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# Particulate Solids Removal from Synthetic and Real Turbid Water and Wastewater by Electro coagulation Using Vertical Expanded Al Anode

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## Abstract

The performance of an innovative cell design in removing particulate solids from synthetic turbid water by electrocoagulation has been investigated. The cell consists of two concentric vertical cylindrical Al-electrodes; the outer electrode is a cylindrical solid Al- cathode, whereas the inner electrode is an expanded cylindrical Al-anode. The distance between the two electrodes is 1 cm apart. The performance of the present cell has been measured in terms of % removal of particulate solids and power consumption. The effect of key parameters such as electrolysis time, current density, pH, initial particulate solid concentration, NaCl concentration and solution velocity on the % removal of particulate solids has been investigated. The results revealed that as current density increases the % removal increases. Whereas as NaCl concentration and solution velocity increase, the % removal decreases. The optimum pH corresponding to the maximum % particulate solids removal and minimum power consumption is 10. At the optimum condition an energy consumption of 0.48 kW.h is required for the removal of one kg of particulate solids. Kinetic study of the present time data revealed that the rate of the removal follows second-order kinetic model. The performance of the present cell has been proven to be efficient for the treatment of real raw and wastewater.

**Keywords:** Particulate solids removal; Turbidity removal; Water treatment; Wastewater; Electrocoagulation; Expanded electrodes; Aluminum electrode; Kaolinite clay removal

**Abbreviations:** A: Active anode area $cm^2$; C0: The initial clay concentration ppm; C: The clay concentration at time t ppm; I: Applied Current A; k: Second order rate constant $(mg.s/l)-1$; t: Time of electrolysis min;

## Introduction

One of the major challenges facing mankind today is providing clean water to a vast majority of the population around the world. The quality and quantity of available water are two particularly critical problems facing not only the third-world countries but also the whole world. Rivers; canals and other water bodies are being constantly polluted due to indiscriminate discharge of industrial effluents as well as other anthropogenic activities and natural processes [1]. Particulate solids pollutants in particular are present in water in two main forms: suspended particles and colloids. Suspended particles; such as sand; vegetable matter and silts; range in size from very large particles down to particles with a typical dimension of 10 μm. Colloids are very fine particles; typically ranging from 10 nm to 10 μm. There are two types of colloids: hydrophilic colloids and hydrophobic colloids. Hydrophobic colloids, including clay and non-hydrated metal oxides, whereas hydrophilic colloids like soap [2].

The presence of such particulate solids such as algae; clays; silts; colloids and organic particles in water often causes it to get turbid. Turbidity is one of the principal physical characteristics of water; excessive turbidity; or cloudiness; in drinking water is aesthetically unappealing; and may also represent a health concerns as it can provide food and shelter for pathogens. If not removed; turbidity can promote re-growth of pathogens in the distribution system; leading to waterborne disease outbreaks; which have caused significant cases of gastroenteritis. Although turbidity is not a direct indicator of health risk; numerous studies showed a strong relationship between removal of turbidity and removal of protozoa [3].

The conventional methods for the removal of turbidity causing particulate solids involve the bulk addition of inorganic coagulants (e.g. aluminum or ferric salts) which are responsible for combining small particles into larger aggregates. As the conventional chemical coagulation has advantages such as it is simply operated; it has also major problems such as high amount of chemicals needed and high amount of sludge produced [4-6].

Electrocoagulation process is a promising technology that can be used for the removal of both suspended solids and colloidal particles. Electrocoagulation is the electrochemical production of destabilization agents that brings about charge neutralization of negative charged surfaces of colloidal or suspended particles. Once charge neutralized; the particles bond together like small magnets to form a largeflocs [7]. These flocs can be easily separated either by gravity settling or by electroflotation where the evolved gas bubbles at the cathode would enhance flocs growth and their separation by flotation.

Electrocoagulation process offers some advantages over traditional chemical treatment: less coagulant ion is required; less sludge is formed; and electrocoagulation equipment is very compact; thus; suitable for installation where the available space is rather limited. Moreover; The EC process has the advantage of removing the smallest colloidal particles; because the applied electric field sets them in faster motion; thereby facilitating the coagulation [8].

Recently EC has been applied successfully to treat lignin and phenol [9] kaolin-polluted wastewater [10] heavy metals [11] chemical mechanical polishing wastewater [12] oil emulsions [13] and fermentation wastewater [14]. All previous studies have investigated the performance of EC for removal of pollutants using traditional parallel plate electrode cell. There is scant attention has been given to the use of innovative cell designs.

The aim of the present study is to investigate the performance of a new EC cell configuration for the removal of kalointe as source of particulate solids from synthetic turbid solution. The present EC cell consists of two vertical cylindrical Al sheets separated by 1 cm gap. The outer cylinder is solid Al sheet cathode; whereas the inner cylinder is a screen mesh Al anode. The small electrode gap could minimize the IR drop; while the mesh screen anode would provide high specific surface area.

Optimum conditions of electrocoagulation process for the kaolinite clay removal were studied in relation to the following key parameters: i)-Electrolysis time; ii)-Current density; iii)- pH; iv)- Clay concentration; v)- NaCl concentration and vi)- solution velocity. In addition the performance of the present study was investigated to treat real turbid raw and waste water effluent.

## Material and Methods

### Materials

Figure 1 shows a schematic diagram of the batch experimental setup. It consisted mainly of a plexi glass container; a cell and an electric circuit. The cell consisted of a solid cylindrical Al cathode of 12 cm diameter and 20 cm height which was insulated from the container side and was supported on the inner wall of the container. The anode was a cylindrical Al anode screen of 10 mesh number; 10 cm diameter and 15 cm height. Four baffles were supported on the cathode to keep a fixed distance of 1cm between the anode and the cathode to avoid short circuit of the cell. The electric circuit consisted of a D.C power supply; a multi-range ammeter connected in series to measure the cell current and a voltammeter connected in parallel to measure the cell voltage.

The study was conducted on a synthetic turbid solution using kaolinite clay. The kaolinite clay was supplied from LECICO for ceramics company; Alexandria; Egypt. Table 1 shows the chemical composition of main oxides present in the used clay. All the regents and chemicals used in the present work are analytical reagent grade.
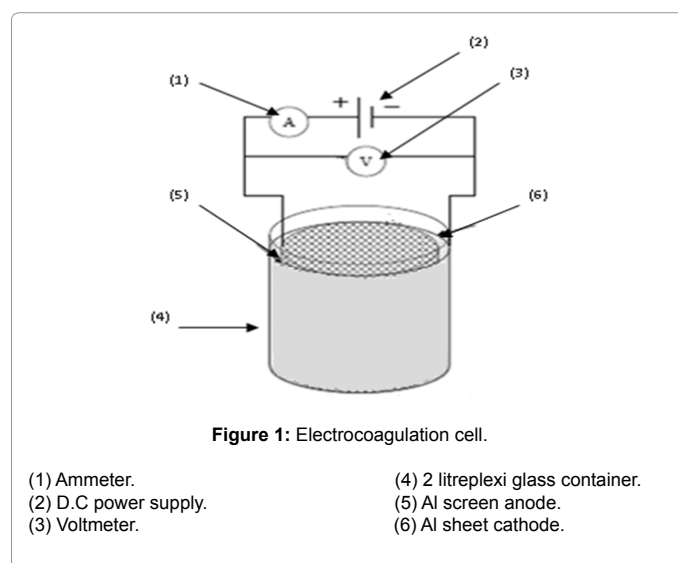
Figure 2, shows a schematic diagram of the flow system experimental setup. It included beside to the above mentioned components a flow system. The flow system consisted of 5 liters storage tank; a 0.12 hp plastic pump to deliver the clay solution to the EC cell and a filter screen was supported in the overflow weir to prevent the recirculation of the sludge to the storage tank.

### Methods

Before each run the electrodes were pickled in a 10% HCl for 10 mins to remove any oxide. A stock of 500 ppm of the kaolinite clay solution was prepared using distilled water and few drops of 1N NaOH were added to the solution as peptizer to ensure deflocculation of clay. Batch experiments were carried out by placing 1.5l of freshly prepared clay solution in the cell. The pH of solution was measured before and after each experiment using a microprocessor pH meter (HANNA pH 211; Italy). NaCl was used as an electrolyte. Current was adjusted to predetermined values using a D.C power supply (BK Precision
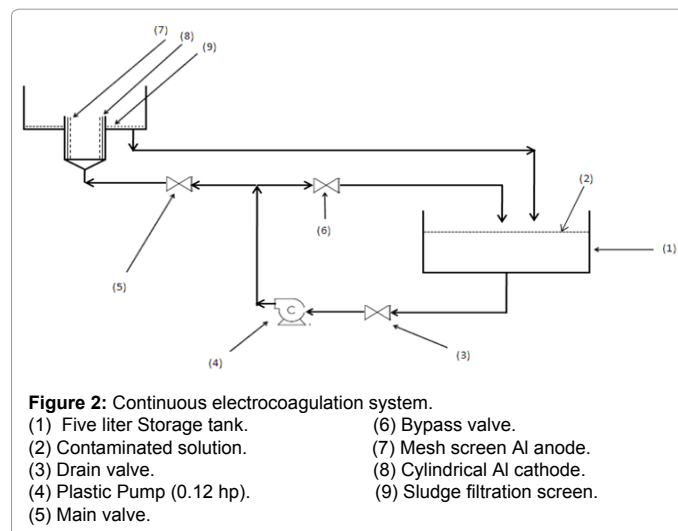
model 1686) whereas cell voltage was recorded during the run using an avometer (EXCEl DT9205A; China). EC progress was followed by taking a sample from the cell every 2 minutes from the same location in the cell and each sample was left for 10 mins before analysis to allow settling. The absorbance of each sample was measured using a spectrophotometer (ZUZI spectrophotometer 4201/20; Spain) at a wave length 340 nm which corresponding to maximum absorbance. Initial pH of the solution was adjusted either using 30% caustic soda (NaOH) or concentrated sulfuric acid ($H_2SO_4$).

In case of studying the effect of solution velocity; the flow rate of the solution was estimated by measuring the time of delivering a known volume. The variation of flow rate was done by adjusting the main and/or the bypass valve.



**Figure 1:** Electrocoagulation cell.

| | |
|---|---|
| (1) Ammeter. | (4) 2 litreplexi glass container. |
| (2) D.C power supply. | (5) Al screen anode. |
| (3) Voltmeter. | (6) Al sheet cathode. |

| Components | Percentage (%) |
|---|---|
| $SiO_2$ | 46.6 |
| $Al_2O_3$ | 36.5 |
| $H_2O$ | 13.9 |
| Impurities | 3 |

**Table 1:** Chemical composition of the kaolinite clay.



**Figure 2:** Continuous electrocoagulation system.

| | |
|---|---|
| (1) Five liter Storage tank. | (6) Bypass valve. |
| (2) Contaminated solution. | (7) Mesh screen Al anode. |
| (3) Drain valve. | (8) Cylindrical Al cathode. |
| (4) Plastic Pump (0.12 hp). | (9) Sludge filtration screen. |
| (5) Main valve. | |

## Results and Discussion

The effectiveness of the present cell was measured in terms the % of clay removal using the following equation:

$$\text{\% clay removal} = (C_0 - C)/C_0 \qquad (1)$$

Where; $C_0$: The initial clay concentration; C: The clay concentration at time t.

### Effect of electrolysis time

Figure 3, depicts the effect of electrolysis time on % clay removal at different current densities. The % clay removal increases rapidly to reach about 77.4 to 94.5 % in a 2 mins (reactive stage) then it approaches almost a constant removal rate (stable stage) at approximately 12 mins. Rahmani [4]; and Kilic and Hosten [15] have observed the same trend. Whereas Holt et al. [16,17]; have indicated that in the removal of clay or colloidal matters by EC there are three operating stages: i) lag (where no significant change in clay removal takes place); ii) reactive stage (in which most of clay removal occurs) and finally iii) stable stage (where clay removal is approximately constant). The absence of a lag stage in the present study can be attributed to the high anode surface area. This high area can release sufficient $Al^{+3}$ into the solution for effective destabilization of the colloidal particles. Mollah et al. [6] and Canizares et al. [10] indicated that the main mechanisms responsible for the clay or colloidal matters removal during EC are:

i. Charge neutralization of negatively charged particles of the clay through the electrophoresis migration of those particles towards the anode under the influence of electrical field.

ii. Charge neutralization of the negatively charged clay particles by adsorption of monomeric and polymeric hydrolysis species of $Al^{+3}$.

iii. The charge neutralized clay particles coalesce upon collision as a result of their Brownian movement or their electrophoretic migration to form a larger floc which can be easily removed.

iv. Sweep flocculation which takes place as the $Al(OH)_3$ reaches its minimum solubility and precipitates and during its precipitation clay particles may be enmeshed between $Al(OH)_3$ and removed from the bulk.

v. The coalesced clay particles may adhere to $H_2$ bubbles generated at the cathode and float to the surface and can be easily removed.

It should be noted that all the above mechanisms contribute to a certain degree in the removal of clay during reactive stages. However; during stable stage; the concentration of clay particle decreases and charge neutralization through electrophoretic migration diminishes; on the other hand the pH reaches neutrality and $Al(OH)_3$ precipitates. Thus sweep flocculation or enmeshment is the main dominant removal mechanism in that stage [17].

A time of 12 mins was chosen as the optimum electrolysis time for further experiments.

### Effect of current density

Figure 4, shows the effect of current density on the % clay removal and power consumption. It is noted that as current density increases from 10.13 to 29.1 $A/m^2$; the % clay removal increases slightly from 96.9 to 99.1 % and power consumption increases from 1.05 to 6.03 kW.hr/

kg. The increase in the % removal with increasing current density may be attributed to the increase of the electrophoretic motion under the applied electrical field; beside to the increase of the concentration of $Al^{+3}$ ions generated at the anode according to Faraday's law. The increase of both electrophoretic motion and concentration of $Al^{+3}$ ions enhance charge neutralization of clay particles which is believed to be the main mechanism responsible for their removal. Moreover; as current density increases hydrogen bubble generation rate increases and bubble size decreases. Which could improve floc formation and growth and their subsequent flotation [18]. The optimum current density of 10.13 A/$m^2$ was selected for further experiments based on the minimum power consumption.

### Effect of NaCl concentration

Figure 5, shows the effect of NaCl concentration on % clay removal and power consumption. It is well seen that as NaCl concentration increases from 0.25 to 1 g/l the % clay removal decreases from 99.39 to 92.6 % while the power consumption decreases to a minimum value and then increases once again. This effect of NaCl concentration on % clay removal may be attributed to that the increase of NaCl concentration
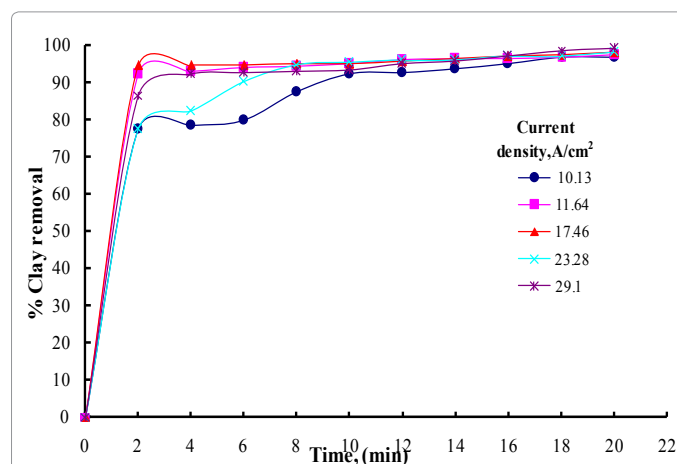


**Figure 3:** Effect of electrolysis time on the % clay removal [Clay concentration= 500ppm, pH=10.52, NaCl concentration=1g/l].
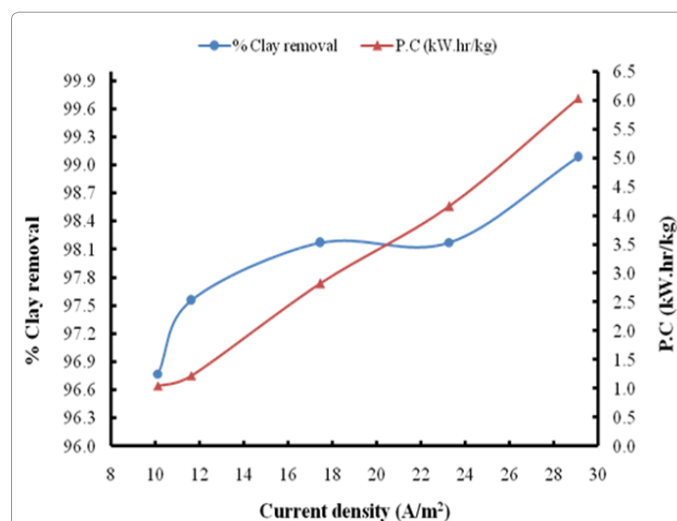


**Figure 4:** Effect of current density on the % clay removal [Clay concentration= 500ppm, pH=10.52, NaCl concentration=1g/l, Electrolysis time=12 min].

causes an increase in the solution ionic strength which could affect the electrophoretic mobility of the clay particles. In addition; the Cl⁻ could retard the electrophoretic mobility of the clay particles as it has a higher mobility than the clay particles towards the anode. Fouad et al. [19] found that the demulsification of a crude oil emulsion by electrophoresis decreases with increasing NaCl concentration. They attributed their results to that the competing chloride migrates to the anode surface inpreference to the negatively charged clay particles. Lung Chou et al. [20] have indicated that an excess amount of NaCl in the solution is detrimental to removal of turbidity. The present trend is in agreement with the work of Can et al. [21]. However; Emamjomeh and Sivakumar [22] and Merzouk et al. [23] showed a trend in contrast to the present work.

The optimum NaCl concentration of 0.75 g/l was selected for further experiments based on the minimum power consumption.

## Effect of initial pH

Figure 6, shows the effect of initial pH on % clay removal and power consumption. It can be noted that the initial pH has a little effect on the % clay removal as the % removal ranges between 93.44 to 97.8 % within the investigated pH range (4-11). Maximum % clay removal (97.8) corresponding to pH 10. Solak et al. [24] found that maximum removal of suspended solids by EC on Al anode is at pH 9. Kilic and Hosten [15] found that the highest % turbidity removal occurred near pH =9 where the zeta potential approached the isoelectric point of kaolinite particles.

The insignificant effect of pH on the clay removal may be explained by the presence of different mechanisms which contribute to the clay removal as stated previously.

The optimum pH was found to be 10 based on maximum % clay removal and minimum power consumption.

## Effect of initial clay concentration

Figure 7, shows the effect of initial clay concentration on both % clay removal and the power consumption. It is well noted that as the initial clay concentration increases from 250 to 700 ppm; the % removal decreases slightly from 98 to 95. 6% and power consumption decreases from 1.17 to 0.53 kW.hr/kg. The insignificant effect of initial clay concentration on the removal may be due to that as the initial clay concentration increases; the chance for coalescence by electrophoretic migration increases at the same time the adsorption capacity of $Al(OH)_3$ consumed rapidly for fixed current density and the removal by sweep coagulation decreases and due to the presence of such two opposing effects; the net result is the slight dependence of % removal on the initial clay concentration .

Merzouk et al. [18,23] showed a decline in % turbidity removal or clay removal as the initial concentration increases.

## Effect of solution velocity

Figure 8, shows the effect of solution velocity on % clay removal and power consumption. It is noticed that as the solution velocity increases from $2.83 \times 10^{-3}$ to $8.51 \times 10^{-3}$ m/s; the % clay removal decreases from 90.53 to 84.44. Matteson et al. [25] have indicated that vigorous stirring rate will hinder the coagulation because particles are removed from the region near the anode before they have chance to charge neutralized by the generated ions. At the same time if flocs are formed; they will not have the sufficient time to allow flocs aggregation to form larger flocs. Moreover; large flocs may be broken to smaller flocs due to
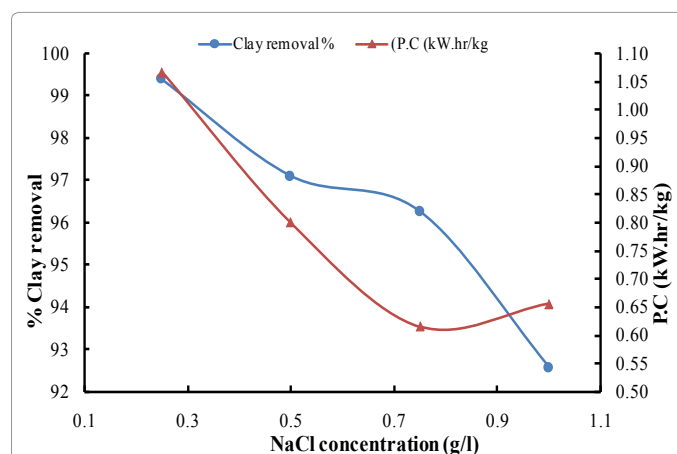


**Figure 5:** Effect of NaCl concentration on the % clay removal [Clay conc. = 500ppm, pH=10.50, Current density=10.13 A/m2, Electrolysis time=12 min].
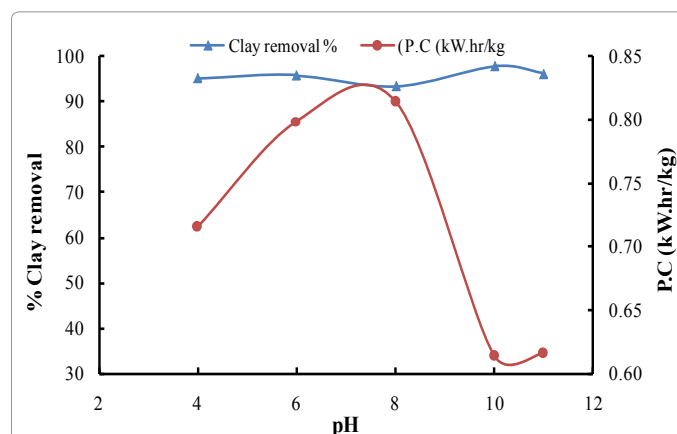


**Figure 6:** Effect of initial pH on the % Clay removal [Clay concentration = 500 ppm, Current density=10.13 A/m2, NaCl concentration=0.75 g/l, Electrolysis time = 12 min].
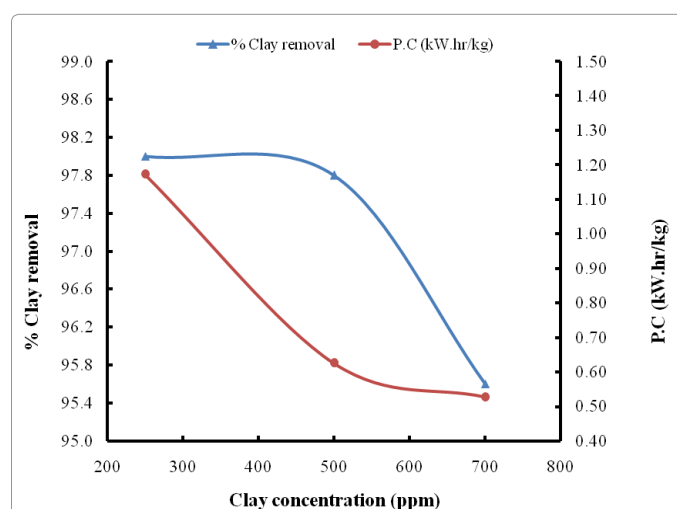


**Figure 7:** Effect of initial concentration on the % clay removal [Current density=10.13 A/m2, pH=10, NaCl concentration =0.75g/l, Electrolysis time=12 min].

vigorous stirring. Emamjomeh and Sivakumar [22] showed the same trend of solution velocity on % removal. A velocity of $4.25*10^{-3}$ m/s was chosen as the optimum velocity. It should be mentioned that under the optimum investigated operating conditions the corresponding power consumption was found to be 0.48 0.48 kW.hr/kg.

## Kinetics of electrocoagulation

There are many models to describe some of the physical processes taking place in the electrocoagulation. In the present study it was assumed that the process undergoes a second order reaction rate. Hence; the rate of electrocoagulation can be expresses by the following equation:

$$-[dc/dt]=kC^2 \qquad (2)$$

By integration yields:

$$[(1/C)-(1/C_0)]=kt \qquad (3)$$

Where:

C: Clay concentration at time t; $C_0$: Initial clay concentration; k: second order rate constant; t: electrolysis time.

Figures 9-11, show the plot of 1/C versus time at different conditions. The data fit the second order kinetic model to a fair extent. The present results are in agreement with kinetic model proposed by Matteson [25]. According to their model it is proposed that the ions generated by the electrodissolution of the anode neutralize the superficial charge of the colloidal particles; and that the efficiency of the process is a function of the electrophoretic velocity of colloidal particles toward the anode and not of the Al generation rate. The electrocoagulation rate is represented by a second order rate equation that incorporates the electrophoretic migration of particles toward the anode. Figure 12 shows the effect of electro-generated Al dose on % clay removal. It is well noted that the Al dose has insignificant effect on the % clay removal which could also support the proposed kinetic model.

## Case study

The efficiency of turbidity removal from real wastewater and raw water obtained from El-Maamoura water treatment plant (Alexandria; Egypt) were examined using the present cell. Table 2 and 3 shows the main characteristics of wastewater and raw water.



**Figure 8:** Effect of solution velocity on the % Clay removal [current density=33.85 A/m2, pH=10, NaCl concentration =0.75g/l, Electrolysis time=12 min].



**Figure 9:** (1/C) vs. time at different current densities [Clay concentration= 500ppm, pH=10.52, NaCl=1g/l].



**Figure 10:** (1/C) vs. time at different NaCl concentrations [Clay concentration= 500ppm, pH = 10.52, C.D=10.13 A/m2].
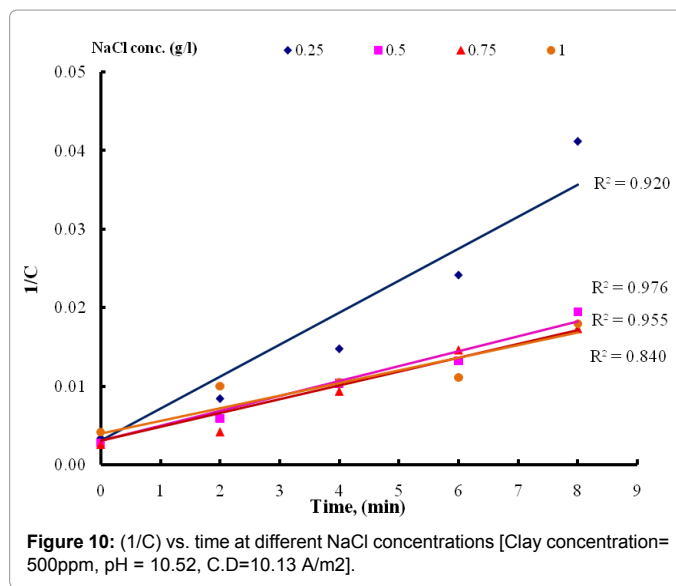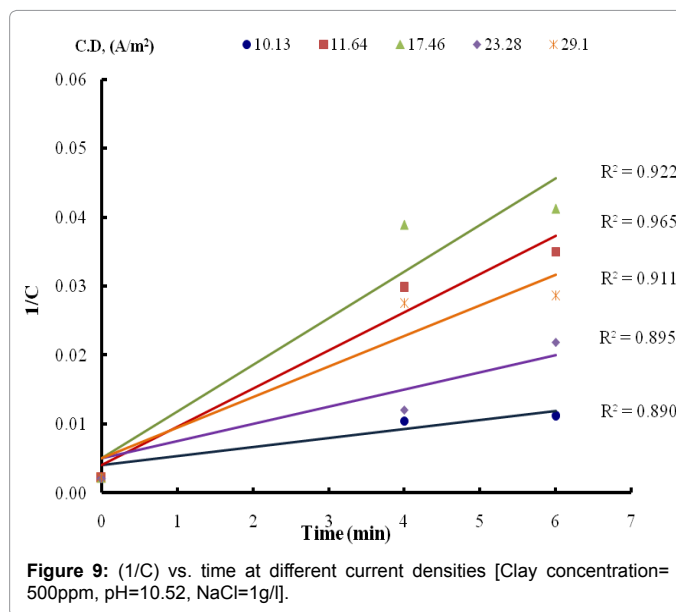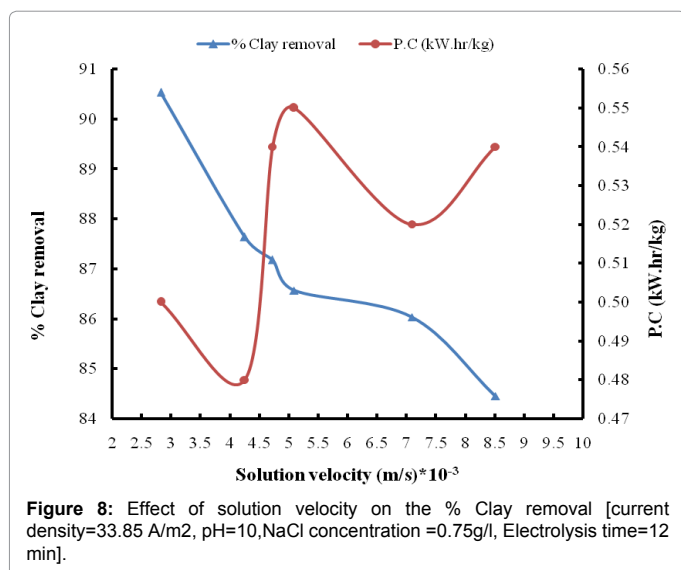
Figure 13 and 14 show % turbidity removal versus time for the wastewater and raw water respectively. Figure 13 shows that there is a region at which % turbidity is approximately constant with the increase of electrolysis time. The presence of such constant % turbidity removal with time may be attributed to the presence of interfering dissolved solids which can affect the ionic strength of the solution and may also affect the zeta potential of the colloidal particles. A 91 % turbidity removal and 43% COD reduction were achieved after 12 minutes of electrolysis at current density of 33.85 A/m$^2$ for the wastewater. Whereas a 96.3% turbidity removal ; a 100% algae removal and 49% COD reduction were achieved at 12 minutes of electrolysis and current density of 33.85 A/m$^2$ for the raw water.

## Conclusions

The present work has investigated the removal of clay from synthetic solution in both batch and flow electrocoagulation systems.
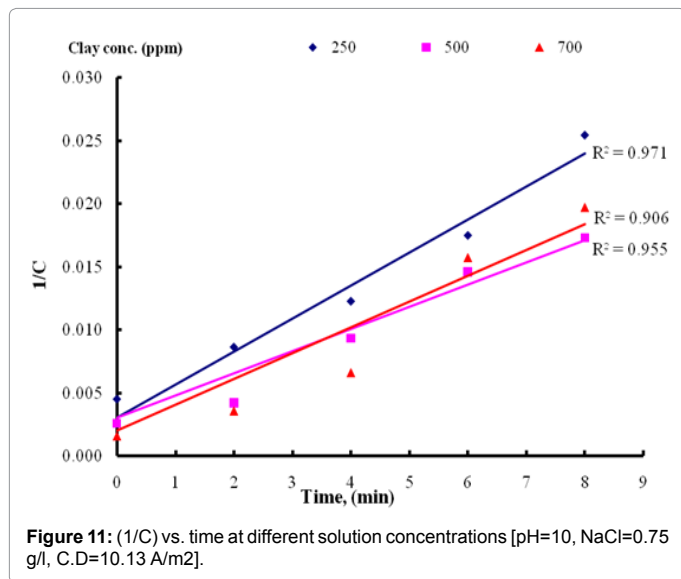
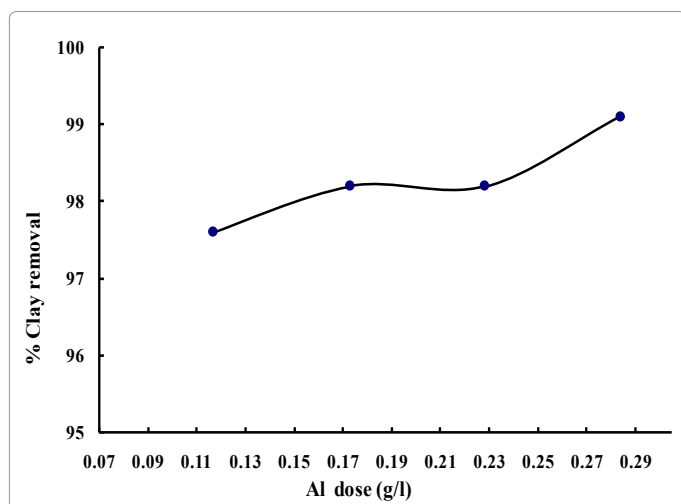**Figure 11:** (1/C) vs. time at different solution concentrations [pH=10, NaCl=0.75 g/l, C.D=10.13 A/m2].



**Figure 12:** % clay removal versus Electro-generated Al dose [ clay concentration=500 ppm, time= 20 mins, pH=10, NaCl concentration=0.75 g/l].

| Parameter | Before electrocoagulation | After electrocoagulation |
|---|---|---|
| **Turbidity, NTU** | 245.4 | 22.12 |
| **pH** | 7.27 | 7.74 |
| **Temp, °C** | 14.7 | 16 |
| **COD, mg/l** | 26.1 | 14.9 |
| **TDS, mg/l** | 1410 | 1387 |
| **Dissolved Al, mg/l** | 0.084 | 3.37 |

**Table 2:** Characteristics of wastewater influent before and after electrocoagulation.

The performance was expressed in terms of percentage clay removal and power consumptions calculations. Different parameters have been studied

The following conclusions have been withdrawn:

- % Clay removal increases as both current density and electrolysis time increase.
- As the NaCl concentration increases the % clay removal decreases.

- The optimum pH corresponding to the maximum % clay removal and minimum power consumption is 10
- The initial clay concentration has a slight effect on the % clay removal.
- The % clay removal was found to decrease with increasing the solution velocity.

| Parameter | Before electrocoagulation | After electrocoagulation |
|---|---|---|
| **Turbidity, NTU** | 112.7 | 4.15 |
| **pH** | 8.03 | 8.31 |
| **Temp, °C** | 16.4 | 17 |
| **COD, mg/l** | 14.84 | 7.58 |
| **TDS, mg/l** | 1258 | 1118.4 |
| **Algae number, Cell/ml** | 396746 | 0 |
| **Dissolved Al, mg/l** | 0.325 | 8.5 |

**Table 3:** Characteristics of raw water influent before and after electrocoagulation.
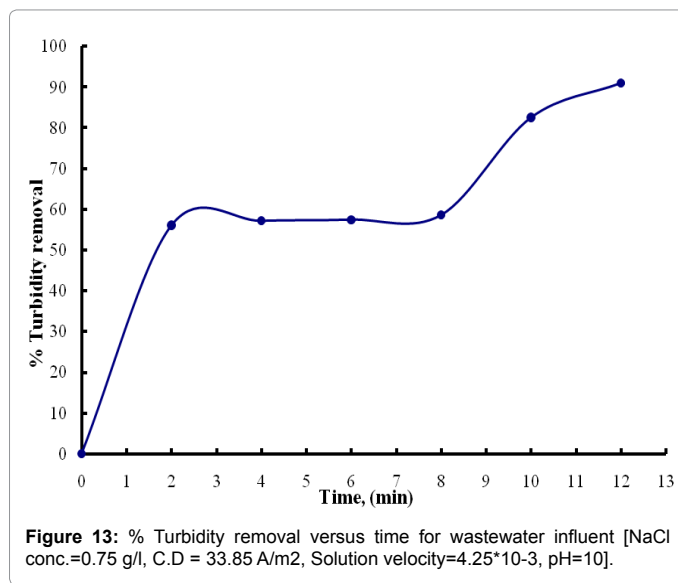


**Figure 13:** % Turbidity removal versus time for wastewater influent [NaCl conc.=0.75 g/l, C.D = 33.85 A/m2, Solution velocity=4.25*10-3, pH=10].
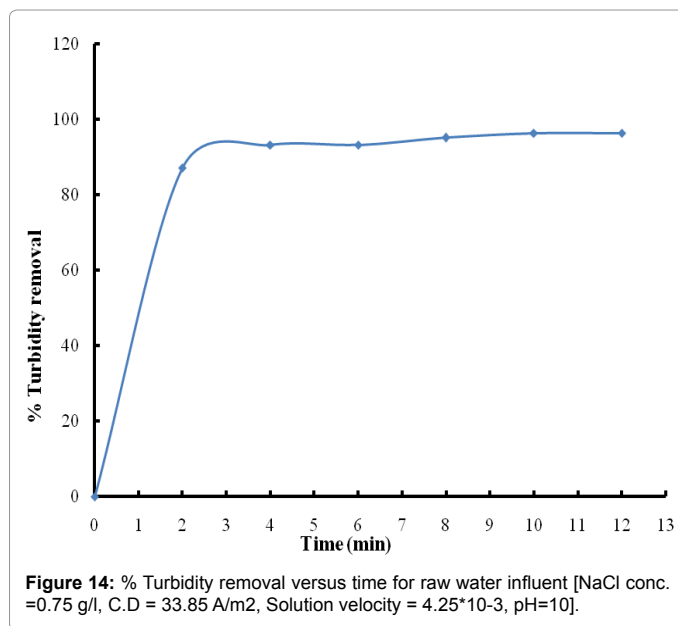


**Figure 14:** % Turbidity removal versus time for raw water influent [NaCl conc. =0.75 g/l, C.D = 33.85 A/m2, Solution velocity = 4.25*10-3, pH=10].

- Power consumption (PC) is a very important economical parameter in Electrocoagulation. The results showed that as the current density increases; PC increases whereas as NaCl concentration increases; PC decreases.

- At optimum operating conditions of the present flow cell a 0.48 kW.h is required per one kg of clay removed.

- A kinetics study revealed that the rate of clay removal follows second-order reaction kinetics.

- Treatment of raw water influent by the present flow system showed promising results in terms of turbidity removal. It has been found that under optimum conditions 96.3% turbidity removal; 49% COD reduction and 100 % algae removal have been achieved.

- Treatment of wastewater influent by the present flow system showed that under the optimum conditions 91% turbidity removal and 43% COD reduction has been achieved.

- The present new cell configuration has proven to be efficient in terms of technical and economic aspects for the removal of suspended and colloids from raw and wastewater.

- In view of the ability of the present cell to remove algae completely; it may be used as a pretreatment of feed water of reverse osmosis plants to reduce biological fouling.

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