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Study of an electrocoagulation (EC) unit for the treatment of industrial effluent of Ouagadougou, Burkina Faso

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ABSTRACT

The assessment of industrial liquid waste of Ouagadougou shows 91262 $m^3\ yr^{-1}$ total quantity of effluent composed mainly of tannery effluent. Treatment experiment by EC of these effluents allowed to eliminate chromium and to lower COD up to 86% abatement. The process designed for the treatment of liquid waste from tannery works at 10.5 $m^3\ hr^{-1}$ for current density of 67.5 $A.m^{-2}$, 62.5 V, 1.2 kWh m^{-3} energy consumption, and produces 86,000 m^3 of clear water with 200 mg L^{-1} COD, 0 turbidity, 91% color abatement, 0 ppm chromium. The treatment produces nearly 480 $m^3\ yr^{-1}$ of sludge after compression using filter-press and 216 T of dry matter containing chromium and iron hydroxides, organic and inorganic pollutants.

Keywords: Electrocoagulation, iron, wastewater, tannery, equipment calculation.

INTRODUCTION

The population of Ouagadougou rise from 300 000 in 1990 to more than 1.5 million people today. This resulted in an increase of consumption thereby leading to increase in liquid and solid waste from households and industries. Solid waste is relatively well managed but the wastewater is difficult to manage due to the collection and drainage to the station. Only few plants, hotels and shopping malls are connected to the network of wastewater. In addition to these reasons, the high toxicity of some industrial effluents making them unsuitable for biological treatment station, leads some industries to pretreat their effluent before discharging or lead them to the treatment station. Today, the tannery is the largest factory rejecting the largest amount of effluent, but remained not connected to the station due to the inefficient pretreatment.

Electrocoagulation (EC) is a primary technique for treatment of various wastewater from industry, agriculture or urban areas [1, 2, 3]. The EC process creates in the water to be purified, the metal hydroxide flocks by electrodissolution soluble anode (iron or aluminum). At pH values close to neutral or acidic (4-7), aluminum and iron dissolved in their cationic form, react with water to form divers complexes such as $Al_2(OH)_5^+$, $Al_2(OH)_2^{4+}$, $Al(OH)_3$, $Fe(OH)_2$ or $Fe(OH)_3$. These forms act as coagulant; aggregates of particles are formed, decanted and water is then "purified." The electric field in the electrolytic cell induces the migration of colloidal particles to the anode, which has the effect of increasing the probability of encounter, thus promoting the coagulation - flocculation. The electrolysis of water also induces the formation of small bubbles of oxygen and hydrogen (whose average size is less than 100 micrometers) respectively to the anode and cathode. These bubbles consist mainly of hydrogen because oxygen is the formation of a secondary reaction, often of minor importance to the anode. These micro bubbles are absorbed by the flocculated material and lead them to rise. The impurities can then be treated by flotation. The foam can be formed of poor stability and oxidizable materials fall to the bottom of the decanter. Despite this, many light and heavy particles remain suspended and we must resort to their separation by settling or filtration.

This paper presents some results of EC treatment obtained in laboratory, based on which it proposed then a design of processing equipment for treatment tannery effluents of Kossodo.

MATERIALS AND METHODS

2.1. The EC process

Several technologies of electrocoagulation were focusing on the scale of the laboratory and in the industrial scale [4]. Electrochemical units can be combined with the other treatment modalities such as the biological treatments or the physical processes like sedimentation, settling or filtration [5, 6]. It is possible to have in the domain of electrocoagulation, numerous variants according to the forms of electrodes (flat, cylindrical, fixed beds of spherical balls or rotary electrodes) or according to their way of electric connection [7]. It distinguish for this last point as for the other electrochemical processes, the mass monopolar mode, the serial bipolar mode and the monopolar mode in parallel is used for the present study.

It choose a pilot with continuous recirculation and agitated reactor with electrochemical reactor composed of two flat electrodes in parallels.

The components of the used electrochemical pilot are assembled according to the following plan:

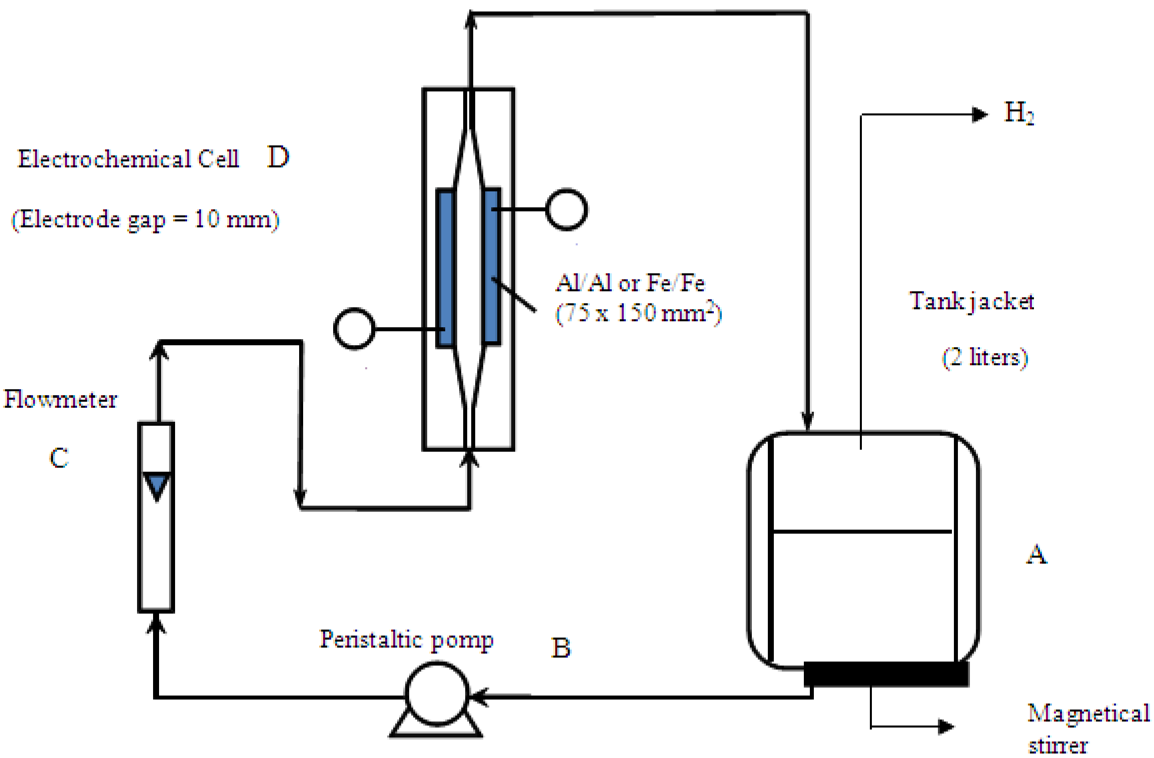

Figure 1: Pilot of treatment

The starting point is the tank jacket (A) which is responsible for 2 liters per treatment. As a stirred reactor, peristaltic pump (B) ensures the gradual rise of the effluent to the electrochemical cell (D). From the electrochemical cell, as a result of pressure imposed by the pump and the gravity effect, the effluent returns to the tank jacket which provides agitation to homogenize the dissolved metal to pass through the electrochemical cell. The pump continues to draw the effluent into the cell continuously for the duration of the experiment.

Agitated reactor allows homogenization of the effluent but the agitation is maintained at a relatively low speed (100 rpm) so as not to break the flocks and also facilitate the settling. This also allows recirculation of effluent not to saturate the metal dissolved in the electrochemical cell. The agitation in the reactor can also separate the gas from the effluent and also to limit the foam which hinders the smooth operation of the electrocoagulation.

2.2. Analytical methods

During the treatment, some of the data is continuously recorded by various sensors, while the acquisition of other data such as the composition of the effluent requires analysis. Samples were then collected and submitted to analysis. .

2.1.1. Analysis or measurements continuously

pH measurements are performed by a pH meter Consort C931 model with a glass electrode containing a solution of 4M KCl concentration. The pH meter is calibrated with standard solutions of phosphate, pH 4, 7, 10 and 12. The accuracy standards given by the supplier is ± 0.02 units at 20 ° C. The pH of each sample taken at the stirred reactor is taken immediately. The voltages are directly measured on the display of the power supply.

2.1.2. Analysis requiring sampling

At the end of electrocoagulation, tests are performed on the samples. These include measurements of the dissolution of sacrificial metal (Al or Fe) and indicators of pollution (COD, TOC and turbidity, absorbance, Chromium VI, total chromium).

- Determination of the concentration in dissolved metal

The measurement of the concentration of dissolved metal is done by taking a quantity of the effluent after homogenization of the effluent collected. Samples are acidified, diluted and filtered through a syringe filter of 0.45 mm prior to analysis in atomic absorption spectrometer [3]. Total chromium, aluminum and iron were measured by this way.

- Measurement of COD, turbidity and absorbance

COD, turbidity, absorbance and the concentrations of chromium VI and total chromium were measured after decantation and adjustment of the supernatant to the pH of flocculation: The pH is of 6.5-7 for the treated effluent by aluminum electrodes and more than 6 for those treated with iron electrodes [8].

We used type Hanna's device instruments LP 2000 containing an infrared diode of wavelength 890 nm and a detector of reflected light which is a device with direct reading for the measure of the turbidity. The measure is based on the absorption or the distribution of rays of light by particles in suspension.

The COD is defined as an expression of the amount of dissolved oxygen required to oxidize by chemical means, without the intervention of living things, all oxidizable substances. It is expressed as mg O_2 per liter of solution. Analyses are conducted according to AFNOR standard and in accordance with standard of U.S. SMEWW.

The method S-diphenyl carbazide was used for the determination of chromium VI.

- Monitoring the color of the effluent by absorbance in the UV visible

The absorbances of samples were measured on the clear supernatant. Prior to the clear supernatant of untreated raw effluent decanted undergoes different wavelengths to determine the maximum absorption wavelength. Then, the reduction is followed during the treatment by samples. These measures are made in visible UV spectrometry after taking baseline with deionized water. The UV visible spectrometer is controlled by a computer.

Table 1 : Effluent characteristics

Characteristics	Amount
pH	9.04
Turbidity / NTU	397
COD / mg O_2 L^{-1}	1,237
Conductivity / mS cm^{-1}	2.9
$[CO_3^{2-}]$ / mg L^{-1}	1,475
$[NO_3^-]$ / mg L^{-1}	11.1
$[H_2PO_4^-]$, $[HPO_4^{2-}]$ / mg L^{-1}	2.6
$[SO_4^{2-}]$ / mg L^{-1}	56
$[Cl^-]$ / mg L^{-1}	27.9
Total chromium (mg/l)	185

The values given may vary according to:

- The type of dye used in the treatment,
- The type of treatment (bleaching, finishing or dyeing),
- The current activity in the plant (rinsing or functioning).

2.3. Effluents and their characteristics

Waste water of tannery is particular by their relatively important organic load, and the presence of organic colouring agents and chromium are fatal in the conventional biological treatments. The contribution of the electrocoagulation is to have after the treatment effluent that can be thrown to the conventional treatment stations. It means that the waste water is exempted from his colouring agents and from its strong inorganic load. Table 1 shows the characteristics of the effluent carried from tannery industry. The conductivity was sufficient (Table 1), and so all the effluents were treated with no added salt. The concentration of hexavalent chromium is between the mean values of tanneries (3-350 ppm) [9]. The concentration of chromium (VI) was found about 185 ppm for all the treated effluent.

2.4. Choice of experiments and objectives

2.4.1. Sampling and data acquisition

Treatment with continuous recirculation allows for the end of time sufficient dissolved metal able to flocculate all the pollution of the effluent in most cases, as shown by preliminary tests.

Handling takes 1 hour. Samples are taken at 1, 2, 3, 4, 5, 7, 10, 15, 20, 25, 30, 40, 50 and 60 min, as well as pH measurements and readings on the generator voltage stabilized. This allows to follow the kinetics of the treatment by monitoring the amount of pollutants in the different samples taken over time and to ensure continuity of treatment by the tension and pH.

These samples are fixed to a suitable pH by adding a dilute solution of HNO_3, depending on the metal used to be at the optimum pH for the precipitation of metal hydroxides with adsorbed impurities, controllers.

The two electrode materials are compared by varying the current densities of 50 to 200 $A.m^{-2}$ with an increment of 50 $A.m^{-2}$. These current densities are set at moderate levels to avoid any side reaction such as the release of oxygen or overheating. This work allowed to know the effect of current density on the reduction of chromium, COD, turbidity and in the Faraday efficiency, pH, cell voltage, charge and energy consumed ([3, 8]. Each sample taken shows the evolution of different parameters and indicators of pollution in terms of kinetics. It also allows discovering the behavior of the electrodes.

2.4.2. *Treatment of tannery effluent*

This work allows to study at first experimentally and the elimination of chromates, in theory, to study the different reactions during the electrocoagulation. Chromium is very harmful especially in its hexavalent form and its maximum allowable limit of 50 ppb in drinking water in France.

RESULTS AND DISCUSSION

3.1. Treatment appearance

Figure 2: Presentation of samples

In figure 2, it observes in the visible orderly first one the effluent station treaty with iron electrodes in the density of current of 200 A. m^{-2} and sampled in 1, 2, 3, 4, 5, 7, 10, 15, 20, 25, 30, 40, 50, 60 min respectively from left to right. As seen in Figure 2, samples taken during treatment and positioned in the debit order visually illustrate a reduction of the color over time. It is precisely these reductions we want to quantify as indicators of pollution.

3.2. Sizing of a unit of wastewater treatment

3.2.1. Proposed treatment for industrial effluents untreatable by biological methods

The assessment of industrial liquid waste treated by biological way shows that several do not give satisfactory results [10]. Table 2 shows that of all industries, tannery (Tan Aliz) is one that rejects the largest amount of wastewater to be treated on its own and rejects 90,000 m^3. This plant has a biological treatment plant which seems inadequate and fails to adequately treat the COD and heavy metals. So that the effluents can't meet the criteria for admission to the collective network of sewage treatment which is operated at the National Office for Water and Sanitation (ONEA). This leads to reject the tannery in the wild waters, causing odors of the plant and the dam of Massili receiving effluents. It is common for many fishes and other freshwater animals find died on the shore of river.

Our previous work [3, 8] showed that electrocoagulation is suitable for tannery effluents by eliminating all chrome and allowing a significant reduction of COD.

Table 2: Flow of Non-biodegradable wastewater

Industries	Quantity of effluent discharged (m^3/yr)	COD en mg d'O_2 . L^{-1}
Oil industry	1,176	8,457
Food industry	20	4,000
Nana Metallic industry	60	7,235
Hage Metallic industry	5.7	7,235
Tannery industry	90,000	1,340
Total (Average)	**91,262**	**1,436**

3.2.2. First approach to analyze the role of EC in Burkina Faso

Treatment with EC can be applied to all effluents as shown in Table 2. It is true that apart from the food industry all industrial companies listed in this table 2 are the site of the industrial area of Kossodo. The present study is limited to tannery wastewater representing 90,000 m^3 per year which are COD of 1,340 mg O_2 per Liter and 200 ppm chromium.

3.2.3. Operating conditions and design

It considers treatment with iron electrodes that gave the best discounts chromium and COD. Work on the tannery effluent showed the kinetics of reduction of COD and chromium presented respectively in the two following figures.

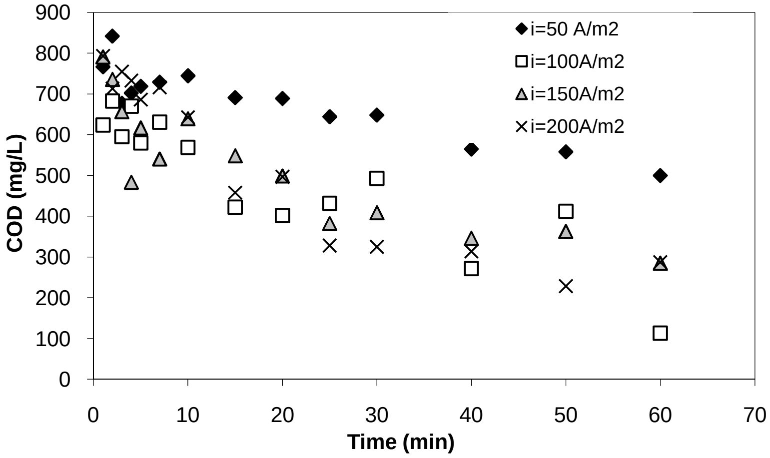

Figure 3: Evolution of COD of the effluent from tanning during treatment with iron electrodes in electrocoagulation

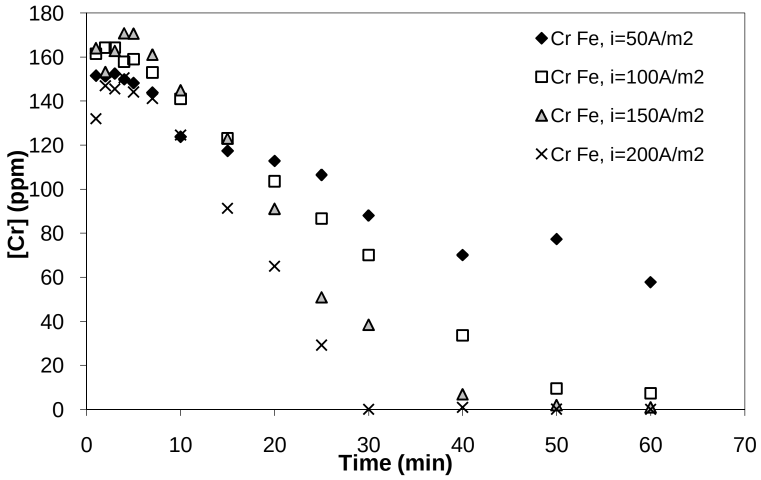

Figure 4 : Evolution of the concentration of chromium in tannery effluent during treatment with iron electrodes in electrocoagulation.

Figure 3 shows the evolution of the COD of the effluent from tanning during treatment with iron electrodes. It shows that COD is approximately 200 mg O_2 per Liter at the end of treatment. The COD value is the lowest achieved for both electrode materials (aluminum and iron), which leads to the choice of iron electrodes.

Figure 4 shows the evolution of the concentration of chromium in simulated tannery effluent during treatment with iron electrodes. Only the treatment with iron electrodes arrives to remove chromium, which still justifies its choice. The efficiency of iron electrodes on tannery effluent treatment is presented in several works [11- 14].

In addition to these technical reasons, it is easier to use mild steel plates as aluminum in Ouagadougou, which is a favorable criterion in the selection of iron electrodes [15].

3.2.4. Sizing of the treatment process by electrocoagulation

The design of a device for sewage treatment must take into account two factors:
- The volume of effluent to be treated and its characteristics
- Expectations of treatment in terms of efficiency or residual concentrations of pollutants.

The first is well known by the quantitative and qualitative assessment of waste water (90,000 m3/day, 1,340 mg O_2/L COD and 200 mg/L of chromium) and the second is a set of factors that lead to a characteristic of the effluent discharge (treated water to about 200 mg O_2/L of COD and totally free of chromium).

In the definition of factors related to expectations of treatment, several kinds of criteria can be used:
- Economical
- Environmental
- Technical

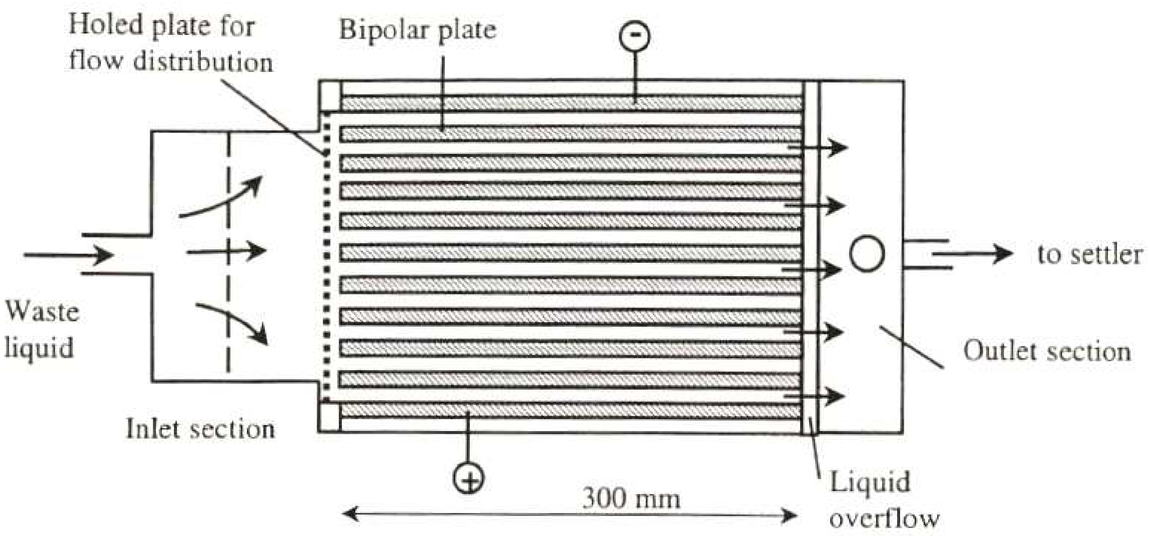

Figure 5 : Configuration of the electrocoagulation cell with bipolar electrodes [17]

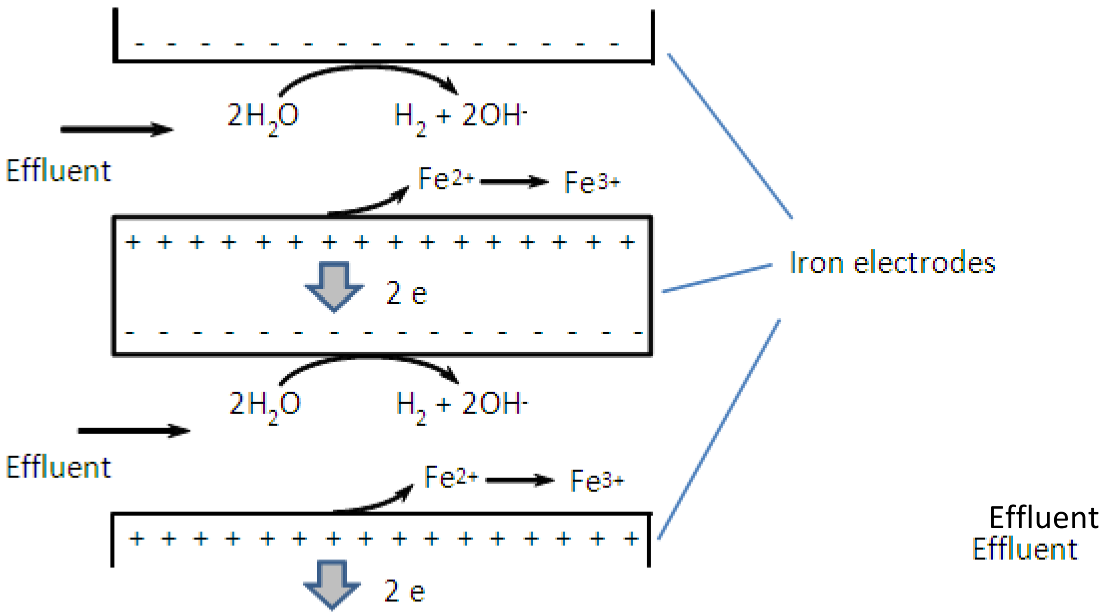

Figure 6: Principle from one cell to bipolar electrodes of iron: only two cell reactions associated with are represented here.

The economic criterion, in this case relates to the energy consumed in addition to investment costs, environmental criteria related to the byproducts of the treatment and the technical aspect is related to the feasibility and effectiveness of the process. For a given effluent, the effectiveness of treatment can be known from the results of laboratory tests for appropriate ranges of current density and amount of metal cations generated at the electrodes. However, for the design of a large installation, it will take into account the mechanical and technological (height and weight of the reasonable or cells, voltage and current to impose etc.).

For the design of the cell, we started with an already developed in the laboratory reactor that had the advantage of being easy assembly, low pressure drop and suitable for the treatment of a continuous flow of 100 L per hour effluent in a single pass, ie, without recirculation of the effluent. The effluent was a suspension of soluble oils with a COD level of around 100 g/L; preliminary tests had shown that the dose required to treat dissolved aluminum was closed to 800 ppm. The cell shown in Figure 5 consists of 16 aluminum plates, connected in parallel, 285 mm long, 155 mm wide and 12 mm thick. The plates are separated by 3 mm and only the two end plates are connected to two terminals of the electrical generator and each aluminum plate acts as a bipolar electrode (Figure 6): one side acts as an anode, providing the dissolution of aluminum, the other is the cathode, the place of hydrogen evolution. Given the size of the cell and flow, the time of passage of the liquid to be treated is about 75 s. In such system, each cell element, consisting of two sides of electrodes separated by a film of solution to be treated (Figure 6), is powered by the same current. Thus, the dissolution of aluminum is the same in each unit cell in the cell aggregate. The cell shown schematically in Figure 5 includes 15 cell elements. The treatment was carried out continuously, for a current up to 20 A, allowing up to 1500 ppm of dissolved aluminum as the current efficiency of the dissolution of aluminum is much greater than iron [3, 16].

This problem is to treat 90,000 m^3 per year about 11 m^3 / h, on the basis of just over 8,000 hours per year. Experiments [18] showed a maximum reduction of COD and chromium as the concentration of iron in the effluent reached 400 ppm. The stream processing in question requires a minimal amount of dissolved iron equal to 4.4 kg of iron per hour. The current I flowing in a single cell (with a cathode and an anode) used for the production of iron ions by anodic dissolution is given by the formula

$$I = \frac{z_{fer}.F.\dot{m}_{fer}}{M_{fer}.\Phi_{fer}.} \qquad (1)$$

with z_{fer} the number of electrons involved, F the Faraday number, M_{fer} the atomic weight of iron, Φ the coulombic efficiency, m_{fer} the mass of dissolved iron. Anodic dissolution of iron led to the species Fe^{2+} (and thus $z_{fer} = 2$), this species oxidizes rapidly in air to Fe (III) which has significant coagulant properties. We have shown that the Faraday efficiency of dissolution of iron was close to 80% for a current density of up to 200 A m^{-2}. The application of relation (1) leads to a current of about 5000 A, as we cannot consider a single cell.

We therefore opted for a facility with electrochemical cells with each consisting of M (N+1) iron plates, connected in a bipolar manner, as shown in Figure 5 and 6. The M cells (different of M_{fer}) are connected electrically and hydraulically in parallel, and in each cell, the plates form N components of cells electrically connected in series. The overall current to provide for the conversion will be equal to M times the current in a cell (I) and the cell voltage will be worth (NxUc) (Figure 7).

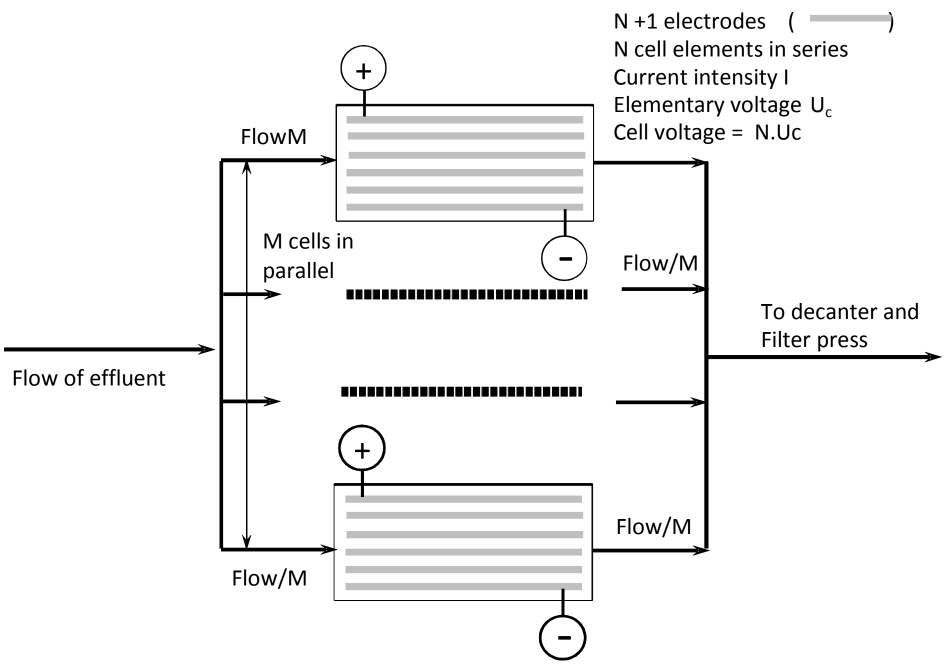

Figure 7: Schematic view of part of the process of electrochemical treatment by electrocoagulation: M cells in parallel, each cell consisting of N elements of cell.

The voltage of a cell can be estimated using the empirical relationship [19].

$$U_c = 0.86 + \frac{e}{\kappa} i + 0.20 Ln(i) \qquad (2)$$

e is the electrode gap, set at 3 mm, i the current density in A m^{-2}, Ln logarithmic and κ the electrical conductivity of the effluent to be treated, here equal to 2 mS cm^{-1} as we were measured. The effluent stream is split into M shares. Many couples (M, N) allow the design of the installation of EC. However, the solutions we offer below will meet the following requirements - except the workflow of Fe^{2+} ions.

• currents and voltages to levels compatible with those offered by rectifiers and power converters
• Dimensions of the cell in accordance to those of industrial electrochemical cells, particularly with iron electrodes of an acceptable weight, in order to maintain an inter-electrode space of 3 mm at any point in the cell without deformation or crushing
• Current density between 50 and 200 A m^{-2}
• Time of passage of the fluid in a cell sufficient to allow the contact of the species Fe (II) and Fe (III) respectively in contact with Cr (VI) and entities in suspension.

The proposed solution is to distribute the effluent in 10 cells (M = 1) in parallel, each with 26 plates (N = 25) iron 1 x 0.30 m^2 and 12 mm thick. The current in each cell crossed by 1.1 m^3 / h is 20.2 A, corresponding to a current density of 67.2 A m^{-2}.

Elementary voltage Uc is estimated at 2.71 V using the rel. (2). Within each cell, the fluid is distributed in 25 areas of the cell: the average velocity of the fluid is 1.3 cm / s, corresponding to a transit time of 75 s between two neighboring iron plates.

The electric power consumed by the electrochemical installation is:

$$P = M \times N \times I \times Uc \qquad (3)$$

Approximately 13.7 kilowatts. Given the hourly flow of effluent to be treated, this power corresponds to energy of about 1.2 kWh m^{-3}, a value consistent with the energy consumption of most methods of electrocoagulation.

3.3. Preliminary design for other elements

It is necessary to store untreated effluents before treatment, other tanks are useful to store treated effluent to adjust the pH to that of flocculation between 6 and 7. These basins will be equipped with valves for filling of a clear liquid and a shipment of the sludge-rich water to the filter press.

The ponds will store at least the amount of effluent corresponding to two days of activity about two tanks of 300 m^3 for the storage of untreated effluent decanters and three of the same volume for the treated effluent. This high-volume storage also takes account of possible power cuts or malfunction.

The use of a filter press for sludge compression and partial dehydration will facilitate and optimize the separation giving sludge cake with a solids content of about 45% and a much reduced volume. The clear liquid collected after the filter could also join the first and be recycled within the unit. After the pH is reduced to a value around 6, decanting is done after 24 hours.

The sludge cake could possibly be enhanced by dissolution of chromium in acid if its concentration is sufficient for a possible reuse of industrial site. This will also concern the iron dissolution and the remaining solid should be filtered: all of these steps should be studied more thoroughly in order to assess its viability.

3.4. Expected impact on the ecosystem

The expected impact on the ecosystem is determined by what is lost in nuisance by treating the effluents. The statement today is summed up by the fact that the tannery effluents are discharged to the air in nature that reaches rivers and pollute its way across the land. At the shores of the river where the waters meet, the effect of the toxicity of water is visible on the river fauna. Around the industry, there are odors caused by hydrogen sulfide (H_2S) strong presence in these waters. H_2S is reported on the EINECS list (European Inventory of Existing Commercial Chemical Substances) as extremely flammable, highly toxic by inhalation, highly toxic to aquatic organisms and harmful to the environment. Effects on the nervous system have been reported [11]. In addition, hydrogen sulfide can be oxidized to sulfuric acid, a toxic and aggressive, particularly on human tissue.
Other nuisances no less important are related to the chromium in tannery effluent. The different forms of chromium have been reported as carcinogenic to the respiratory tract after long exposure, very toxic to aquatic life and pollute the soil.

In addition to these two very toxic components, COD is not low enough to join the collective treatment plant wastewater. And therefore quite logically, the dissolved oxygen in reservoirs of water is used for the slow degradation of the effluent and not for aquatic species.

To sum, hydrogen sulfide, chromium or COD are harmful to people around the rivers and the entire wastewater circuit, soils and aquatic flora are destroyed.

It knows that these pollutants are harmful to the growth of microorganisms responsible for biological treatments, that is the reason for refusal to collective waste water treatment station.

We start from a tannery effluent COD of 1340 mg O_2 / L and chromium content of 185 ppm in the effluent discharged into the Massili. Analysis showed that the sludge volume after settling was about 5% of the total volume of treated effluent [20]. In industrial plant, well above the depth of the settlers should allow for better compression of sludge by gravity, and it could be argued that the sludge after settling represent about 3% of the total volume of treated effluent is 2700m^3.

Given the amounts content of dissolved iron, the solids content of sludge is about 8%. After compression in the filter press, we should get about 480 m^3 of sludge per year containing about 216 T of dry matter (hydroxides of chromium and iron, organic and inorganic pollution from the effluent global).

CONCLUSION

This work shows that EC have a limit beyond which the treatment does nothing. Studied effluent considered in this work have a volume of 91,262 m^3/year and consists mainly tannery wastewater with the respective values of COD and [Cr] of 1436 mg O_2 / L and about 185 ppm. For practical reasons only tannery effluent were selected for the study. Treatment requires the use of an electrochemical reactor of 10.5 m^3 hr^{-1} flow operating at a current density of 67.5 A m^{-2} (or 201.6 A) and 62.5 V for energy consumed in 1.2 kWh m^{-3} effluent, and produce 86 000 m^3 of clear water of 200 mg O_2 / L of COD, 0 NTU turbidity, 91% abatement of color, 0 ppm of chromium. This treated effluent will be able to join the local station. The treatment will also produce about 480 m^3 of sludge per year after the compression filter press and 216 T of dry matter consisting of hydroxides of chromium and iron, organic and inorganic pollution. Electrocoagulation is a possible solution to tannery wastewater treatment because it allows the total elimination of chromium is found in the sludge and can be recycled. The effluent after treatment has a COD less than 200 mg O_2 / L, which allows it to be sent to the local plant [3]. The interest is double: economic and environmental. The technical feasibility study is a good base for future industrial units of the EC. For its feasibility is confirmed, it would be interesting to complete the technical study by the following studies:

- A study of practice and confirmation process optimization we offer
- A financial study: The study will evaluate the financial profitability of a processing unit and the gains it brings to the unit even in the long term through increased sales and a boost in reputation.
- A study of the life cycle.
- A study of energy related to the specific case of Ouagadougou. It is about finding an affordable and sustainable alternative energy.

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