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Operating cost analysis of electrocoagulation of textile dye wastewater

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Abstract

Electrocoagulation (EC) is an efficient method for textile wastewater treatment. Researches are mainly focused on the technical performance of this process, while its economic aspect has been usually neglected. This paper deals with a simplified operating cost analysis for the treatment of a textile wastewater by EC using iron and aluminium electrode materials. The effects of various parameters such as wastewater conductivity and pH, current density and operating time, on the operating cost have been discussed for two electrode materials, separately.

Keywords: Textile wastewater; Cost; Electrocoagulation; Aluminium; Iron

1. Introduction

Wastewaters from dying and finishing processes in textile industry are characterized by intense colour, high levels of Chemical oxygen demand (COD) and dissolved solid, and highly fluctuating pH [1–3].

Conventional methods for dealing with textile wastewater consist of various combinations of biological, physical and chemical methods [4–7]. Due to high capital and operating costs of these methods, there is an urgent need to develop more efficient and inexpensive methods which require minimum chemical and energy consumptions, as well as minimum installation space when high land price are taken into account. In recent years, investigations have been focused on the treatment of wastewaters using EC. Various kinds of wastewater which have been tested successfully by EC are: egg proces wastewater [8], restaurant wastewater [9,10], arsenic containing smelter wastewater [11], saline wastewater [12], rendering wastewater [13], tanneries and landfill leachates [14–16], urban wastewater [17], carpet wastewater [18], tar sand and oil shale wastewater [19], food and protein wastewater [20], chemical fiber wastewater [21], paper pulp industry wastewater [22], oily wastewater [23,24], and yeast wastewater [25].

EC treatments of textile dye-containing synthetic or real wastewater samples have been investigated on laboratory scale and good removals of COD, color, turbidity and dissolved solids at varying operating conditions have been obtained [7,26–36]. These researches are mostly concentrated on elu-

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Table 1
Characteristics of wastewater

Character	Value
COD (mg/l)	3422
TSS (mg/l)	1112
TOC (mg/l)	900
Conductivity (μS/cm)	3990
Turbidity (NTU)	5700
pH	6.95

ciating the effects of various process variables and wastewater characteristics on the performance of EC process. Meanwhile, it is clear that a technically efficient process must also be feasible economically as regard with its initial capital and operating costs, to be practically applicable to environmental problems. The economic aspect of the electrocoagulation (EC) process is not well investigated, except a few researches [37–39]. In this respect, the effects of the electrode material type as well as process variables on process economics need to be studied in detail.

In this study, the treatment of textile wastewater by EC using aluminium and iron electrode materials is investigated by determining the effects of relevant wastewater characteristics and operational variables on the operating cost, as well as on technical performances such as COD and turbidity removal efficiencies. In the calculation of the operating cost, only material and energy costs are considered, other cost items such as labour, maintenance, solid/liquid separation costs are not taken into account. The simplified cost equation is used to evaluate the effect of various process variables on the operating cost.

2. A brief description of EC

Electrocoagulation is a complex process occuring via serial steps such as; electrolytic reactions at electrode surfaces, formation of coagulants in aqueous phase, adsorption of soluble or colloidal pollutants on coagulants which are removed by sedimentation or flotation.

The most widely used electrode materials in EC process are aluminium and iron. In the case of aluminium, main reactions are as

$$\text{Anode}: \quad Al \rightarrow Al^{3+} + 3e \tag{1}$$

$$\text{Cathode}: \quad 3H_2O + 3e^- \rightarrow \frac{3}{2}H_2 + 3OH^- \tag{2}$$

On the other hand, at high pH values, both cathode and anode may be chemically attacked by OH^- ions [40]:

$$2Al + 6H_2O + 2OH^- \rightarrow 2Al(OH)_4{}^- + 3H_2 \tag{3}$$

Al^{3+} and OH^- ions generated by electrode reactions (1) and (2) react to form various monomeric species such as $Al(OH)^{2+}$, $Al(OH)_2{}^+$, $Al_2(OH)_2{}^+$, $Al(OH)_4$, and polymeric species such as $Al_6(OH)_{15}{}^{3+}$, $Al_7(OH)_{17}{}^{4+}$, $Al_8(OH)_{20}{}^{4+}$, $Al_{13}O_4(OH)_{24}{}^{7+}$, $Al_{13}(OH)_{34}{}^{5+}$, which transform finally into $Al(OH)_{3(s)}$ according to complex precipitation kinetics [31–33, 41–44].

$$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+ \tag{4}$$

Freshly formed amorphous $Al(OH)_{3(s)}$ "sweep flocs" have large surface areas which is beneficial for a rapid adsorption of soluble organic compounds and trapping of colloidal particles. Finally, these flocs are removed easily from aqueous medium by sedimentation or H_2 flotation.

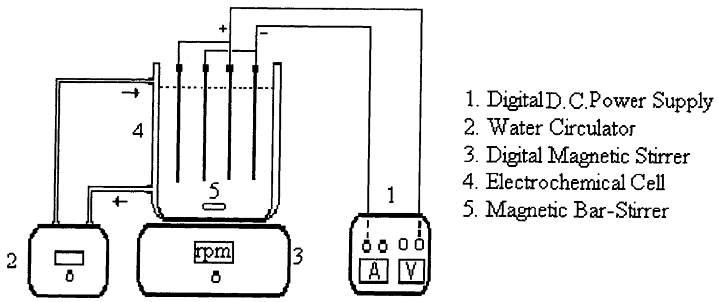

Fig. 1. A schematic diagram of experimental set-up.

In the iron case, two mechanisms have been proposed [31–34,45–47].

- Mechanism 1:

$$\text{Anode}: \quad 4Fe \rightarrow 4Fe^{2+} + 8e \tag{5}$$

$$4Fe^{2+} + 10H_2O + O_2 \rightarrow 4Fe(OH)_3 + 8H^+ \tag{6}$$

$$\text{Cathode}: \quad 8H^+ + 8e \rightarrow 4H_2 \tag{7}$$

$$\text{Overall}: \quad 4Fe + 10H_2O + O_2 \rightarrow 4Fe(OH)_{3(S)} + 4H_2 \tag{8}$$

- Mechanism 2:

$$\text{Anode}: \quad Fe \rightarrow Fe^{2+} + 2e \tag{9}$$

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \tag{10}$$

$$\text{Cathode}: \quad 2H_2O + 2e \rightarrow H_2 + 2OH^- \tag{11}$$

$$\text{Overll}: \quad Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2 \tag{12}$$

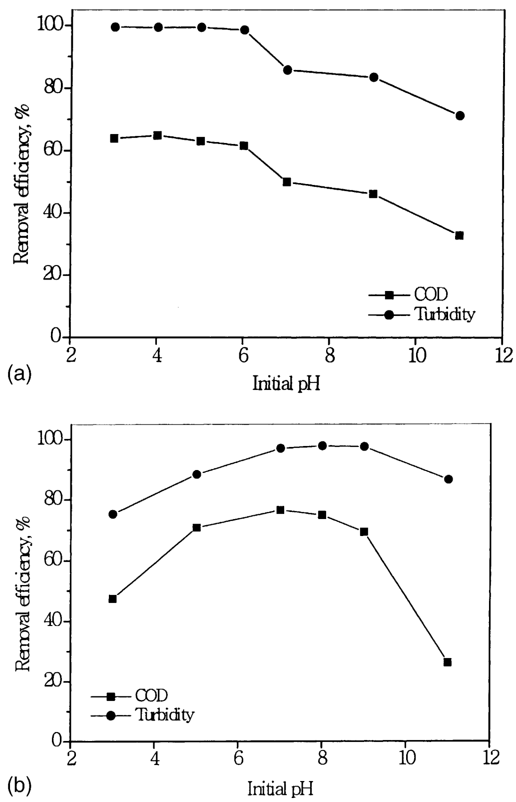

Fig. 2. (a) Effect of initial pH on COD and turbidity removal by aluminium electrodes and (b) iron electrodes.

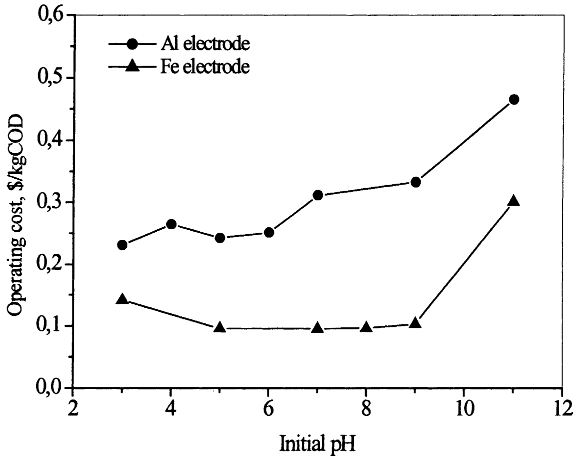

Fig. 3. Effect of initial pH on cost.

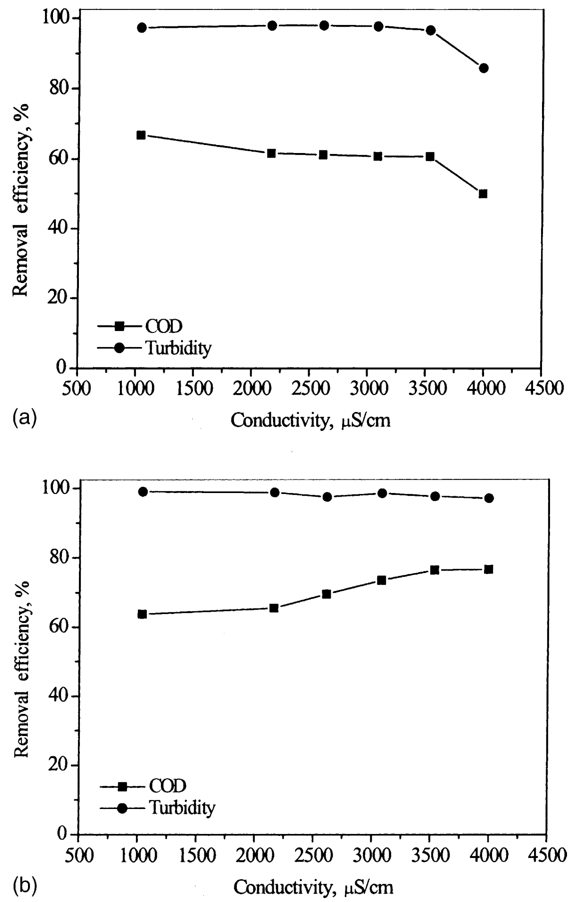

Fig. 4. (a) Effect of wastewater conductivity on COD and turbidity removal by aluminuim electrodes and (b) iron Electrodes.

If anode potential is sufficiently high, secondary reactions may occur also, such as direct oxidation of organic compounds and of Cl^- ions present in wastewater [9,12].

3. Experimental

Wastewater is obtained from a tank containing a mixture of exhaust dyeing solutions at a textile factory in Turkey (Gebze) producing aproximately 1000 m^3 of wastewater per day. The composition of the wastewater is shown in Table 1. The wastewater is first filtered using a screen filter to remove large suspended solids before it was used for the subsequent studies.

The experimental setup is shown in Fig. 1. The thermostat electrocoagulator is made of plexiglass with the dimensions 65 mm × 65 mm × 110 mm. There are four monopolar electrodes, two anodes and two cathodes of the same dimensions. Both aluminium (Al: 99.53%) or iron (Fe: 99.50%), cathodes and anodes were made from plates, with dimensions of 46 mm × 55 mm × 3 mm. The total effective electrode area is 78 cm^2 and the spacing between electrodes was 11 mm. The electrodes were connected to a digital dc power supply (Topward 6306D; 30 V, 6 A) with potentiostatic or galvanostatic operational options.

All the runs were performed at constant temperature of 25 °C and stirring speed 200 rpm. In each run, 250 cm^3 of wastewater solution was placed into the electrolytic cell. The current density was adjusted to a desired value and the operation was started. At the end of EC, the solution was filtered, the filtrate was centrifugated at 2000 rpm, and was analysed. Before each run, the electrodes were washed with acetone to remove surface grease, and the impurities on the aluminium or iron electrode surfaces were removed by dipping for 5 min in a solution freshly prepared by mixing 100 cm^3 HCl solution (35%) and 200 cm^3 of hexamethylenetetramine aqueous solution (2.80%) [30]. At the end of the run, the electrodes was washed throughly with water to remove any solid residues on the surfaces, dried and weight again. The same experiments are runned with both electrode materials, for comparative purpose.

COD, total suspended solids (TSS), total organic carbon (TOC) and turbidity were out according to the Standard Methods for Examination of Water and Wastewater [48]. COD was analysed by closed reflux colorimetric method. Shimadzu Model UV-160 double beam spectrophotometer was used for COD and turbidity measurements. For TOC analysis, Euroglas 1200 total organic carbon analyser was used. The pH and conductivity were adjusted to a desirable value using NaOH or H_2SO_4, and NaCl (Merck), respectively.

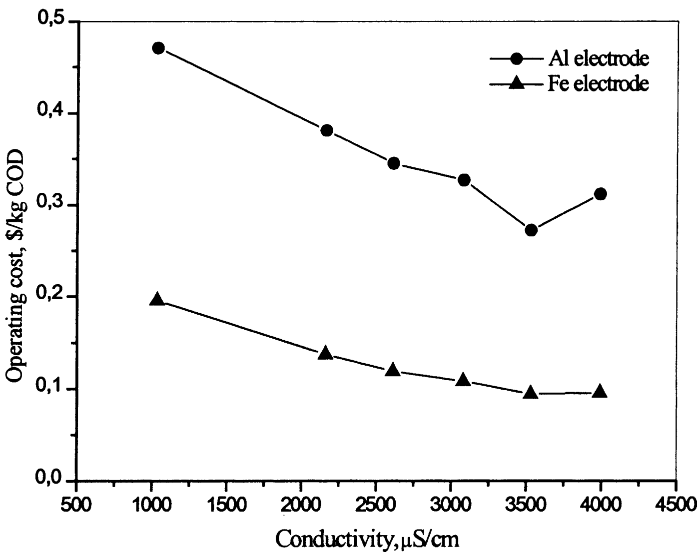

Fig. 5. Effect of wastewater conductivity on cost.

4. Results and discussion

The operating cost includes material (mainly electrodes) cost, utility (mainly electrical energy) cost, as well as labor, maintenance and other fixed costs. The latter costs items are largely independent of the type of the electrode material. Thus, in this preliminary economic study, energy and electrode material costs are taken into account as major cost items, in the calculation of the operating cost as kWh per kg of COD removed;

$$\text{Operating cost} + aC_{\text{encrgy}} + bC_{\text{electrode}} \tag{13}$$

where C_{energy} and $C_{\text{electrode}}$, are consumption quantities per kg of COD removed, which are obtained experimentally. Unit prices, a and b, given for Turkey Market, November 2002, are as follows:

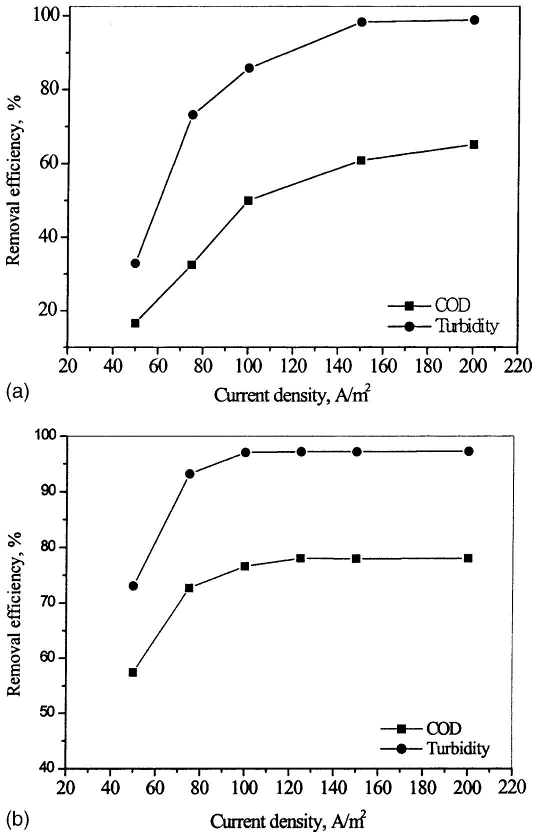

Fig. 6. (a) Effect of current density on COD and turbidity removal by aluminium electrodes and (b) iron electrodes.

(a) electrical energy price 0.06 US$/kWh.
(b) electrode material price 1.80 US$/kg for aluminium and 0.30 US$/kg for iron, respectively. Based on preliminary experimental results, the effects of pH and conductivity have been explored at constant current density 100 A/m^2 and operating time 10 min.

4.1. *Effect of initial pH*

pH is an important operating factor influencing the pefformance of EC process, as observed also by other investigators [7,9,27–34]. The pH of the medium changes during the process, depending on the type of electrode material and initial pH. Meanwhile, EC process exhibits some buffering capacity, especially in alkaline medium, which prevents high changes in pH [9].

The effect of the initial pH on the COD and turbidity removal efficiencies is presented in Fig. 2a for the aluminium electrode; in acidic medium, the turbidity removal is as high as 98%, and COD removal is between 61 and 65%, both removals drop dramatically above pH 6. For iron electrode, as seen in Fig. 2b, in the initial pH range 3–7, the turbidity and COD removals reach 98–75% and 77–47%, and above pH 10, they drop to 87 and 26%, respectively. Thus, it may be concluded that in acidic medium, higher removal efficiencies are obtained with aluminium, while in neutral and weakly alkaline medium iron is more efficient.

Fig. 3 depicts the effect of the initial pH on the operating cost, comparatively for two materials. In the case of aluminium, operating cost increases steadily with increasing pH, while in the case of iron, it is almost independent of the initial pH between 5 and 9, and it is three times lower than that of aluminium. Almost a constant percantage of the total cost, 78%, accounts for the material cost in the aluminium case, while for iron electrode, 58–62% of the total cost results from electrode material consumption.

4.2. *Effect of conductivity*

Textile wastewaters exhibit a broad variation in ionic strength, due to the high concentrations of various chemical substances added during dyeing and finishing processes. It is well known that increasing electrical conductivity cause an increase in the current density at constant cell voltage, or a decrease in the cell voltage at constant current density. Meanwhile the effect of the conductivity on COD and turbidity removals, as well as on the operating cost is not very straightforward, which need to be investigated experimentally. Wastewater conductivity is adjusted by adding an appropriate amount of NaCl or deionized water to raw wastewater. This adjustment has shown negligible effect on the initial pH of the wastewater, approximately 0.3 pH units, with mean pH value 6.8.

Fig. 4a and b show the effect of wastewater conductivity on the performance of the EC process, for aluminium and iron electrodes, respectively. As seen, the turbidity removal efficiency remains almost unchanged in the conductivity range 1000–4000 μS/cm, for both electrode materials, whereas with increasing conductivity, the COD removal efficiency is slightly reduced in the case of aluminium, and, it is slightly enhanced for iron electrode, as also reported by Lin and Peng [7].

The effect of wastewater conductivity on the operating cost is shown in Fig. 5; For both electrode materials, operating cost decreases with increasing conductivity. For aluminium, the percentage of the electrode consumption cost to the total cost, is nearly constant as 76%. For iron, on the other hand, this ratio increases from 33 to 58%, by increasing conductivity from 1000 to 4000 μS/cm.

4.3. Effect of current density and operating time

Fig. 6a and b depict the effect of current density on COD and turbidity removal efficiencies, for iron and aluminium electrode materials, with operating time constant at 10 min. In the case of aluminium, minimum 150 A/m^2 is required for good removal efficiencies, with a charge loading approximately equal to 28 Faradays/m^3. In the case of iron, 80–100 A/m^2 is sufficient with a charge loading 17 Faradays/m^3. These efficiencies and consumption values show the high performance of iron over aluminium as electrode material, at a current density between 80 and 100 A/m^2 as an optimal value for the wastewater studied in this paper.

Fig. 7 shows the operating cost as function of the current density, for two electrode materials comparatively. The cost curve of aluminium exhibits a minimum point at approximately 100 A/m^2 this results from the fact that electrode cost decreases while energy cost increases, with increasing current density. For the case of iron, operating cost is almost linear function of the current density. By increasing current

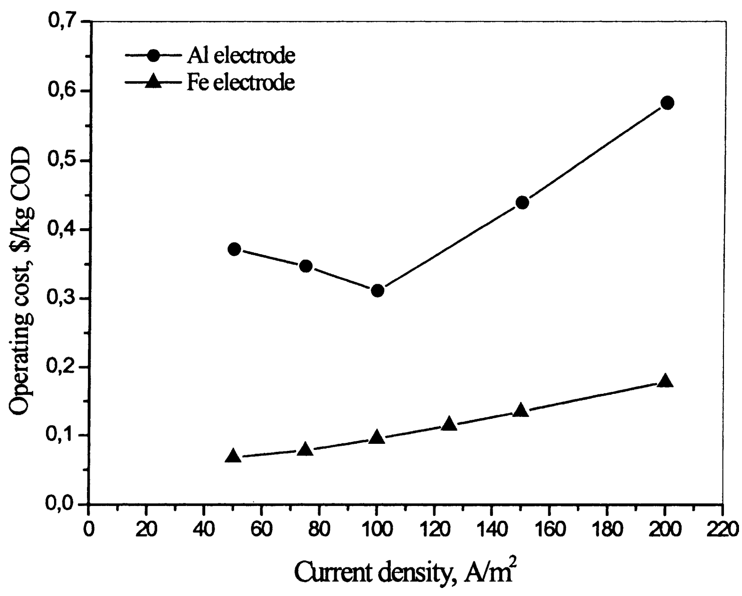

Fig. 7. Effect of current density on cost.

density from 50 to 200 A/m^2, the ratio of electrode cost to the operating cost increases steadily from 48 to 62%.

The effect of operating time is explored at constant current density of 100 A/m^2. As seen in Fig. 8a, the aluminium electrode requires at least 15 min for good removal efficiencies, while for iron electrode, 10 min is sufficient according to Fig. 8b. On the other hand, by comparing Figs. 6 and 8, it is easily seen that the current density and the operating time exhibit similar effects on process performance. This suggest to combine the two variables as a new variable which is the charge loading expressed as Faraday per unit volume (or mass) of wastewater.

Finally, Fig. 9 depicts the total cost curves, for two electrode materials, as a function of time. Similar to curves in Fig. 7, the cost curve of aluminium has a minimum for an operating time of 7.5 min. The ratio of electrode consumption cost to the total cost shows also a weak minimum for an operating time of 10 min. On the other hand, the cost curve of iron is linear function of the operating time, and the percentage of the electrode consumption cost to the total cost decreases from 61 to 57%, by increasing operating time from 5 to 30 min.

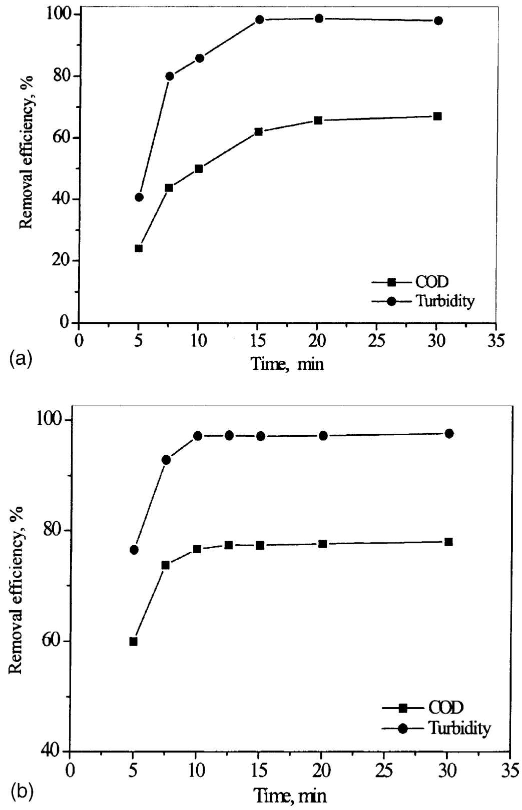

Fig. 8. (a) Effect of electrocoagulation time on COD and turbidity removal by aluminium electrodes and (b) iron electrodes.

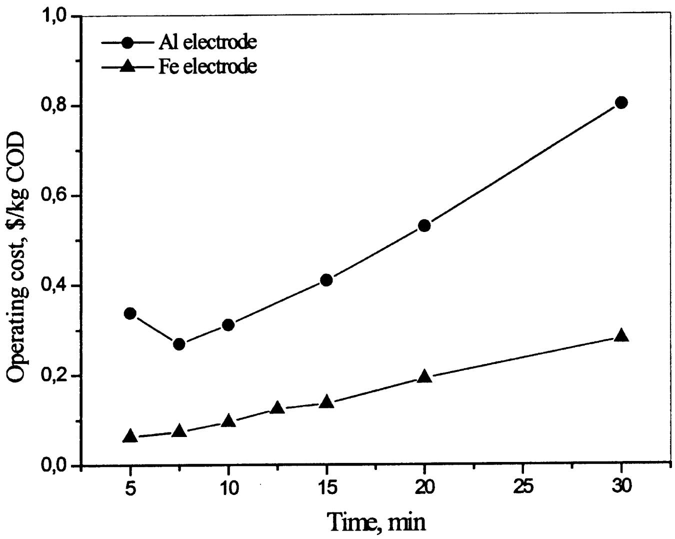

Fig. 9. Effect of electrocoagulation time on cost.

5. Conclusion

Iron and aluminium are used as sacrificial electrode materials in the treatment of textile wastewater by EC. In acidic medium, COD and turbidity removal efficiencies of aluminium are higher than those of iron, while in neutral and weakly alkaline medium iron is more efficient. High conductivitiy is in favor of high process performances and low operating cost. For the same turbidity and COD removal efficiencies, iron requires a lower current density than aluminium. Operating time and current density exhibit similar effects on the process performances and the operating cost. The energy consumption is lower with iron, while the electrode consumption is lower generally with aluminium.

Cost calculations show that, in the case of iron electrode, operating cost is approximately 0.1 US$ per kg COD removed, and for aluminium, it is 0.3 US$ per kg COD removed. Electrode consumption cost accounts nearly 50% of the total cost for iron, and 80% of the total cost for aluminium.

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 for a more precise comparison of the electrode material. The simplified approach used in this study provides only preliminary data for a detailed analysis.

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