive the journey or the new environmental conditions where they are discharged. However, some species survive in the host environment under favorable circumstances. At this

point, the environmental impact of these last species often results in unpredictable ecological, economic and social impacts [2–4].

The methodology recommended by the IMO guidelines for ballast water treatment involves its exchange to reduce the risk of transfer of harmful aquatic organisms. Nevertheless, this method has ship-safety limitations because it is not completely effective in removing organisms from ballast water. Then, effective ballast water management and/or treatment methods should be developed in order to replace the ballast water exchange at sea. So far, several technologies have been suggested for ballast water treatment, including filtration [5], irradiation with ultraviolet light [6,7], sterilisation with ozone [8,9], disinfection with chlorine species [10] or hydrogen peroxide [11], addition of biocides to ballast water to kill organisms [12,13] and sonication [14].

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In recent years, electrochemical processes have been tested for water disinfection [15–18]. Electrochemical disinfection can be defined as the eradication of microorganisms using an electric current passed through the water by means of suitable electrodes. The advantages of electrochemical water disinfection in comparison to other chemical methods include (i) simplicity of the equipment, (ii) easy automation of the process, (iii) the fact that additional chemicals are not required since the disinfectant dose can be easily controlled varying the current density applied, and (iv) the relatively low current requirement that may allow the use of green energy sources such as solar cells or fuel cells [19–21]. Furthermore and in the specific case of saline water treatment, electrochemical disinfection takes advantage of the electrolytic production of chlorine species such as hypochlorite and hypochlorous acid (i.e., electrochlorination) [22–25].

The selection of a proper anodic material is a key point in electrolytic processes. In this way, dimensionally stable anodes (DSAs) present good efficiencies in the production of hypochlorite, which is critical for the wide use of electrochemical technology in many environmental applications [22,26]. Nevertheless, a new anode material, namely boron-doped diamond (BDD), has been developed in recent years and it exhibits good properties for electrochemical applications. The BDD anode allows operation at harsh oxidation conditions and, consequently, promotes the generation of several oxidants such as peroxosalts, ozone or hydrogen peroxide, which would be difficult or even impossible to be produced with other anodic materials [27–32].

The efficacy of electrochemical disinfection in killing a wide spectrum of microorganisms has been reported in the literature [33–35]. The high bactericidal capacity is attributed to several functions such as the generation of toxic oxidants like persulphate [36] or chlorine species [37], direct oxidation on the electrode surface [34,38], inactivation by reactive intermediate products such hydroxyl radicals, ozone, and hydrogen peroxide. [39–41], and/or the electric field effect [33,38,41]. To the best of our knowledge, the electrochemical disinfection of ballast water has only recently been reported in the literature; seawater spiked with *E. coli* [42,43] or *Enterococcus faecalis* (*E. faecalis*) [42] was treated on a titanium anode and process performance was assessed in terms of energy consumption to achieve IMO discharge standards and post-treatment environmental implications (e.g. corrosion of materials, ecotoxicity to seawater species).

In this context, the main objective of this study was to examine the potential of electrochemical disinfection over BDD to treat simulated ballast water. *Artemia salina* (*A. salina*) was chosen as an indicator organism, while *Escherichia coli* (*E. coli*) was selected as indicator bacterium. The influence of salinity, current density and operation mode on *A. salina* and *E. coli* mortality rates, as well as on chlorine production was investigated.

## 2. Materials and methods

### 2.1. Test organism

The artificial water was prepared diluting sodium chloride into osmosis water to obtain a final concentration of 30 g/L NaCl (seawater) or 3 g/L NaCl (brackish water).

*A. salina* in the form of dehydrated cysts was provided by the Hellenic Center of Marine Research (Greece). *A. salina* cysts were kept refrigerated (4–5 °C) in the absence of light. Prior to use, they were hatched into nauplii larvae for 24 h. To initiate the growth procedure a volume of 25 mL of the cysts was placed in 1 L of artificial seawater [17]. A water bath was used to keep the temperature at 28 °C [44]. Continuous aeration was provided through

constant airflow. The hatching of *A. salina* was complete after a period of 24 h. Then, the *A. salina* suspension was diluted to 10 L of artificial sea or brackish water (feed water).

The bacterial strain used in the present study was *E. coli* (DSMZ 498) (DSMZ, German Collection of Microorganisms and Cell Cultures). One hundred microliters of the bacterial strain of *E. coli* were spread over the surface of the appropriate solid agar medium (HiCrome™ Coliform Agar, HiMedia Laboratories) in 90 mm Petri dishes and then incubated for 24 h at 37 °C. Finally, the bacterial pellet was suspended in sterile 0.8% (w/v) NaCl aqueous solution and diluted to the required cell density corresponding to a cell concentration of approximately  $10^6$ – $10^7$  CFU/mL [35,45]. The concentration of the suspensions was adjusted measuring the optical density according to the McFarland standards [46].

### 2.2. Electrochemical experiments

Experiments were carried out in a DiaCell (type 100) single compartment electrolytic flow-cell manufactured by Adamant Technologies (Switzerland). BDD on silicon was used as anodic and cathodic material. Both electrodes were circular with a diameter of 10 cm each and an electrode gap of 10 mm.

Experiments were carried out in both batch and single pass modes and under galvanostatic conditions (Fig. 1). Polarity was automatically inverted every 10 min to avoid operational problems such as the formation of films of carbonates on the surface of the cathode or the passivation of the anode. In batch mode, 10 L of simulated ballast or brackish water were loaded in a vessel and continuously recirculated in the cell by means of a peristaltic pump at a constant flowrate of 20 L/min, whereas in single pass mode, 30 L of simulated ballast or brackish water were loaded in the vessel. A spiral coil immersed in the effluent vessel and connected to tap water supply was used to remove the heat released from the electrolytic process. Thus, all experiments were conducted at uncontrolled temperature which never exceeded 30 °C.

### 2.3. Experimental procedure

The current density ranged between 0 and 1273 A/m<sup>2</sup>, which corresponds to current values from 0 to 10 A. The mechanical stress control was performed with the run at 0 A/m<sup>2</sup>. The gradient velocity was calculated and it ranged from 700 to 1300 s<sup>-1</sup>, which is between or slightly higher than that typically used in a coagulation process [47]. Two samples of 0.1 L each were collected in beakers: the first beaker contained 2 mL sodium thiosulphate (Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub>·5H<sub>2</sub>O purchased from Merck, Germany) stock solution (1 N) in order to instantly destroy free chlorine produced during electrolysis and avoid microorganisms death during sample handling due to residual chlorine. The second beaker did not contain any sodium thiosulphate and it was used to measure total residual chlorine. Here, it is important to point out that 2 mL of 1 N sodium thiosulphate solution were sufficient to reduce up to 200 mg/L of residual chlorine in seawater [17]. Samples were collected from the outlet of the electrochemical cell. In batch experiments, samples were taken at 5, 10, 15, 30, 45, 60, 75 and 90 min and analyzed with regard to the population of *A. salina* or at 2, 5, 10, 15, 30, 60 and 90 min and analyzed with regard to the CFU/mL concentration of *E. coli*. In single-pass experiments, just a sample was taken at each current density studied after 5 s. The influence of total residual chlorine was also studied adding the appropriate amounts of 2 g/L sodium hypochlorite stock solution (without water pumping or electricity) to the effluent vessel in order to achieve levels of 50, 100 and 200 mg/L free residual chlorine [17].

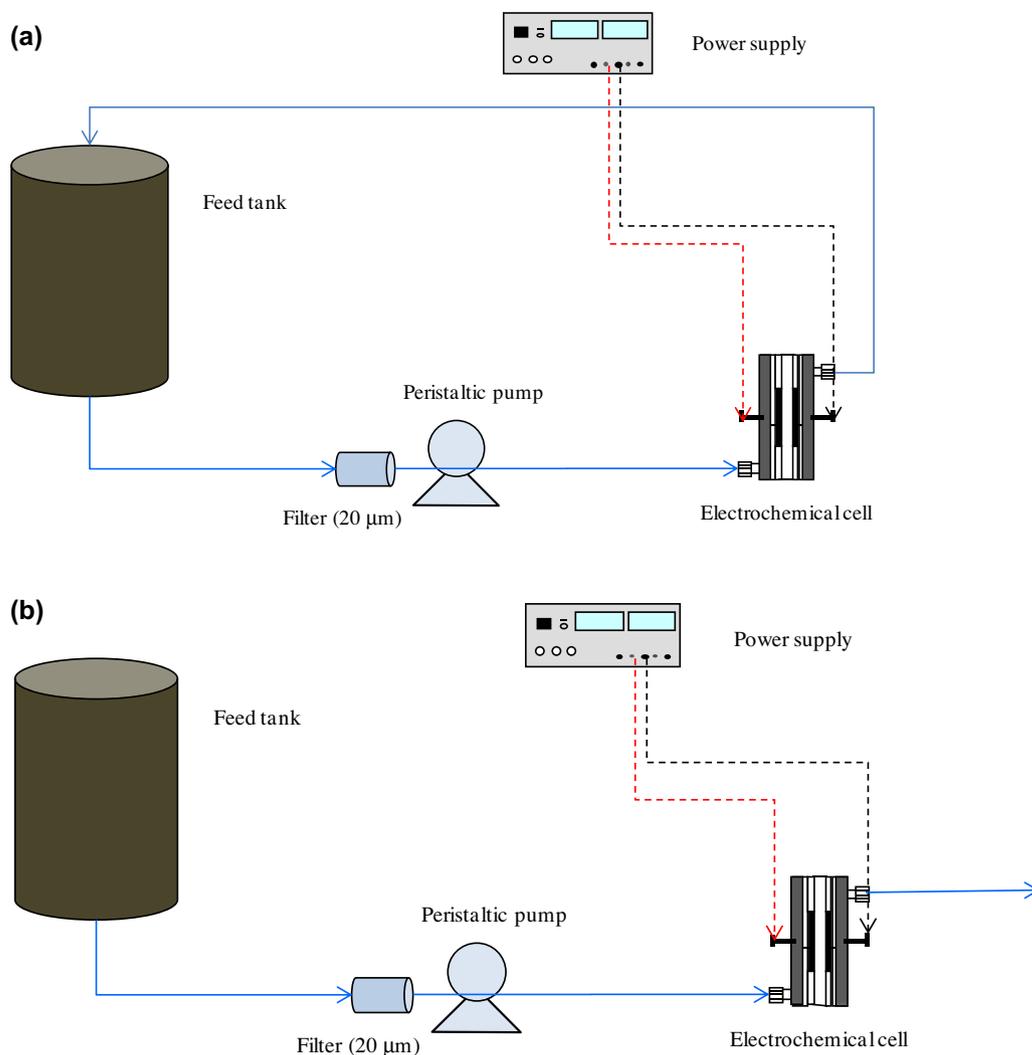


Fig. 1. The experimental set-up used in this work: (a) batch mode and (b) single-pass mode.

#### 2.4. Analytical methods

Sampling and measurement of *A. salina* (before and after electrochemical treatment) were done in triplicate. The volume of each sample used for the measurement of *A. salina* was 5 mL. Each sample was transferred into Petri dishes (90 mm in diameter), where the measurement of *A. salina* was conducted with a colony counter apparatus. The living-dead judgment was made according to organism movement.

Sampling and measurement of *E. coli* (before and after electrochemical treatment) were also done in triplicate. About 3 mL of the reaction mixture were withdrawn at specific time intervals. The detection and enumeration of *E. coli* in the reaction solution were performed using the serial dilution spread plate agar technique. Serial dilutions of the reaction solution were performed in sterile 0.8% (w/v) NaCl aqueous solution and 0.1 mL of each dilution were inoculated and spread onto HiCrome coliform agar plates (HiMedia Laboratories), which is a selective *E. coli* culture medium. The plates were incubated at 37 °C for 24 h. Finally, *E. coli* colonies were counted with colony counter apparatus.

Residual chlorine was measured according to standard method 4500 Cl-B method I [48]. Acetic acid and potassium iodide used in titrimetric determination of residual chlorine were purchased from Carlo Erba and Fluka, respectively. Conductivity and pH measurements were conducted with a Crison meter.

### 3. Results and discussion

#### 3.1. Production of total chlorine

Fig. 2 shows the influence of salinity and current density on the production of total residual chlorine. Salinity was varied between 30 g/L, which is a typical concentration of sodium chloride in seawater, and 3 g/L, which corresponds to the sodium chloride concentration in brackish water. The experiments were carried out in batch mode and in the absence of microorganisms to avoid interferences in the production of chlorine species.

The total residual chlorine concentration increases when both sodium chloride concentration and current density increase. During the early stages (i.e. 30 min), the salinity level does not seem to have a significant influence on the production of total residual chlorine when lower current densities are applied. However, total residual chlorine concentration becomes as high as about 1500 mg/L after 90 min when sodium chloride concentration is 30 g/L and the highest current density is applied. Thus, current density is observed to be an important parameter in the production of total residual chlorine, as has previously been reported in the literature [49].

The mass balance for residual chlorine in the feed tank is:

$$QC_e - QC_t = \frac{dC_t}{dt} V_t \quad (1)$$

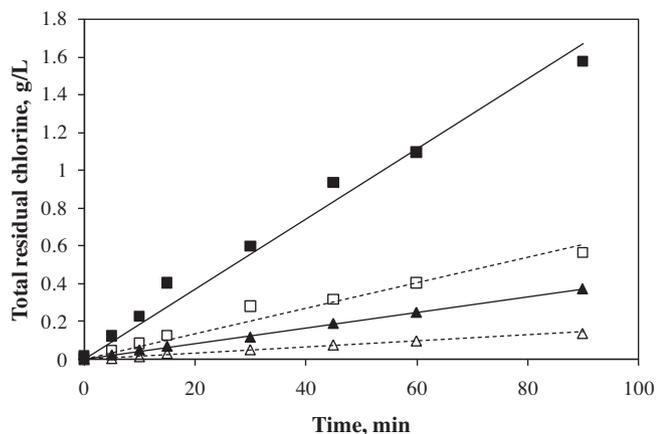


Fig. 2. Production of total residual chlorine as a function of electrolysis time. Experimental conditions: batch mode; salinity: 30 g/L NaCl (solid points), 3 g/L NaCl (open points); current density: ( $\blacktriangle$ ) 255 A/m<sup>2</sup>, ( $\blacksquare$ ) 1273 A/m<sup>2</sup>.

where  $Q$  is the flowrate,  $C_e$  is the residual chlorine concentration in the effluent of the electrode (influent to feed tank),  $C_t$  is the residual chlorine concentration in the feed tank (assuming complete mixing) and  $V_t$  is the feed tank volume. The mass balance for residual chlorine in the electrode is:

$$QC_e - QC_t = r_e V_e \quad (2)$$

where  $V_e$  is the volume of electrolytic cell,  $r_e$  is the rate of chlorine generation in the electrolytic cell (i.e. mg Cl per cell volume per time).

Since the rate of chlorine generation for constant current density and salinity (conductivity) is constant, the second term of Eq. (2) is constant. Combining Eqs. (1) and (2) and integrating give:

$$C_t = \left( \frac{V_e}{V_t} r_e \right) t = St \quad (3)$$

Eq. (3) indicates a linear relationship between residual chlorine concentration in the feed tank and electrolysis time with slope equal to  $S$ , which is in agreement with the linear trends shown in Fig. 2.

Since  $r_e$  can be estimated by single pass experiments and the two volumes are known, chlorine generation in the recirculation tank can be estimated from mass balance calculations. These estimated values can be compared to the actual experimental (measured) values during batch operation. Experiments with simulated seawater under batch conditions were performed at 286, 714, 1071 and 1428 A/m<sup>2</sup> and the actual  $S$  values (based on the measured  $C_t$ -time profiles) were 4, 10, 13.4 and 18.4 mg/(L min), respectively. On the other hand, the corresponding  $S$  values taken from the mass balance and based on single-pass chlorine generation rates (under similar operating conditions, i.e. current densities) were 4.6, 21.3, 24.8 and 28.4 mg/(L min), thus showing agreement at the lowest density but 40–50% deviation at higher densities. Interestingly, the actual values are lower than the theoretical ones and this may be due to the fact that upon batch conditions (i) chlorine, in the form of hypochlorite, is partially reduced to chloride ions on the cathode, and (ii) NaCl concentration continuously decreases in comparison to single-pass experiments.

The temporal evolution of pH was also followed (data not shown) and it was maintained at about 8–9, irrespective of the applied current density and salinity. Electrolysis often is a pH-buffering process and this can be explained taking into account the main side reactions, namely water oxidation Eq. (4) and reduction Eq. (5) occurring on the surface of the anode and cathode, respectively:



Hydroxyl anions produced on the cathode are neutralized by protons coming from water oxidation. Thus, pH values remain relatively unchanged throughout the course of the experiments. Moreover, conductivity is maintained constant because there is no addition of any chemicals during electrolysis.

In addition, it is worth noting that an increase of current density using BDD electrodes is believed to promote the production of harmful species such as chlorates or perchlorates due to the harsh oxidation conditions obtained by conductive diamond electrolysis [50]. The formation of these chlorine species, which are associated with potential risks to the environment, is typically favored at alkaline pH, high current densities and large current charge passed, due to the production of large quantities of hydroxyl radicals at these conditions [51,52].

### 3.2. Inactivation of test organisms during batch operation

Fig. 3 shows the influence of salinity and current density on the inactivation of *A. salina* as a function of electrolysis time (main graph indicating inactivation rates) and applied charge (inset graph indicating inactivation efficiencies) at two different salinities and current densities during batch operation. A control run was performed without applying current and the results are also shown in Fig. 3. As seen in Fig. 3, *A. salina* was totally inactivated after about 60 min of contact time at either sodium chloride concentration presumably due to the mechanical stress produced along the process. On the other hand, its mortality rate increased with increasing current density and/or salinity. For example, complete mortality could be achieved after 45 min at 30 g/L NaCl salinity and 255 A/m<sup>2</sup> current density, whereas 60 min was necessary to achieve complete mortality at 3 g/L NaCl and the same current density. This can be explained bearing in mind that the total residual chlorine concentration increases at high values of salinity and current density. These chlorine species may chemically react with *A. salina* to inactivate it. Likewise, *A. salina* can also be inactivated by direct oxidation at the anode surface [17].

By comparison, the mortality of *A. salina* was also examined in simulated seawater, when sodium hypochlorite had been added without water pumping (i.e. no mechanical stress) or electricity.

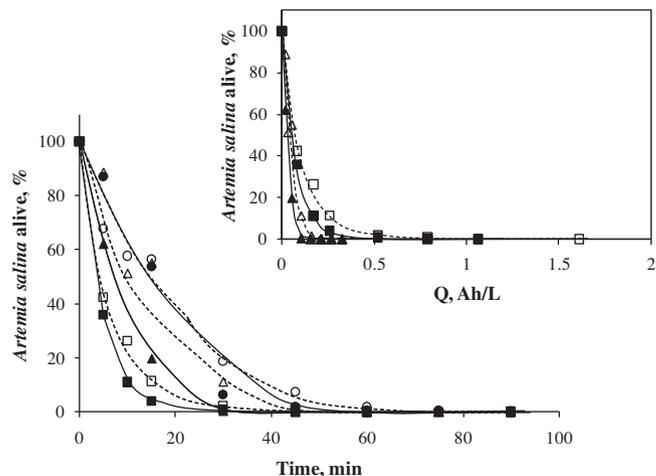
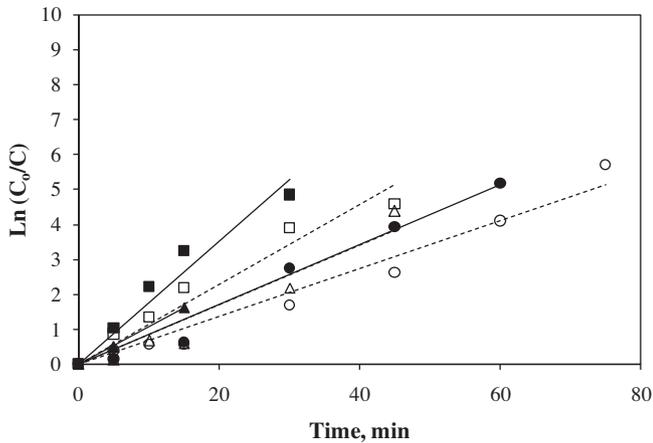


Fig. 3. Inactivation of *A. salina* as a function of electrolysis time (main graph) and applied charge (inset graph). Experimental conditions: batch mode; salinity: 30 g/L NaCl (solid points), 3 g/L NaCl (open points); current density: ( $\bullet$ ) 0 A/m<sup>2</sup>, ( $\blacktriangle$ ) 255 A/m<sup>2</sup>, ( $\blacksquare$ ) 1273 A/m<sup>2</sup>.



**Fig. 4.** First order kinetics of *A. salina* inactivation. Experimental conditions: batch mode; salinity: 30 g/L NaCl (solid points), 3 g/L NaCl (open points); current density: (●) 0 A/m<sup>2</sup>, (▲) 255 A/m<sup>2</sup>, (■) 1273 A/m<sup>2</sup>.

**Table 1**

First order kinetics for the inactivation of *A. salina* at various salinities and current densities and batch operation. A: 30 g/L NaCl; B: 3 g/L NaCl.

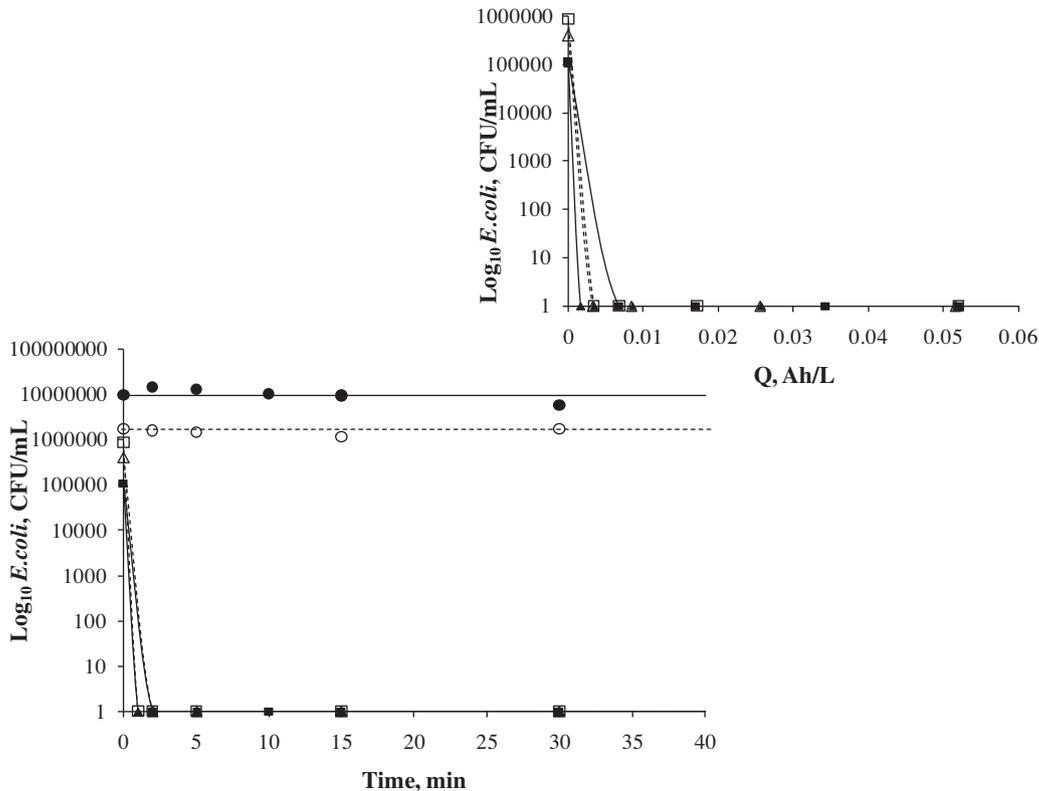
Current density	0 A/m <sup>2</sup>	255 A/m <sup>2</sup>	1273 A/m <sup>2</sup>
(A) Kinetic equations	$\ln \frac{C_0}{C} = 0.085 \cdot t$	$\ln \frac{C_0}{C} = 0.107 \cdot t$	$\ln \frac{C_0}{C} = 0.176 \cdot t$
(A) Regression coefficients	$r^2 = 0.976$	$r^2 = 0.997$	$r^2 = 0.946$
(B) Kinetic equations	$\ln \frac{C_0}{C} = 0.068 \cdot t$	$\ln \frac{C_0}{C} = 0.085 \cdot t$	$\ln \frac{C_0}{C} = 0.114 \cdot t$
(B) Regression coefficients	$r^2 = 0.968$	$r^2 = 0.927$	$r^2 = 0.945$

When 80 mg/L hypochlorite-chlorine was added, the mortality of *A. salina* was 40% after 120 min of contact time and it increased to 90% at 240 min contact time. Under batch electrolytic conditions and equivalent amounts of total chlorine produced (at 255 A/m<sup>2</sup> current density), 80% mortality was observed at 15 min, while mortality was almost 100% at 30 min. This indicates that electrolytic disinfection is more efficient than simply adding hypochlorite-chlorine due to the generation of a variety of oxidation species, mechanical stress and direct oxidation at the anode surface.

According to the literature [14], 92% mortality in ballast water was reached when *A. salina* cysts were exposed for over 20 min to a combined oxidative treatment comprising sonication, hydrogen peroxide and ozone. In this work, the same performance in ballast water can be achieved after 15 min of electrolysis at 1273 A/m<sup>2</sup> and 25 min at 255 A/m<sup>2</sup>.

The inset of Fig. 3 shows the dependence of the efficiency of electrolysis to inactivate *A. salina* on the charge passed as a function of salinity and current density. Efficiency is evidently maximized at low current densities and high salinities. Therefore, *A. salina* contained in ballast water could be efficiently removed after 45 min of batch electrolysis using low values of current density.

Fig. 4 shows a plot of the logarithm of the normalized *A. salina* population against electrolysis time at the experimental conditions of Fig. 3. The inactivation of *A. salina* appears to follow first order kinetics since straight lines passing through the origin fit the experimental data reasonably well. The respective kinetic equations and regression coefficients of the linear fitting are summarized in Table 1 with the kinetic constants taking values between 0.068 and 0.176 min<sup>-1</sup>. According to the literature [53–55], first order kinetics suggest that the electrochemical inactivation of *A. salina* may be controlled by mediated reagents (oxidizing/reducing agents in the target solution) or by mass transfer.



**Fig. 5.** Inactivation of *E. coli* as a function of electrolysis time (main graph) and applied charge (inset graph). Experimental conditions: batch mode; salinity: 30 g/L NaCl (solid points), 3 g/L NaCl (open points); current density: (●) 0 A/m<sup>2</sup>, (▲) 127 A/m<sup>2</sup>, (■) 255 A/m<sup>2</sup>.

Further experiments were performed to test the electrochemical inactivation of *E. coli*. Unlike *A. salina*, *E. coli* did not suffer any damage due to mechanical stress as clearly seen in Fig. 5. Nevertheless, *E. coli* was readily inactivated at very low values of current density, where the concentration of total residual chlorine was less than 20 mg/L. Nadeeshani Nanayakkara et al. [43] reported that complete inactivation of  $10^4$ – $10^6$  CFU/mL of *E. coli* in simulated ballast water could be achieved within 1–2.5 min (depending on initial concentration) of electrochemical treatment at  $12.5 \text{ A/m}^2$  in a recirculating reactor comprising a titanium anode. Li et al. [56], who compared several advanced oxidation and conventional treatments to inactivate *E. coli*, *Staphylococcus aureus*, *Bacillus subtilis* and an isolated *Bacillus* in water, reported that disinfection capacity decreased in the order: electrochemical process > ozonation > chlorination > monochloramination. In this context, complete inactivation of *E. coli* could be achieved within the first 5 min irrespective of the salinity and current density employed. According to the literature [57–60], the inactivation of *E. coli* is attributed to the action of reactive oxidants such as chlorine or sulphate species and hydroxyl radicals produced during BDD electrolysis, and/or the electrosorption of negatively charged *E. coli* cells to the anode surface followed by a direct electron transfer reaction.

The inset of Fig. 5 shows that treatment efficiency is not really influenced by the current density, i.e. even at the lowest current density the disinfection efficiency was the highest. This behavior is in agreement with literature, where the lethal effects of using low current densities can achieve complete disinfection of simulated or natural seawater [61] and/or treated wastewaters for reuse [62], while avoiding the occurrence of undesired species such as chlorate, perchlorate or organo-chlorinates. The same effect has

also been observed for large concentrations of chloride, promoting the formation of hypochlorite and preventing the formation of chlorates and perchlorates [63].

### 3.3. Operation in single-pass mode

All the experiments discussed so far were performed in batch mode, i.e. the ballast or brackish water was recirculated through the cell. A final set of experiments was performed to assess the performance of disinfection operating the cell in single-pass mode and the results are summarized in Fig. 6.

As clearly seen, the extent of *A. salina* inactivation increased with increasing current density and/or salinity. Nevertheless, *A. salina* could not be completely inactivated at the experimental conditions in question; for example, inactivation did not exceed 90% and 60% at the highest current density in seawater and brackish water, respectively. However, it should be noted that the residence time in the electrolytic cell was extremely low (0.24 s corresponding to an electrolytic cell volume of 78.5 mL and a flowrate of 20 L/min). Fig. 6 also shows that *A. salina* does not suffer mechanical stress during single pass due to very low residence time.

The low mortality observed during single-pass operation is due to the lower concentrations of total residual chlorine produced in single pass experiments than in batch operation, as seen in Fig. 7. For instance, the concentration of chlorine does not exceed 15 mg/L working at 30 g/L sodium chloride and maximum current density; this value is 100 times lower than the maximum values obtained during the respective batch experiments. In turn, this low chlorine generation is related to the low residence time in the electrolytic cell.

*E. coli* inactivation occurs readily in single-pass experiments at low current densities and irrespective of the salinity. This implies that chlorine concentrations in the order of 10 mg/L are sufficient to destroy *E. coli*.

### 3.4. Energy consumption

Electrochemical oxidation is regarded as an energy-intensive process and, therefore, we attempted to estimate the energy needed for the complete inactivation of either test organism. Regarding *A. salina*, consumption took values up to  $8.6 \text{ kW h/m}^3$  in seawater and  $20.2 \text{ kW h/m}^3$  in brackish water and batch mode; the lower value was  $1 \text{ kW h/m}^3$  corresponding to operation for 45 min at 30 g/L NaCl, 6.7 V and  $255 \text{ A/m}^2$ . These energy consumption values are of the same order of magnitude with those reported

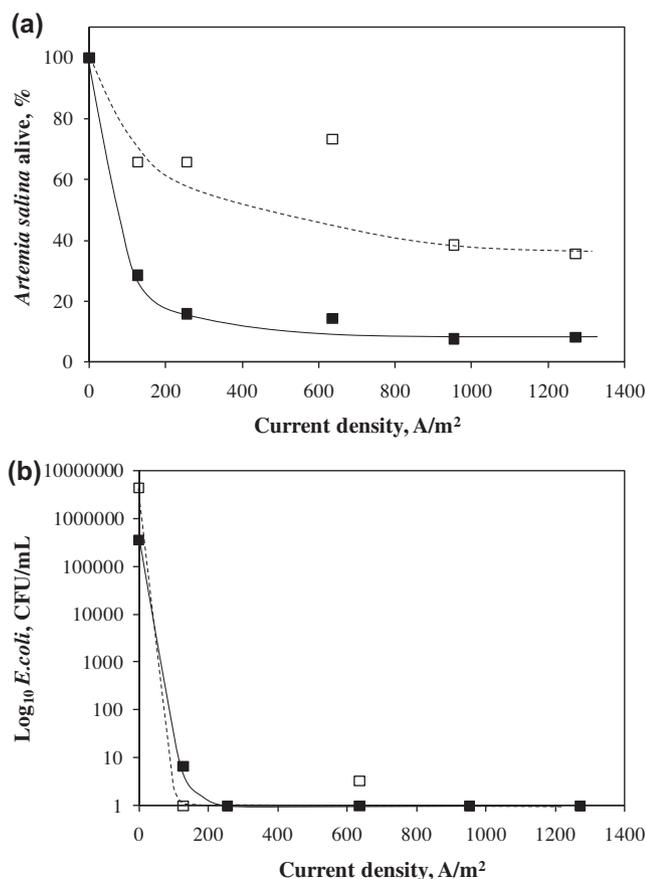


Fig. 6. Inactivation of (a) *A. salina* and (b) *E. coli* as a function of current density. Experimental conditions: single-pass mode; salinity: (■) 30 g/L NaCl, (□) 3 g/L NaCl.

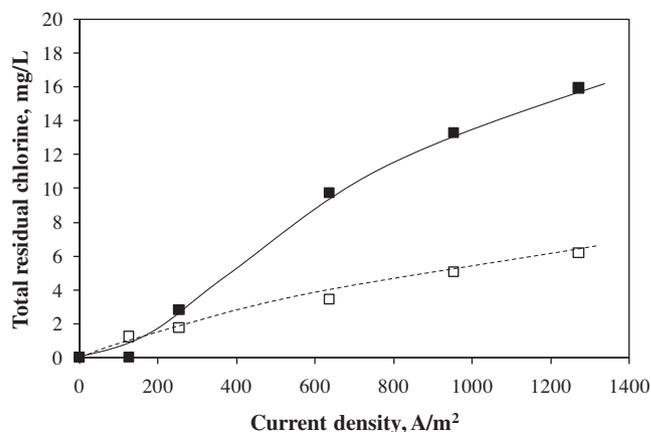


Fig. 7. Production of total residual chlorine as a function of current density. Experimental conditions: single-pass mode; salinity: (■) 30 g/L NaCl, (□) 3 g/L NaCl.

in the literature for the electrolytic disinfection of simulated ballast water using *A. salina* as indicator [17].

On the other hand, *E. coli* being more readily susceptible to electrochemical inactivation required up to 0.042 kW h/m<sup>3</sup> in seawater and 0.031 kW h/m<sup>3</sup> in brackish water and batch mode; these values are 2–3 orders of magnitude lower than those required for *A. salina*. Likewise, *E. coli* can be completely inactivated in single-pass mode. Here, energy consumption took values up to 0.088 kW h/m<sup>3</sup> in seawater and 0.229 kW h/m<sup>3</sup> in brackish water and single-pass mode. Thus, these energy consumption values are of the same order of magnitude with those reported in the literature for the inactivation of *E. coli* in Na<sub>2</sub>SO<sub>4</sub> electrolyte using BDD anode [59]. The lower value was 0.005 kW h/m<sup>3</sup> corresponding to single-pass operation at 30 g/L NaCl, 5.7 V and 127 A/m<sup>2</sup>.

#### 4. Conclusions

From the results obtained in this work the following conclusions can be drawn:

- Current density is an important parameter affecting the production of total residual chlorine in ballast or brackish water. Low current densities may avoid the production of harmful chlorine species.
- The degree of inactivation increases with increasing current density and salinity and also depends on the test organism in question. *A. salina* is less susceptible to electrochemical inactivation than *E. coli* requiring longer times and higher current densities for complete destruction. This is reflected to an energy consumption of 1 kW h/m<sup>3</sup>, which is 100 times greater than the respective value for *E. coli*.
- Operating the process in single-pass mode yielded lower efficiencies (this is more pronounced for *A. salina*) due to the very low residence time resulting in lower chlorine production rates compared to the respective batch operation. Further experimentation is required on electrolytic cells, which will allow longer residence times (larger volume of cell and/or lower flowrates).
- The main inactivation mechanisms involve (i) mechanical stress (only for *A. salina*), (ii) direct oxidation on the surface of conductive diamond anode, and (iii) chemical reactions with chlorine species and/or reactive oxygen species (hydroxyl radical, ozone or hydrogen peroxide).

#### Acknowledgements

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