

Advanced Electrochemical Technologies in Wastewater Treatment. Part II: Electro-Flocculation and Electro-Flotation

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Abstract

This paper aims to provide an overview of electrochemical technologies in wastewater treatment. First part was focuses on the development, basic theory and application of electro-coagulation whereas the second part is consecrated to the development, and application of electro-flocculation and electro-flotation. The basic designs of electrochemical units are also presented. An appropriately constructed single unit can be used to successively coagulate, flocculate and float the pollutants. The coagulated and flocculated pollutants could be removed easily by sedimentation/filtration or by capturing them with the bubbles generated on the electrodes and then floating them to the water surface. In wastewater treatment plants these three processes must be operated synergistically to effectively remove the pollutants.

Keywords: electro-flocculation; electro-flotation; wastewater; design of electrochemical units.

1. Introduction

The removal of particles from a liquid is one of the basic types of separations in both drinking water and wastewater treatment. In most cases the particles are in the micron or sub-micron size range and are difficult to remove by conventional methods like sedimentation or filtration. It is necessary to increase the average particle size by coagulation and flocculation to enhance solids removal. Coagulation indicates the process when colloidal particles and very fine solid suspensions are destabilized so that they can begin to agglomerate.

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Flocculation refers to the process by which the destabilized particles conglomerate into larger aggregates (flocs) that will increase significantly the weight of the particles, to have a large enough mass so they can be easily separated from the wastewater by sedimentation, filtration or flotation. Generally, coagulants have a higher net charge and a lower molecular weight than flocculants.

In flocculation, the size of the formed flock depends on the frequency of collisions of the destabilized colloids [1]. For better flocculation, moderate agitation is recommended [2]. If the agitation is very vigorous, it is possible to break up the floc that was just formed [3]. Flotation is a single process that floats the coagulated and flocculated pollutants to the top of the water body by tiny bubbles of gas introduced into the liquid. In this paper, before more detailed overview of electro-flocculation and electro-flotation, firstly it will be shortly described the traditionally used processes of flocculation and flotation.

2. Flocculation

Flocculation is the process of making the dissolved or suspended particles larger [4]. The process of flocculation is closely connected with coagulation. The terms flocculants and coagulants are often used interchangeably and IUPAC does not make a sharp distinction between flocculation and coagulation. However it is traditionally accepted that: the term coagulant belongs to the chemicals that contribute to molecular aggregation, rather than the particles' aggregation. In drinking and wastewater treatment the colloidal particles may be aggregated into microscopic particles by a coagulant and then these particles can be flocculated into a macroscopic floc with flocculants. The flocs may then float to the top of the liquid, or settle by sedimentation to the bottom of the liquid, figure 1.

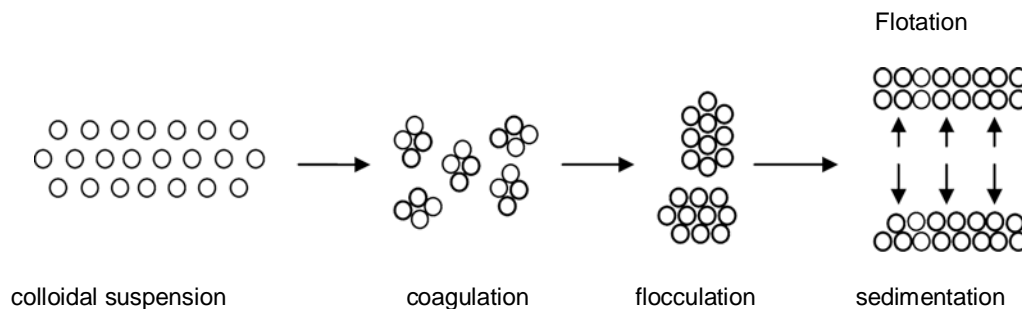


Figure 1: Graphical presentation the processes of coagulation, flocculation an sedimentation

To float the floc on the liquid surface the formation of bubbles by dissolving or introducing a gas under pressure at the bottom of the liquid is required. Flocculation destabilizes colloidal particles by bridging [5]. This can be done in an easier way by adding a polymer that will act as glue between the colloids [6]. The polymer chain will be adsorbed onto different particles and help the particles aggregate. For emulsions, flocculation describes clustering of individual dispersed droplets together while the individual droplets do not lose their identity [7]. As it can be seen from figure 1, the suspended particles first agglomerate and then flocculate and form larger particles.

Once the floc has reached its optimal size and strength, the water is ready for the sedimentation process [8]. Sedimentation is a physical process of water treatment used to settle out suspended solids in water under the influence of gravity. It is a solid-liquid separation process for removing suspended solids from water. Flocculants are chemicals used to precipitate insoluble substances. The most used chemical compounds for flocculation are hydroxide flocs [9-12] and multivalent cations such as: hydrated aluminum potassium sulfate $KAl(SO_4)_2 \cdot 12H_2O$, aluminum chlorohydrate $Al_nCl_{(3n-m)}(OH)_m$, calcium oxide CaO , sodium aluminate $Na_2O \cdot Al_2O_3$ or $Na_2Al_2O_4$ polymer salts etc. [13].

3. Electro-flocculation.

Coagulation-flocculation in general is two phase process aimed at removing stable particles by forming larger aggregates that can be separated by subsequent separation step [14]. The preliminary phase is the coagulation phase in which destabilization is induced by reduction of repulsive forces between particles, (see part I of this paper). In industry the process of electro-flocculation generally refers to the electrolytic addition of the metal ions, Al and Fe at the anode and the formation of gas bubbles (H_2) at the cathode. The gas bubbles capture the pollutants to which the metal ions have attached and float most of them to the water surface as a stable floc. Only a small percentage of the floc sink to the bottom. But generally flocculation process is enhanced for 10 to 15 %, when instead of chemical flocculation the electro-flocculation techniques have been used [15]. According to some authors, electro-flocculation is a combination of the processes of electro-flotation and electro-precipitation [16]. These two processes occur at the same time in the electro-flocculation tank. The insoluble product, separated from the liquid, is called precipitate. Electro-precipitation is a flocculation process where the flocculating agent is ions of metal which are precipitated from the anode. The metal ions are released in the electrolyte and adsorb onto the surface of colloidal particles. The authors in ref. [17] used an electro-flocculation unit consisting an electrolytic cell with an Al anode and a stainless steel cathode. According to these authors the anode must be more easily oxidisable than the cathode to give the correct effect. The most commonly used anode materials are iron and aluminum, because they produce trivalent ions. Other cheaper and more easily accessible metals produce bivalent ions. It should be pointed out that trivalent ions have a higher ability to be adsorbed onto particles in the water than bivalent ions, because they have a higher charge density. The authors in ref. [18] proposed that the destabilization of colloidal emulsions could be performed with the assistance of the hydroxyl radicals which are generated during the ferrous-ion oxidation, according to the reactions [19]



In reactions (30) and (31) the peroxide, also called Fenton's reagent.

The oxidation of organic substrates by Fe(II) and hydrogen peroxide is called the “Fenton Chemistry”. As described in ref. [19], H. Fenton first observed the oxidation of tartaric acid by H₂O₂ in the presence of ferrous iron ions. Alternatively, the name “Fenton reaction” or “Fenton reagent” is often used. Fenton reagent defines as a mixture of hydrogen peroxide and ferrous iron. It is currently accepted as one of the most effective method for the oxidation of organic pollutants. Fenton reagent is effective in treating various industrial wastewater components including aromatic amines [20], a wide variety of dyes [21-23] pesticides [24-26], surfactants [27-29] etc. Electro flocculation has been applied to treat a variety of wastes such as those associated with the textile industry [30,31], metals and heavy metals [32-35], humic substances [36] etc. With respect to the aluminum, it is very difficult to propose any mechanism of colloidal destabilization because aluminum ions are very unstable. It is suggested that aluminum ions react with the hydroxyl ions and form a network (made up of a chain with three hydroxyl ions per aluminum ion), that is adsorbed onto the colloidal particles [37].

3.1. Parameters affecting electro-flocculation

Taking into account that coagulation and flocculation occur in successive steps, intended to overcome the forces stabilizing the suspended particles, the parameters affecting electro-flocculation are similar to those affecting electro-coagulation, presented in the part I of this work. It is difficult to find separate investigations in literature of parameters affecting electro-flocculation and electro-coagulation. Regarding electrode materials, the authors in reference [16] investigated many different electrode materials such as: iron, steel, zinc, copper, aluminum alloys and bronze.

They concluded that all of the investigated materials produced significant amounts of floc with a satisfactory degree of separation. However, the most accessible and cheapest materials should always be used. They also investigated the power consumption of other parameters that influence the flocculation process. They concluded that according the Ohm’s law, a high conductivity of the electrolyte and a small distance between the electrodes gives lower power consumption. The settling velocity of multi-fractal flocs formed in coagulation process has been investigated from authors in reference [39]. It was shown that a number of different mechanisms are involved in the formation of flocs. These mechanisms generally depend from the pH of the solution and potential applied during the electro-flocculation. For example two flocs with same size may have been formed by different mechanisms of aggregation and therefore have different arrangement of primary particles. Two flocs with the same size may have different masses or mass distributions and therefore, different settling velocity. The multifractal spectra indicated the existence of multiple fractal dimensions.

These fractal dimensions may provide information on the flocs aggregation and distribution of mass inside the flocs. The authors in ref. [40] investigated the processes of iron oxidation in an electroflocculation cell for a pH range from 5 to 9 and electric currents of 0.05 – 0.4 A. It was shown that iron anode dissolves as Fe²⁺ and oxidation rates of the Fe²⁺ to Fe³⁺ strongly dependent on the pH. The authors in reference [41] investigated the direct and alternative current mode in efficiency of electroflocculation. They noticed that application of direct current mode provoke formation of an impermeable oxide layer on the cathode causes the declining of the efficiency. This disadvantage has been reduced by adopting alternating current at pH 9.

4. Flotation

Flotation is a widely used process in wastewater treatment and mineral processing industries [42]. In wastewater treatment flotation is used for removing suspended solid matter (colloids and flocs), oil, fats and greases from emulsions in water. The removal is achieved by dissolving air or introducing gas into the wastewater, under pressure. The released air forms the bubbles which adhere to the suspended particles and float to the surface of the wastewater. Then, the floated particles can be easily removed by the skimming device or through overflow in a suitable container. Flotation can separate the small solid particles according to their varying capacities to float. The flotation process consists of four basic steps: (i) Introduction of gas into the wastewater and promotion of its bubbling, (ii) Contact between gas bubbles and suspended particles, or oil drops, (iii) Gas bubble adsorption on the surface of particles, or oil drops, (iv) Raise of gas bubbles, along with the floc or oil drops to the surface [43-46]. At the water surface a layer of foam will be created consisting of gas bubbles and the floated particles or oil drops that can be removed by skimming.

The rate of flotation is a function of several parameters such as: the surface tension among the water particles or oil drops and gas bubbles, the size of the particles or oil drops, the diameter of gas bubbles, the temperature, pH and the particles or oil drops distributions. In practice, various flotation methods are used, but the conventional process involves blowing air through nozzles at the bottom of the flotation tank using a compressor. The efficiency of the flotation technologies depends on the size of the bubbles. The small bubbles have a large surface area per unit volume of gas and provide a larger surface area for particles or drops to attach. Another method is dissolved air flotation, which gives a better bubble distribution in the water. The air is injected into the water under pressure. The air is released until the water is supersaturated with air [47]. Vacuum flotation is a method that uses vacuum to release air bubbles from water that is saturated with air at atmospheric pressure [48,49]. The disadvantage of all these methods is that they are not continuous processes and the control of the bubble flux is fairly complicated.

5. Electro-flotation

Electro-flotation EF was initially proposed in 1905 for flotation of usable minerals from ores [50]. Electroflotation refers to the process of electrolytically forming bubbles to float pollutants to the water surfaces. It replaces bubbles generated from dissolve air. In the EC technology only hydrogen bubbles are produced at the cathodes, whereas in the EF technology the hydrogen bubbles are produced at the cathodes and oxygen bubbles at the anodes. The oxygen gas will be generated at the anodes only at higher current density. At the cathode there is also evolution of hydroxyl ions that is an additional advantage for maintaining the pH of the electrolytes. The current density can be easily regulated by controlling the applied voltage between the anode and cathode, and the surface area of the electrodes. There are three basic steps in the development of gas bubbles; nucleation, growth and detachment from the electrode surface. It is well known that the electrode surfaces are not ideally flat and the micro-roughness of these surfaces have various energy-favorable places, like pits and scratches. Because pits and scratches have a higher current density than the rest of the electrode surface, nucleation begins in these places.

Growth is initiated by two mechanisms; super-saturation and coalescence of gas in the electrolyte where expansion is provoked by a high internal pressure and transport of dissolved gas through the gas/liquid interference [51]. Coalescence occurs when two or more gas bubbles touch each other and coalesce into a single gas bubble [52]. Coalescence is also possible when one gas bubble rolls across the cathode surface and coalesces with every gas bubble it finds on its path. Coalescence is not favorable for the flotation rate because the gas bubbles with a bigger diameter are less effective than the gas bubbles with a smaller diameter. The last step is detachment of the gas bubbles from the electrode surface which depends on the size of the bubbles and the angle of bubble contact. This step can be accelerated with the addition of surface active substances in the electrolyte, in order to reduce the surface tension between the electrolyte, the electrode surface, and the gas bubbles. Mainly, the diameter of the hydrogen and oxygen bubbles generated in the EF ranges from 17 to 50 μm . In chemical flotation technologies the typical mean diameter ranges from 48 to 60 μm [53]. Usually the diameter of the bubbles generated by EF obeys a log-normal distribution with over 90% of the bubbles ranging from 15 to 45 μm , if titanium based anode is used [54].

The bubbles that are generated electrochemically are smaller than those generated by injecting gases, which makes this method of flotation more efficient. During electro-flotation with electrically soluble anodes made from Al, as in the case of electro-flocculation/electro-flotation, on the Al electrode, the following reactions occur [55-57]



Electroflotation can be used as separate method, but it is frequently combined with electrocoagulation or coagulation, with electroflocculation or flocculation, or with both electrocoagulation and electroflocculation [58-61]. In industrial practice electro-flotation is frequently used for treatment of surface water [62] treatment of different types of industrial wastewater for removing: heavy metals [63], heavy metals from washing soil [64], heavy metals from textile wastewater [65], synthetic solutions and textile wastewater [66], reduction of copper ions concentration in wastewater of galvanoplastic industry [67], removal of zinc [68] and fluoride from drinking water [69]. This method is also applied for removing oil substances [70], separation of pollutants from tannery effluents [71], removal of COD from laundry wastewater [72], biomass from microalgae separation [73] etc.

5.1. Factors affecting electro-flotation

Electro-flotation is a continuous process and the gas bubbles are generated as the water flows between two opposite electrically charged electrodes.

The electrodes are built from inert insoluble, dimension stable and resistant materials and they do not participate in the reactions. The three main factors which affect the efficiency of electro-flotation are: pollutant removal, electrode material consumption, and power consumption. The electrode material, current density and pH affect the bubble size and consequently the efficiency of electro-flotation. Smaller gas bubbles have smaller buoyancy and longer residence time in the electrolyte. This increases the possibility for collisions between the bubbles and the suspended particles. In order to obtain fine sized gas bubbles it is necessary to control the pH, temperature, reagent concentration and to choose the most suitable electrode materials.

(i) *Electrode material.* Similar to electrocoagulation and electroflocculation, in EF electrodes are usually made from Al, Fe and stainless steel as a one unit process electrocoflocculation/electroflotation. It was found that the smallest gas bubbles are produced at the stainless steel electrodes [53]. This phenomenon could be explained by the corrosion resistance of stainless steel and the augmentation the electrode surface roughness during the electrolytic processes. Stainless steel is more resistant than the electrodes that are typically used and during the electrolytic processes its surface roughness is not easily changed compared to other electrode materials [74]. The mechanical polishing that creates a mirror like surface on the stainless steel electrode produces the finest bubbles. In ref. [75] the authors describe the methods for bubble size measurements in electroflotation. Today various companies build commercial in-confidence stable electrodes using Ti, Ta₂O₅, IrO₂, RuO₂, Sb₂O₅, SnO₂ etc., as a base [76-79]. In the last decade special attention was devoted to the production of long service life electrodes with the ability to be reversed automatically during the polarization process of the electrode (self-cleaning effect) [80].

(ii) *pH* of the solution strongly influences the size of the formed gas bubbles. The smallest hydrogen bubbles are produced at neutral or slightly acidic conditions. Authors in reference [81] have reported that the hydrogen gas bubble size increases with increase in temperature and the smallest ones were formed at pH 7. In contrast, the size of the oxygen bubbles increased with increase in pH. Authors in ref. [82] reported that the recovery of sphalerite is optional at pH between 3 and 4. At this pH range the hydrogen bubbles are the smallest, about 16 μm.

At pH 2 the hydrogen bubbles are about 23 μm, while at pH 6 they are about 27 μm. The critical review for electro-flotation taking in consideration the parameters affecting electroflotation was described from authors in ref. [83]. The authors in this ref. describe in detail the effect of electrode material and pH of the medium on the bubble dimensions. They concluded that the minimum bubble dimensions occur in a neutral medium (no matter what cathode material is used) and in an alkaline medium. In the acid medium the effect of the cathode material on the size of the bubbles is extremely pronounced.

The value of the mean bubble diameter being found to vary in the range between 20 and 70 microns. The effect of the cathode material on the dimension of the hydrogen bubbles becomes less marked in an alkaline medium, the mean diameter of the bubble varying between 15 and 30 microns. In the neutral medium the size of the hydrogen bubbles is practically independent of the cathode material, mean diameter of the bubble being found to be limited to the range between 15 and 20 microns.

(iii) *Current density*. Current density is an operational parameter that can be controlled continuously. This parameter directly determines the bubbles' generation rate, solution-mixing and mass transfer at the electrodes. In literature there is some controversy with respect to the reported effects of current density on the size of the bubbles produced at the cathode. The Authors in reference [75] reported that depending on the current density, significant quantities of hydrogen produced at the cathode are dissolved in the electrolyte solution. According of their results, the bubble diameter is a function of the hydrogen production rate, bubble nucleation rate and the dissolved gas concentration. On the other hand, the authors in reference [84], as well as the authors in reference [51] and authors in reference [81] have found that with increase in current density the bubbles' size decrease. For current density values higher than 200 A/m^2 the size of the bubbles ranges from $20 - 38 \mu\text{m}$. The modeling and measurements of bubble formation and growth in electroflotation process was presented in reference [85,86]. The authors calculated the flux equivalent to current density of 152 A/m^2 minus flux of gaseous hydrogen evolving in the form of detaching bubbles. Initial diameter of the bubbles (just after detachment) was based on experimental observations was $22\mu\text{m}$. It was shown that the Lagrangian-Eulerian Discrete Particle CFD model can be efficiently used to simulate hydrodynamics, mass transfer and bubble size variations.

6. Electrochemical reactors, design and operation

In literature and in practice three types of electrochemical reactors can be found: (i) only electrochemical dissolution, (ii) electro-coagulation/electro-flocculation and (iii) electro-coagulation/electro-flocculation with electro-flotation [87]. In figure 2, the electrochemical processes which occur in electrochemical reactors are presented schematically.

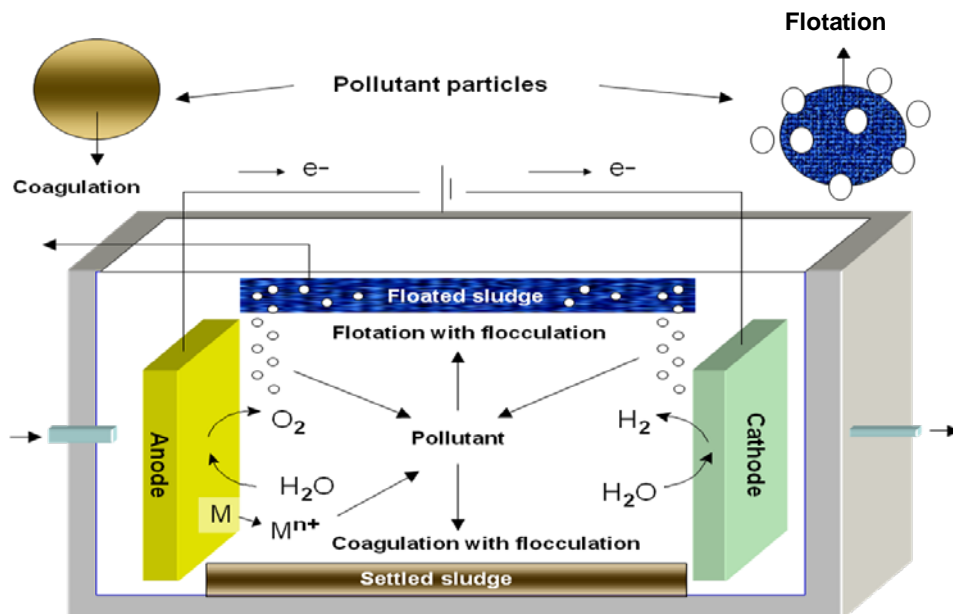


Figure 2: Schematic presentation of electro-coagulation, electro-flocculation and electro-flotation

The reactors can be constructed as batch and continuous reactors [88-90]. Batch reactors are generally used for smaller quantities of waste water and during operation the volume of treated water is constant. Continuous reactors are better suited for large scale treatment processes and they are generally less costly than batch systems.

6.1. Electro-coagulation reactors

The operation system for electrocoagulation consists of: an electrochemical reactor, electrodes, a power supply, pipes and pumps. The key components in electrocoagulation reactors are: coagulants, contaminants and generated bubbles. The interactions between these components are the basis for the reactor design. There is not any one set of uniform instructions, or an empirical or a systematic approach that will give a more scientific recommendation for the design of an electrocoagulation reactor and its operation. Electrocoagulation, EC is usually performed in small, high throughput reactors. The water goes into settling tanks where the process occurs (incubates) and then the pollutants are removed. Generally, the reactors are designed for a specific process, quantity and types of pollutants including operational parameters, bubble path, coagulation, current effectiveness, the mode of operation (batch or continuous) [91] etc. In the design phase, as is proposed in reference [91,92], the following physical and mechanical factors must always be considered: reactor geometry, scale-up issues and current density.

The design geometry of the reactor is strongly influenced by the operational parameters including: effectiveness of the electrocoagulation, electro flocculation and electro flotation, fluid flow regime, mixing and settling characteristics and the path of the gas generated bubbles [93-95]. Typically the reactors have a cylindrical form and the quantity of inflow water must be balanced with the quantity of dissolved metal ions from anodes released in the reactor. For a specific type of pollutant it is recommended that first testing is performed on a laboratory scale in order to determine the operational parameters [96,97].

The reactor scale-up defines the relationship between the laboratory size and full scale equipment. One of the most important scale-up parameters is the surface area S to volume V ratio, i.e. S/V . The analysis of this parameter was reported in reference [92] and it was shown that it varies in the range from 18.8 to 42.5 m^2/m^3 . The current density (current value per unit active electrode surface area) and the S/V ratio can be used as the basic scale-up parameters for a design. If the current density is too large, there is a great chance that excess electrical energy will be used (wasted) for heating up the water, and the current efficiency can significantly decrease. In order for the electrocoagulation system to operate for a longer period of time without maintenance, it is suggested that a current density of 20-25 A/m^2 be used. To ensure high current efficiency the current density selection should be determined based on other operating parameters such as: pH, temperature, flow rate etc. The experimentally determined operating current density is the best starting point for adjusting the current until the optimal current density is obtained.

The electrocoagulation process does not remove the pollutants from the wastewater itself. It only transforms the pollutants to ease separation by: electro-flotation, sedimentation, filtration etc. The separation can occur in the reactor or in downstream units. Sometimes, to achieve successful removal of pollutants, the electrocoagulation processes can be combined with other units, including: sand filtration, electro-flotation, micro-filtration etc. For example the authors in reference [98] studied Cr(VI) removal by EC combined with granulation activated carbon at pH 8. The optimal separation was achieved with a current density of 26.7 mA/cm^2 and an operation time of 100 min. The other combination method, EC-ultrafiltration, has been applied by the authors in reference [99] for removal of Cu, Cd and Pb from wastewater.

In an electrochemical reactor the electrodes can be arranged in several ways. Water flows between the electrodes and can follow in a vertical or a horizontal direction, therefore, in practice; two types of electro-coagulation reactor units are used: with horizontal and vertical flows, figure 3.

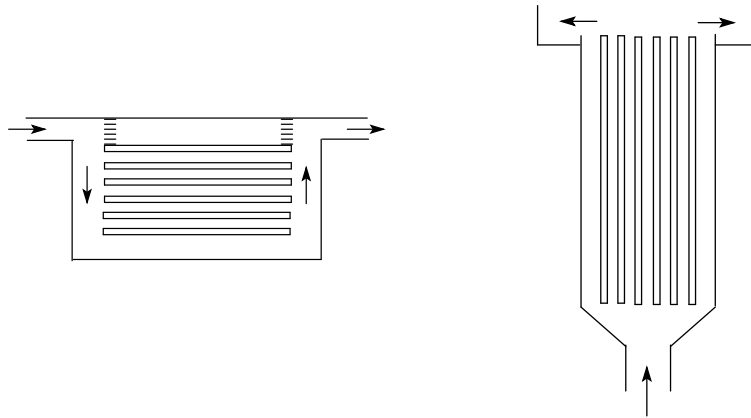


Figure 3: Electrocoagulation units, horizontal and vertical flows

The electrodes in the reactor units are typically constructed as parallel plate electrodes separated by a few millimeters with low voltage applied at high current densities and water flowing through the spaces between the electrodes [100].

The electrodes can be monopolar or bipolar [101]. In monopolar systems all anodes are connected to each other and all cathodes are also connected to each other, Figure 4 (a). In a bipolar system, only the outermost electrodes are connected to the power source, but the current passes through the inner electrodes connected in a series, as shown in figure 4, (b)

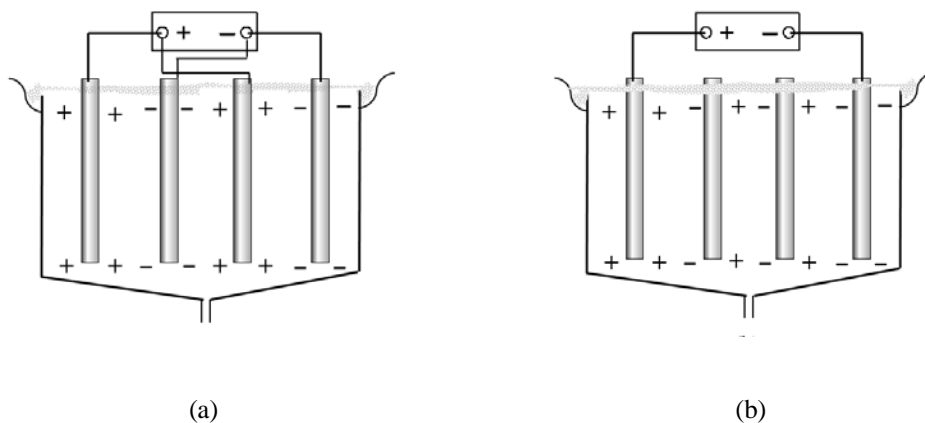


Figure 4: (a) monopolar connection, (b) bipolar connection

The pollutant removal efficiencies and operating costs of the monopolar and bipolar configurations have been compared in several studies so far [102-104].

The authors in reference [101] treated a slaughterhouse wastewater using mild steel and aluminum electrodes arranged in a monopolar and bipolar configuration. They found that the best performance was obtained with the mild steel electrodes in a bipolar configuration. On the contrary, the authors in reference [105] used mild steel electrodes in the removal of Cr^{3+} and reported that the current efficiency was lower when the electrodes were in a bipolar configuration, i.e. (64.6%) than when they were in a monopolar configuration (91.7%). Additionally, complete removal of Cr^{3+} was obtained with a bipolar electrode configuration. The fluoride removal from drinking water by EC with monopolar and bipolar electrode configurations has been studied by the authors in reference [106]. They have shown that the bipolar electrode configuration is more efficient but the operational costs are higher than the ones for a monopolar configuration. Other authors have reported that the use of monopolar electrode configuration in wastewater treatment is better for: oily bilge water [107], textile wastewater [108] and laundry wastewater [109]. The studies of the above mentioned authors showed that generally a monopolar configuration has lower operating costs but a bipolar configuration has higher removal efficiency. Monopolar and bipolar configurations of Al and iron electrodes were analyzed by the authors in reference [107] for treatment of oil bilge water at a laboratory scale. They reported that the removal efficiencies of electrocoagulation at optimal conditions were: 93% *BOD*, 95.6% oil and grease, 99.8% *TTS* and 98.4% turbidity. There are two types of channel construction for water flow through the space between the electrodes: single or multiple channels, figure 5. It has been concluded that multiple channels are simpler to construct than a single channel, but the flow rate in each of the multiple channels is smaller than in a single one [110].

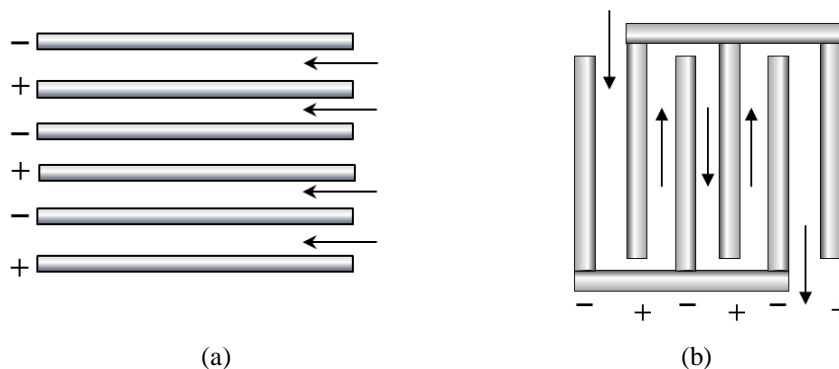


Figure 5: Mode of water flow: (a) horizontal multiple channels, (b) vertical single channel

6.2. Electro-flotation reactors

The reactor design influences the operational parameters including: flotation effectiveness, formation of floc, fluid flow regime, bubble path and mixing/settling characteristics. Depending of the reactor's geometry the electrodes in electroflotation, EF reactor can be placed horizontally or vertically. In older reactors, the horizontal electrode design was used more frequently [111-113]. Nowadays the electrodes in the reactor are usually installed vertically. Anodes are placed at the bottom of the reactor, whereas the cathodes are fixed at 10 – 50 mm above the anodes [82,110]. The efficiency of the EF process will depend on the conductivity of the wastewater and on the inter-electrode spacing. The authors in reference [110] tested the horizontal electrode configuration and proposed the construction of a reactor schematic with a more efficient electro-flotation.

Taking into account that the ohmic potential drop is proportional to the inter-electrode distance, reducing this distance will reduce the energy consumption.

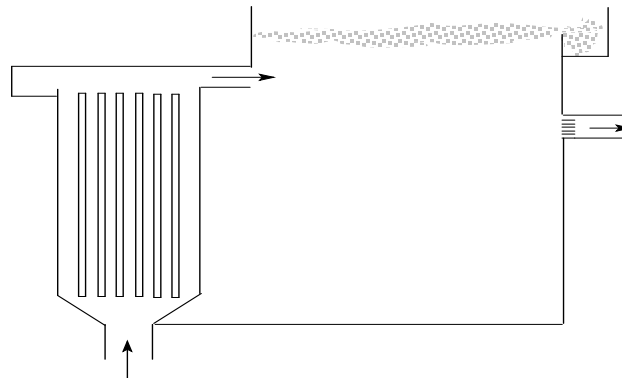


Figure 6: Combined electro-coagulation and electro-flotation

The EF system is usually combined with EC Fig.9. Besides anodes and cathodes, the EF system also contains a power supply and a handling unit. The reactor design should allow intensive mixing of pollutants in the wastewater before flotation as well as intensive contact between the colloidal and other suspended particles which will lead to agglomeration and flocculation into larger particles. In literature, equations can be found that can be used to design EF for industrial operations [114] however, laboratory studies for a specific purpose should always be considered.

7. Conclusion

From the presented theoretical and practical literature knowledge of electro-flocculation and electro-flotation the following conclusions can be drawn:

- Electro-flocculation is habitually combined with electro-coagulation or with electro-flotation. In this process, to reach operational efficiency, the anodes must be more easily oxidizing than the cathodes. Generally anodes are built from Al whereas the cathodes from stainless-steel. The flocs formed in an electrochemical way are similar to the chemically formed ones, but they are larger and more stable, containing less bound water and can be separated faster. Electro-flocculation has proven to be highly efficient especially in removing fecal matter, coliforms and parasites which represent a threat to human health.
- Electro-flotation has many advantages in comparison with conventional flotation methods. The conventional flotation methods include the following processes: (i) Release of air gas bubbling through a liquid. It is achieved by using a compressor. In this flotation method the distribution of air gas bubbles is not uniform and the size of the formed bubbles is not small enough. (ii) Dissolved air flotation. In this flotation method first the air is injected into the water under pressure just when the water is supersaturated. Then, the air is released as bubbles. The distribution of gas bubbles is better than in the previous method, but it is not a continuous process and it is difficult to control the bubble flux. (iii) Vacuum flotation.

In this flotation method water is saturated with air at atmospheric pressure. When vacuum is applied, air bubbles will be released. This method has the same disadvantages as dissolved air flotation. Different from the conventional flotation methods, electro-flotation is a continuous method and the bubbles are generated by electrolysis of water. The main advantages of electro-flotation are: (i) The generated gas bubbles are very small with approximately the same size. (ii) By varying the current density at the electrodes it is easy to adjust the gas bubble flux. (iii) The bubbles are produced over the whole area of the electrodes and their distribution across the solution is uniform. (iv) The gas bubbles produced during the electrolysis can carry the pollutant to the top of the solution where it can be easily concentrated, collected and removed.

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