WATER PURIFICATION BY ELECTROCAGULATION PROCESS

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ABSTRACT

Electrocoagulation is an electrochemical method of treating polluted water.

Electrocoagulation and electroflotation are two techniques involving the electrolytic addition of coagulation metal ions directly from sacrificial electrodes by introducing an electrical current into the medium for the treatment of a wide range polluted water in an even wider range of reactor design, application of an electrical field prompts electrolysis of the water medium and generates particular quantities of hydrogen gas.

The process works best with water's pH in range 7.0-7.5 and will still often work less efficiently in the range $3.5 < pH < 9$.The effects of electrocoagulation process are in reduction water turbidity in relation to electrical current and operation period.

The Electrocoagulation process gives removal efficiency of turbidity by about 85% for batch process and by about 62% for continuous flow and removal efficiency of total suspended solid by about 96% for batch process and 66% for continuous process.

The optimum temperature was found to be at 35 C^0 to give high efficiency in removal of turbidity, total suspended solid and sulphate ions.

الخلاصه

تعتبر طريقة التلبيد الكهروكيمياوي إحدى الطرق الكهروكيمياويه لمعاملة الماء.

إن كلا من تقنيتي التلبيد الكهروكيمياوي (electrocoagulation) والتطويف باستخدام التيار الكهربائي (electroflotation) طريقه تتضمن إضافة ايونات المعادن المكونه للتكتيل والتلبيد بصوره مباشره من الأقطاب إلى داخل المحيط المائي لمعالجة مختلف أنواع الملوثات وباستخدام تصاميم مختلفه من المفاعلات .إن استخدام التيار الكهربائي يحفز تحلل الماء كهربائيا لينتج كميات من غاز الهيدروجين الذي يساعد على رفع وتطويف العوالق المائيه.

تعمل هذه الطريقه بصوره كفوءه لمعاملة الماء الذي تكون دالته الحامضيه ضمن المدى (7.0 – 7.5) ولكنها تعمل بصوره اقل كفاءه للمديات(9 > 3.5 <) وباستخدام هذه الطريقه ترتفع الحامضيه بمقدار 0.25 - 1

لقد أظهرت الدراسة تأثيرات عملية التلبيد الكهروكيمياوي في اختزال عكورة الماء بالعلاقة إلى التيار الكهربائي المستخدم وزمن التشغيل . فقد أعطت عملية التلبيد الكهروكيمياوي كفاءة إزالة العكوره بحدود 85% لمفاعل الدفعه الواحدة (batch process) وحوالي 62% لمفاعل الجريان المستمر (continuous process) وكفاءة إزالة المواد العالقة بحدود 96% لمفاعل الدفعه الواحدة و 66% لمفاعل الجريان المستمر.
لقد وجد إن أفضل درجه حرارية تكون عندها أفضل النتائج عند $35C^0$ لتعطي أعلى كفاءة لازاله كل من العكوره,المواد ألصلبه العالقة والكبريتات.

General

At the turn of the last century, it was estimated that some 1.1 billion people (one-sixth of the worlds population) were without an improved water supply (WHO/ UNICEF/ 2000) while in the foreseeable future the demand for water is only expected to grow as human population and industrialization increases [(1)].

Coagulation and flocculation are traditional methods and most important physicochemical operation for the treatment of polluted water. In these processes coagulating agent (e.g. alum or ferric chloride) and other additives (e.g. poly electrolytes) are dosed to produce larger aggregates for smaller particles which then can be separated physically by sedimentation, filtration or flocculation.

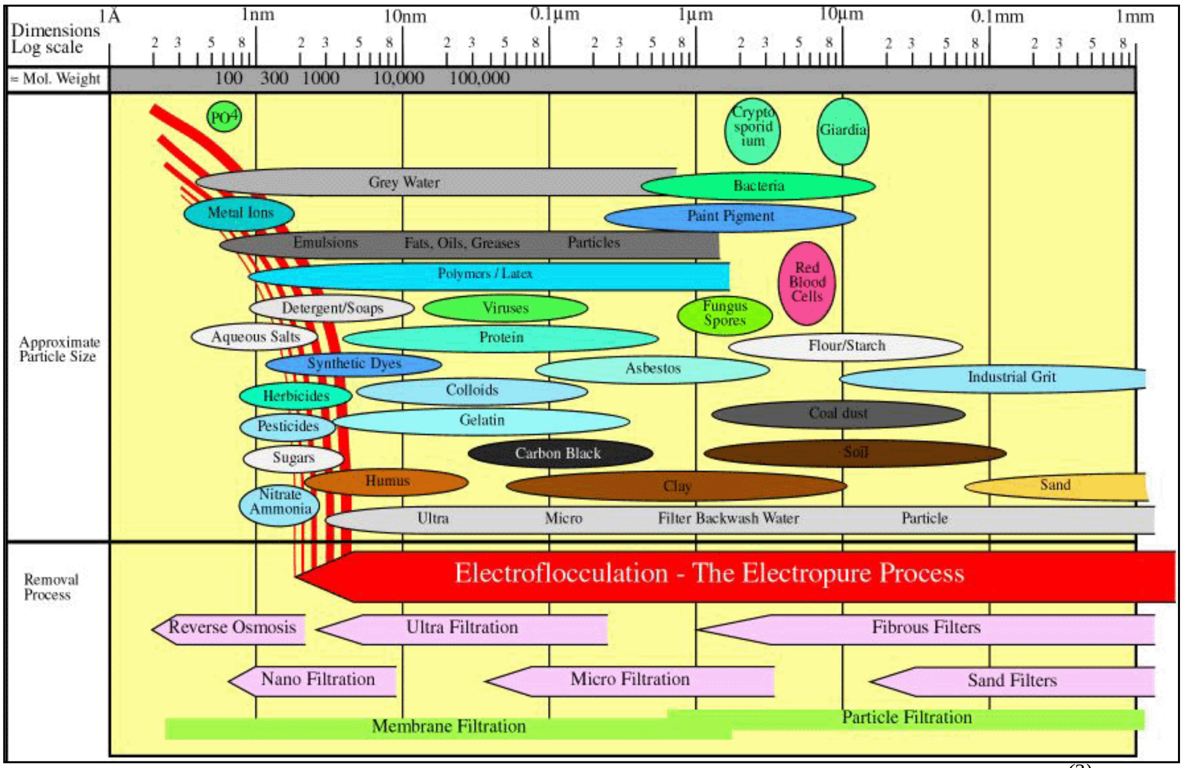


Fig.(1) Examples of some material removed with some different method[(3)]

The electrocoagulation technology introduces low concentrations of nontoxic aluminum hydroxide species into the aqueous media by the electrochemical dissolution of aluminum-containing electrode or pellets. The aluminum species that are produced neutralize the electrostatic charges on suspended material and / or prompt the co-precipitation of certain soluble ionic species and thereby facilitate their removed [2].

Electrocoagulation has been demonstrated to enhance the filtration and dewatering rates for solids removed from an effluent, such enhancements are prompted by growth in the mean particle size from typically 0.3 µm in diameter to as much as 150 µm depending on the degree of electrocoagulation as shown in Fig (1)[3]. So that electrocoagulation process can handle most of the pollutants that can be handled by particle filtration, micro filtration, ultra filtration combined and dissolved air flotation. Significant reductions in the total suspended solids (TSS) loading of particulate slurries and in the concentrations of metals (lead, copper, zinc, chromium), fluorides and phosphates from aqueous streams under certain pH conditions. This is suitable for waste water that is largest problem associated with waste and byproduct production and great quantities of water are used to remove small amounts of pollutants, in additional many different techniques are required including a variety of filters, chemical dosing, reverse osmosis and similar operations. On the other hand many of these are either pollutant specific or more expensive than dumpling and using more water.

Electrocoagulation Theory: -

One of more common methods of treating polluted water has been to dose it with chemical coagulation agent such as aluminum sulphate or ferric chloride. The metal ions agglomerate the pollutants, causing them either to sink to the bottom or become sufficiently larger than they can be filtered out, or floated out using dissolved air flotation [6]. One of the difficulties associated with this progress is that the ionic contents of the water are increased by the addition of these salts. Although the metal ions are removed during the process, the salt content of the water has been greatly increased, often preventing the ability to use water in recycling or other applications. One method of overcoming, it has been to use a process known as electrocoagulation in which the metal ions are added electrolytically.

In electrocoagulation, sacrificial electrodes are used and the passage of an electric current through the water from the electrodes causes the metal to go into solutions as ions, via the anode reaction.

A current is passed through a metal electrode, oxidizing the metal (M) to its cation (M^{n+}) as in equation (1). Simultaneously, water is reduced to hydrogen gas and the hydroxyl ion (OH^-) as in equation (2).

Electrocoagulation thus introduces metal cations in situ, electrochemically, using sacrificial anodes, (usually aluminum or iron) inside a processing tank [(3)].

The reactions at the anode and cathode are respectively:

$M \rightarrow M^{n+} + ne^-$ ……….. (1)

$2H_2O + 2e^- \rightarrow 2OH^- + H_2$ ……….. (2)

So that;

$AI - 3e^- \rightarrow AI^{3+}$ ……….. (3)

$Fe - 3e^- \rightarrow Fe^{3+}$ ……….. (4)

The cation hydrolyzes in water forming a hydroxyl with the dominant species determined by solution pH.

Many other reactions forms may accrue as follows [(4)]:

$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ ……….. (5)

$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ ……….. (6)

$2H^+ + 2e^- \rightarrow H_2$ ……….. (7)

The metal ions combine with (OH^-) ions from the water to form highly charged coagulants which adsorb pollutants to form insoluble floc particles; so that Al^{+3} reacts with H_2O to form Al $(OH)_3$. Thus, each mole of dissolved Al^{+3} is added to reduce one mole of Al $(OH)_3$.

Highly charged cations destabilize any colloidal particles by the formation of poly hydroxide complexes. These complexes have high adsorption properties forming aggregates with pollutants. Evaluation of hydrogen gas is aid in mixing and hence flocculation. Once the floc is generated, the electrolytic gas creates a flotation effect removing the pollutants to the floc-foam layer at the liquid surface [(10, 14)].

There are a variety of ways in which species can interact in solution [(3)]:-

1- Migration to an oppositely charged electrode (electrophoresis) and aggregation due to charge neutralization.

2- The anion or hydroxyl ion $(OH)^-$ forms a precipitate with the pollutant.

3- The metallic cation reacts with $(OH)^-$ to form a hydroxide, which has high adsorption properties thus bonding to the pollutant (bridge coagulation).

4- **The hydroxides from larger lattice-like structures and sweeps through** the water (sweep coagulation).

5- Oxidation of pollutants to less toxic species.

6- Removal by electroflotation and adhesion to bulk.

<u>Aluminum Dosing</u>: -

In electrocoagulation, the electrodes of the electrochemical cell are connected to an electrical power source. Faraday's law can be used to describe the relationship between current density (Amp cm^{-2}) and the amount of aluminum which goes into solution (gm Al cm^{-2}) [3,5].

$W = I\ t\ m / z\ F$ ……….. (8)

Where:

w= aluminum dissolving (gm Al cm^{-2}) or may express as electrode consuming rate (Ec)

I= current density (Amp cm^{-2})

t= time (sec.)

m= molecular weight of Al (M=27)

z= number of electrons involved in the oxidation / reduction reaction (z=3)

F= Faraday's constant 96,500 (Colomb/g-eq.)

The theoretically calculated by Eilen [6] the amount of Al dissolved at various raw water temperatures is compared with the weighed values of Al dissolved; the correlation found was relatively good (r^2=0.94) and suggests making further experiments, the Al dose was calculated based on Faraday's law. The coefficient of dissolved metal can be calculated according to the formula [5]:

$\eta = Q_\Gamma / Q$ ……….. (9)

where:

η = metal dissolubility coefficient;

Q_Γ = actual quantity of dissolved metal (Kg Al);

Q = theoretical quantity of dissolved metal (Kg Al) .

Electrode working time can be calculated as:

$T = S_a\, b\, \rho\, \eta_3 / (10 * Q)$ ……….. (10)

where

T = working time (days);

S_a= total anode surface area (m^2);

b = electrode thickness (m);

ρ = specific weight of electrode material, (Kg/m^3)

η_3= electrode usage coefficient; η_3=0.8

Electrode Material :-

The electrode material impacts markedly on performance of the electrocoagulation reactor. The anode material determines the cation introduced into solution. Several researchers have studied the electrode material using a variety of theories according to the preference of a particular material. The most common electrodes are aluminum or iron plates .Do and Chen (1994) compare the performance of iron and aluminum electrodes for removing color from dye solution[(3)]. Their conclusion is that the optimal electrocoagulation conditions vary with the choice of iron or aluminum electrodes, which in turn is determined by:-

1.initial pollutant concentration.

2.pollutant type.

3.stirring rate.

Passivations:-

One of the greatest operational issues with electrocoagulation is electrode passivation [(3)]. Passivation is lack of a systematic approach to electrocoagulation reactor design / operation thus limiting electrode reliability and its implementation [(1)].

There are various methods for preventing and / or controlling electrode passivation including:-

1. Changing polarity of the electrode.
2. Hydro mechanical cleaning.
3. Introducing inhibiting agents.
4. Mechanical cleaning of the electrodes.

According to these researchers, the most efficient and reliable method of electrode maintenance is to periodically clean the electrodes which for large-**scale,** continuous processes is arduous issue. On other hand, to avoid electrode passivation and to ensure uniform electrode usage their polarity is periodically reversed (reversal period being not more than 1 day) [(5)].

SOME APPLICATIONS OF ELECTROCOAGULATION PROCESS [(8)]: -

* Clay Water / Suspended Solids
* Fats, Oils and Grease (FOGs)
* Sewage Treatment Plant and Effluent Aeration Treatment Units
* Removal of Heavy Metals
* Cyanide and Arsenic Removal
* Printing / Ink
* Textile Dye Plants
* Food Processing.

- Experimental work:

In order to achieve the goals of study, there was a plan to study a batch process by changing the current density, pH solution, temperature of water, and current concentration to get optimum conditions of these parameters, to reverse these conditions and compare the results with these of continuous process that has optimum condition. The effects of electrolytic cell in water treatment are evaluated in this study in different water conditions. It is decided to use the final turbidity, total suspended solid, calcium ions concentration as parameters of range of treatment. These parameters indicate the effective process of electrocoagulation in water treatment when comparison is made after and before treatments.

*** Batch Process: -**

It is divided two categories:-

4-1-A By using (111 mm L x 168 mm W x 1 mm) of one aluminum electrode as a node and two plates of stainless steel electrodes plot on two sides as cathode with 6 mm distance between electrodes and with total anode area used as 374 cm^2.These experiments were done to test the parameter changes along height level of container; so the results show the pH; Calcium ions; Sulphate ions and Aluminum ions change at three levels: surface, middle and bottom level.

4-1-B By using ladder series of electrolytic cell which consists of four blades aluminum anodes, each of it is (110 mm L x 85 mm W x I mm thick) and five blades stainless-steel cathodes as shown in Fig. (2).

The two categories above use:

1- glass container with volume of 13 lit.

2- electrical device (power supply) that generates low voltage at maximum 32 volt with maximum D. C. current at 10 Amp.

The electrolytic cell is constructed to achieve a concentric gap of about 20mm between the central anode and the surrounding cathode. This arrangement allows the hydrogen bubbles to rise up, carrying all containments and water pollutants to the water surface.

Continuous Process: -

Pilot scale model consisting of raw water storage tank (T-101) is connected to packed bed by using centrifugal pump with 120 lit / min and (5.5 -40 m) head; Flow was adjusted by using Gate valves with Rotameter . The reactor formed from 10 cm diameter, Schedule 80, PVC pipe; 30 cm high, equipped with aluminum electrode as anode at inlet side and stainless-steel electrodes at outlet side and whose interior was filled with (0.8 cm O.D. x 0.55 cm I.D x 0.125 cm Thickness x 1 cm length) aluminum rushing ring with effective area 10245 cm^2 [(12)], as shown in Fig. (3).The total high of packed is 25 cm; the unit was powered at 0.5 – 10 Amp depending on the position of bed – vertical or horizontal.

Throughout the various phases of the experimental studies; samples of the treated effluent were collected and allowed to settle for 1 hour and then analyzed for turbidity ,TSS, (Ca, Mg, Al…etc) ions.

Study No. 1 Changing of (pH, Ca, Mg and Al) with time at three levels of reactor depths:-

This study considers the changes that may happen at three levels of containers; at the surface, middle and the base of the container. It was done by using 374 cm^2 of aluminum anode area; the results are shown in Fig (4A) to Fig (4E) .

The pH changing was studied with time; the result is shown in Fig. (4A).It is shown that pH value rises up about 0.25 unit; to a value of 7.69 during the five minute of starting the operation; that results from the aluminum hydroxide formation and then falls down suddenly to a value below of 7.25, that is because aluminum hydroxide is consumed by water containments, then it gradually rises up to a value of primary magnitude

Study No. 2 Effects of Current Density Change on Removal Efficiency in Electrocoagulation Process:-

This study considers current density change effects by using 730 cm^2 aluminum electrode area with 6 liter volume of water at 19C°, under four electric current values namely (0.5, 0.9, 1.5 and 3) amp. Figs. (5A),(5B) and (5C) show the results of current density effects after 1 hr operation on (turbidity, TSS, SO_4, Ca, Al and conductivity) in which aluminum dosage varies with current changes.

A little change were shown between 1.5 Amp and 3 Amp to produce 2.64 NTU and 2.48 NTU respectively but a little effects shown with calcium ions, to produce 63.57 to 65.38 ppm respectively, while it has effects on removal of total suspended solid to point of 60 ppm and 21 ppm respectively

Study No. 3 Effects of pH Change on Removal Efficiency in Electrocoagulation Process:-

Another consideration in this study is the effect of pH in electro coagulation process which uses the current density at 1.5 Amp with different pH variation at (3, 6.35, 7.25 and 9) adjusting with HCl acid and NaOH base by using 730 cm^2 aluminum electrode anode area and 6 liter volume of water at 19C°; the results were plotted in Figs (6A,B,C) in which show that most effects of aluminum dosage at pH of raw water ranged from (6.35 to 7.24) Study No. 4 Effects of Temperature Change on Removal Efficiency in Electrocoagulation Process:-

The consideration of this experimental study is shown in Figs. (7 A,B,C), which show 730 cm^2 aluminum electrode and 6 lit volume of water at 1.5 Amp. The temperature values used are (2, 19, 35 and 65) C°; where the results are optimum at 35 C°; the final turbidity is 1.74 NTU while it is at high value 2.46 NTU at 2 C° and 1.98 NTU at 65 C° as shown in Fig. (7 B).

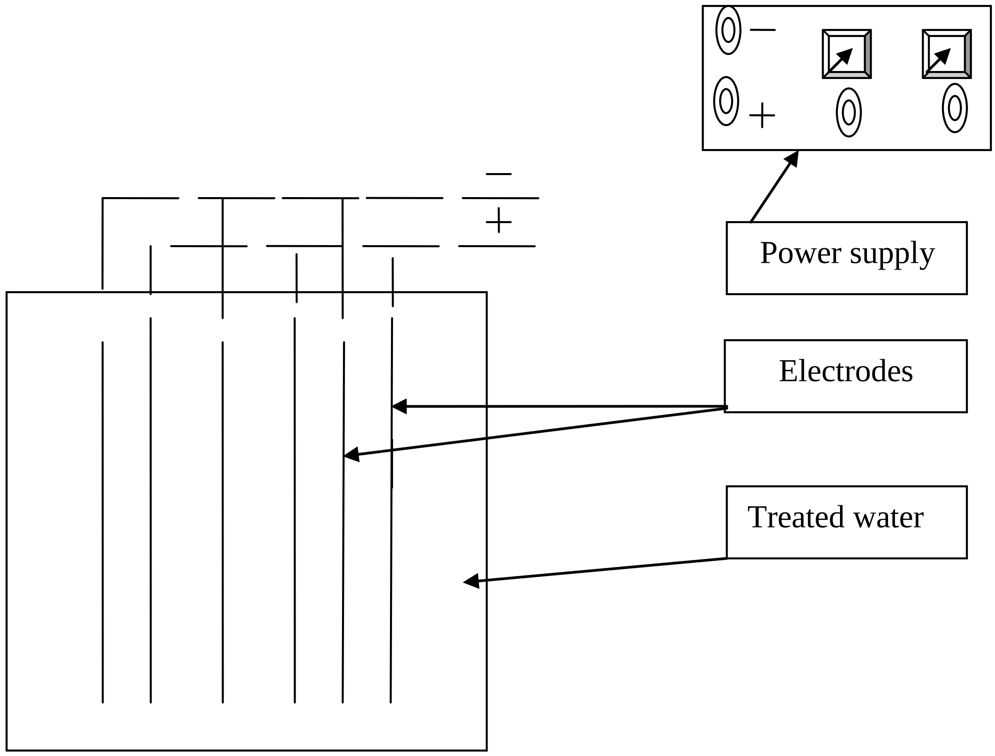


Fig (2) Batch process

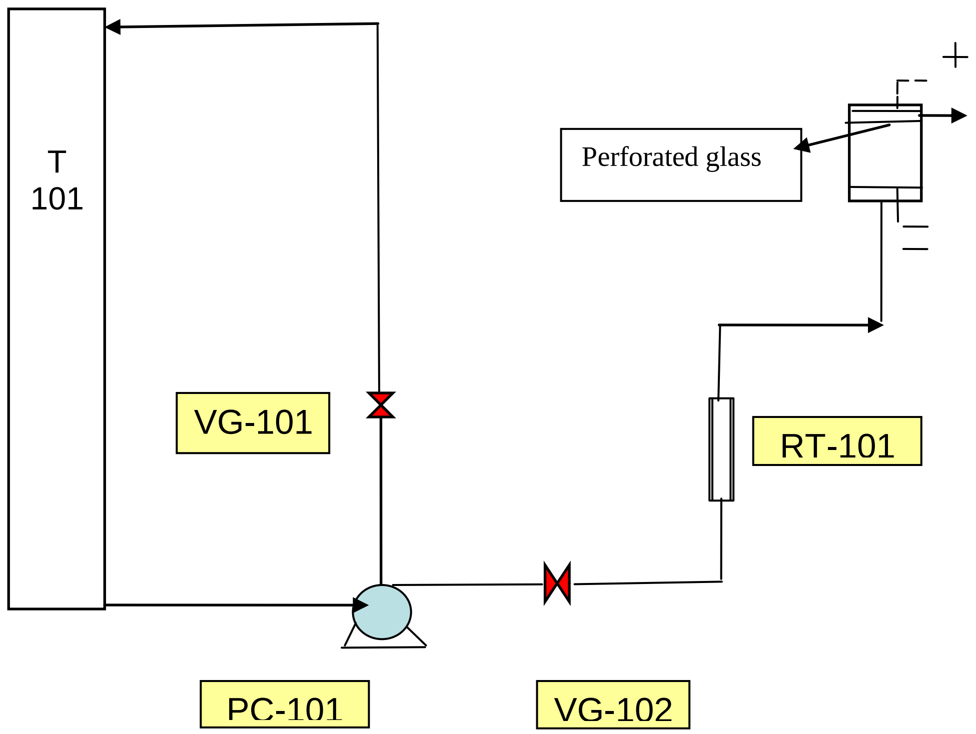


Fig (3) Continuous process flow diagram

Pc-101	Centrifugal pump
R-101	Packed bed reactor
RT-101	Rotameter
T-101	Storage Tank

VG-101	Gate valve
VG-102	Gate valve

Study No. (5) Effects of Water Volume Change on Removal Efficiency in Electrocoagulation Process (Effects of Current Concentration Changes):-

This group of experimental work considers the effects of changing volume of water treated on purification, 730 cm^2 aluminum electrodes are used as anode at 1.5 Amp and 20 C° Figs (8A,B,C), show that using of minimum volume gives an optimum condition of water treatment and it consider the volume of 6 lit water as a maximum volume which is suitable for 730 cm^2 aluminum anode area and this means the optimum current concentration is (166.7) Amp per m^3 of water treated and (8.11) m^3 of water per m^2 of aluminum anode area.

Study No. (6) Effects of Current Density Change at Continuous flow rate on removal efficiency in electrocoagulation Process:-

Figs (9A,B) show flow rate change in which D.C. electrical current changes (0.1, 0.5, 0.8, and 1.5) Amp with packed bed of (30 cm high x 10 cm diameter) with 25 cm packing high of rushing rings.

Study No. (7) Effects of Flow Rate Change on Removal Efficiency in Electrocoagulation Process:-

By using the D.C. electrical current at 1.5 Amp with flow rate values of (0.66, 23.4, 75.6 and 120) l/hr which indicate an optimum flow rate at 23.4 lit/hr; as shown in Figs. (10A,B).

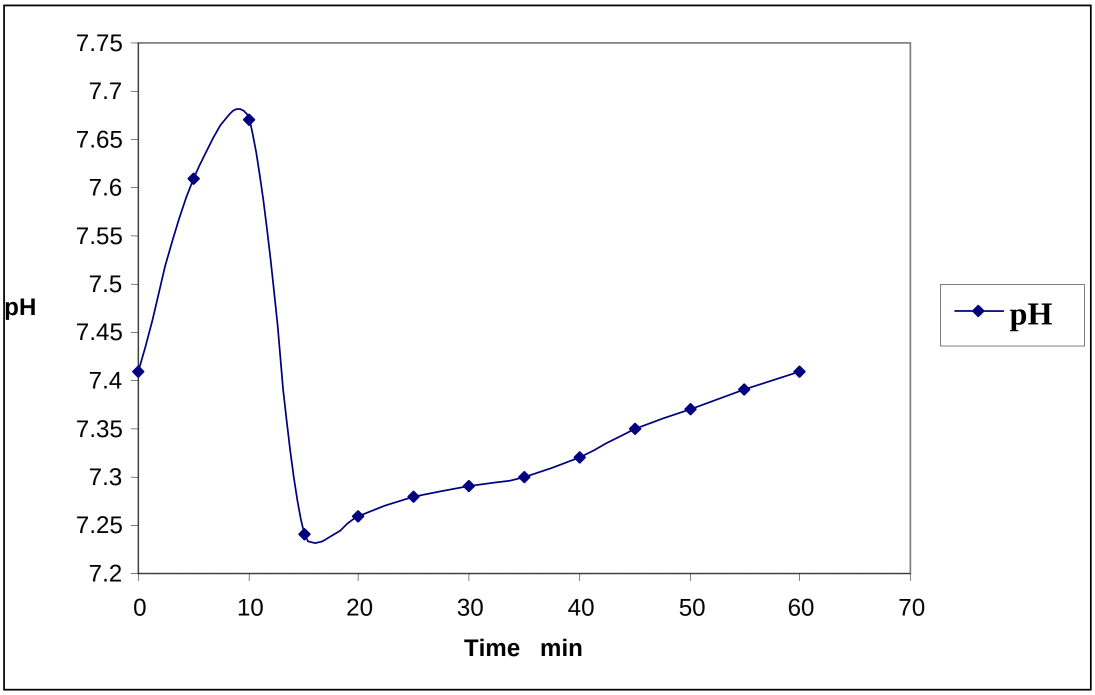


Fig. (4A) pH changing with time due to hydroxide formation

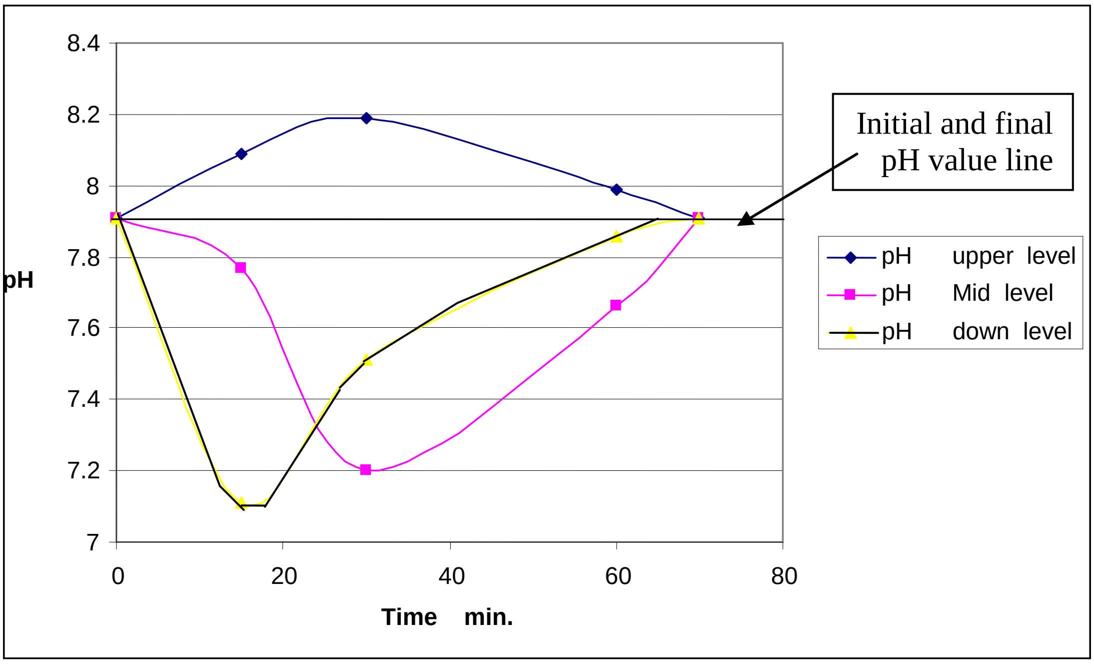


FIG (4B) pH changing with time at different levels of reactor

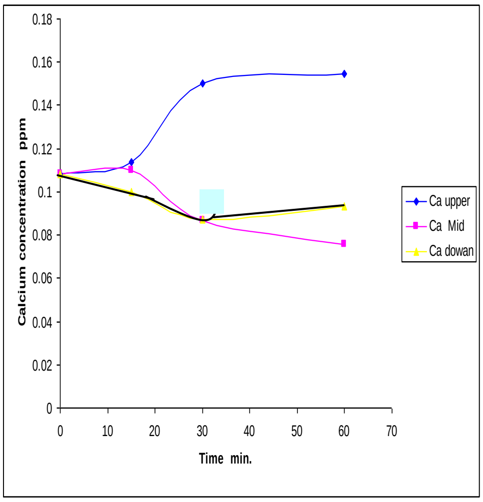


FIG (4C)

Calcium changing with time at different levels of reactor

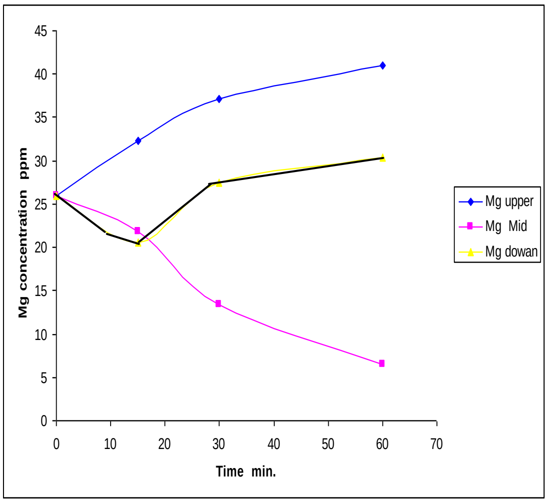


FIG (4D)

Magnesium changing with time at different levels Of reactor

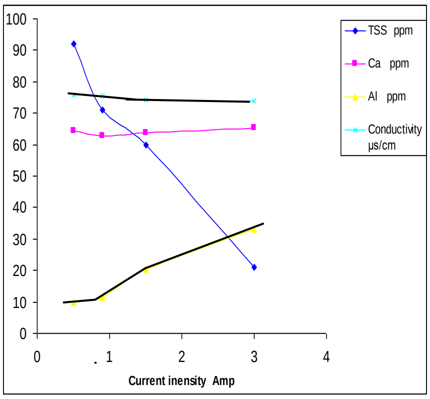


FIG.(4 E)

Aluminum changing with time at different levels of reactor

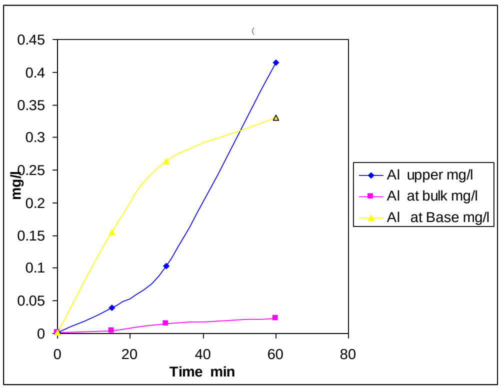


FIG (5A)

Current intensity changes effect on water quality

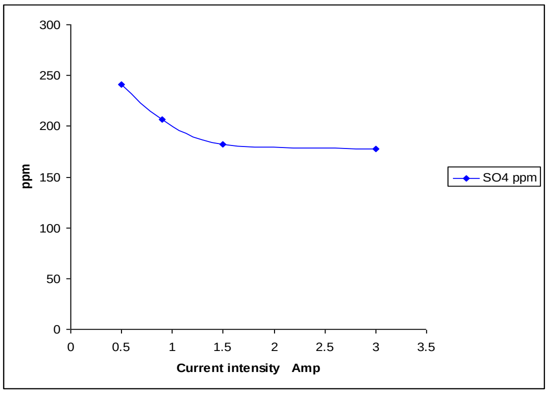


FIG (5C)

Current intensity changes effect on water quality

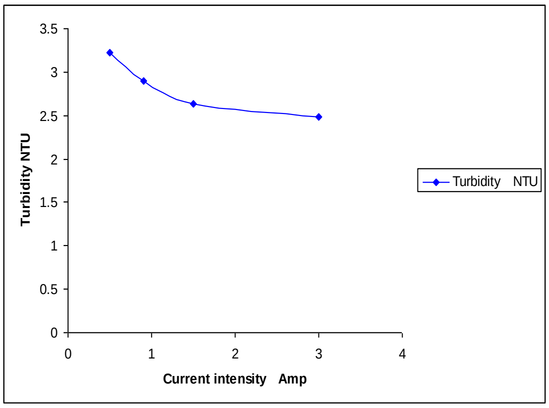


FIG (5B)

Current intensity changes effect on water quality

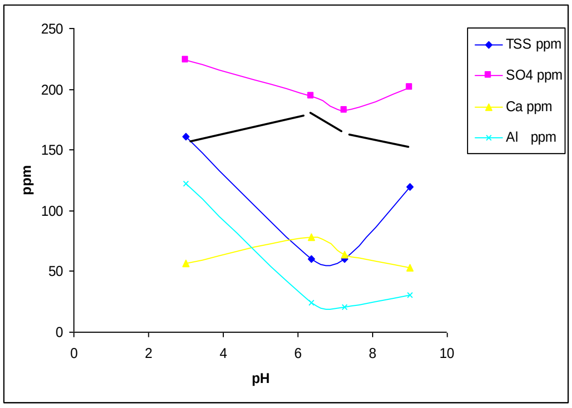


FIG (6A)
pH changes effect on water quality
*By using HCl adjusting

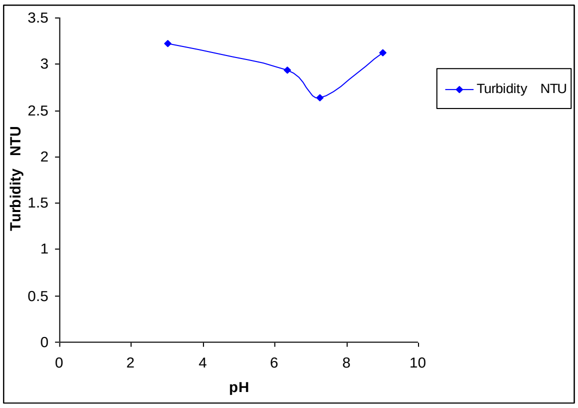


FIG (6B)
pH changes effect on water quality
*By using HCl adjusting

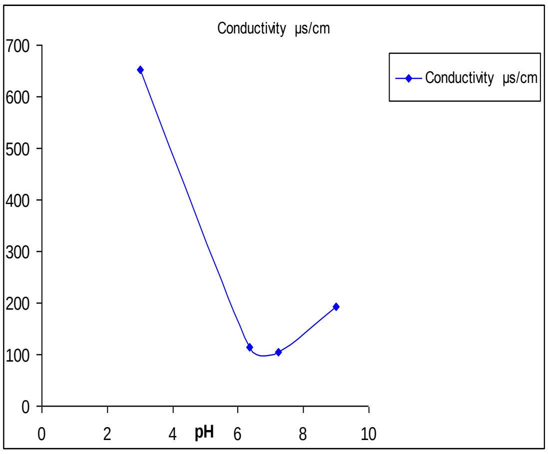


FIG (6C)
pH changes effect on water quality
*By using HCl adjusting

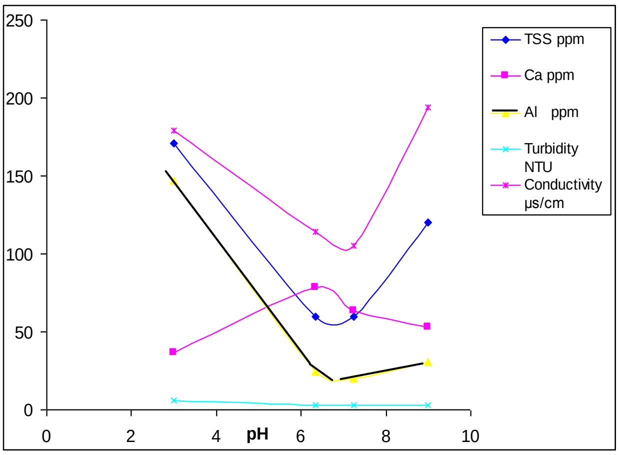


FIG (6D)
pH changes effect on water quality
* By using H_2SO_4 adjusting

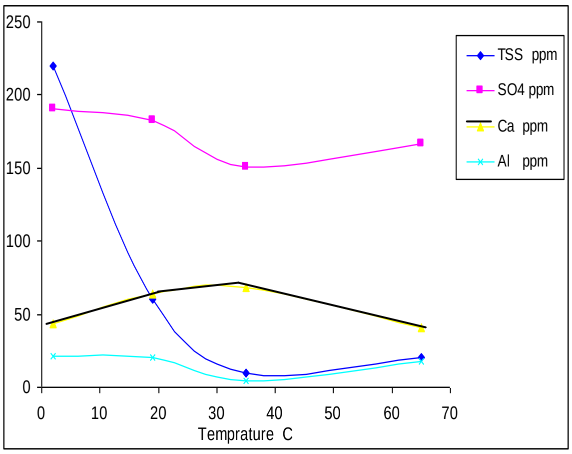


FIG (7A)
Temperatures change effect at constant current density

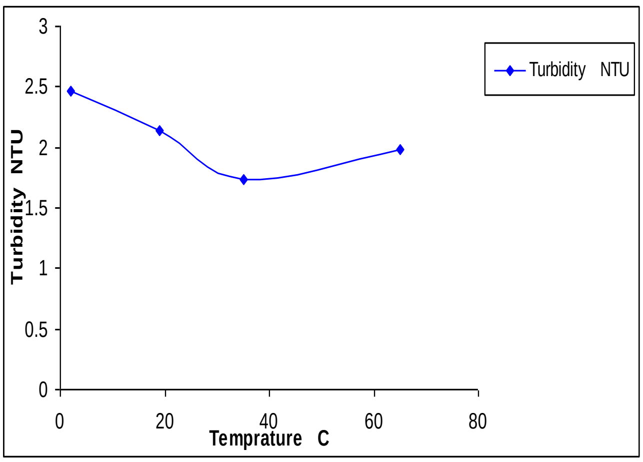


FIG (7B)
Temperatures change effect at constant current density

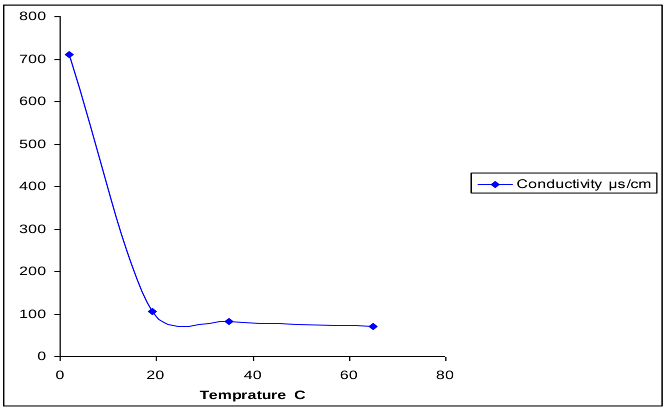


FIG (7C)
Temperatures change effect at constant current density

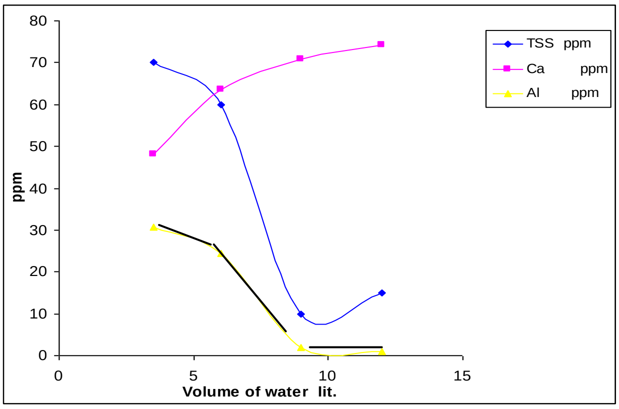
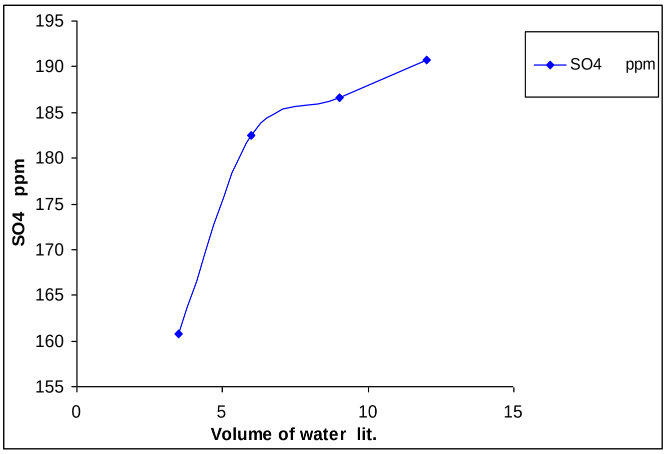


FIG. (8A)
Volume of water changes effect on water quality



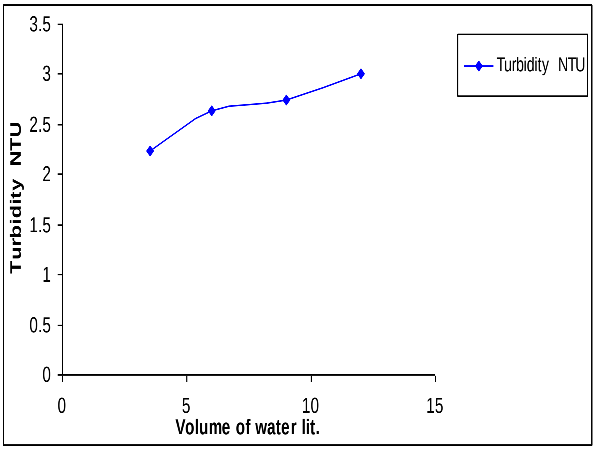


FIG. (8C)
water quality Volume of water changes effect on water quality

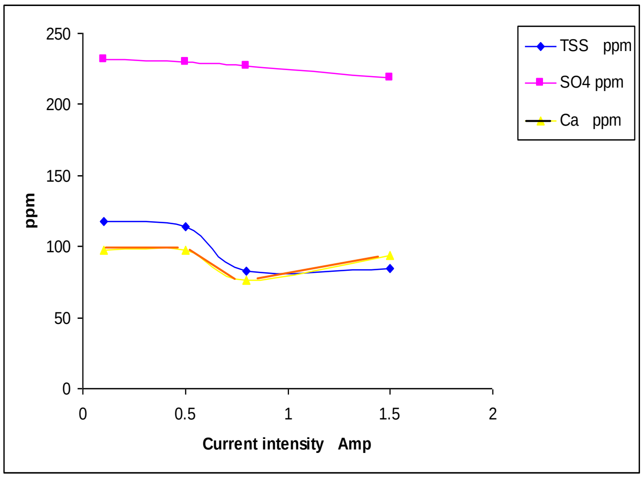


FIG (9A)
Current density changes effect at constant flow rate
(23.4 l./hr)

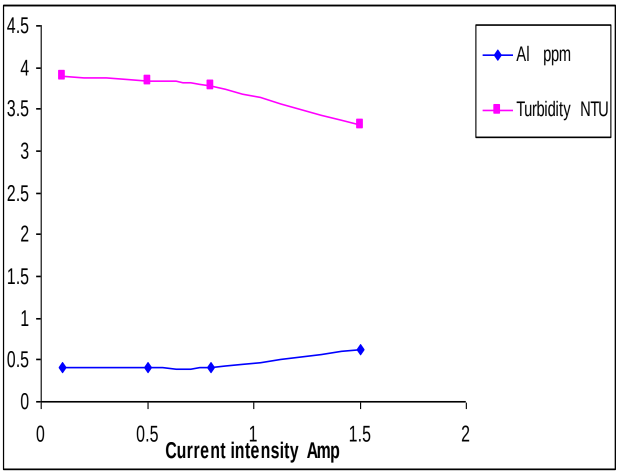


FIG (9B)
Current density changes effect at constant flow rate
(23.4 l./hr)

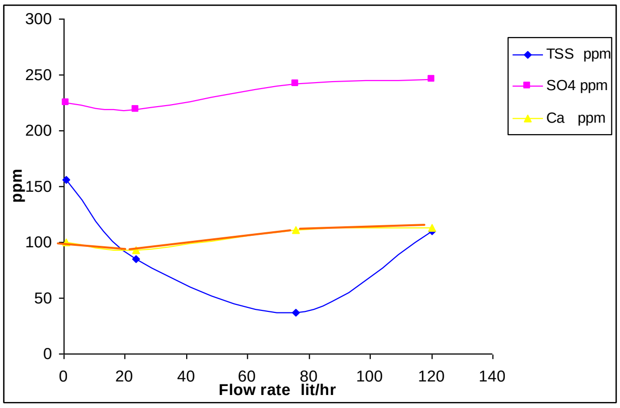


FIG (10A)
Flow rate Changes effect at constant Current density
(1.5 Amp)

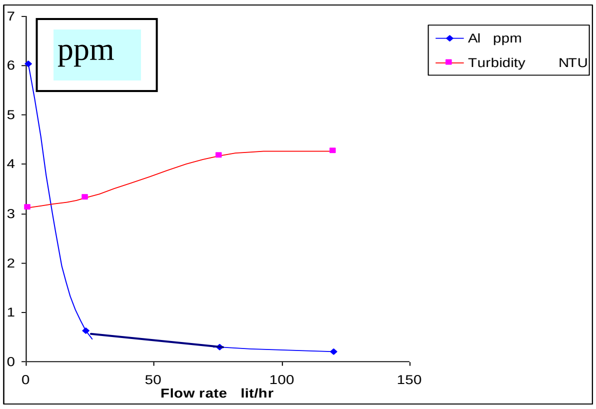


FIG (10 B)
Flow rate Changes effect at constant Current density
(1.5 Amp)

CONCLUSIONS:-

* The removal efficiency of turbidity with electrocoagulation process is due to the dosage of aluminum in which production increases with current density increasing.
* It is shown that the optimum efficiency of electric current is at 0.9 Amp but in where the removal of others matters like calcium ions and sulfate ions and total suspended solids are taken in consideration, the electric current 1.5 Amp is the optimum current density to be adopted for an area equal to 730 cm^2 which is used in this investigation. By that is meant the optimum current density is 20.54 Amp/m^2
* By testing different value pH of water, the optimum pH lies at 7 – 7.5, while gives a higher effectiveness of electrocoagulation process.
* The optimum temperature used is at 35 C° while it is at lower or higher than the removal of other materials.
* The study shows the optimum current concentration at (166.7) Amp/m^3.
* The proportion of optimum aluminum area to volume of water used is at (8.11) m^2/m^3.
* It was found that packed bed unit must be used at a horizontal situation that will allow the hydrogen gas formation and other upper floating flock to rise without causing any obstruction between two electrodes.
* In compare with previous study by Naomi, It seems that rushing ring produce high quality water than fluidized bed, in addition to low current using in.
* The optimum current used in continuous flow rate for packed bed has effective area equal to 10245 cm^2 and at D.C. electrical current equal to 1.5 Amp. This achieves higher efficiency. That means the optimum current density is 1.46 Amp/m^2.
* The optimum flow rate of continuous flow used for packed bed is at (23 Lit / hr) which has achieved higher efficiency.

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