Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2015.1130917

57 (2016) 22824–22834
October

Taylor & Francis
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Removal of copper from simulated wastewater by electrocoagulation/floatation technique

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Received 31 July 2015; Accepted 6 December 2015

ABSTRACT

Many industries, such as tanning, metal processing, electroplating, etc., include copper in their processes and discharge it in wastewater streams. The permissible limit of copper in wastewater is 1.3 mg/L, accordingly, industries must lower their copper limits to meet their local legal guidelines. This can be done by numerous methods including chemical precipitation, oxidation–reduction, ion exchange, etc. Electrocoagulation (EC)/floatation (ECF) technique, however, is an effective, cheap and simple electrochemical method for treating wastewater containing copper (Cu(II)) ions, which involves generation of coagulants using sacrificial electrodes when a DC voltage is applied; simultaneously generating hydrogen gas at the cathode which can help in the floatation of the formed particles. In the present work, a specially devised and innovated bench-scale EC apparatus was constructed and used in the removal of Cu(II) ions from aqueous solution. Numerous factors were investigated for their effect on the efficiency of removal of Cu(II) ions and those were: initial Cu(II) ion solution concentration, speed of magnetic stirring in the EC cell, number and type of sacrificial electrodes (aluminium (Al) or iron (Fe) electrodes), mixed electrodes, aspect ratio of the EC cell and the addition of a supporting electrolyte. It was found that lower initial concentrations required the minimum time to effect 100% removal of the Cu(II) ions, and that there existed an optimum speed of magnetic stirring in the EC cell, it was found that when C_0 was 3 g/L it took only 25 min for complete removal of Cu(II) ions at 300 rpm, whereas, when C_0 was 10 g/L it required 45 min at 120 rpm for complete removal, while at medium C_0 (6.5 g/L) 30 min were needed to effect 100% removal at 240 rpm, and that Fe electrodes were more efficient in removing Cu(II) ions than Al. Regarding the floatation chamber (FC),

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Presented at EuroMed 2015: Desalination for Clean Water and Energy Palermo, Italy, 10–14 May 2015. Organized by the European Desalination Society.

it resulted in the production of totally clean water at its outlet and decreased the time required for complete Cu(II) removal to one third its value without FC which proved its importance in effecting good separation.

Keywords: Electrocoagulation/floatation; Copper; Mixed electrodes; Aspect ratio

1. Introduction

Fast industrialization is a noteworthy reason for the arrival of heavy metals into nature. Nowadays, treatment of water to remove heavy metals has turned out to be progressively essential because of their irritable and persevering nature in the earth, being non-biodegradable, exceedingly poisonous and carcinogenic [1]. Contamination of water by heavy metals has prompted various ecological issues [2]. They can accumulate in ecological components, and thus represent a considerable danger to human health and aquatic life [3]. Accordingly, it is basic to treat industrial effluents before release to fluid streams, in order to secure general human health [4].

Copper ions, specifically, are known to cause mucosal aggravation, hepatic and renal failure, gastrointestinal problems and conceivable necrotic changes in the liver and kidney, on prolonged exposure. The primary strategies, which have been used to diminish the substantial metal particle substance of effluents, include adsorption, bio-sorption, filtration, reverse osmosis and chemical coagulation, of which some create a considerable quantity of sludge and are cost prohibitive [5–8].

Electrocoagulation (EC) is a straightforward and proficient strategy whereby flocculated species are created by electro-oxidation of an anode of iron (Fe) or aluminium (Al). In this technique, the treatment is done without including any synthetic coagulant or flocculant, thus reducing the amount of sludge which must be disposed of [9]. The electrochemical nature of EC technique has the advantage of the creation of polyvalent cations from oxidation of corrodible anodes. The gas bubbles convey the pollutant to the highest point of the waste where it can be all the more effectively gathered and removed. The metallic particles can react with the OH^- particles delivered at the cathode, amid the development of H_2 gas, yielding insoluble hydroxides that will sorb poisons out of the solution [10,11].

EC has been effectively used to treat oil wastes, with removal efficiencies as high as 99% [12,13], comparative achievement was reached when treating dye-containing solutions [14–17], potable water [18], urban and restaurant wastewater [19,20] and nitrate- or fluoride-containing waters [21–24]. Besides, a great deal of work performed in the two last decades [25,26] has exhibited that EC is a suitable advancement for the treatment of heavy metal-containing wastes [27,28].

Accordingly, in the present work, an investigation on the removal of Cu(II) ions from aqueous solution, through application of the electrocoagulation–floatation (ECF) technique, has been conducted. An original lab-scale set-up was constructed for the purpose. Variables studied for their effect on the per cent of Cu(II) removed, included initial Cu(II) ion solution concentration, speed of stirring in the EC cell, type and number of sacrificial electrodes, mixed electrodes, aspect ratio of EC cell, presence of a supporting electrolyte during EC, and conducting EC and flotation in series.

2. Materials and methods

2.1. Materials

Copper sulphate pentahydrate and cupric chloride (product of Chemajet Chemical Company, Egypt) were used as a source of Cu(II) ions. Iron (Fe) and/or aluminium (Al) plates (purity: 95%, product of Egyptian Copper Company, Alexandria, Egypt) functioned as sacrificial electrodes in the EC reactor. Sodium chloride (NaCl) (product of Chemajet Chemical Company, Egypt) was used as supporting electrolyte.

2.2. Experimental set-up

A laboratory bench-scale perspex EC reactor of dimensions: height = 20 cm, length = 10 cm and width = 8 cm for short cell and another long cell of the same the same dimensions except for the height which is 30 cm, was designed and constructed (Fig. 1). The electrochemical cell contains eight Fe or Al plates with dimensions of 16 cm × 7.7 cm × 0.3 cm. The electrodes were completely immersed up to 15 cm inside the aqueous solution in the EC reactor, and connected using a bipolar configuration, while for the long cell, the complete electrode was dipped inside the aqueous solution. To attain uniform mixing, stirring was achieved using a magnetic stirrer with its bar placed at the reactor bottom. A drain tube was installed at the bottommost of the cell, and a sampling valve was fit for drawing samples of treated water at different time intervals. The anode and cathode were connected to a 12 V battery

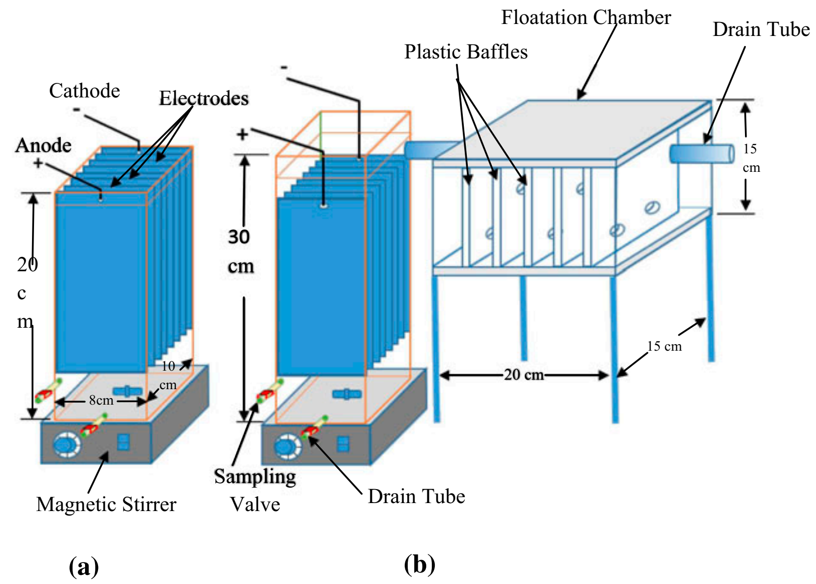

Fig. 1. Schematic diagram of set-up, (a) without FC and (b) with FC.

with current 250 mA (product of El-Nasr Varta Germany-Alexandria) to provide a DC current. Two avometers (Sunwa, China) were used, of which one functioned as a voltmeter while the other functioned as ammeter. A rheostat was connected in the circuit for the adjustment of voltage and current intensity.

The floatation chamber (FC) (20 cm length × 15 cm width × 15 cm height) is a small parallel-piped perspex chamber, which contains five equi-distant baffles, which completely divides the chamber into six narrow compartments, with two holes with diameter of 1.5 cm in each baffle alternating successively up and down to provide a wavy motion of the fluid.

2.3. Procedure

A stock solution of Cu(II) ions was prepared (10 g/L) from which different concentrations were prepared (3, 6.5, and 10 g/L, at pH range 6.8–7.1). The cell and the electrodes were cleaned by washing twice with tap water then with distilled water. The solution was added to the cell after fixing the electrodes in place. The solution was stirred magnetically at the required speed. A 5-mL sample from the solution in the cell was drawn at five minutes intervals, for analysis.

2.4. Variables investigated

The effect of different variables on the % removal of Cu(II) ions was studied. These variables were: initial Cu (II) ion solution concentration, speed of stirring, material of sacrificial electrodes (Fe or Al), number of Fe or Al electrodes, mixed sacrificial electrodes, addition of supporting electrolyte, using FC and size of EC cell.

2.5. Analysis

Cu(II) ion concentration was determined by following this procedure where a 5-mL sample of the different Cu(II) solutions in the EC cell was taken at different periods of time. Atomic absorption spectrophotometry (Hitachi, Z-5000) was used to estimate the Cu(II) ion concentration in the sample using its respective hollow cathode lamp.

2.6. Electrocoagulation process

The EC process involves many chemical and physical mechanisms [29]. Generally, Al and Fe are dissolved by anodic dissolution. A range of coagulant species and hydroxides are formed which destabilize and coagulate the suspended particles or precipitate and adsorb dissolved contaminants. It is generally accepted that the EC process involves three successive stages [7,29,30].

(1) Formation of coagulants by electrolytic oxidation of the sacrificial anode, in which the main reaction occurring at the anode is dissolution:

$$\mathrm{Me}_{(s)} \rightarrow {\mathrm{Me}_{(aq)}}^{3+} + 3\mathrm{e}^{-} \qquad (1)$$

where in the present study Me refers to Fe or Al, and subscripts (s) and (aq) refer to solid phase and aqueous phase. Additionally, water electrolysis occurs at the cathode and anode:

$$2H_2O_{(aq)} + 2e^- \rightarrow H_{2(g)} + 2OH^- \text{ (cathodic reaction)} \tag{2}$$

$$2H_2O_{(aq)} \rightarrow 4H^+{}_{(aq)} + O_{2(g)} + 4e^- \text{ (anodic reaction)} \tag{3}$$

where subscript (g) refers to gas phase.

(2) Destabilization of the contaminants (Cu(II) in the present study), particulate suspension and breaking of emulsions takes place. A direct electrochemical reduction of metal cations (Me^{n+}) may occur at the cathode surface:

$$Me^{n+} + ne^- \rightarrow nMe^0 \tag{4}$$

Furthermore, the hydroxide ions formed at the cathode increase the pH of the wastewater thereby inducing precipitation of metal ions as corresponding hydroxides, and co-precipitation with metal hydroxides:

$$Me^{n+} + nOH^- \rightarrow Me(OH)_{n(s)} \tag{5}$$

(3) Coagulation of the destabilized phases to form flocs. In addition, anodic metal ions and hydroxide ions generated at the electrode surfaces react in the bulk waste water to form various hydroxides and build up big particles:

$$Me^{3+} + 3OH^- \rightarrow Me(OH)_{3(s)} \tag{6}$$

$$nMe(OH)_{3(s)} \rightarrow Me_n(OH)_{3n(s)} \tag{7}$$

However, depending on the pH of the aqueous medium other ionic species, such as dissolved $Me(OH)^{2+}$, $Me_2(OH)_2^{4+}$ and $Me(OH)_4^-$ hydroxo complexes may also be present in the system. The suspended Me hydroxides can remove pollutants from the solution by sorption, co-precipitation or electrostatic attraction, followed by coagulation [30].

For a particular electrical current flow in an electrolytic cell, the mass of Me theoretically dissolved from the sacrificial anode is quantified by Faraday's law [30]:

$$m = \frac{nItM}{zF} \tag{8}$$

where m is the weight of anode material dissolved (g), n is the number of anodic electrode surfaces, I is the current intensity per one anodic surface (A/cm^2), t is the electrolysis time (s), M is the specific molecular weight (g/mol), z is the number of electrons involved in the reaction and F is the Faraday's constant (96,485.34 C/mol). The mass of evolved hydrogen and formed hydroxyl ions can be calculated correspondingly. The amount of coagulant dosed into the solution can be increased by increasing the current and the reaction time. On the other hand, increasing the current density leads to a decreased current efficiency. Influencing factors of the EC process are current density, conductivity, pH and electrode material [30,31].

2.7. Kinetic representations

The former observations can also be supported by regression analysis applied to fit the various variables as a function of EC operation time to the pseudo-first-order-kinetic expression as given below:

$$\ln \frac{C_t}{C_0} = -k_c t \tag{9}$$

where C_t and C_0 are the concentrations at time t and time zero, respectively, t is the EC treatment time (min) and k_c is the pseudo-first-order reaction rate constant (min^{-1}). ln C_t/C_0 was plotted against time to calculate k_c. The calculated pseudo-first-order rate constants will be presented in table form [32–34].

3. Results and discussions

3.1. Effect of speed of stirring

Figs. 2–4 present the effect of stirring speed at different initial concentrations (C_0): 10, 6.5, and 3 g/L, respectively, in which five stirring speeds (60, 120, 180, 240, and 300 rpm) were used for each C_0. It is clear from the figures that the lowest speed (60 rpm) was insufficient to cause renewal of the solution along the length of the electrodes. On the other hand, maximum speed (300 rpm) caused rapid mixing to be mostly in the bottom region below the electrodes, while still providing some appreciable mixing between the electrodes. Accordingly, for all C_0s, this high speed led to best removal of Cu(II) by EC. It is noticed, however, that at this high speed, EC is rapid at first indicated by the linear relation between the per cent Cu(II) removal and time, followed by a sudden decline in the removal rate. This may be attributed to the concentration of Cu being high initially thus

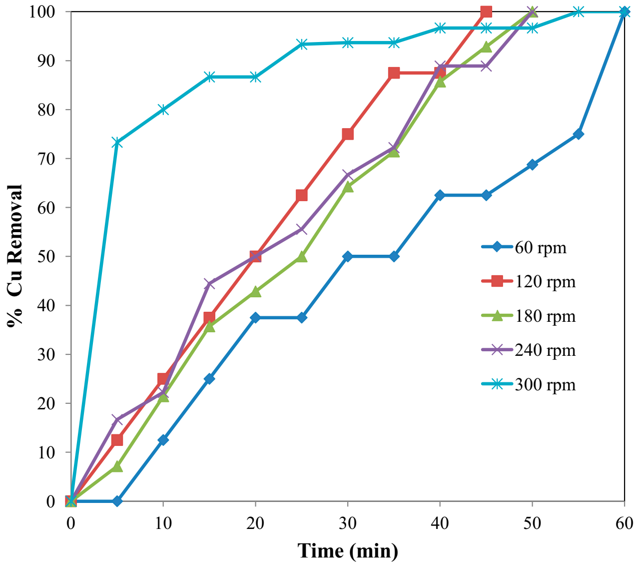

Fig. 2. Effect of speed of stirring, $C_0 = 10$ g/L, 8 Fe electrodes, short cell, current = 250 mA, voltage = 12 V.

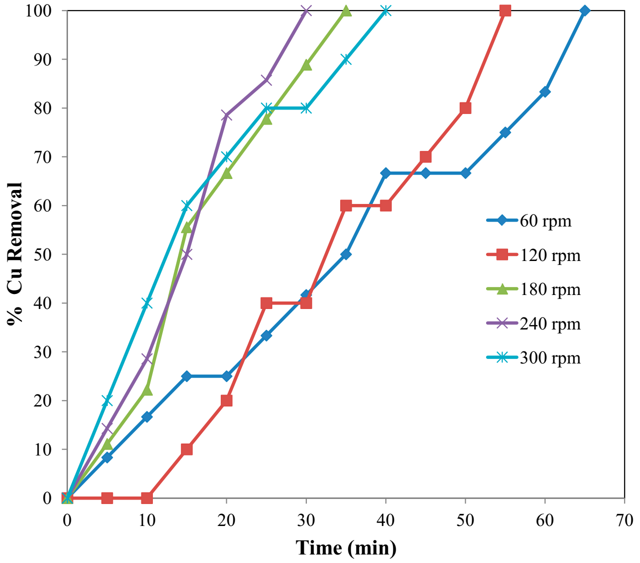

Fig. 3. Effect of speed of stirring, $C_0 = 6.5$ g/L, 8 Fe electrodes, short cell, current = 250 mA, voltage = 12 V.

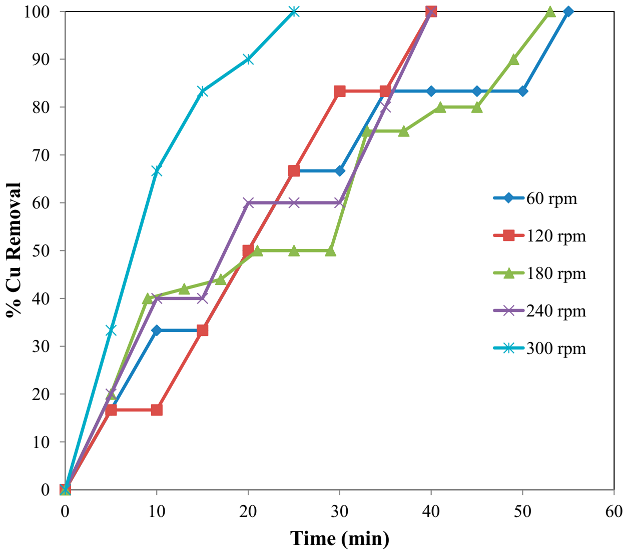

Fig. 4. Effect of speed of stirring, $C_0 = 3$ g/L, 8 Fe electrodes, short cell, current = 250 mA, voltage = 12 V.

providing plenty of Cu ions in solution, but as EC progresses the driving force for EC slows down which affects the rate of Cu ion removal. However, at medium speeds (120, 180, and 240 rpm) extraction was more or less intermediate, which may be attributed to sufficient liquid motion in the lower part of the cell, that also causes the liquid between the electrodes to be renewed more frequently, than when the speed is low. At the same time, at medium speeds, the liquid does not suffer from swirling, which is absent at the low speed, resulting in some stagnancy amidst the electrodes preventing turbulence from taking place. Table 1 confirms the aforementioned findings, since the rate constants (k_c) are much higher in case of using high stirring speed. It is noticed that in the case when the stirring speed was 300 rpm, the rate was the highest in the initial stage of EC, then slowed down as EC progressed, which is due to higher probability of collision between the Cu(II) ions in solution and the sacrificial Fe electrode on the onset of the process.

3.2. Effect of initial Cu(II) ions solution concentration

From Figs. 2–4, it is realized that the difference between the time required for complete extraction at 60 rpm was almost identical (60, 65, and 55 min), for $C_0 = 10$, 6.5, and 3 g/L, respectively. This result proved that stirring at the lowest speed is not influential in enhancing the rate of extraction and that the most pronounced factor in controlling the time was the presence of sufficient quantity of dissolved Fe(III) ions due to the presence of eight electrodes. Accordingly, an average value of 60 min was required for the three concentrations investigated.

At speed 120 rpm and on comparing the time required for complete removal of Cu(II) ions when $C_0 = 10$, 6.5, and 3 g/L, it is clear that the time was 45, 55, and 40 min, respectively (Figs. 2–4). Furthermore, when speed 180 rpm was used at the same C_0s, the time required for complete extraction was 50, 35, and 65 min, respectively.

The required time for complete removal of Cu(II) ions from initial concentrations 10, 6.5, and 3 g/L and

Table 1
Cu removal rate coefficients for EC applied under different applied speed of stirring (at 8 Fe electrodes, short cell, current = 250 mA, voltage = 12 V)

C_0	Speed of stirring (rpm)	k_c (min^{-1})	Removal time (min)	Dissolved Fe (g)
10	60	0.0229	60	0.023
10	120	0.0484	45	0.017
10	180	0.0434	50	0.019
10	240	0.0436	50	0.019
10	300	0.0831	55	0.023
6.5	60	0.0243	65	0.025
6.5	120	0.0247	55	0.021
6.5	180	0.0619	35	0.013
6.5	240	0.0683	30	0.011
6.5	300	0.0609	40	0.015
3	60	0.0405	55	0.021
3	120	0.0476	40	0.015
3	180	0.0383	53	0.025
3	240	0.0397	40	0.015
3	300	0.1195	25	0.0096

at speed of stirring of 240 rpm, was 50, 30, and 40 min, respectively. Moreover, the same aforementioned observation at speed 180 rpm was noticed here as well.

The complete removal of Cu(II) ions from $C_i = 10$, 6.5, and 3 g/L at stirring speed 300 rpm, took place at 55, 40, and 25 min, respectively. Moreover, it is observed that the relation is more or less inversely proportional as expected, maximum speed coupled with minimum concentration, required minimum time among all the experiments.

Conclusively, one can observe the important results on examining Table 1. At first, in case of $C_0 = 10$ g/L, at stirring speed = 120 rpm k_c was higher compared to all other speeds except that at 300 rpm, and at which the time for complete removal was the least among the set of speeds conducted. At the same time, the dissolved Fe was least at this particular speed (120 rpm) as well. On the other hand, at speed 300 rpm, at the same C_0, the rate constant almost doubled but the time increased 22% only, while the amount of dissolved Fe was increased almost 1.4 times that at stirring speed 120 rpm. Thus, it can be stated that 120 rpm stirring speed proved to be the best at this particular C_0 since minimum time was required and simultaneously, minimum amount of Fe dissolved. On the other hand, at $C_0 = 6.5$ g/L and stirring speed 240 rpm, the optimum k_c was obtained while time was minimum (30 min) and amount of dissolved Fe, as well.

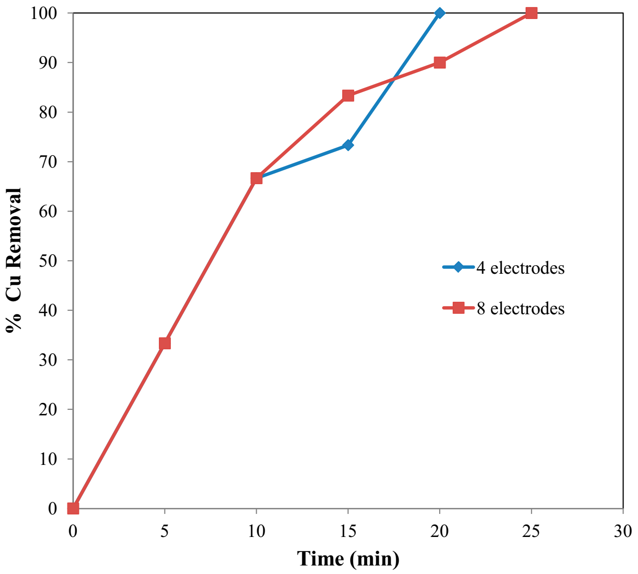

Fig. 5. Effect of number of Fe electrodes, $C_0 = 3$ g/L, stirring speed = 300 rpm, short cell, current = 250 mA, voltage = 12 V.

3.3. Effect of number of sacrificial electrodes

On inspecting Fig. 5, it is observed that using four electrodes, requires slightly less time (20 min) for complete removal of the Cu(II) ions than when using eight electrodes (25 min). The reason may be probably due to the fact that when the number of electrodes was few, stirring at high speed results in appreciable turbulence between the electrodes, which causes more Fe (III) ions to form in the solution forming different hydroxides that react with copper leading to its precipitation. On the other hand, despite that less turbulence takes place between the eight electrodes, yet the presence of more electrodes leads to the formation of abundant Fe(III) ions in solution which promptly react with Cu(II) ions precipitating them. In conclusion,

Table 2
Cu removal rate coefficients for EC applied in presence or absence of additives with number and type of electrodes ($C_0 = 3$ g/L, stirring speed 300 rpm, short cell, 8 electrodes, current = 250 mA, voltage = 12 V)

Type of electrodes and additives	k_c (min^{-1})	Removal time (min)	Dissolved Fe/Al (g)
4Fe + No additives	0.0938	20	0.0038
8Fe + No additives	0.1195	25	0.0096
8Al + No additives	0.0691	50	0.0190
4Fe + 4Al + No additives	0.0419	35	0.0130
4Fe + 4Al + 0.5 g NaCl	0.0859	20	0.0070

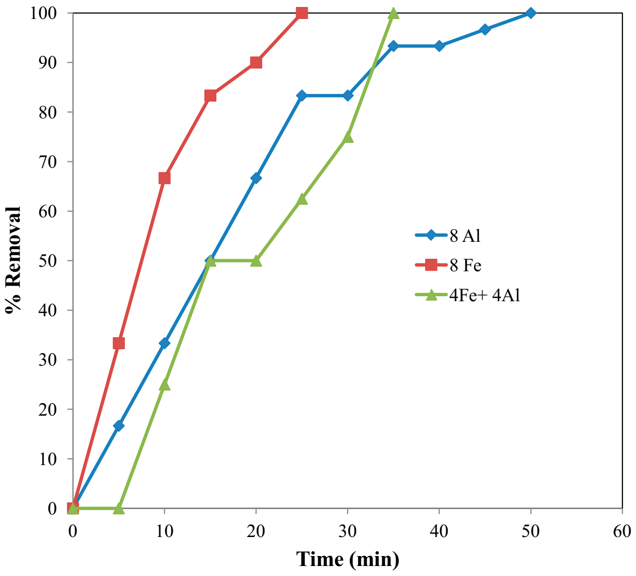

Fig. 6. Effect of material of sacrificial electrode, $C_0 = 3$ g/L, stirring speed = 300 rpm, short cell, current = 250 mA, voltage = 12 V.

the aforementioned two cases lead to almost identical results, so that complete removal requires almost the same time period. The same discussion can be confirmed from Table 2 in which the rate constants in the two cases are almost the same.

3.4. Effect of material of sacrificial electrode

For investigating this factor, three cases were compared: Al, Fe and both types of material (Al+Fe) as electrode. The comparison is clear from Fig. 6, in which it is evident that Al electrodes required 50 min compared to only 25 min for Fe electrodes. Moreover, mixed Al–Fe electrodes, as expected, required a time intermediate between each type of material alone (35 min). To this end, this factor is important when one material is insufficient, while the other could compensate for it. Conclusively, Fe is preferred due to it

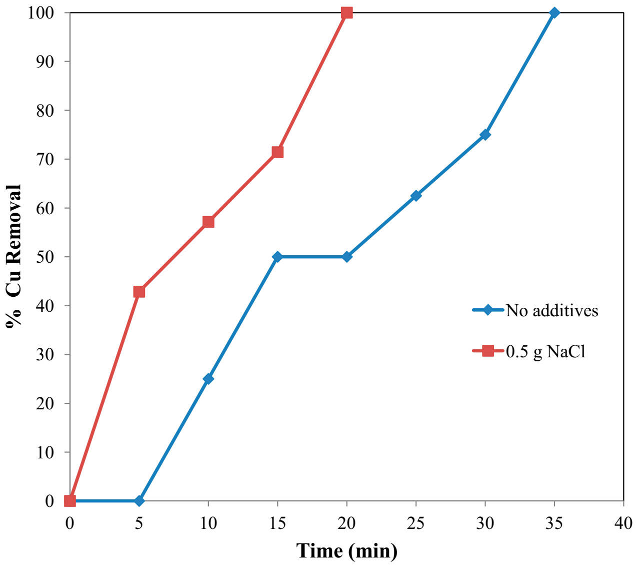

Fig. 7. Effect of presence of supporting electrolyte, $C_0 = 3$ g/L, stirring speed = 300 rpm, Short cell, 4Al electrodes + 4Fe electrodes, current = 250 mA, voltage = 12 V.

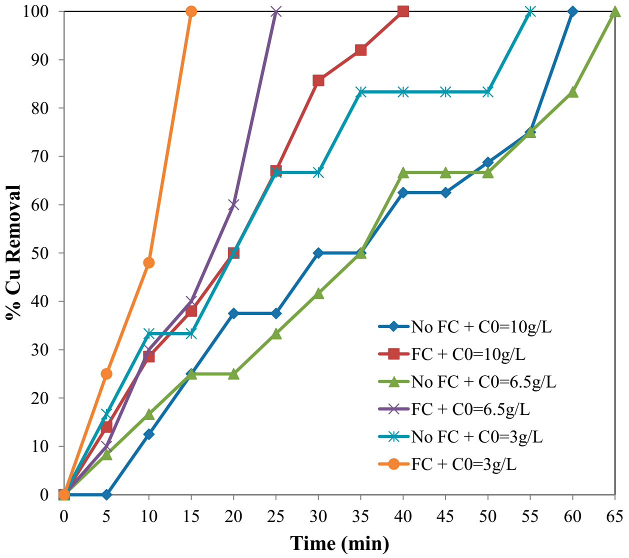

Fig. 8. Effect of using FC, 8Fe electrodes, stirring speed = 60 rpm, short cell, current = 250 mA, voltage = 12 V.

Table 3
Cu removal rate coefficients for EC applied in presence or absence of FC (stirring speed 300 rpm, short cell, 8 electrodes, current = 250 mA, voltage = 12 V)

C_0 + presence or absence of FC	k_c (min^{-1})	Removal time (min)	Dissolved Fe/Al (g)
10 g/L	0.0229	60	0.023
10 g/L + FC	0.0540	20	0.063
6.5 g/L	0.0243	65	0.015
6.5 g/L + FC	0.0201	25	0.007
3 g/L	0.0405	55	0.019
3 g/L + FC	0.1386	15	0.048

being cheaper than Al, and the reason for this result could be partially attributed to the liability of Al to passivate [35,36]. By inspecting Table 2, it is very clear that the rate constant in case of using Fe is almost double that for Al, which proves that Fe is preferred to Al as electrode material. However, it is clear that using mixed electrodes accelerates the rate of reaction in a limited way compared to using Fe electrodes alone.

3.5. Effect of supporting electrolyte

As mentioned in the literature, increasing the electrolyte (NaCl) concentration accelerates inorganic and organic pollutants removal, decreases the power consumption and shortens the reaction time [31,37]. In addition, chloride may generate chlorine/hypochlorite serving as an oxidizing agent during EC process at a proper pH range (pH < 11) and for appropriate electrode material [37,38]. The following reactions describe the process taking place:

$$2\text{Cl}^-_{(\text{aq})} \rightarrow \text{Cl}_{2(\text{g})} + 2\text{e}^-$$

$$2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_{2(\text{g})} + 2\text{OH}^-$$

$$\text{Cl}_{2(\text{g})} + \text{H}_2\text{O} \rightarrow \text{HOCl}_{(\text{aq})} + \text{H}^+ + \text{Cl}^-$$

$$\text{HOCl} \leftrightarrow \text{H}^+ + \text{OCl}^-$$

The chlorine/hypochlorite couple oxidizes the pollutants to chloride ions [37,39,40]. On inspecting Fig. 7, it is noticed that in presence of NaCl as supporting electrolyte, it took 20 min only compared to 35 min in its absence for complete removal of Cu(II) ions, which proves that the presence of NaCl increases the electrical conductance of the solution, thereby, assisting in faster EC. From Table 2, it can be seen that the rate constant in presence of NaCl is much higher than in its absence which emphasizes the former discussion. In addition, the quantity of Fe/Al dissolved in the presence of NaCl is almost one half that in its absence, which is advantageous. All the previous discussions are confirmed by inspecting and comparing the values in Table 2.

3.6. Effect of using FC

The design of the flotation chamber (FC) is based on the fact that as the fluid flows through the FC, it is subjected to two forces in series: firstly, deviation of the direction of flow as it leaves the lower orifices in one baffle to the others at the top of the following baffle, causes slowing down of the fluid through this wavy flow pattern; secondly, as the flocs bombard with the baffle and with each other during motion, enlargement of the flocs takes place due to these collisions, and as a result they become larger and heavier and settle down between the baffles, enabling their continual removal through the side discharge outlets.

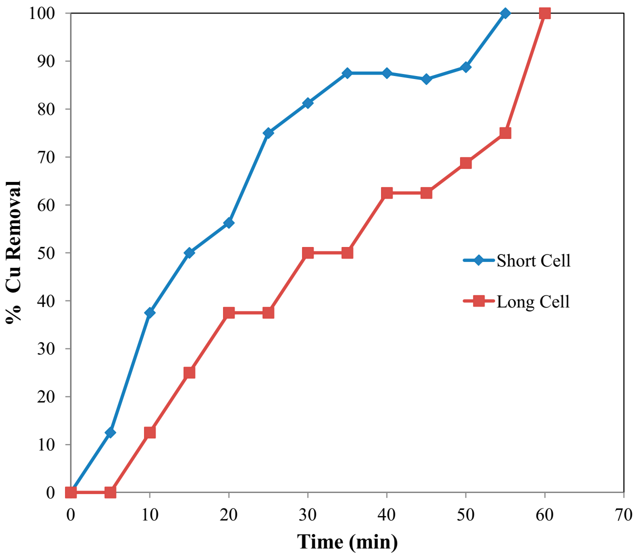

Fig. 9. Effect of size of the EC cell. C_0 = 10 g/L, stirring speed = 60 rpm, 8Fe electrodes, current = 250 mA, voltage = 12 V.

Table 4
Cu removal rate coefficients for EC applied under different applied cell size ($C_i = 10$ g/L, stirring speed 60 rpm, 8 Fe electrodes, current = 250 mA, voltage = 12 V)

Size of cell	k_c (min^{-1})	Removal time (min)	Dissolved Fe (g)
Short	0.0491	55	0.021
Long	0.0229	60	0.023

It was found that using the FC decreases the time required for complete extraction in the three initial concentrations tested. From Fig. 8, it is obvious that using the FC not only decreased the time for complete extraction, but also improved the rate of extraction. As regards the values of k_c, time of removal of Cu(II) ions and the quantity of dissolved metals, which are presented in Table 3, it is realized that the values of k_c are at least twice as large when the FC is connected to the EC reactor. This is translated in a much shorter time that is almost a third at most that in absence of FC, and a smaller amount of dissolved Fe/Al metal as well.

3.7. *Effect of size of electrocoagulation cell*

This factor was investigated by conducting only one experiment in which another EC cell available in our laboratory, in which the height was 30 cm instead of 20 cm as in the original cell, keeping the other two dimensions the same as before. From Fig. 9, it is realized that the rates slightly differed, however, the time required for complete EC to take place was 55 and 60 min in the short and long cells, respectively, which may be attributed to the increased stagnancy in the upper regions between the longer electrodes in the long cell. Accordingly, further investigation is necessary in order to simulate the situation via a mathematical model relating the per cent extraction of the Cu(II) ions to initial Cu(II) ion concentration, speed of stirring, type and number of sacrificial electrodes, using mixed electrodes, presence of supporting electrolyte and the cell aspect ratio, which is currently being investigated in our lab. Table 4 showed that the rate constant in case of using the short cell is much higher than that in the case of using the long cell, which confirms the conclusion that in the short cell mixing was better than in the long cell, due to a stagnant zone, which prohibited the EC process.

4. Conclusions

ECF is an effective, cheap and simple electrochemical method for treating wastewater containing heavy metals, compared to other methods of treatment. In this work, a simple ECF unit was constructed and used for treating aqueous solutions containing Cu(II) ions. It was found that the speed of stirring in the EC cell was of prime importance in that it may or may not provide turbulence amidst the electrodes, and that low and high speeds gave poor extraction due to insignificant and high turbulence, in respective order.

It was found that % extraction was related to speed of stirring and that it did not follow a particular pattern as explained in the text. In addition, the material and number of sacrificial electrodes were found to affect the rate and extent of extraction, and that Fe functioned as a more satisfactory sacrificial electrode than Al, due to passivation of the latter. Moreover, the number of electrodes provided two opposing effects which governed the EC process being on the one hand a low % extraction achieved when their number is low due to less Al or Fe ions available in solution; on the other hand, when their number is high, more Al and Fe ions are available in solution but stirring does not lead to the desired result due to poor turbulence between the electrodes. Furthermore, using alternating Al and Fe electrodes led to intermediate time interval for complete extraction than each metal alone. Moreover, addition of supporting electrolyte assisted in faster EC process and the description of the reactions taking place are clarified in the text, however, caution must be taken in case analysis of the influent wastewater clarifies presence of organic pollutants in order to prevent the formation of polychlorinated compounds. As regards using the combined ECF unit it was proven that the FC decreased the time required for complete extraction in all cases tested. It is noteworthy that the ECF unit may be used in a continuous manner after few modifications and/or additions to the present unit. The configuration of the EC cell emphasized the importance of the aspect ratio on the rate and per cent extraction of Cu(II) ions.

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