



# An Insight in Electrocoagulation Process through Current Density Distribution (CDD)

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## Abstract

Electrocoagulation (EC) is a flourishing technique in the field of water treatment implementations. Numerous investigations have been performed to assess the performance of EC to eliminate different pollutants; however, the more basic electrochemical features of the technique are usually ignored. Scientists such as McBeath *et al.* [1] provided an understanding of the essential link of water flow, electrochemical metal dissolution, and current density distribution (CDD) via computational fluid dynamic (CFD) models, mathematical models, and *in situ* CDD determination tests. They established, in theory, that current distributed over the electrode was inversely proportional to the water flow rate. By means of the CFD models and current distribution determining technique, they noted that current density was distributed unequally and pursued the tendency anticipated via theory. Eliminating natural organic matter was decreased as much as 79% when the inter-electrode distance was diminished from 10 to 1 mm. As a perspective, more efforts are required to better understand the CDD at the anodes surface and electric charges transfer from electrodes to the bulk of the solution. Mechanisms related to interactions of anodic metallic cations and various pollutants should be more investigated.

## Subject Areas

Environmental Sciences

## Keywords

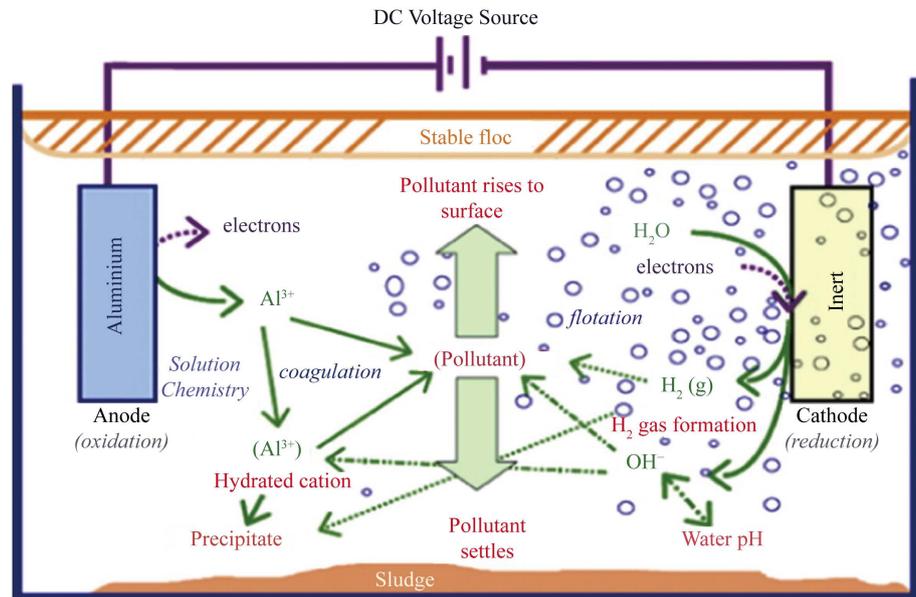
Electrocoagulation, Computational Fluid Dynamic (CFD), Current Density Distribution (CDD), Natural Organic Matter (NOM), Fluoride, Arsenic

## 1. Introduction

Numerous electrochemical techniques have acquired great interest for next combination into water treatment technologies [1] [2] [3] [4] [5]. Electrocoagulation (EC) has been found encouraging as a substitutional method to classical chemical coagulation for some potable water, municipal and industrial wastewater implementations [6] [7] [8]. EC avoids the chemical supply chain needed for traditional coagulation [9] [10] [11] [12], since coagulant chemicals are electrochemically formed *in situ* and on-demand [13]. Through applying current with an external power supply to an electrochemical setup, the two half-cell reactions of anodic metal dissolution and cathodic reduction of water make possible the global formation of metal hydroxide and metal oxide species: *i.e.*, the coagulant chemicals [14]. As current furnished to the cell augments, the rate of anodic metal dissolution and water reduction at the cathode surface augments, therefore leading to the elevated generation of coagulant [15] [16]. Until now, much of the EC study has focused on the process's capability to eliminate diverse pollutants, comprising both organic and inorganic products and microorganisms [17]-[23], while investigating the effect of various process variables such as metal loading (coagulant dose) [24], charge loading [25] [26], pH [27] [28] [29] [30], anode metal material (usually aluminum or iron) [31]-[39], reactor design [40], supporting electrolyte [41], initial contaminant concentrations [42] and scale-up [43] [44] [45] [46] [47].

Another factor that has been largely tested is the impact of the current density on the EC performance [48] [49]. Several scientists have followed the influence of current density on the reduction of different pollutants throughout the EC application (**Figure 1**). As an example, the impact of current density on the reduction of organic dyes present in textile wastewaters was observed to be very little; however, a proportional elevation of dye elimination and current density augmentation was yielded [50]. Additional scientists noted a huge augmentation in dye reduction with elevating current density [51]. The augmented removal of sulfide and chemical oxygen demand from spent caustic wastewater was as well shown with elevating current density [52]. In both investigations, current density was commanded via varying the applied current, as opposed to modifying the electrode surface area at constant current operation. Due to this, the consequences of augmented coagulant production and dosing on bigger pollutant elimination at more important current densities stay obscure [1].

The influence of current density on the EC technology has as well been largely studied for drinking water treatment applications [24] [26] [31]. Scientists [53] [54] [55] discovered that current density had few impact on the reduction of fluoride from groundwater. They imputed the augmented removal of fluoride at more important current densities to the elevated coagulant production at the higher metal loading related to greater current density. Current density was as well established to hugely touch the efficiency of EC to eliminate arsenic from groundwater; however, in this situation arsenic reduction capability diminished



**Figure 1.** Interactions taking place inside EC reactor [48] (although on this figure, there is an inert cathode, in discussion, the cathode has been often considered made of the same material as the anode to explain chemical dissolution [49]).

with augmenting current density [1]. Additional investigation has noted the adverse influence for arsenic reduction, but this was over more possibly because of the augmented metal loading that joined the augmentation in applied current [56]. Several batch-scale trials have illustrated that the reduction of natural organic matter (NOM) from synthetic and raw surface water as well augmented when current density was decreased [57]. When an identical method was scaled-up to a continuous flow mode, the impact was reduced and no obvious tendency was shown among current density and the elimination capability of NOM [1]. Current density has also been established to possess an influence on local pH near the electrode, as well as dissolved oxygen level, then touching the speciation of iron hydroxide coagulants which are produced throughout the EC method [58].

Even if the influence of current density has been broadly studied, in company with additional technique factors, there are no great attempts dedicated to comprehending the basic electrochemical and transport phenomena fundamentally regulating the distribution of current on the electrode surface. Especially, there has been a shortage of studies to sense the link among the variable movement of water across an EC electrode surface and its dependent impact on the current density distribution (CDD). In almost all previous EC investigations, it was supposed that current density stays constant over the entire electrode surface throughout the galvanostatic operation. Such as other electrochemical techniques, below most conditions, this is possibly not achieved because of several parameters comprising electrolyte (water) velocity fluctuations across the electrode surface. The decomposition of the sacrificial anode may take place because of three principal causes: electrochemical oxidation (debated here), chemical

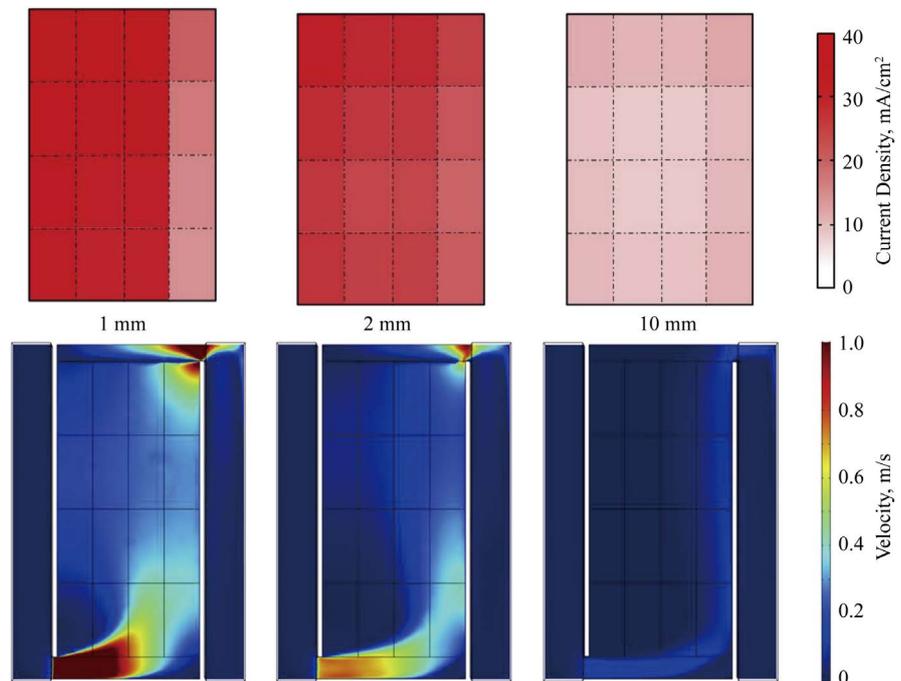
dissolution, and mechanical erosion. In the existence of an oxidation current, the proportions of the two other phenomena are minor if contrasted to electrochemical oxidation. As a result, the distribution of the anode decomposition is related to the inhomogeneity in the electric current distribution [1].

In many former investigations, current density has been modeled for an EC technique and was determined to be a fundamental parameter for assessing the electrode order and geometry for energy consumptions, since it was not uniformly expanded [59]. It has as well been before illustrated via modeling, that this irregular expansion of current and potential over an EC electrode may touch coagulant production, in the end influencing the EC efficacy [60]. Computational fluid dynamic (CFD) modeling has as well been employed for the divination of electrolyte flow changes inside an EC device, showing elevated changes of fluid velocity inside the setups, as a consequence of numerous parameters involving cell geometry and arrangement [49] [61]. Broadly, CFD modeling is a largely utilized tool in electrochemical engineering to comprehend electrolyte mass transport phenomena. Phenomenological studies of the EC method have explained the mixing [62] and technique [63] regulation procedures. Fresh numerical investigations on EC have been dedicated to the contribution of the setup arrangement in the electric field and mass transport [1]; however, the action of local reaction circumstances on the identical electrode plate has not been examined [64].

## **2. *In Situ* Evaluation of Current Density Distribution (CDD) and Fluid Modeling of an EC Method**

With a view to comprehend the fluctuation of the current distribution over an electrode surface, McBeath *et al.* [1] utilized an *in situ* manner to meter and chart the CDD. Further, water flow patterns into and out of the EC device got via CFD modeling, with a view to give penetration towards the fluid and current flow bond (Figure 2). Besides giving an essential comprehension of current and mass transport importance for enhanced and foreseeable EC applications, as well as furnishing a new method implementation for distinguishing current distribution in an EC setup, findings may conduct to the ameliorated CDD and so enhanced reactor design; a basic parameter for the design of an energy-efficient and thus more economical EC reactor and process [1].

McBeath *et al.* [1] focused on the key link of water flow, electrochemical metal dissolution, and CDD via CFD models, mathematical models, and *in situ* CDD identification tests. In theory, it was established that current distributed across the electrode was inversely proportional to the water flow rate. The turbulent flow into and out of the EC setup was simulated with changing inter-electrode distances and flow rates; however, the average velocity segments over the electrode surface was evaluated, corresponding to the identical segments utilized to experimentally assess the current distribution. By means of the CFD models and current distribution assessing manner, McBeath *et al.* [1] noted that current



**Figure 2.** Current density (partial electrode approach) and water velocity profiles (CFD models) for 1.35 L/min flow at 1, 2 and 10 mm gaps [1].

density was distributed unequally and pursued the tendency prevised by theory. Regions of lower current density were frequently joined by the higher-velocity flow. The more regular current was yielded with larger inter-electrode distances, because of the greater flow regularity. However, working with a 1 mm distance, the current and water velocity changed over the electrode by  $\Delta 27.6$  mA/cm<sup>2</sup> and  $\Delta 0.220$  m/s, and was decreased to  $\Delta 3.6$  mA/cm<sup>2</sup> and  $\Delta 0.062$  m/s at a 10 mm distance. Even if current regularity was augmented, the global current density diminished greatly because of the bigger ohmic resistance related to the greater distance. The elimination of NOM was decreased as much as 79% when the inter-electrode separation was decreased from 10 to 1 mm.

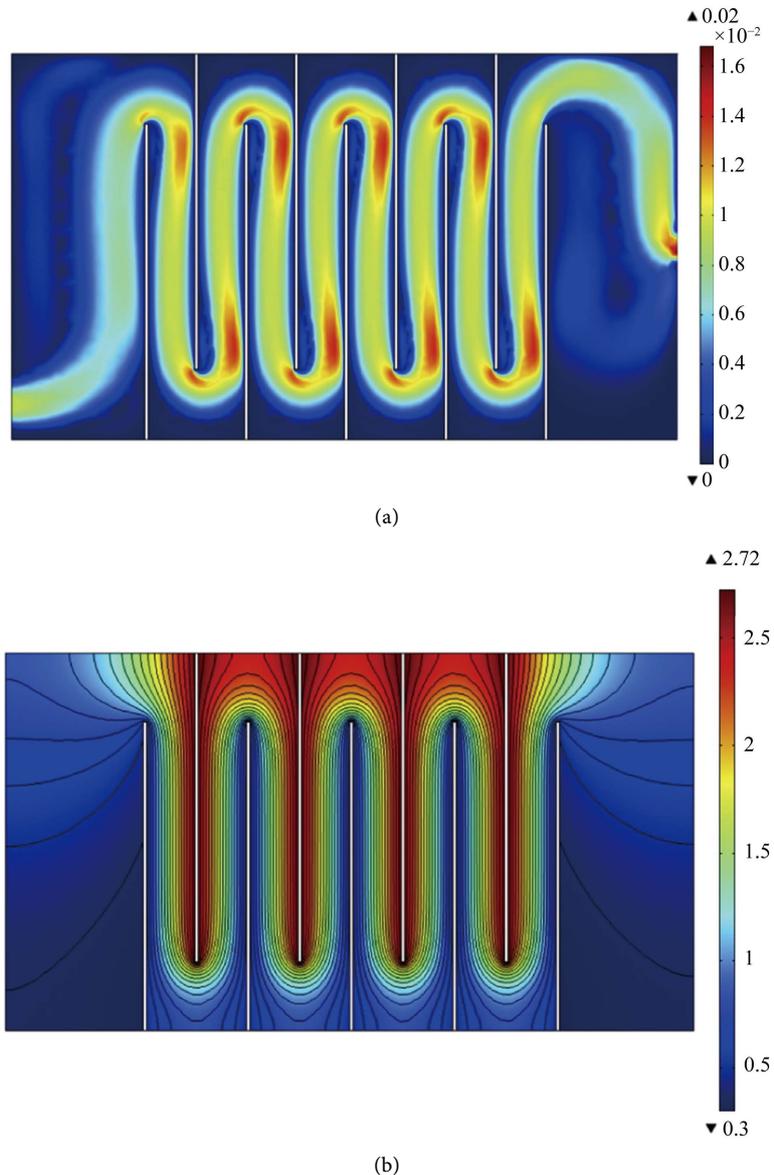
### 3. Reviewing EC Modeling Procedures

Hakizimana *et al.* [49] published a thorough discussion of EC development and design. They focused on the theoretical comprehension of pathways controlling contamination removal, modeling manners, CFD simulations (Figure 3), and techno-economic optimization.

Further, Hakizimana *et al.* [49] discussed the most important parameters that affect EC process efficiency (Figure 4).

### 4. Discussing EC for Arsenic Removal

Song *et al.* [65] presented the fresh development of arsenic elimination via EC method involving the impacts of main working factors, optimization of the EC efficiency, as well as the estimation of EC device arrangements. They contrasted



**Figure 3.** (a) Flow pattern (b) velocity magnitude and secondary potential distributions throughout an EC cell at a flow rate 0.5 L/min [49].

the efficiency of EC and other techniques and focused on future research needs for arsenic removal in the EC process. They concluded that EC appears as an environmentally friendly and performant technology for arsenic elimination. Nevertheless, it is affected by many restrictions like high energy consumption in large scales and difficulty of EC reactor design. More researches are needed to get the better of the disadvantages to expand the handy usage and pointedly examine the EC efficiency of arsenic elimination.

### 5. CFD Simulation of Biphasic Flow in EC Device

The mass transport efficiency of  $Al^{3+}$  ion is in charge of the formation of the coagulant within the EC device, and, therefore, removing pollutants is a function

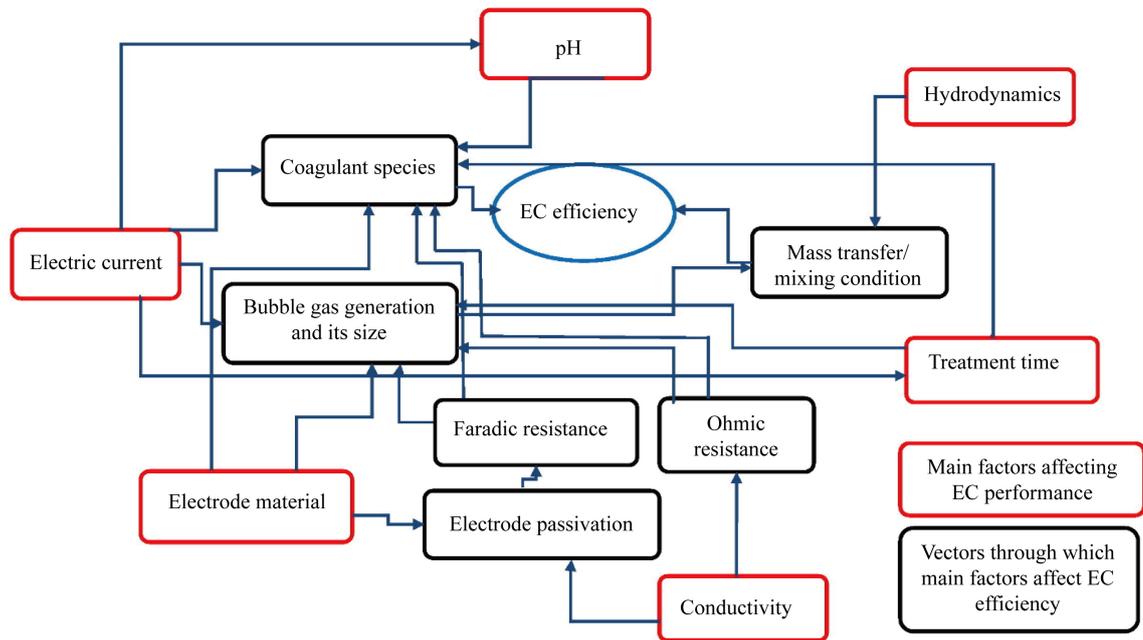
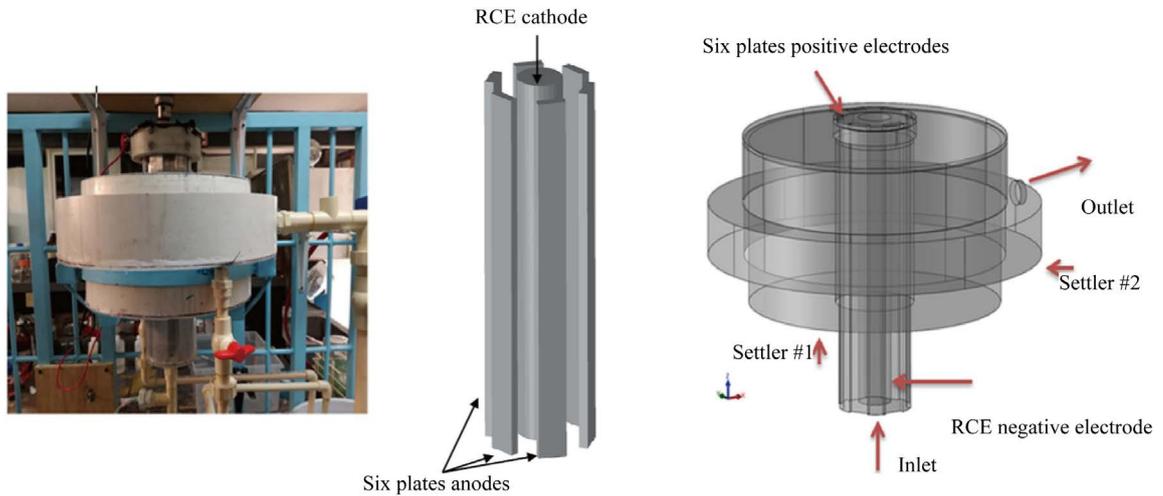


Figure 4. Principal parameters touching EC technology [49].

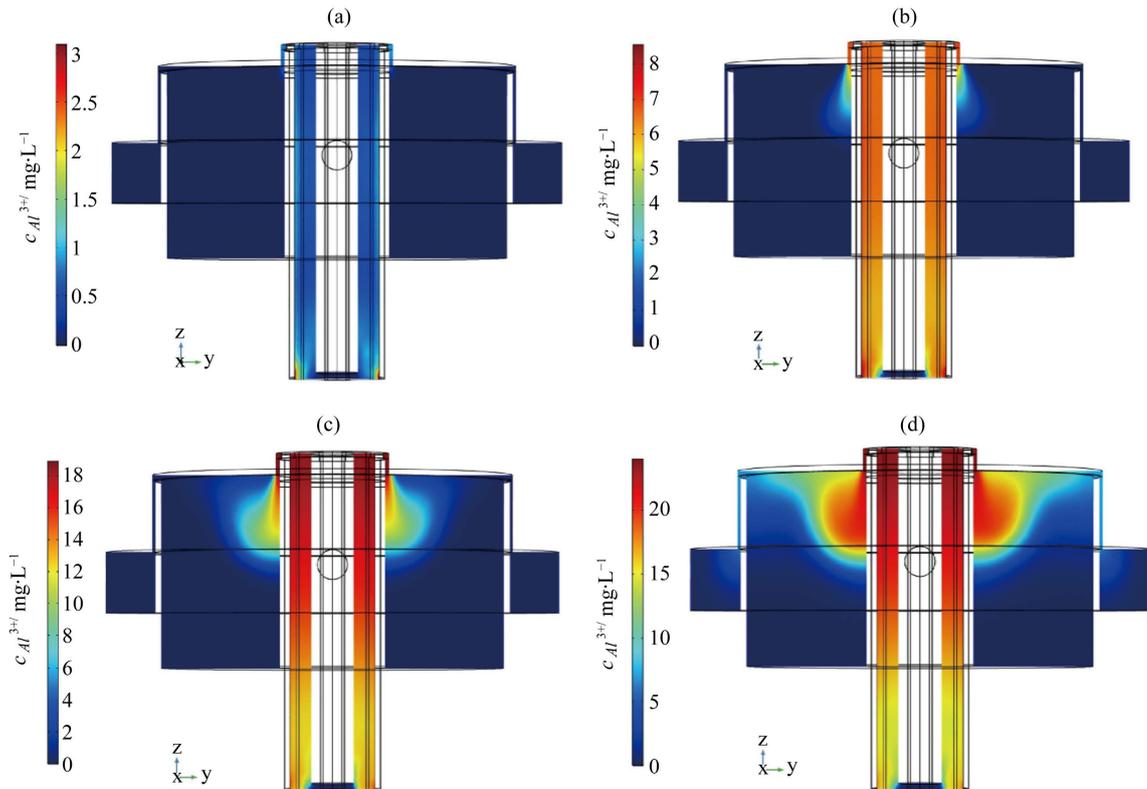
of it. In identical fashion, the hydrogen gas emanation in the counter-electrode touches the setup efficiency because of the resistivity produced in the solution and the biphasic fluid dynamics (Figure 5). The suggested model explains at once the secondary current distribution, the mass transport of aluminum and hydrogen, and the momentum transfer of a turbulent biphasic system in a continuous rotating cylinder electrode (RCE) reactor combined with two sedimentation tanks [66]. The theoretical analysis for this system showed well-mixed circumstances and a quasi-uniform current distribution in the RCE reactor thanks to the geometrical design and the low quantities of hydrogen gas formed at the different current values investigated (Figure 6). For the present, slow flow velocities and dead zones were noted within the sedimentation tanks. Plus, comparisons among experimental, and theoretical  $\text{Al}^{3+}$  concentrations under stationary regime are also presented, found a good correlation [66].

## 6. Eliminating Fluoride and Hydrated Silica by EC in a Flow Channel Reactor

Castañeda *et al.* [67] focused on the concomitant elimination of fluoride and hydrated silica from groundwater (4.08 mg/L fluoride, 90 mg/L hydrated silica, 50 mg/L sulfate, 0.23 mg/L phosphate, pH 7.38 and 450  $\mu\text{S}/\text{cm}$  conductivity) via EC, employing an up-flow EC setup, with a six-cell stack in a serpentine array, opened at the top of the cell to favor gas liberation (Figure 7). Aluminum plates were employed as sacrificial electrodes. They assessed the impact of current density ( $4 \leq j \leq 7 \text{ mA}/\text{cm}^2$ ) and mean linear flow rate ( $1.2 \leq u \leq 4.8 \text{ cm}/\text{s}$ ), implemented to the EC reactor, on the elimination of fluoride and hydrated silica. The elimination of fluoride satisfied the WHO guideline ( $<1.5 \text{ mg}/\text{L}$ ); however, the

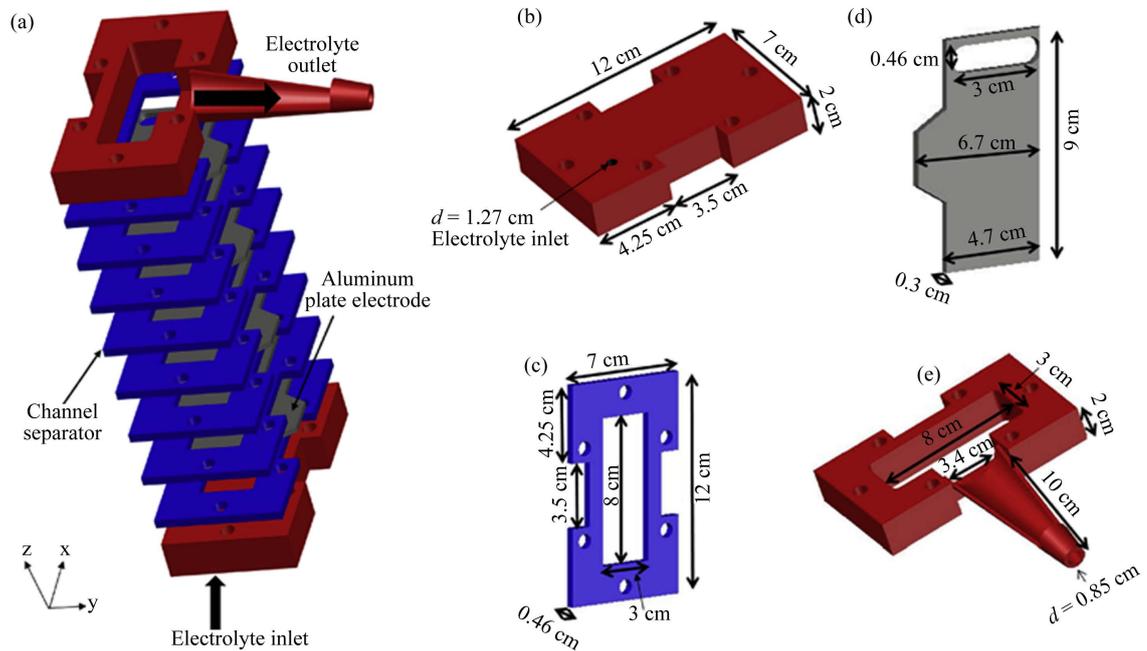


**Figure 5.** (a) EC lab configuration system, (b) electrodes arrangement inside the reactor and (c) 3D computational domain of the system [66].



**Figure 6.** Aluminum ion concentrations in the middle of the domain at  $z$ - $y$  plane at different times of (a) 5 s, (b) 50 s, (c) 200 s and (d) 500 s for  $j_{ave} = 32 \text{ A/m}^2$  at 100 rpm with an input flow of 0.4 L/min [66].

hydrated silica was reduced at  $7 \text{ mA/cm}^2$  and  $1.2 \text{ cm/s}$ , with energy consumption of  $2.48 \text{ kWh/m}^3$  and an overall operational cost of  $0.441 \text{ USD/m}^3$ . Spectroscopic analyses of the flocs by XRD, XRF-EDS, SEM-EDS, and FTIR proved that hydrated silica reacted with the coagulant forming aluminosilicates, and fluoride replaced a hydroxide from aluminum aggregates, while sulfates and phosphates



**Figure 7.** (a) Sketch of the reactor, (b) bottom plate, (c) channel separator, (d) aluminum electrode, and (e) electrolyte collector at the exit [67].

were removed by adsorption process onto the flocs. The well-engineered EC device allowed the simultaneous elimination of fluoride and hydrated silica.

## 7. Conclusions

From this work, the following conclusions can be drawn:

1) An *in situ* manner for the determination of CDD for an EC method was used in parallel with mathematical and CFD modeling for iron dissolution and water velocity variation analysis, respectively [1]. The current density information coincided well with the models; however, regions of elevated current density were inversely matched to regions of low-velocity fluid flow and thus, augmented  $\text{Fe}^{2+}$  dissolution. As the inter-electrode separation augmented, water velocity fluctuations greatly diminished, conducting to importantly elevated current density regularity. From the current distribution information, a more precise view of iron dissolution efficiency is reached, whereby local  $\text{Fe}^{2+}$  dissolution rates could be evaluated. Throughout 1 mm inter-electrode distance trials, current and water velocity fluctuations were  $\Delta 27.6 \text{ mA/cm}^2$  and  $\Delta 0.220 \text{ m/s}$ , respectively. If the inter-electrode distance augmented to 10 mm, this variance diminished to  $\Delta 3.6 \text{ mA/cm}^2$  and  $\Delta 0.062 \text{ m/s}$ . This augmented current uniformity did have effects on the global achievable current density; nevertheless, because of the importantly elevated ohmic resistance related to the broader distance. In addition to reduced current density, the related elevation in electrical potential hugely elevates running energy needs. Moreover, NOM elimination suffered at bigger inter-electrode separations, whereby dissolved organic carbon removal was observed to increase from 16, 29 and 46%, during 10, 2 and 1 mm opera-

tions.

2) Regardless of EC being a robust and versatile technology, it stays harder to simulate than other water treatment techniques, like biological methods. Two main investigation fields appear fundamental for a more successful exploration of the EC process. The first one implicates the implementation of CFD to EC method that needs to be expanded and should involve mixing phenomena, and the second one focuses on the separation stage of EC, via flotation or settling, in the existence of an electric that both require experimental and theoretical analysis [49].

3) Recently, there is huge progress in terms of investigating the EC process especially in the influence of CDD. Nevertheless, more efforts are required to better understand the CDD at the electrodes surface and electric charges transfer from electrodes to the bulk of the solution. Mechanisms related to interactions of anodic metallic cations and various pollutants should be more investigated.

### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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