

Removal of Fe(II) from tap water by electrocoagulation technique

D. Ghosh, H. Solanki, M.K. Purkait*

Department of Chemical Engineering, Indian Institute of Technology, Guwahati 781039, India

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Abstract

Electrocoagulation (EC) is a promising electrochemical technique for water treatment. In this work electrocoagulation (with aluminum as electrodes) was studied for iron Fe(II) removal from aqueous medium. Different concentration of Fe(II) solution in tap water was considered for the experiment. During EC process, various amorphous aluminum hydroxides complexes with high sorption capacity were formed. The removal of Fe(II) was consisted of two principal steps; (a) oxidation of Fe(II) to Fe(III) and (b) subsequent removal of Fe(III) by the freshly formed aluminum hydroxides complexes by adsorption/surface complexation followed by precipitation. Experiments were carried out with different current densities ranging from 0.01 to 0.04 A/m². It was observed that the removal of Fe(II) increases with current densities. Inter electrode distance was varied from 0.005 to 0.02 m and was found that least inter electrode distance is suitable in order to achieve higher Fe(II) removal. Other parameters such as conductivity, pH and salt concentration were kept constant as per tap water quality. Satisfactory iron removal of around 99.2% was obtained at the end of 35 min of operation from the initial concentration of 25 mg/L Fe(II). Iron concentration in the solution was determined using Atomic absorption spectrophotometer. By products obtained from the electrocoagulation bath were analyzed by SEM image and corresponding elemental analysis (EDAX). Cost estimation for the electrocoagulation was adopted and explained well. Up to 15 mg/L of initial Fe(II) concentration, the optimum total cost was 6.05 US\$/m³. The EC process for removing Fe(II) from tap water is expected to be adaptable for household use.
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Keywords: Electrocoagulation; Iron removal; Inter electrode distance; Aluminum electrode; SEM

1. Introduction

Iron is one of the most abundant metals of the Earth's crust. It occurs naturally in water in soluble form as the ferrous iron (bivalent iron in dissolved form Fe(II) or Fe(OH)⁺) or complexed form like the ferric iron (trivalent iron: Fe(III) met in the precipitate Fe(OH)₃) or bacterial form, too. The occurrence of iron in water can also have an industrial origin; mining, iron and steel industry, metals corrosion, etc. There are many industrial situations where iron or impurities must be removed from solutions. This is usually induced by the precipitation of iron oxide/oxyhydroxides and often involves the co-removal of inorganic and organic impurities because of the strong adsorptive capacity of iron oxyhydroxides. Such processes are commercially significant. Iron precipitates are notoriously gelatinous, metastable, and difficult to settle and filter. This can make the process bottleneck [1]. World Health Organization (WHO) has

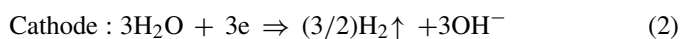
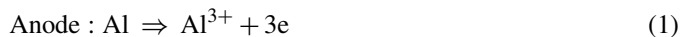
set a guideline value of 0.3 mg/L, of iron in drinking water [2]. There are several methods for removal of iron from drinking water like ion exchange and water softening [3], activated carbon and other filtration materials [4], supercritical fluid extraction [5], bioremediation [6] and limestone treatment [7], oxidation by aeration, chlorination, ozonation followed by filtration [8], by ash [9], by aerated granular filter [10] and by adsorption [11]. Aeration and separation is the most common method for removal of iron from groundwater in public water supply systems, which is however not so popular at domestic level. Apart from impressive amount of scientific research on the treatment of iron by different processes, a detail investigation on the economic analysis of each process is scant. On the other hand, electrocoagulation has been found a promising technique in treating urban waste water [12] treatment of restaurant waste water [13], treatment of potable water [14], potato chips waste water [15], arsenic removal [16], fluorine removal from underground and waste waters [17], treatment of poultry slaughterhouse waste water [18], treatment of copper, lead and cadmium in natural water and simulated waste waters [19], treatment of laundry waste water [20], boron removal [21], olive mill waste waters [22], alcohol

* Corresponding author. Tel.: +91 361 2582262; fax: +91 361 2582291.
E-mail address: mihir@iitg.ernet.in (M.K. Purkait).

distillery waste water [23]. This is clearly a motivation for experimental investigation of iron removal from water/waste water by EC process. Compared to other processes, EC process bears merits such as ambient operability, large volume handling ability, non-toxicity because of non-consumption of chemicals and no eventual secondary pollutants to discard at acceptable physical and chemical condition. It also requires comparatively less treatment time and very effective removal efficiency with simplified operation. In this work, electrocoagulation was tested as an alternative method for treating the Fe(II) ranging concentration up to 25 mg/L. Effects of different parameters such as applied current density, initial concentration of Fe(II) and inter electrode distance over the extent of Fe(II) removal were studied in detail. Performance of the EC process and the operating cost for the removal of Fe(II) were calculated and presented well. In the calculation of the operating cost, only material and energy costs were considered, other cost items such as labor, maintenance, solid/liquid separation costs were not taken into account. The simplified cost equation was used to evaluate the operating cost. This fundamental study will be helpful for further application in designing an electrocoagulation unit for the treatment of water containing heavy metal ions beyond their permissible limits.

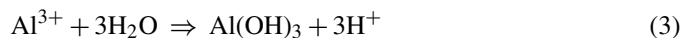
2. Iron removal mechanism by electrocoagulation

Electrocoagulation or enhanced coagulation accompanied by electro floatation is an emerging electrochemical water and waste water treatment technology. In electrocoagulation process an applied potential generates the coagulant species *in situ* as the sacrificial metal anode (aluminum or ferric) dissolves, while hydrogen is simultaneously evolved at the cathode. Coagulant species is believed to be the responsible in aggregation as well as precipitation of suspended particles and simultaneously adsorption of dissolved contaminants. Tiny bubbles of hydrogen and oxygen, which are formed during electrolysis of water, collide with air bubbles and float the pollutant particles. Choice of electrode material depends on various criteria such as; low cost, low oxidation potential, inertness towards the system under consideration, etc. Different electrodes have been reported in the literature like carbon [24], mild steel [25], graphite, titanium [26], iron [27] and aluminum [28]. But iron and aluminum have been reported to be very effective and successful in pollutant removal at favorable operating conditions. The electrode reactions are summarized as follows:

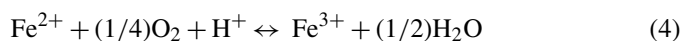


During the final stages, coagulated aggregates interact with bubbles and float to the surface or settle to the bottom of the EC bath. Flotation is the dominant pollutant removal path for high operating currents, while sedimentation is dominant at lower currents. The shift is due to the bubble number concentration at low currents is insufficient to remove the aggregated material, allowing sedimentation to dominate [29]. Al(III) and OH⁻ ions generated by electrode reactions (1) and (2) react to form various monomeric species such as Al(OH)⁺²,

Al(OH)⁺², Al₂(OH)₂⁴⁺, Al(OH)₄⁻ and polymeric species such as Al₆(OH)₁₅³⁺, Al₇(OH)₁₇⁴⁺, Al₈(OH)₂₀⁴⁺, Al₁₃O₄(OH)₂₄⁷⁺, Al₁₃(OH)₃₄⁵⁺, which transform finally into Al(OH)_{3(S)} according to complex precipitation kinetics

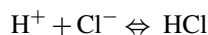
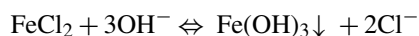
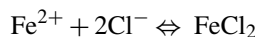


Freshly formed amorphous Al(OH)_{3(S)} occurs as “sweep flocks” having large surface areas. These flocks are active in rapid adsorption of soluble organic compounds and trapping of colloidal particles and are easily separated from aqueous medium by sedimentation or H₂ flotation. These flocks polymerizes as $n\text{Al(OH)}_3 \Rightarrow \text{Al}_n(\text{OH})_{3n}$. Iron exists in solution in the ferrous state, it can only remain in solution in the absence of oxygen, and generally when the pH is below 6.5, ferrous ion is oxidized in air according to the following reaction:



Presence of chloride ion may undergo the following reactions

Bulk



Anode



The state of iron in water depends above all on the pH and the redox potential. By increasing the pH, dissolved iron, i.e. Fe(II) or Fe(III) hydrolyzes to form precipitates [30]. The ferrous ion hydrolyzes to produce the array of mononuclear species FeOH⁺ to Fe(OH)₄⁻² between pH 7 and 14. The ferric ion, Fe(III) hydrolyzes much more readily than the ferrous ion, Fe(II). Baes and Mesmer [31] presented diagrams, which show that iron at the range of pH 7–8 is a precipitate. The rates of ferrous ion oxidation by air increase with pH and about 90% conversion may be achieved in a few minutes at a pH of 7 [32–35]. Precipitation depends on the size and shape of the particle which is formed after coagulation followed by the adsorption on the active surfaces of the coagulants formed during the electrocoagulation process. At the higher pH, removal of iron is achieved mainly by adsorption of iron hydroxide in the form of brown flocks due to the sufficient availability of coagulants in the medium. Therefore, the flocks formed were large in size and settled down as a precipitate at the bottom of the container shortly after the completion of the experiment. Considering all the factors as above aluminum is selected as electrode material for the present

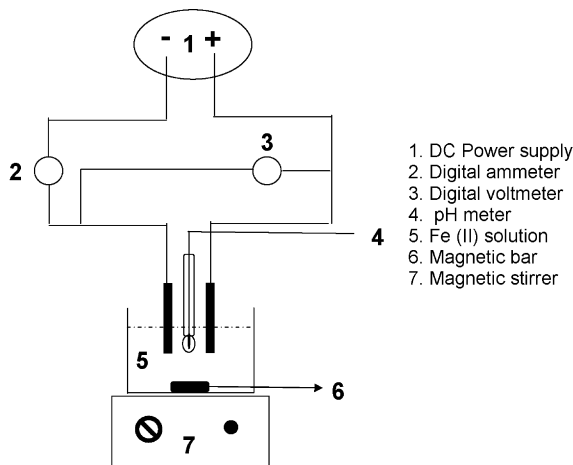


Fig. 1. Schematic diagram of electrochemical cell for the removal of Fe(II).

investigation. In this work, electrocoagulation was tested as an alternative method for treating the Fe(II) ranging concentration up to 25 mg/L. Effects of different parameters such as applied current density, initial concentration of Fe(II) and inter electrode distance over the extent of Fe(II) removal were studied in detail. Performance of the EC process and the operating cost for the removal of Fe(II) were calculated and presented well.

3. Materials and methods

3.1. Experimental setup and procedure

Perspex made tank having dimensions of $0.18\text{ m} \times 0.18\text{ m} \times 0.18\text{ m}$ with a working volume of about 3 L was used to conduct the experiments. Aluminum sheets of $0.15\text{ m} \times 0.1\text{ m} \times 0.002\text{ m}$ were used as electrodes for electrocoagulation. The gap between the anode and cathode was varied from 0.005 to 0.02 m. The entire electrode assembly was fitted on non-conducting wedges and hanged from the top of the electrocoagulation tank. The effective surface area of each electrode was $40\text{ m} \times 10^{-4}\text{ m}$. The assembly was connected to D.C. power source (Textronics 36 D, Agarwal Electronics, Mumbai, India) to constitute an electrochemical cell with galvanostatic mode for constant current supply. Schematic diagram of electrochemical cell is shown in Fig. 1. The electrode assembly was placed in the cell and the electrodes were connected to the respective anode and cathode leads to the D.C. rectifier and energized for a required duration at a fixed current. All the runs were performed at constant temperature of $25\text{ }^\circ\text{C}$ and stirring speed 200 rpm. In each run, 1 L Fe(II) solution was placed into the electrolytic cell. The current density was adjusted to a desired value and the operation was started. After the experiment, the power was switched off and the electrodes were dismantled. The treated Fe(II) sample collected at different time interval was filtered before analysis. Before each run, the electrodes were washed with acetone to remove surface grease, and the impurities on the aluminum electrode surfaces were removed by dipping for 5 min in acetone solution. After each experiment the used anode and cathode plate was interchanged for effective electrode utilization. The param-

eters chosen in the present experiments were current density (ranging $0.01\text{--}0.04\text{ A/m}^2$), initial Fe(II) concentration (ranging $5\text{--}25\text{ mg/L}$) and inter electrode distance (ranging $0.005\text{--}0.02\text{ m}$). Experiments were carried out up to 35 min.

3.2. Methods

$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ was used in this study for preparing Fe(II) solution. It was supplied by Aldrich Chemical Company, USA. A measured quantity (1 L) of freshly prepared solution of Fe(II) using tap water was taken into the electrochemical cell. Conductivity and pH of tap water is 12 S/m and 7.5 , respectively. Fe(II) concentration was determined using Atomic absorption spectrophotometer (Model No. 240 FF, Varian, Netherlands). Microscopic observation of by products from the electrocoagulation unit was carried out by a scanning electron microscope (SEM, Make: LEO 1430VP, UK), which directly provided the visual information of morphology of electrocoagulation by product. Energy dispersive X-ray analysis (EDAX) was an integrated feature of a scanning electron microscope (SEM). This analysis was performed to identify the elemental composition of the by products obtained from electrochemical unit. By products has been collected after the filtration of the solution at the end of the electrocoagulation process using a filter paper of grade HM2 and size 11 cm (Make: INDIACHEM, India).

4. Results and discussions

4.1. Effect of current density

In any electrocoagulation process current density (A/m^2) and time of electrolysis are important operational parameters setting the ultimate removal and defining the electrical energy and power consumption so eventually the ultimate operating cost for the process. Some investigators have reported that in electrocoagulation, current density can influence the treatment efficiency [12], while others have reported that current density has no significant role on pollutant removal [13]. Therefore, it remains unclear that whether the current density affects the treatment efficiency or not. Choice of electrode material is also vital affecting the cell voltage (different oxidation potential for different electrode materials) and the separation achieved. In our work aluminum was selected as the electrode material because of its cheapness, ready availability, non-harmfulness and it requires comparatively less oxidation potential. Fig. 2 shows the removal of Fe(II) from tap water as a function of time for four different current densities. It may be seen from the figure that a steep increase in Fe(II) removal just at the beginning of the process for all the current occurred and becomes gradual there after. It may also be found that lower current density has lesser effect on the final total Fe(II) removal, but removal is rapid with high current density. From the figure it may be observed that the removal of iron is 55% at the end of 5 min and 67% at the end of 35 min of operation at current density of 0.01 A/m^2 for the initial iron concentration of 25 mg/L . Almost complete removal is observed at the end of 35 min of operation when current density increases to 0.04 A/m^2 . In electrocoagulation, initially

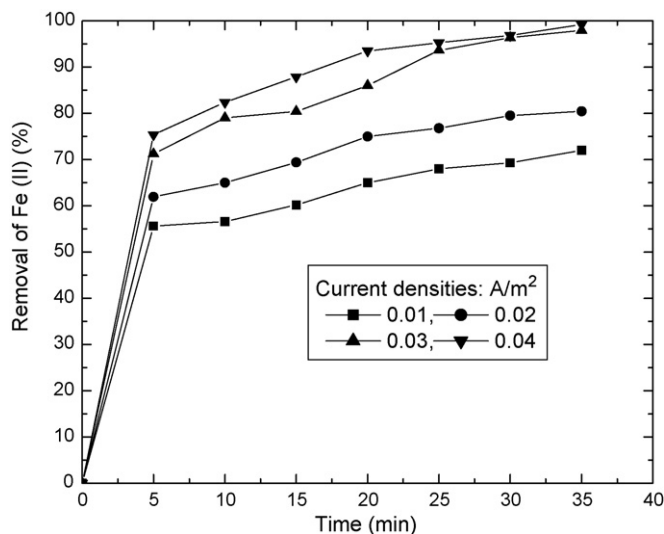


Fig. 2. Variation of percentage removal of Fe(II) with time at different current densities. Inter electrode distance: 0.005 m, initial Fe(II) concentration: 25 mg/L, pH: 7.5, conductivity: 12 S/m.

the aluminum cations contribute to charge neutralization of the pollutant particles as the isoelectric point is attained. Here a sorption coagulation mechanism occurs resulting in the formation of loose aggregates. As time progresses, further aluminum cation addition results in amorphous aluminum hydroxide precipitation that promotes pollutant aggregation via a sweep coagulation followed by precipitation mechanism. During the final stages, coagulated aggregates interact with bubbles and float to the surface or settle to the bottom of the reactor. As shown in the figure there is sharp decrease in concentration due to fresh electrodes surfaces initially but the concentration reduction is achieved further as the time progresses with more generation of aluminum hydroxides for coagulation of the particles.

4.2. Effect of pH

The solution pH plays an important role in the autocatalytic disappearance of aqueous Fe(II) with the motivation of iron removal in slightly basic (pH >7) range, electrocoagulation is believed to be a favorable technology due to the formation of more OH⁻ ions in the electrolysis of water [36]. In electrocoagulation where Al electrode is used, it has been observed that at slightly basic ambience Al(OH)₃ precipitation occurs and the sweep-flock mechanism dominates [37]. Therefore, in the present investigation, initial pH of the solution has been kept at 7.5 in association with the application of different current densities (0.01, 0.02, 0.03 and 0.04 A/m²) for an initial iron concentration of 25 mg/L. Duration of the process was 40 min and after every 5 min pH of the solution has been checked using a digital pH meter (CONSORT, C863, Make: Belgium). At the end of the process pH has been reached to a value of 7.70, 7.77, 7.82 and 7.88, respectively for different current densities. A reddish-brown sludge due to the formation of iron hydroxide (as discussed in Section 2) was observed at the bottom of the cell shortly after the completion of the experiment. It might be the generation of more aluminum hydroxides which in turn

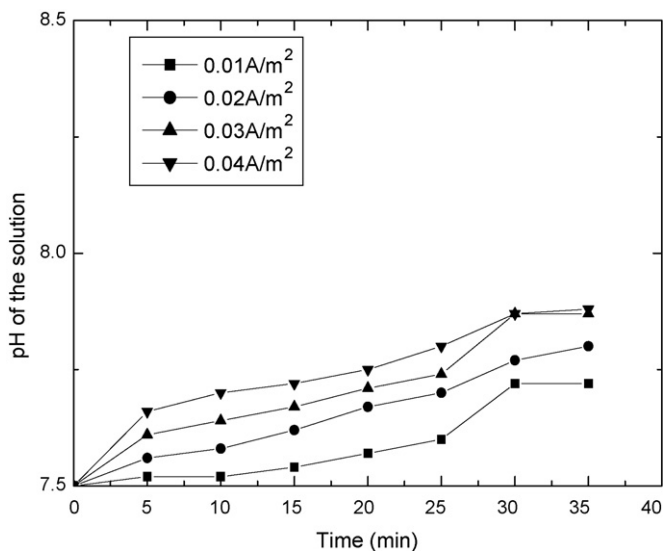


Fig. 3. Variation of pH of Fe(II) with time at different current densities. Inter electrode distance: 0.005 m, initial Fe(II) concentration: 25 mg/L, initial pH: 7.5, conductivity: 12 S/m.

adsorbed iron hydroxide from the solution and got precipitated at the bottom. Hence it confirms the above-mentioned phenomenon (sweep-flock mechanism). From Fig. 3 it was seen that with the variation of current density pH increases slowly and reaches to its maximum value 7.88 at the end of 35 min with an applied current density of 0.04 A/m². It seems that the pH of the solution changes a little or in other words it remains merely constant throughout the process.

4.3. Effect of initial Fe(II) concentration

The Fe(II) solutions with different initial concentrations of 5, 10, 15, 20 and 25 mg/L are treated by EC at a current density of 0.04 A/m². Variations of percentage removal of Fe(II) are shown in Fig. 4. It is seen from the figure that the percentage removal increases with time. Up to the concentration of 10 mg/L, complete removal is observed at the end of 5 min of operation. Again, the required time for 100% Fe(II) removal increases with initial Fe(II) concentration up to 25 mg/L. It is well known that among the salts of Fe(II), Fe(III) and Al³⁺, only Fe(III) gives brown color in its hydroxide form. The formation of a gelatinous reddish-brown precipitate was observed at the bottom of the batch cell after the electrocoagulation. This (reddish-brown color of the precipitate) revelation confirms the presence of Fe(III) in the precipitate. It seems that oxidation of Fe(II) to Fe(III) occurs which are subsequently trapped by the aluminum hydroxide with time. The Fe(II) removal has been increased with time initially, later it has been decreased gradually as the total Fe(II) concentration was decreased. This decrease in both Fe(II) and Fe(III) concentrations may be due to the adsorption on to the freshly generated aluminum hydroxides hence precipitation in the bath.

In EC process, Fe(II) is removed in two steps. Fe(II) is converted to Fe(III) in first step and then it is adsorbed in aluminum hydroxide complexes in second step. At lower concentration

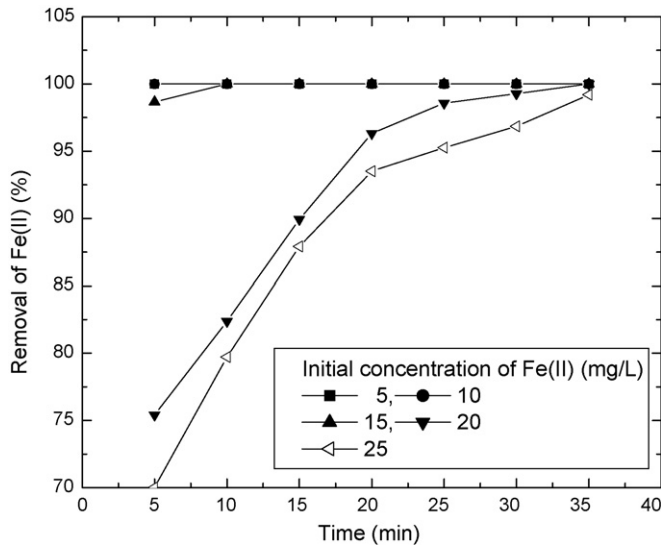


Fig. 4. Variation of extent of Fe(II) removal with time for different initial Fe(II) concentrations. Inter electrode distance: 0.005 m, current density: 0.04 A/m², pH: 7.5, conductivity: 12 S/m.

(up to 15 mg/L) available aluminum hydroxide complexes are sufficient to remove the Fe(II) molecules within 10 min with suitable oxidizing environment. The rate of generation of aluminum hydroxide complexes are not sufficient to remove high Fe(II) concentration (>15 mg/L) within 10 min of operation. For example, 35 min is required for complete removal of 25 mg/L of initial Fe(II) solution. Hence longer residence time is required for EC of high Fe(II) concentration. Therefore, it is quite clear that under the present experimental conditions up to 10 mg/L of initial Fe(II) concentration complete removal of Fe(II) is possible within 5 min.

4.4. Effect of inter electrode distance

The setup of electrode assembly is very important for required effective surface area of electrode and inter electrode distance. Variation of percentage removal of Fe(II) with inter electrode distance is shown in Fig. 5. It may be observed from the figure that with the increase of inter electrode distance, percentage removal of Fe(II) decreases. It is well known that, during the electrocoagulation as the potential is applied to the electrodes initially, the anodic oxidation is started. Now as the time proceeds a very fine film of metal hydroxides would get formed on the anode generating an extra resistance that even increases with increasing inter electrode distance. Therefore, as a result, after some time of the operation current falls down. To maintain a constant current, applied potential has to be increased. Now it is very much clear that current is remained constant but the resistance is increased. Therefore, the ohmic loss (IR resistance) increases which in turn inhibits the rate of anodic oxidation. As the rate of anodic oxidation becomes lower, numbers of cations at anode also decreases. These cations are responsible for the formation of coagulant. Therefore, at higher inter electrode distance, rate of aggregation of suspended particles as well as adsorption of contaminants would be low. This may be the reason behind the

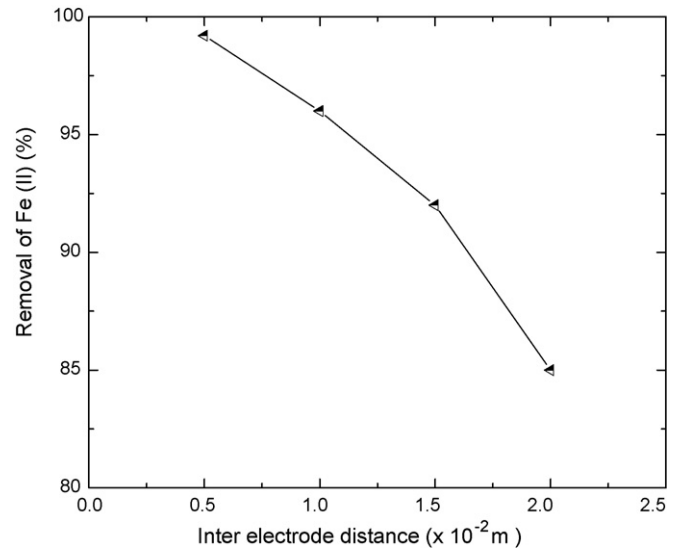


Fig. 5. Effects of inter electrode distance on the Fe(II) removal. Current density: 0.04 A/m², conductivity: 12 S/m, initial Fe(II) concentration: 25 mg/L, time: 35 min, pH: 7.5.

lower removal efficiency at higher inter electrode distance. At minimum inter electrode distance the resistance for current flow in the solution medium is lower that facilitates the electrolytic process for enhanced Fe(II) removal. The variation in IR drop is governed by following equation

$$\eta_{IR} = I \cdot \frac{d}{A \cdot \kappa} \quad (5)$$

where I is the current (A), d is distance between the electrodes (m), A is active anode surface (m²), κ is specific conductivity (10³ mS/m) [14].

Above equation infers that at constant anodic surface area and conductivity of solution, voltage drop (IR) increases with the increase of inter electrode distance. The increase in IR drop is not recommended for EC process in order to have acceptable energy consumptions as well as desired effective separation. In order to achieve 100% removal for the initial Fe(II) concentration of 25 mg/L, the optimum inter electrode distance is 0.005 m.

4.5. Variation of energy consumption

Current efficiency (φ) is very important economical parameters in EC process. Different parameters such as current density and dissolved amount of contaminants affect the current efficiency. Lower current density would not be sufficient to achieve the desired separation, however, it lowers the possibility of the film-formation on the anode surface. Higher current density shows a better removal of dissolved contaminants. If the amount of dissolved contaminant is large then the removal process gets slowed down due to the accumulation of gelatinous aluminum hydroxide film on the anode even on the application of higher current density. As a result current efficiency falls down.

After each experiment the electrodes were cleaned, dried and weighed to estimate the amount of dissolved of the electrodes. Noticeable amount of weight loss was observed due to anodic

dissolution only. The extent of anodic dissolution varied with different operating conditions considered herein. For example, 7.4 and 8.12 mg of anode dissolution were estimated for the treated tap water containing initial iron concentration of 5 and 10 mg/L, respectively, at current density of 0.04 A/m².

Current efficiency (φ) for different operating conditions are calculated as:

$$\varphi = \frac{\Delta M_{\text{exp}}}{\Delta M_{\text{theo}}} \times 100 \quad (6)$$

This calculation is based on the comparison of experimental weight loss of aluminum electrodes (ΔM_{exp}) during EC process with theoretical amount of aluminum dissolution (ΔM_{theo}) according to the Faraday's law:

$$\Delta M_{\text{theo}} = \frac{MI t_{\text{EC}}}{nF} \quad (7)$$

where M is the molecular weight of the aluminum (g/mol), n the number of electron moles, F is the Faraday constant ($F = 96487 \text{ C/mol}$) and t_{EC} is the time (s) of EC operation. As $\text{Al}(\text{OH})_3(\text{s})$ is supposed to be the formed species, the number of electron moles in dissolution reaction is equal to 3. Current efficiency (φ) depends on anodic dissolution which is also varied with time of EC and other operating condition as well.

The specific electrical energy consumption (S_{eec}) is calculated as a function of aluminum electrodes weight consumption during EC in kWh/(kg Al) [32,33].

$$S_{\text{eec}} = \frac{n \times F \times U}{3.6 \times 10^3 \times M \times \varphi} \quad (8)$$

Effect of current density on the percentage removal of Fe(II) and specific electrical energy consumption is shown in Fig. 6. The result shows that an increase in the current density causes an increase in Fe(II) removal as well as specific electrical energy consumption. So, to achieve an optimized current density, both percentage removal of Fe(II) and specific electrical

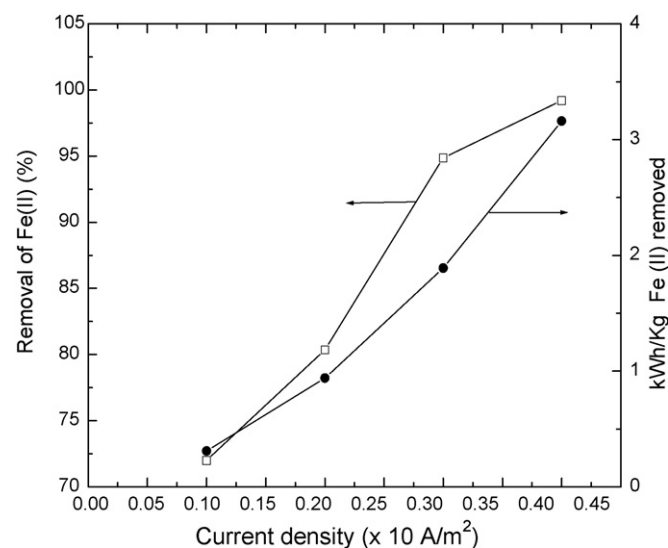


Fig. 6. Effect of current density on the removal of Fe(II) and specific electrical energy consumption. Inter electrode distance: 0.005 m, initial Fe(II) concentration: 25 mg/L, pH: 7.5, conductivity: 12 S/m.

energy consumption should be evaluated. More current density favors formation of more number of aluminum complexes, which also enhances the removal of Fe(II) as expected. This causes the higher weight loss of aluminum electrode and therefore increases the specific electrical energy consumption. Sludge formed during the electrocoagulation experiment was filtered out of the chamber, dried and weighed. It was observed that with the increase in the initial iron concentration and current density, sludge production increased. On the other hand, sludge production was decreased with the increase in inter electrode distance. At current density of 0.04 A/m² and inter electrode distance of 0.005 m, the weight of sludge estimated as 30.95, 42.56 and 96.3 mg for treating the tap water having initial iron concentration of 5, 10 and 25 mg/L, respectively.

4.6. Operation cost

In any electrical process cost is incurred due to electrical energy demand, which affect the operating cost. For EC process the operating cost includes material, mainly electrodes and electrical energy costs, as well as labor, maintenance, sludge dewatering and disposal, and fixed costs. The latter costs items are largely independent of the type of the electrode material [19,37]. In this preliminary economic investigation, energy and electrode material costs have been taken into account as major cost items in the calculation of the operating cost (US\$/m³ of Fe(II) solution).

$$\text{Operating cost} = aC_{\text{energy}} + bC_{\text{electrode}} \quad (9)$$

where C_{energy} (kWh/m³ of Fe(II) solution) and $C_{\text{electrode}}$ (kg Al/m³ of Fe(II) solution) are consumption quantities for the Fe(II) removal, which are obtained experimentally. "a" and "b" given for Indian market in June 2007, are as follows: "a" electrical energy price 0.0065 US\$/kWh; "b" electrode material price 0.3 US\$/kg Al. Cost due to electrical energy (kWh/m³ Fe(II) solution) is calculated as

$$C_{\text{energy}} = \frac{U \times I \times t_{\text{EC}}}{v} \quad (10)$$

where U is cell voltage (V), I is current (A), t_{EC} is the time of electrolysis (s) and v is the volume (m³) of Fe(II) solution. Cost for electrode (kg Al/m³ Fe(II) solution) is calculated by the following equation by Faraday's Law

$$C_{\text{electrode}} = \frac{I \times t \times M_w}{z \times F \times v} \quad (11)$$

where I is current (A), t is time of electrolysis (s), M_w is molecular mass of aluminum (26.98 g/mol), z is number of electron transferred ($z = 3$), F is Faraday's constant (96487 C/mol) and v is volume (m³) of Fe(II) solution [15].

Cost due to electrical energy consumption as well as electrode assembly is calculated for different initial Fe(II) concentration (up to 25 mg/L) and shown in Fig. 7 for 100% Fe(II) removal at optimum operating conditions. A model calculation is shown in Appendix A. It may be seen from the figure that both the consumption quantities (electrical and electrode) remains almost unchanged up to the initial concentration of 15 mg/L,

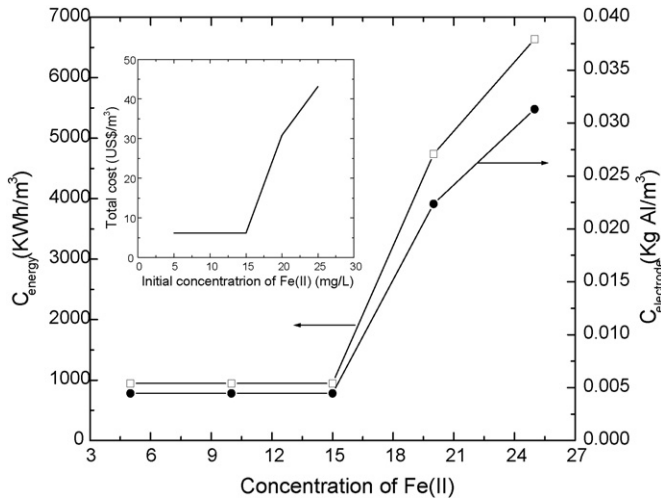


Fig. 7. Cost for the treatment tap water containing different concentration of Fe(II). Current density: 0.04 A/m^2 , conductivity: 12 S/m , pH: 7.5, inter electrode distance 0.005 m .

beyond that it increases with the initial Fe(II) concentration. Operating cost also increases with the initial Fe(II) concentration as shown in the inset of Fig. 7. It is found that about $6.05 \text{ US}\$/\text{m}^3$ is required for the treatment of water containing initial iron concentration up to 15 mg/L at the end of experiment at 0.04 A/m^2 . Kobys et al. [15] have also determined the operating cost for the treatment of potato chips manufacturing waste water using EC process. They found that operating costs were varied $0.48\text{--}5.42 \text{ }\$/\text{m}^3$ wastewater at $50\text{--}300 \text{ A/m}^2$, and 0.62 and $6.32 \text{ }\$/\text{m}^3$ wastewater at 5 and 40 min, respectively. The Fig. 8 represents the variation of operating cost with applied current densities. It seems that the operating cost is increased almost linearly due to increase in consumption of electrical energy as well as electrode material.

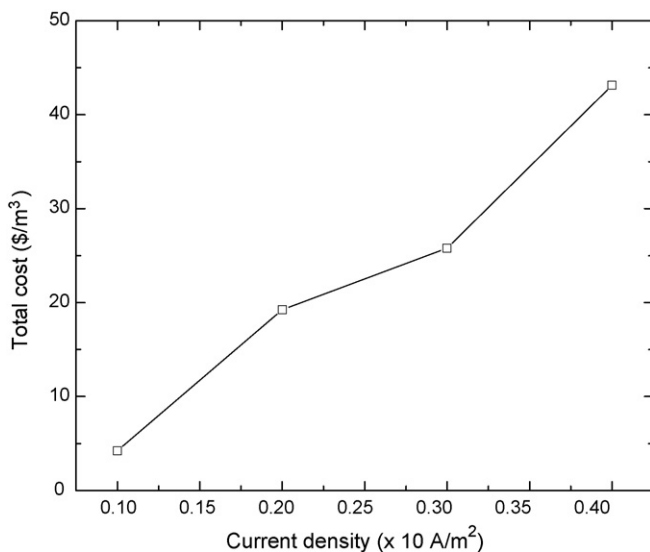


Fig. 8. Effect of current densities on total cost for the treatment of tap water. Conductivity: 12 S/m , pH: 7.5, inter electrode distance: 0.005 m , initial concentration of Fe(II): 25 mg/L .

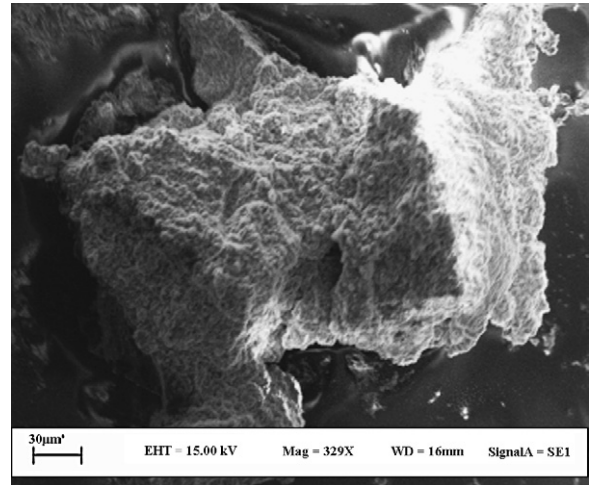


Fig. 9. SEM image of by products obtained from EC bath.

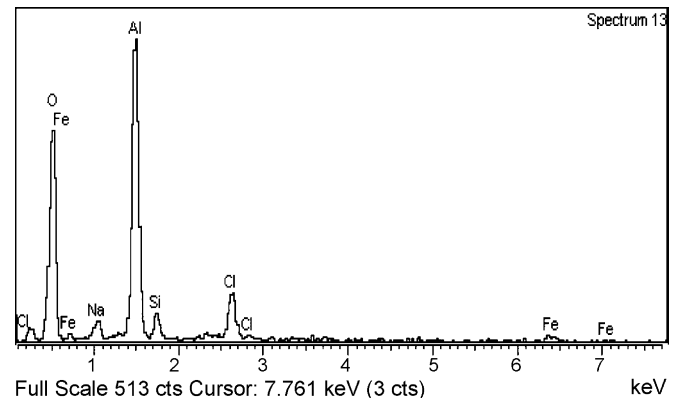


Fig. 10. Elemental analysis of by products obtained from EC bath.

4.7. Characterization of treated Fe(II) solution and by products obtained from EC bath

SEM image and EDAX spectra of solid precipitate (by product of EC) are presented in Figs. 9 and 10, respectively. SEM image shows the morphology of various aluminum hydroxides precipitate impregnated with iron hydroxides which is confirmed by the elemental analysis (EDAX). The observation of peaks and trends in the EDAX graph convey that the by product of EC consisted of aluminum (Al), oxygen (O), iron (Fe), sodium (Na) and chlorine (Cl). Presence of silica (Si) is due to glass slit used for EDAX analysis of the sample.

5. Conclusion

Electrocoagulation technique was carried out to remove Fe(II) from synthetic solution using tap water. Variation of percentage removal of Fe(II) with different operating parameters such as, current density, initial concentration of Fe(II) and operating time were studied in detail. Electrocoagulation was carried out for 35 min for iron concentration as high as 25 mg/L and satisfactory removal of 99.2% was obtained. The results showed that the removal efficiency increases with the increase in current

density from 0.01 to 0.04 A/m². At the optimum current density of 0.04 A/m² the electrolysis time was reduced to mere 5 min for concentration range of 5–10 mg/L. Thus, electrocoagulation was found to be very fast and effective method for the water containing iron from low to very high concentrations. Operating costs for the treatment of Fe(II) using EC were evaluated for 100% removal of different initial Fe(II) concentrations with optimum operating condition. Operating time and current density exhibit similar effects on the process performances and the operating cost. Finally, it must be recalled that an EC process comprises also other equipments than the electrolysis unit. A detailed technical and economic analysis of the whole process is necessary. The simplified approach used in this study provides only preliminary data for a detailed analysis.

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Appendix A

Calculation of operating cost for the initial concentration of 10 mg/L.

Operating cost is determined using the following relation as mentioned in Section 4.4.

$$\text{Operating cost} = aC_{\text{energy}} + bC_{\text{electrode}}$$

where $a = 0.0065$ US\$/kWh; $b = 0.3$ US\$/kg.

$$C_{\text{energy}} = \frac{U \times I \times t_{\text{EC}}}{v}$$

$$U = 19.75 \text{ V}$$

$$I = 0.16 \text{ A}$$

$$t_{\text{EC}} = 300 \text{ s}$$

$$V = 1 \times 10^{-3} \text{ m}^3$$

Cost due to electrical energy is calculated using above values.

$$C_{\text{energy}} = 948 \text{ kWh/m}^3$$

$$C_{\text{electrode}} = \frac{I \times t \times M_w}{z \times F \times v}$$

$$M_w = 26.98 \text{ g/mol}$$

$$z = 3$$

$$F = 96,487$$

Cost for aluminum electrode is calculated using above values.

$$C_{\text{electrode}} = 0.0149 \text{ kg/m}^3$$

$$\text{Operating cost: } 6.16 \text{ US\$/m}^3$$

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