Electro Coagulation Applications in Water and Wastewater Treatment: A Review

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Abstract— Aim of this work was to review studies, conducted mainly during 2007-2011, on the wide and versatile range of EC applications employed in the purification of different types of water and wastewater. The EC applications discussed here were divided into 5 following categories: Pulp and paper industry wastewater; Oily wastewater; surface water & other natural water; other types of industrial wastewater and Heavy metals

Index Terms— Electrocoagulation, wastewater, water, current density, electrode, heavy metals, COD

1. Introduction

One of the major challenges facing mankind today is to provide clean water to a vast majority of the population around the world. The need for clean water is particularly critical in Third-World Countries. Rivers, canals, and other water-bodies are being constantly polluted due to indiscriminate discharge of industrial effluents Coincide with the recent concerns about pollution, industries become under great pressure to find innovative ways to comply with environmental regulations, electro-coagulation has been re-emerged as a viable technology. In this paper, electro-coagulation industrial wastewater process applications were described. Electro-coagulation was first proposed by **Vik et al.** describing a sewage treatment plant in London built in 1889 where electrochemical treatment was employed via mixing the domestic wastewater with saline (sea) water. In 1909, **J.T. Harries** received a patent for wastewater treatment by electrolysis using sacrificial aluminium and iron anodes in the United States. Electrocoagulation (EC), the passing of electric current through water, has proven very effective in the removal of contaminants from water. Electrocoagulation systems have been in existence for many years (Dietrich, patented, 1906) using a variety of anode and cathode geometries, including plates, balls, fluidized bed spheres, wire mesh, rods and tubes. Electrocoagulation (EC) is an emerging technology that combines the functions and advantages of conventional coagulation, flotation, and electrochemistry in wastewater treatment. EC has been known for over a century. Aluminium/ iron-based electro-coagulation was patented in the US already in 1909.

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2. General principles of the electro-coagulation process

The electro coagulation process basically involves the dissolution of metal cations from the reactor anode with the simultaneous formation of hydroxyl ions and hydrogen gas at the cathode:

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

$2\,H_2O \rightarrow OH^{-} + H_2(g)$ - (2)

A current is passed through a metal electrode, oxidising the metal(M) to its cation (M+) (Equation(1)).Simultaneously, water is reduced to hydrogen gas and the hydroxyl ion (OH−) (Equation (2)).

2.1 Electrocoagulation Process

The (EC) technology includes coagulation and precipitation of contaminants by a direct current electrolytic process followed by the separation of flocculent (settling or flotation) with or without the addition of coagulation-inducing chemicals. The water is pumped through a unit which consists of pairs of metal sheets called electrodes, that are arranged in pairs of two anodes and cathode electrodes made of iron or aluminium are installed. A direct current electric field is applied to the electrodes to induce the electrochemical reactions needed to achieve the coagulation. Treated water is discharged from the system for reuse or disposal. When the cathode electrode makes contact with the wastewater, the metal is emitted into the apparatus.

This process involves three successive stages:

I. Formation of coagulants by electrolytic oxidation of the ”sacrificial electrode”

II. Destabilization of the contaminants, particulate suspension and breaking of emulsions.

III. Aggregation of the destabilized phase to form flocks.

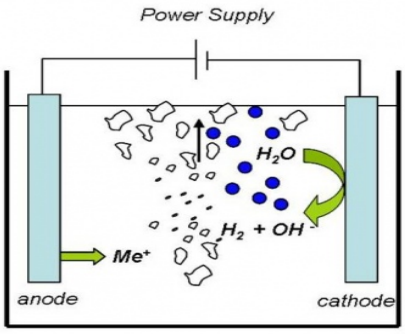

Figure 1. Electocoagulation Setup

2.2 Overview of Different Types of water and Wastewater Treated by Electrocoagulation:

2.2.1 Pulp and Paper Industry: The pulp and paper industry, consuming large volumes of water in the preparation of feed material and in the overall production process. The most significant sources of pollution among various operation stages in pulp and paper industry pulping, wood debarking, pulp washing, pulp bleaching and paper making processes. Pulp and paper industry wastewaters are characterized by high levels of organic matter (e.g. COD and TOC), suspended solids and strong colour. Hence, researchers have focused on the effects on the treatment of pulp and paper industry wastewaters by electro coagulation. In these studies it has been reported that removal efficiencies in terms of COD, BOD5, turbidity and colour as well as phenol content were increased with increasing current density to an optimum value; however, further increase did not show any significant improvement in treatment performance.

In the study of **Zaied** and **Bellakhal(2009)** the highest current (16.7mA/cm2) produced the quickest treatment, with 80% COD reduction occurring after only 30min by using aluminium electrodes. Electrocoagulation was proposed as a suitable technology to meet standards of water discharge and, even better, as a treatment option for removal of turbidity by Terrazas et al. In their work, electro coagulation using aluminium plate electrodes was evaluated in terms of turbidity removal, and the effects of current density and cell voltage in the overall process were discussed.

Vepsäläinen et al. (2011) studied the removal of dissolved sulphide and phosphorus in pulp and paper industry wastewater by electrocoagulation. According to their results, current density did not have a noticeable effect on the electric charge or iron concentration required per unit of sulphide precipitated. This is important when considering full-scale applications, where the required electrode surface area of the system depends on the current (A) and current density (mA/cm2) targets of the treatment. However, high current density increases the voltage and power consumption of the system, and consequently the operating cost of the electrocoagulation process. In their study, current density did not show a significant effect on phosphorous removal rates at 3.6mA/cm2, 7.1mA/cm2 and 10.7mA/cm2. However, current efficiency decreased slightly when current densities were 14mA/cm2 and 17.9mA/cm2, and this was attributed to a faster flotation and a shorter contact time between pollutants and the coagulants produced.

The electro-coagulation process was proposed as a pre treatment step for pulp and paper industry wastewaters by **Soloman et al**. **(2009)** In their study, the best operational conditions giving maximum improvement in biodegradability of the effluent were determined using response surface methodology. Their study demonstrated that the biodegradability index was directly related to both electrolysis time and current density. There was a decrease in the resulting biodegradability index after treatment duration of 6.9 min and current density of 11.29mA/cm^2. At the early stage of treatment, long chain organic matter such as lignin was converted into lower molecular weight components that did not considerably reduce COD but increased BOD_5, resulting in an increase in biodegradability. The effect of current density on biodegradability index was also explained as a result of the relative contribution of the oxidation and coagulation mechanisms. At a higher current density, the optimal time for maximum biodegradability index was expected to be reached at the early stages of electro-coagulation. In the investigation, the oxidation and coagulation mechanisms started attacking the more easily degradable part at 11.29mA/cm^2 when compared with lower current density values, which may result in a decrease in the biodegradability index.

Parama Kalyani et al. (2009) concluded that the COD and colour removals were higher in the case of a mild steel anode than the aluminum anode for the same operating conditions. Katal and Pahlavanzadeh recommended effective electrode combinations for removal efficiencies in treating pulp and paper industry wastewater in the following order: (i) aluminum–aluminum electrode combination for removing color; (ii) iron–iron electrode combination for removing COD and phenol; and (iii) aluminum– iron or iron–aluminum electrode combination for removing colour, COD and phenol at high efficiencies. Ugurlu et al. concluded that formation of the coagulant depends on the structures of the contaminants, thus on the ability of contaminant molecules to be adsorbed on hydrolysis products or flocs. In their study, it was observed that experiments carried out at 12V, treatment time of 2 min and a current intensity of 77.13 mA were sufficient for the removal of lignin, phenol, BOD_5 and COD with aluminum and iron electrodes. The removal capacities of the process using an aluminum electrode were 80% of lignin, 98% of phenol, 70% of BOD_5 and 75% of COD after 7.5 min. By using iron electrodes the removal capacities were found to be 92%, 93%, 80%

and 55%, respectively.

Zodi et al. (2011) for COD and arsenic removal. In their study, the maximum COD removal at 10 and 15mA/cm² were 47% and 68%, respectively, with aluminum electrodes, and 32% and 41%, respectively, with iron electrodes. In their study, more than 91.5% of arsenic was removed with aluminum electrodes at 10mA/cm². Arsenic removal efficiency reached 86% and 88% at 10 and 15mA/cm2, respectively, when iron electrodes were used.

2.2.2 Oily Wastewater: Oily wastewaters with greatly varying compositions and very high pollutant levels are generated by various sources, such as petroleum refineries, discharge of bilge and ballast water, workshops, petrol stations, rolling mills, restaurants, edible oil and soap factories, as well as other general industrial sources. Oil-in-water can be found as free-floating oil, as an unstable oil/water emulsion, and also as a highly stable oil/water emulsion, which are all difficult to treat. Table 1 presents a summary of recent applications of electro-coagulation in the treatment of oily industry wastewater.

Table 1
Applications of EC in the treatment of oily industry wastewater

Wastewater or water type	Anode/ Cathode material	Reactor type	Optimum current density	Optimum treatment time	Initial pH	Initial pollutant levels (mg/l)	Optimum removal efficiency (%)	Research group
Industrial oil-in-water emulsion	Al/SS	Batch	250	22	7	COD: 62300 Turbidity: 29 700 [NTU]	COD: 90 Turbidity: 99	Tir & Moulai-Mostefa (2008)
Olive mill wastewater	Al	Batch	250	15	4-7	COD: 20000 Polyphenols: 260 Color: n.d.	COD: 84 Polyphenols: 87 Color: 92	Hanafi et al. (2010)
Waste metal cutting fluids	Al/ Fe	Batch	60	25	6-7	COD: 17312 TOC: 3155 Turbidity: 15350 [NTU]	COD: 92 TOC: 82 Turbidity: 100	Kobya et al. (2008)
Rose oil processing wastewater	Fe	Batch	80	20	6.4 - 7.1	COD:15000	COD: 80 BOD: n.d. Turbidity:nd TS:nd	Avsar et al. (2007)
Vegetable oil refinery wastewater	Al	Batch	350	90	5-7	COD: 30980 O & G: 6020 SS:340 Methanol: 10667	COD: 9599	Un et al. (2009)
Palm oil based biodiesel wastewater	Al	Batch	20 [V]	25	6		COD: 55 O & G: 97 SS:98 Methanol: nd	Chavalparit & Ongwandee (2009)

2.2.3. Surface Water and Other Natural Water

Table 2 presents a summary of recent applications of EC in the treatment of surface water and other natural water.

Table 2
Applications of EC in the treatment of Surface Water and Other Natural Water

Wastewater type Or water	Anode/ Cathode material	Reactor type	Optimum current density	Optimum treatment time	Initial pH	Initial pollutant levels (mg/l)	Optimum removal efficiency (%)	Research group
Water containing algae (cyanobacteria	Al[b]/ Fe	Batch	10	45	4-7	Cyanobacteria: 1.2×10^{8} - 1.4×10^{8} [cells/l]	Cyanobacteria 100	Gao et al. (2010) [111]
Micro-polluted raw water	Al[b]/Fe	Batch	50	20	5-7.5	TOC: 5 - 16.2 Oil: 0.8 - 1.5 NH3-N: 0.75 - 1.26	TOC: 70 Oil: 86 NH3-N: 75	Li et al. 89l. (2008)
Marine water containing microalgae (for biodiesel production	SS	Batch	10[V]	15	4-9	Microalgal: 600/300	Microalgal 98/99	Uduman et al. (2011)
Pesticide-contaminated (metribuzin, MB) groundwater	Fe/SS	Batch Batch + UV	18	80	5-6 6-7	MB:50-300 (Optimum 200)	MB:89 95	Yahiaoui et al (2011)
Geothermal waters containing boron	Al	Batch	15[b]/ 30[b]/ 60	30	8	B:24	B: 73[b]/84[b]/96	Yilmaz et al. (2008)
Riverwater containing mercury(II)	Al Fe[b]	Batch	125	15	3-7	Hg^{2+}: 4 Hg^{2+}: 4 COD:378	Hg^{2+}: 100 Hg^{2+}: 100 COD:90	NanseuNjiki et al. (2009)
Surface water (river) containing a high concentration of NOM (paper mill inlet flow	Al	Batch	4.8	12i	4.3	DOC: 18.35 UV 254 nm: 0.64 [absorbance] Turbidity: 0.51 [NTU]	DOC: 80 UV254: 91 Turbidity: nd	Vepsäläinen et al. (2009)

2.2.4. Other Types of Industrial Wastewater:

Table 3 presents a summary of recent applications of EC in the treatment of other types of industrial wastewater

Table 3

Applications of EC in the treatment of Other Types of Industrial Wastewater

Wastewater or water type	Anode/ Cathode material	Reactor type	Optimum current density (A/m^2)	Optimum treatment time (Min)	Initial pH	Initial pollutant levels (mg/l)	Optimum removal efficiency (%)	Research group
Galvanic wastewater	Al Fe (Al +Fe)[b]	Batch	(1.0 [A] + 0.05 [A])[g]	180	5	Ni: 2000 Cu: 2500 Cr: 700	(Ni: 95 Cu: 100 Cr: 95)[g]	Heidmann & Calmano (2010)
Metal plating wastewater	Al/Al Al/Fe Fe/Fe Fe/Alb	Batch	100	20	7-9	Ni: 394 Cu: 45 Cr: 44.5	Ni: 100 Cu: 100 Cr: 100	Akbal & Camcı (2011)
Complexed wastewater from metal plating industry	SS	Batch	90	180	6-7	TOC: 170 - 173 Zn: 217 –236 Ni: 248 – 282	TOC: 66 Zn: 100 Ni: 100	Kabdaşlı et al. (2009)
Alcohol distillery wastewater	Fe	Batch	44.65	120	8	COD: 15600 BOD: 7200 TS: 34100 TDS: 2290	COD: 51 Color: 95 TS: n.d. TDS: n.d.	Kumar et. al (2009)
Industrial aqueous solution containing polyvinyl alcohal)	Al/Al Al/Fe Fe/Alb Fe/Fe	Batch	10 [V]	120	6.5[d]	PVA: 100	PVA:77	Chou et .al (2010)
Industrial aqueous solution containing salisylic acid (SA)	Al	Batch	12	60 [g]	Nd	SA:100	SA: 87[g]	Chou et al. (2011)
Marble processing wastewater	Al[b]/Fe	Batch	15	0.5[b]/2	8-9	Turbidity: 2640 [FTU] SS: 5178 TDS: 0.21 O & G: 20	Turbidity:99h/100SS: 99h/100 TDS: nd/nd O&G: nd/nd	Solak et.al (2009)
Carwash wastewater	Fe/Ti	Continuous	300	80-(0.025 l/min)	8-11	Colour: n.d. COD: 91 - 111 BOD5: 18 - 28 NH3-N: 4.8 - 5.8	Colour: 91 COD: n.d. BOD5: n.d. NH3 -N: n.d.	Panizza &Cerisola (2010)

2.2.5. Heavy metals:

The central focus of a study by Al **Aji et al. (2012**) in which the authors found that the removal of copper (Cu), nickel (Ni), zinc (Zn) and manganese (Mn) from a model wastewater. The influences of current density (from 2 to 25 mA/cm2), initial metal concentration (from 50 to 250 mg/L) and initial pH (3, 5.68, 8.95) on removal efficiency were explored in a batch stirred cell to determine the best experimental conditions.The results indicated that EC was efficient to remove heavy metals from the model wastewater having an initial concentration of 250 mg/L for each metal under the best experimental conditions. According to initial pH results, high pH values are more suitable for metal removal with EC treatment. At the current density of 25 mA/cm^2 with a total energy consumption of 49 kWh/m3, more than 96% removal value was achieved for all studied metals except Mn which was 72.6%.

Zhao et al. (2010) reported a new and convenient synthetic procedure to obtain the effects of Ca^{2+} andMg^{2+}. The mechanisms and behavior of EC defluoridation in Ca^{2+}containing systems were different from those in Mg^{2+} containing systems. An increase in Ca^{2+}concentration improved the defluoridation efficiency (εF), but it could not change the optimal molar ratio of OH- and F-to Al^{3+} (rOH+F). The highest εF can usually be obtained at (rOH+F) = 3 for defluoridation. Only a small portion of Ca^{2+} entered into the flocs, and Ca^{2+} could not influence the mechanism of EC defluoridation. For the Mg^{2+} containing system, the optimal (rOH+F) increased with increasing Mg^{2+}concentration The optimal (rOH+F) was maintained at 3 after theMg^{2+}concentration was corrected using the obtained correction coefficient of 0.3435. About 50% to 70% of the total Mg^{2+} entered into the flocs. From the XRD analysis, it was found that some Mg-Al-F layered double hydroxides (LDHs) were formed by Mg^{2+}, F-, and Al^{3+} during electrolysis

Martins et al. (2012) stated that the removal of metal ions from synthetic aqueous effluents using a spouted bed electrochemical reactor whose cathode was composed of 1.0mm copper particles. Using a Box–Behnken factorial design, the effects of current (I), electrode thickness (L), draught distance (d) and support electrolyte concentration (Cs) on current efficiency (CE), space-time yield (Y) and energy consumption (EC) were analyzed. The results were statistically analysed and the effect of each variable was evaluated using the surface response methodology. The results showed that Cs is the most important variable to consider in the optimization process. A current of 8.0A can be applied in order to obtain high Y and CE with an acceptable EC. Electrode thicknesses greater than 1.3 cm are not recommended because the irregular potential distribution leads to a Y drop owing to the low CE observed for this condition. The draught distance does not have statistical significance; therefore, the particle circulation rate is not important in this kind of electrochemical reactor.

In another major study **Shafaei et al. (2010**) found that electrocoagulation was capable of removing Mn2+ ions with aluminium electrodes under an optimum pH of 7.0 factors. The authors concluded that the density and electrolysis time, along with initial concentration were capable of determining successful removal rates.

A small-scale study by **Petsriprasit et al. (2010)** reaches different conclusions, finding that Cu, Cr, Pb, and Zn from billet industry wastewater was capable of being removed by 99%, where it was found that density current is 98 A/m2, pH of 5, and 30 minutes electrolysis time. It was noticed that within 120 minutes, pH of 3, and flow rate of 55 mL/min could obtain similar values.

3. Conclusion

This paper has given a review of the successfully EC application, for the removal of specific problematic factors (such as colour, recalcitrance and toxicity) that cannot be removed effectively via conventional treatment methods. However, this paper has argued that the full potential of the EC technique as a water and wastewater treatment alternative is yet to be fully realized. However, a number of possible future studies using the same experimental setup are apparent. For optimal performance and future progress in the application of this innovative technology considerably more work will need to be done in better reactor design, understanding and process control has to be provided. This technology will continue to make inroads into the wastewater treatment arena because of the numerous advantages and the nature of the changing strategic wastewater needs in the world. EC has great potential in purification of various types of water and wastewater and seems to be a feasible and economical alternative in this field, although more research is needed, especially using larger-scale and/or continuous systems and focusing on the fundamentals of the EC process.

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