



## Research article

# Iron removal, energy consumption and operating cost of electrocoagulation of drinking water using a new flow column reactor



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## ABSTRACT

The goal of this project was to remove iron from drinking water using a new electrocoagulation (EC) cell. In this research, a flow column has been employed in the designing of a new electrocoagulation reactor (FCER) to achieve the planned target. Where, the water being treated flows through the perforated disc electrodes, thereby effectively mixing and aerating the water being treated. As a result, the stirring and aerating devices that until now have been widely used in the electrocoagulation reactors are unnecessary.

The obtained results indicated that FCER reduced the iron concentration from 20 to 0.3 mg/L within 20 min of electrolysis at initial pH of 6, inter-electrode distance (ID) of 5 mm, current density (CD) of 1.5 mA/cm<sup>2</sup>, and minimum operating cost of 0.22 US \$/m<sup>3</sup>. Additionally, it was found that FCER produces H<sub>2</sub> gas enough to generate energy of 10.14 kW/m<sup>3</sup>.

Statistically, it was found that the relationship between iron removal and operating parameters could be modelled with R<sup>2</sup> of 0.86, and the influence of operating parameters on iron removal followed the order: C<sub>0</sub> > t > CD > pH. Finally, the SEM (scanning electron microscopy) images showed a large number of irregularities on the surface of anode due to the generation of aluminium hydroxides.

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## 1. Introduction

Iron is one of the most common elements in nature as it represents about 5% of the earth's crust (Ityel, 2011), and it can be found in fresh waters at a concentration of 0.5–50 mg/L (WHO, 2004). This element naturally exists in water in different states: soluble state (as ferrous Fe<sup>2+</sup>), insoluble state (ferric hydroxide Fe<sup>3+</sup>), bacterial state, and organic state (Chaturvedi and Dave, 2012). In addition to the natural occurrence of iron, many industries, such as mining and steel industries, contribute to the occurrence of iron in water (Ghosh et al., 2008a).

Although iron has been classified as a secondary contaminant as it is not harmful for human beings, it causes aesthetic problems such as taste issues, turbidity, and discolouration (Phadke, 2014). Moreover, presence of iron motivates the bacterial growth (iron bacteria such as *Gallionella*, and *Leptothrix*), which block the

plumbing in consequence (Ityel, 2011; Chaturvedi and Dave, 2012). However, iron represents an essential element for human health, where the daily intake of iron is recommended to be between 10 and 50 mg depending on the person's gender, age, physiological status, and the bioavailability of iron (WHO, 2004). Based on these considerations, the World Health Organization (WHO) limits the iron concentration in drinking water to 0.3 mg/L (WHO, 2004).

Indeed, a wide spectrum of treatment methods have been practised to remove iron from water such as oxidation by aeration, chemical oxidation, biological removal, ion exchange, adsorption, membrane filtration, and electrocoagulation (Ghosh et al., 2008a; Ityel, 2011; Chaturvedi and Dave, 2012; Phadke, 2014).

In comparison with other methods, the EC method bears many attractive advantages such as it is simple to install and operate, requires no chemical handling, and there is the possibility of complete automation and integrating with other methods. It produces fewer total dissolved solids, and it has a large treatment capacity and a relatively shorter treatment time (Ghosh et al., 2013; Khandegar and Saroha, 2013; Kamaraj and Vasudevan, 2015; Aghdam et al., 2015). Furthermore, as advancements in the

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production of alternative clean energy resources are made, use of the EC method will become possible even in rural areas (Chaturvedi and Dave, 2012), where sufficient energy can be driven from an attached solar panel (Deokate, 2015; García-García et al., 2015).

However, the EC method still has a clear deficiency in the variety of reactor design (Un et al., 2013), as most of the electrocoagulation reactors still rely on parallel arrangement of simple plate electrodes inside a container. In addition, the availability of models for the EC process is also limited, which represents a limitation in the understanding of this treatment method (Kuokkanen, 2016).

## 2. Aims and objectives

The current study has been devoted to fill a part of the gaps in the literature. The objectives of this study are:

- Suggestion of a new configuration for an electrocoagulation reactor (FCER) which employs a perforated plate flow column (which are widely used in chemical industries).
- Investigate the ability of FCER to remove pollutants from drinking water (iron as a case study). The influence of key operating parameters, such as electrolysis time (t) (0–45 min), initial pH value (4–8), current density (CD) (1, 1.5, and 2 mA/cm<sup>2</sup>), inter-electrode distance (ID) (5–20 mm), initial iron concentration (C<sub>0</sub>) (20–60 mg/L), and water temperature (T) (10–30 °C), will be taking into accounts.
- Development of an empirical model to reproduce the performance of FCER in terms of iron removal.
- Carry out a preliminary economic study to estimate the operating cost of iron removal from drinking water by FCER.
- Estimate the produced amount of hydrogen gas (H<sub>2</sub>), during iron removal, and the yieldable energy from this gas.
- Investigate of the influence of the EC process on morphology of the surface of the aluminium anodes using the SEM (scanning electron microscopy) technology.

## 3. Brief description of reaction mechanism

The concept of the electrocoagulation method is the in-situ generation of the coagulants as the sacrificial metallic anode dissolves due to the applied current, while the cathode generates hydrogen gas that floats the pollutants (Essadki et al., 2009). The electrode material is selected depending on many parameters such as cost, oxidation potential, and targeted pollutant. Although different materials such as steel (Genc and Bakirci, 2015), graphite (Gao et al., 2013), zinc (Vasudevan et al., 2012b), and iron (Ye, 2016), have been used as electrodes in the EC reactors, it has been reported that iron and aluminium are the most effective and successful electrode materials (Chaturvedi and Dave, 2012).

When aluminium (Al) is used as electrodes, the anode produces the Al<sup>3+</sup> ions; these aluminium cations instantly undergo more reactions to form different types of monomeric materials such as Al(OH)<sup>+</sup> and polymeric species such as Al<sub>13</sub>O<sub>4</sub>(OH)<sub>24</sub><sup>7+</sup>, which immediately coagulate to form flocs (Ghosh et al., 2008a; Essadki et al., 2009). These reactions can be summarised by the following equations (Ghosh et al., 2008b; Chaturvedi, 2013):

Anode:



Cathode:



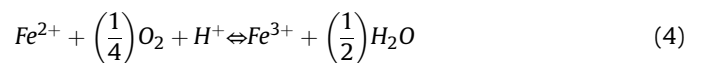
Then, Al<sup>3+</sup> and OH<sup>-</sup> ions react to generate Al(OH)<sub>3</sub>:



Reaction between Al (III) and hydroxide ions results in formation of different aluminium monomeric and polymeric species, such as Al(OH)<sup>+</sup>, Al<sub>2</sub>(OH)<sub>2</sub><sup>4+</sup>, Al<sub>7</sub>(OH)<sub>17</sub><sup>4+</sup>, and Al<sub>13</sub>O<sub>4</sub>(OH)<sub>24</sub><sup>7+</sup>, which transform, according to complex precipitation kinetics, into Al(OH)<sub>3(S)</sub>, (Ghosh et al., 2008a).

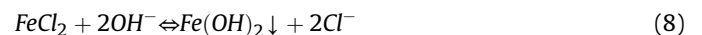
It is believed that aluminium hydroxide flocs, Al(OH)<sub>3</sub>, are responsible for the adsorption and precipitation of the dissolved pollutants, while the small hydrogen bubbles that blow around the cathode are responsible for the floatation of pollutants (Adhoum et al., 2004; Ghosh et al., 2008a). The dominant path of pollutants' removal, sedimentation or floatation, during the last stage is determined by the applied current, where the majority of the dissolved pollutants are removed by floatation at high currents, while sedimentation is the predominant path at low currents (Maximova and Dahl, 2006; Chaturvedi and Dave, 2012).

Generally, iron exists in water in the ferrous form which, in the presence of oxygen and pH below 6.5, immediately undergoes oxidation reactions as follows (Chaturvedi and Dave, 2012):



Additionally, iron ions react with hydroxide ions to form Fe(OH)<sub>3</sub> according to the following reactions (Ghosh et al., 2008a):

Bulk



Anode



## 4. Materials and methods

### 4.1. Experimental set up

A new cylindrical electrocoagulation reactor (FCER) has been designed basing on the innovative use of a perforated-plate flow column. FCER consists of a flow column containing 6 aluminium perforated discoid plates, 5.2 cm in radius and 1 mm in thickness of 99.5% purity provided by IJUM laboratories, Fig. 1. These perforated electrodes were stacked vertically within the reaction vessel with the plane of each plate parallel and perpendicular to the direction of flow. Each electrode had the holes offset from the one above it to ensure that the water will flow in a convoluted path in order to increase mixing efficiency. These plates are held in the required position, inside a hollow Perspex cylinder 25 cm in height and 10.5 cm in diameter, using PVC rods and spacers. The PVC rods are

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