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ORIGINAL PAPER

Costs estimation of an integrated process for the treatment of heavy-metal loaded aqueous effluents

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Abstract This work aims at providing a guide for the calculation of investment and operation costs of a process to treat diluted streams of heavy metal ions. This process is composed of two stages: (1) a metal concentration stage by polymer supported ultrafiltration; (2) a polymer regeneration and metal recovery by electrodeposition. First of all, the most relevant parameters to be used in the process design will be correlated with the key working variables. Next, these parameters will be related with the cost of the main investment of the plant, providing Williams equations based on both literature and suppliers' budgets. Finally, a detailed costs calculation for the most representative values of the working variables will be presented as example.

Keywords Water treatment · Cost · Williams equation · Metal ions · Ultrafiltration · Electrodeposition

1 Introduction

Many industrial processes, as batteries manufacturing or metal surface treatment, produce water effluents loaded with heavy metal ions. As a consequence, the development of techniques to face the treatment of these effluents is a compulsory step to be taken into account in these industrial processes. Moreover, this treatment can also be an economical opportunity as the reuse of concentrated streams of these metal ions in the process, as well as the recovery of these metals in its metallic form, can give an economic return to the main process.

For this reason, costs calculation of water treatment technologies is an unavoidable step to check the viability of the process. Nevertheless, it is not easy to find in the existing literature simple cases of economical assessments applied to actual engineering applications, mainly those focussed on providing figures and equations to be directly used to tackle the costs calculation for a given scenario. More specifically, the previous works regarding economical assessments in the field of water treatment and reuse [1–4] are not conceived to be a guide of the costs calculation process, but they are focussed just on demonstrating if the target process is or not economically viable.

In this context, this study presents a guide to carry out the calculation of the treatment cost of an aqueous effluent loaded with heavy metal ions. The target effluents may be diluted streams (<0.5 g L^{-1}) but with a heavy metal concentration clearly above its allowable disposition limit.

The main aim of the process is the production of a treated effluent with a metal concentration below its discharge limit, as well as the recovery of the heavy metal. The proposed treatment plant would be part of a more complex industrial process (e.g. batteries manufacturing, metal surface treatment, etc.) with the aim of allowing the disposal of the treated effluent and avoiding the costs of its treatment by an authorized waste management company. At this point, it is worth mentioning that this study could be extrapolated to similar effluents loaded with metal ions different from Cu^{2+}.

The first step should be the selection of a suitable technology. According to previous research work [5–7], the proposed process is based on the technique of Polymer Supported Ultrafiltration (PSU), using partially ethoxylated

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polyethylenimine (PEPEI) as water-soluble polymer, and electrodeposition.

Polymer Supported Ultrafiltration (PSU) is based on the addition of a water-soluble polymer, which has the ability to bind heavy metal ions, to the effluent to be treated. After this step, the target metal ion gets macromolecular size so it can be retained by an ultrafiltration membrane. Thus, the effluent is treated by performing an ultrafiltration stage, in which the retentate stream is enriched in the heavy metal ion, being separated from the rest of micro-solutes, which pass through the membrane and become part of the permeate stream [8–12].

This kind of processes is based on two consecutive steps. First of all, the effluent is concentrated in target metal ion by using the PSU technique. Next, it is necessary to regenerate the polymer and recover the metal ion, in order to guarantee the technical, environmental and economical viability of the process [9]. Although some chemical regeneration methods have been previously applied [13], one of the best regeneration techniques in terms of operability and economics is the electrochemical one [6]. This method is based on the metal electro-deposition upon the cathode of an electrochemical cell, meanwhile polymer remains in solution and can be re-cycled [14, 15]. The technical viability of this technique for the Cu^{2+}-PEPEI pair has been proved in previous works, but its economical viability has not been checked yet.

In the present work, the required value of the two key parameters of the system (membrane area for ultrafiltration stage, and electrode area for electrodeposition) will be obtained as a function of the most important variables of the system. Next, two Williams equations will be proposed in order to obtain the cost of the main equipment of the system as a function of these key parameters. Finally, the total investment and operation costs will be calculated for typical working conditions and the influence of current density on the total treatment costs will be also evaluated.

2 Electrochemical recovery of Cu^{2+} effluents from a PSU Process

Figure 1 shows a typical PSU process (part a), capable of concentrating copper wastes, coupled with an electrodeposition stage to recover the metal ion and regenerate the polymer (part b).

The PSU process aims at concentrating the metal ion inlet stream (stream 1) and also obtaining a final stream almost free of metal ion (stream 6). The most important equipments that are involved in the concentration stage of this process are: (1) a storage tank at the process intake, R-1; (2) a feed pump, which increases the intake pressure to the required value in the ultrafiltration module; (3) a recirculation pump, which rises tangential velocity of the module inlet until the design value required at the ultrafiltration module; and (4) ultrafiltration modules.

Although many membrane technologies can be used to concentrate metal-containing wastes, PSU process is one of

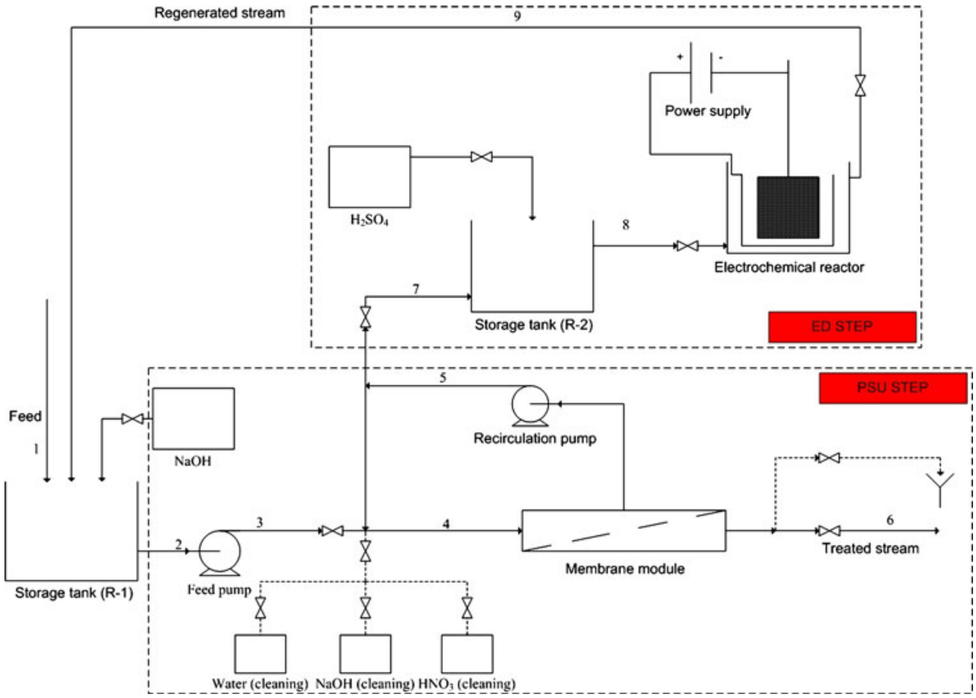

Fig. 1 Schematic plot of the continuous process of heavy metal ions recovery. **a**) PSU stage; **b**) electro-deposition stage

the most innovative technologies because it possesses some advantages with respect to other membrane techniques of lower selectivity and permeate flux as reverse osmosis or nanofiltration (e.g. higher selectivity and higher permeate flux).

With respect to the design of this first stage, it will be considered that ultrafiltration stage is carried out at continuous mode as it is the most economical mode of operation for treatment rates higher than 5 m^3 day^{-1}. Furthermore, it will be considered that from every 8 h of working shift, 6 h will be spent on the retention stage and two on the cleaning process.

Design specifications selection should be carried out based on tests at both laboratory and pilot scales, working with experimental set-ups the results of which can be extrapolated to the industrial plant. In the case of ultrafiltration stage, these variables should be selected on the basis of the evolution of permeate flux and rejection coefficients. For the former, it is important to work outside the zone of mass transfer control, whereas for the latter it is compulsory to assure polymer and metal rejection coefficients high enough to guarantee a good quality of the final effluent. In the case of PSU processes, pH values slightly acidic but close to neutrality are usually selected as both permeate fluxes and rejection coefficients reach their maximum in this zone [16]. With regard to transmembrane pressure, permeate flux is not hardly affected by mass transfer limitations if low polymer concentrations are used and if pressures from 0 to 4 bar are applied [7].

Once pH and transmembrane pressure are selected, the first parameter to be fixed is the polymer/metal loading ratio (LR) that should be used to assure a high rejection coefficient of the target metal ion. For this purpose, it is possible to carry out different experiments with increasing polymer/metal loading ratios and fix a rejection threshold that assures a good quality of the target effluent. Figure 2 shows the evolution of copper rejection coefficients with LR at different transmembrane pressures.

From this figure, it is possible to obtain the loading ratio for a working transmembrane pressure and a required Cu^{2+} rejection coefficient. Once this loading ratio is fixed, the required polymer concentration (C_{pol}) can be calculated from a given metal concentration (C_{Cu}) by using Eq. 1.

$$C_{pol} = LRC_{Cu} \tag{1}$$

This polymer concentration can be used to evaluate the costs of polymer as well as to obtain the ratio between the feed stream (stream 1) and the regenerated polymer stream (stream 9).

Next, the key parameter to be calculated is the membrane area required. This parameter is directly related to both the permeate flux of the selected membranes and the required production of the plant. The variables that most strongly affect permeate flux are transmembrane pressure (ΔP) and temperature. Moreover, membrane structure (e.g. membrane porosity) plays a key role on the membrane permeate flux.

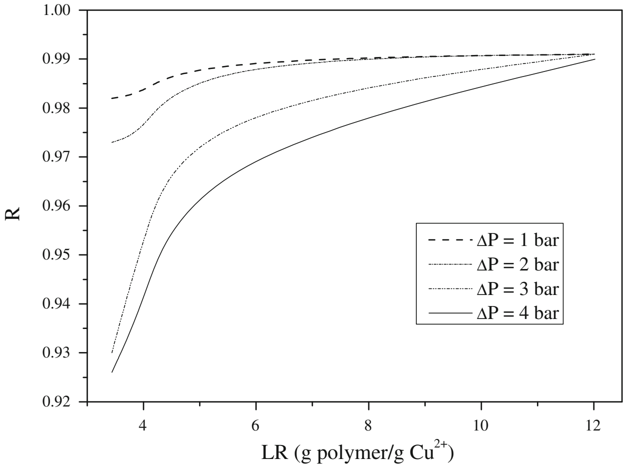

Fig. 2 Change of Cu^{2+} rejection coefficients with polymer/metal loading ratio and transmembrane pressure. Polymer: partially ethoxylated polyethylenimine (PEIPE). Membrane: Carbosep M5; pH 6 [5]

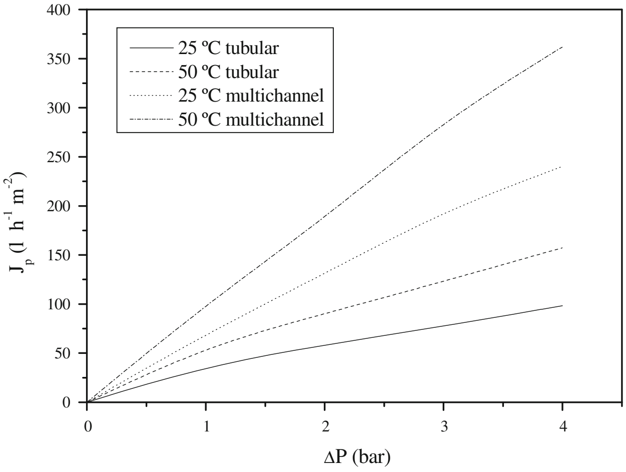

Fig. 3 Cange of permeate flux with temperature and transmembrane pressure for two different membranes: (1) Tubular Carbosep M5, MWCO = 10000 Da; (2) Multichannel Kerasep, MWCO = 15000 Da; pH 6; $[Cu^{2+}]_0$ = 125 ppm. [5, 7]

Figure 3 shows the influence of transmembrane pressure and temperature on permeate fluxes for two different ceramic membranes, one tubular and one multichannel membrane, of different Molecular Weight Cut Off (MWCO) and different porosity.

Then, from Fig. 3 it is possible to estimate the permeate flux that will be obtained from a given temperature, transmembrane pressure and membrane type. Once permeate flux is obtained, membrane area can be directly calculated from the required production (Q_p) by using Eq. 2.

$$A_m = \frac{Q_p}{J_p} \quad (2)$$

Other important variable is the concentration factor, which is defined as the ratio between the concentration of the retentate from the ultrafiltration module (stream 7) and the feed concentration (stream 3). The value of this factor is directly related to the final polymer concentration, which affects permeate flux. Nevertheless, it will be assumed that the feed stream is diluted enough to consider the influence of polymer concentration on permeate flux negligible compared to the influence of temperature and transmembrane pressure.

To finish the design of ultrafiltration section, it is necessary to calculate the pumping power required. This pumping power can be calculated by means of Eq. 3, where Q is the volumetric flow pumped ($m^3\ s^{-1}$), ΔP the pressure (Pa) and η the global yield of the pump.

$$N = \frac{Q\Delta P}{\eta} \quad (3)$$

Feed pump will work during metal retention step but not during cleaning stages. As regards the pressure supplied by the pump, it will be equal to the selected transmembrane pressure, taking into account both the operating pressure in the module and the pressure drop through the membranes. The pressure that recirculation pump must overcome will be pressure drop across the module. To calculate the volumetric flow impelled by this pump, it will be necessary to make use of the required tangential velocity and expression (4), which relates volumetric flow (Q) with tangential velocity (v) and cross section (S):

$$Q = vS \quad (4)$$

With respect to the polymer regeneration and metal recovery stage, it aims at recovering the polymer to be further used in the PSU process and to get the metal contained in the waste in its most valuable form. With PSU and electrodeposition techniques it is possible to reuse the selected polymer in several retention cycles [5–7]. Furthermore, this regeneration method not only allows the polymer regeneration, but also it implies very important water savings with respect to other regeneration methods as chemical regeneration [13].

In the case of regeneration stage, it will also work in continuous mode and it will be considered that working electrode is made from the same material as the metal ion to be removed (in this case, copper). Moreover, in this stage Cu^{2+} concentration will be diminished from the concentration in retentate stream of the ultrafiltration section (stream 7) to the concentration of the inlet stream (stream 1).

Regarding polymer regeneration stage by electrodeposition, electrode area can be considered the most important variable for the design of the regeneration system. To calculate this parameter, a mass balance can be carried out around the regeneration stage (Eq. 5) in order to obtain required deposition rate (r_d, g h^{-1}) to reach the target final Cu^{2+} concentration:

$$Q^7 C^7_{Cu} - Q^9 C^9_{Cu} = r_d \quad (5)$$

where Q^i and C^i_{Cu} are the volumetric flow rate (l h^{-1}) and Cu^{2+} concentration (g l^{-1}) in stream *i*, respectively. At steady state, flow rates of streams 7 and 9 (Q^7, Q^9) should be equal and will be denoted as Q_r from now on. This flow rate (and polymer concentration in stream 9) will determine the polymer/metal ratio in the ultrafiltration stage.

Moreover, the electrodeposition rate can be related to the current density (j, A m^{-2}), the electrode area (A_e, m^2), and the current efficiency (η_d) by using Faraday's law, expression (6):

$$r_d = \frac{jA_e M\, 3600\, \eta_d}{Fn} \quad (6)$$

where r_d is the electrodeposition velocity (g h^{-1}), M is the copper atomic weight (M = 63.54 g mol^{-1}), F is the Faraday constant (F = 96500 C mol^{-1}), n the moles of electrons necessary to reduce a mole of Cu^{2+} (n = 2), and 3600 a factor of units conversion.

Combining Eqs. 5 and 6 and using ΔC as the decrease on copper concentration through the regeneration stage (g l^{-1}), Eq. 7 can be obtained:

$$\theta = \frac{A_e}{Q_r \Delta C} = \frac{Fn}{jM\, 3600\, \eta_d} \quad (7)$$

where θ represents the ratio $A_e/Q_r\Delta C$ (h m^2 g^{-1}).

Finally, it is important to keep in mind that current efficiency depends on both cell design (mass transfer coefficient) and current density. Figure 4 gathers the influence of current density on the value of the parameter θ for different values of the mass transfer coefficient [6].

Once this ratio is obtained, electrode area can be directly obtained by using Eq. 8 for any given regeneration flow rate (l h^{-1}) and decrease in Cu^{2+} concentration (g l^{-1}):

$$A_e = \theta Q_r \Delta C \quad (8)$$

Finally, energy requirements can be obtained from the required power, which is calculated from Eq. 9:

$$W = VI \quad (9)$$

being W the required power (W), V the voltage (V) and I the current intensity (A). Intensity can be obtained by multiplying the selected current density by the calculated electrode area. Finally, voltage can be related with intensity by obtaining an empirical equation that will depend on the selected system.

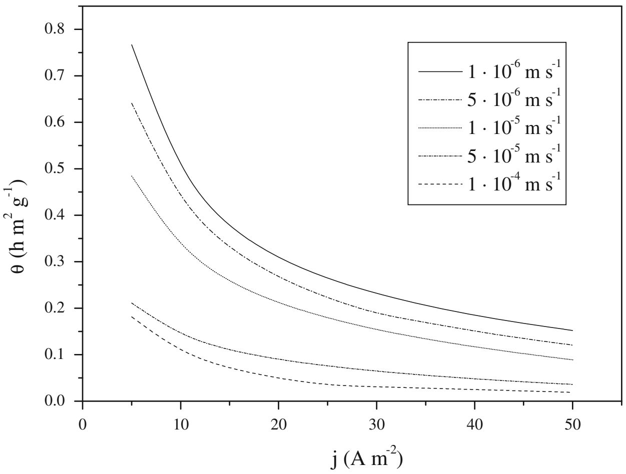

Fig. 4 Value of the parameter θ as a function of current density and mass transfer coefficient. Curves calculated from data contained in literature [6]

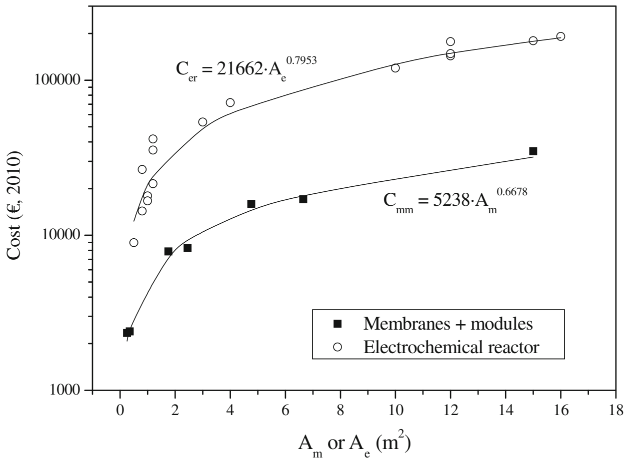

Fig. 5 Cost of the main equipment for ultrafiltration (membrane + modules, C_{mm}) and electrodeposition (electrochemical reactor, C_{er}) and fit to Williams equation. Data taken from: (1) Ultrafiltration: [19], budgets from Novasep®; (2) Electrodeposition: [20–22], budgets from: Electrocell, Skjem, Denmark, 2006; Electrosynthesis Company, Lancaster (NY), USA, 2005

3 Costs calculation procedure

The cost analysis of an industrial process should include both start-up capital and exploitation costs. However, in wastewater treatment processes the immobilized capital is the most important item, being the start-up and the current capital negligible. To calculate the amortization we have decided to suppose a 10-year linear type, without value for money update.

3.1 Investment

Investment of this plant will be calculated on the base of the cost of the two key equipments in the proposed process: membranes and modules for ultrafiltration section, and electrochemical reactor for the polymer regeneration and metal recovery stage. The rest of immobilized capital (piping, instrumentation, valves, etc.) will be calculated as a percentage of this main investment. To calculate the cost of these key equipments, two Williams equations will be obtained. These well-known Williams equations [17] can be defined as empirical expressions that relate the cost of a given equipment, C, with the value of a design parameter, α (power for pumps, volume for tanks, etc.), Eq. 10.

$$C = a\alpha^b \tag{10}$$

where *a* and *b* are empirical parameters obtained from actual cost data.

The cost of membranes and modules can be directly related with the necessary membrane area. Specifically, it is possible to obtain similar values of permeate flux in two systems with similar membranes even though if they have an area ratio 80:1 [18]. Thus, this equation was used in order to relate the cost of ceramic membranes and modules with the required membrane area. In this work, this equation has been obtained from direct manufacturer budgets (Novasep) and from data obtained in literature for a membrane area of 15 m^2 [19].

For the case of the electrochemical reactor, it is possible to obtain data from literature [20–22] and from suppliers budgets (Electrocell, Skjem, Denmark, 2006; Electrosynthesis Company, Lancaster (NY), USA, 2005), and fit also these data to a Williams equation.

In all cases, prices have been updated to October, 2010 by using the evolution of the Spanish industrial cost index obtained from the Spanish official agency of statistics (www.ine.es). Figure 5 represents the price of membranes and modules as a function of membrane area, and the price of the electrochemical reactor related with the electrode area. In both cases, the best fit of the Williams equation is also represented.

Thus, Eqs. 11 and 12 can be applied to obtain the cost of membranes and modules (C_{mm}, €, 2010) related with the membrane area (A_m, m^2) and the cost of the electrochemical reactor (C_{er}, €, 2010) as a function of the electrode area (A_m, m^2)

$$C_{mm}(€) = 5238\,A_m^{0.6678} \tag{11}$$

$$C_{er}(€) = 21662\,A_e^{0.7953} \tag{12}$$

In the case of Eq. 11, it should only be used for ceramic membranes and in the range of membranes areas used to carry out the fitting ($A_m < 15$ m^2). In this range of areas, Williams equation can be applied because it is possible to use higher modules, which work with a bigger number of membranes, in order to increase membrane area. For much

Table 1 Factors for the calculation of capital investment from the immobilized costs basis [23]

Concept	Factor (fraction of the base immobilized)
Equipment and machinery	1
Equipment installation	0.47
Instrumentation and controls (installed)	0.18
Piping (installed)	0.66
Electrical (installed)	0.11
Buildings (including services)	0.18
Yard improvements	0.1
Service facilities (installed)	0.1
Total direct plant cost	2.8
Engineering supervision	0.33
Construction expenses	0.41
Total direct and indirect costs	3.54
Contractors fees	0.21
Contingency	0.42
Fixed capital investment	4.17

higher membrane areas, it is necessary to use several modules and, consequently, scaling-up in terms of economics tends to be linear, this is to say, exponent of Williams equation tends to 1.

To quantify other immobilized costs, the factorial estimation method is used. This method is based on the calculation of the rest of immobilized costs as a fraction of the immobilized costs basis (modules and membranes, and electrochemical reactor). The factors to be used to this calculation depend on the characteristics of the process. In the case of the proposed process, the factors selected are gathered in Table 1 [23].

Although the values gathered in Table 1 are obtained from literature, some remarks should be given here:

(1) The cost of isolation is considered negligible as working temperatures will be always equal or lower to 50 °C.
(2) Finally, the cost of service facilities has been considered smaller than usual as the process will be a subsidiary treatment plant of an industrial process.

Taking these factors into account, the total immobilized cost of the section (C) can be calculated by using Eq. 13:

$$C = 4.17(C_{\mathrm{mm}} + C_{\mathrm{er}}) \tag{13}$$

3.2 Operation and amortization costs

Once the investment has been calculated, it is necessary to evaluate the operation and amortization costs. With respect to the ultrafiltration section, the most important items to be quantified are those related to pumping energy, membrane replacement, reagents consumption, cleaning, labor and maintenance.

Energy costs can be determined from the power of pumps (Eq. 3). An operation factor of 8,000 h year^{-1} for the feed pump and 6,000 h year^{-1} for the recircualtion pump will be selected, as the former will only work during retention cycles but the latter will work during both retention and cleaning stages. The cost of the energy will be set to 0.06 € (k Wh)$^{-1}$.

With respect to membrane replacement, membranes life-time of 2 years will be considered as ceramic membranes have life-times considerably higher than polymeric ones. To calculate the cost of one membrane replacement, it will be considered a cost of 1000 € m^{-2}, according to the data supplied by the manufacturer Novasep. This value is in the range of values reported in literature, where it is mentioned a cost of membrane replacement for inorganic membranes from 500 to 3000 € m^{-2} [19]. As membranes life-time is 2 years, a cost of 500 € m^{-2} year^{-1} will be considered.

Regarding reagents consumption, a special attention should be paid to polymer. According to the bulk offer from supplier Aldrich, the unit cost for a 37 wt%. polymer solution would be approximately 200 € kg^{-1}. Generally, polymers exhibit high stability after successive working cycles [9]. As a criterion to estimate the quantity of pure polymer used in the process, there will be a complete replacement of polymer in the system after each 8000 h of work.

To calculate the quantity of polymer present in the system, it will be considered that tanks R-1 and R-2 operate at 50% of maximum capacity without considering overdimension factor. Polymer concentration in any of these reactors can be obtained from Fig. 2 (to obtain loading ratio) and Eq. 1 for any single metal concentration to be treated. Volume of tank R-1 can be calculated taking into account that it must be able to store the volumetric flow of the feed stream together with the recirculated polymer stream during the cleaning process (2 h). Tank R-2 is also designed with a residence time of 2 h. It will be considered that the rest of chemical reagents are included in the costs of the cleaning process.

With respect to cleaning, it can represent from 10 to 30% of the total operating costs [24]. As the present process is conceived to treat diluted streams, we have considered that cleaning will represent a 10% of the sum of pumping, membrane replacement and reagents costs.

In the case of regeneration stage, the most important operation costs are related with electricity, electrode replacement, labor and maintenance.

The main energy cost of the plant used during polymer regeneration is due to electrodeposition reaction [25]. This cost can be obtained from the power of the power supply

(Eq. 9), and considering a cost of the electricity equal to 0.06 € (k Wh)$^{-1}$, as it was the case for ultrafitration section.

As it has been previously commented, a copper sheet can be used as working electrode. As counter electrode, an inert material as graphite can be used. In this scenario, working electrode presents an added-value that has not been taken into account, following a conservative criterion.

Maintenance costs will be considered together with ultrafiltration section. Usually, these costs fluctuate from 2 to 5% of immobilized capital for this type of installations. In this work, a value of 3% of the base immobilized is selected.

The chemical reagents costs will be negligible in comparison to polymer and the rest of products used during metal retention stage. Finally, labor costs will not be considered as they will strongly depend on the environment where this treatment process is set in: country, type of industry where this process is applied, etc.

4 Total cost of treatment

Tables 2 and 3 gather the required membrane and electrode area for different treatment flow-rates and inlet concentrations for two different current densities, 25 and 50 A m^{-2}, respectively. Tables 4 and 5 summarize, respectively, the investment and operation costs for these two current densities. In these calculations, the main variables that affect ultrafiltration section have been fixed in typical values: required rejection coefficient of 0.97, 3 bar of transmembrane pressure, 1 bar of pressure drop through the membrane module, a concentration factor of 4, and 50 °C of temperature. For electrodeposition section, a mass transfer coefficient of 10^{-4} m s^{-1} has been selected. This value has been selected because, in order to treat diluted heavy metal streams, it is necessary to design reactors that maximize mass transfer [25].

Table 2 Membrane and electrode area calculation for increasing values of the treatment flow-rate (Q_1, 10–40 m^3 day^{-1}) and concentration in the inlet stream (C_1, 0.125–0.25 g l^{-1}) for a current density of 25 A m^{-2}

Q_1 (m^3 day^{-1})	C_1 (g l^{-1})	A_m (m^2)	A_e (m^2)
10	0.125	1.94	1.77
	0.25	1.94	3.54
20	0.125	3.87	3.54
	0.25	3.87	7.08
30	0.125	5.81	5.31
	0.25	5.81	10.63
40	0.125	7.75	7.08
	0.25	7.75	14.17

Table 3 Membrane and electrode area calculation for increasing values of the treatment flow-rate (Q_1, 10–40 m^3 day^{-1}) and concentration of the inlet stream (C_1, 0.125–0.25 g l^{-1}) for a current density of 50 A m^{-2}

Q_1 (m^3 day^{-1})	C_1 (g l^{-1})	A_m (m^2)	A_e (m^2)
10	0.125	1.94	0.99
	0.25	1.94	1.98
20	0.125	3.87	1.98
	0.25	3.87	3.96
30	0.125	5.81	2.97
	0.25	5.81	5.94
40	0.125	7.75	3.96
	0.25	7.75	7.92

As it can be observed, the biggest immobilized cost corresponds to the section of polymer regeneration and metal recovery by electrodeposition. With respect to operation and amortization costs, amortization is the most important one, with a relative cost of around 80% in all cases.

As expected, treatment cost per unit of volume decreases with increasing flow rates of the target stream and increases with increasing inlet Cu^{2+} concentration. With respect to current density (the only working variable that has not been fixed in this example), it has a positive effect on treatment costs as electrode requirements decrease with increasing current densities.

On the other hand, it must be mentioned that the treatment of this type of effluents by an authorized managing company, excluding transport costs, reaches 50–60 € Tm^{-1}. This price turns the proposed technique in this research into an economically viable alternative to carry out the treatment of the proposed effluent. Moreover, it is important to highlight that the value of the recovered copper can represent an important reduction on the treatment cost. According to the London Metal Exchange (the world's premier non-ferrous metals market), the price of copper is around 9000 \$ Tm^{-1} and its price has increased by a factor of 3 within the last 2 years. As an example, for a treatment flow-rate of 20 m^3 day^{-1} and an inlet concentration of 0.25 mg l^{-1}, the total mass of copper recovered per year is 1667 kg, which means an economical return of around 11280 € year^{-1}. For a current density of 25 A m^{-2}, this economical return implies a reduction in treatment costs from 8.56 € m^{-3} to 6.87 € m^{-3}, this is to say, close to a 20% decrease in this costs of treatment. Even in a less favourable scenario (inlet concentration of 0.125 mg l^{-1} and a price of copper 30% lower), the sell of the recovered copper would represent a reduction of 14% on the treatment costs (from 5.33 to € m^{-3} to 4.74 € m^{-3}) for the same current density.

Consequently, the present study confirms that this regeneration method implies important economic savings

Table 4 Investment (€, 2010) and operation (€ m^{-3}, 2010) costs for increasing values of the treatment flow-rate (Q_1, 10–40 m^3 day^{-1}) and concentration of the inlet stream (C_1, 0.125–0.25 g l^{-1}) for a current density of 25 A m^{-2}

Q_1 (m^3 day^{-1})	C_1 (g l^{-1})	C (€)	C_{mm} (%)	C_{er} (%)	Total (€ m^{-3})	Energy (%)	Amortiz. (%)	Rest[a] (%)
10	0.125	176261	19	81	6.36	5	83	12
	0.25	280915	12	88	9.83	3	86	11
20	0.125	300905	18	82	5.53	5	82	13
	0.25	482526	11	89	8.56	4	85	11
30	0.125	411656	17	83	5.11	6	81	14
	0.25	662389	11	89	7.90	4	84	12
40	0.125	514283	17	83	4.83	6	80	14
	0.25	829475	10	90	7.47	5	83	12

[a] Membrane replacement, chemicals, cleaning and maintenance

Table 5 Investment (€, 2010) and operation (€ m^{-3}, 2010) costs for increasing values of the treatment flow-rate (Q_1, 10–40 m^3 day^{-1}) and concentration of the inlet stream (C_1, 0.125–0.25 g l^{-1}) for a current density of 50 A m^{-2}

Q_1 (m^3 day^{-1})	C_1 (g l^{-1})	C (€)	C_{mm} (%)	C_{er} (%)	Total (€ m^{-3})	Energy (%)	Amortiz. (%)	Rest[a] (%)
10	0.125	123541	27	73	4.67	6	79	14
	0.25	189422	18	82	6.90	5	82	13
20	0.125	209412	26	74	4.07	7	77	15
	0.25	323746	17	83	6.02	6	81	14
30	0.125	285347	25	75	3.76	8	76	16
	0.25	443188	16	84	5.57	6	80	14
40	0.125	355503	24	76	3.56	8	75	17
	0.25	553922	15	85	5.27	7	79	14

[a] Membrane replacement, chemicals, cleaning and maintenance

during treatment. This economical feasibility is joined to the technical and environmental viability of the electrochemical process of polymer regeneration, which was demonstrated in previous works.

5 Conclusions

This work presents a guide to the calculation of the costs related with a treatment process that involves two stages: a previous membrane process and a subsequent electrodeposition stage. This treatment process should be used to concentrate and recover diluted streams with heavy metal ions.

Throughout this work, it is possible to obtain the most important design parameters (membrane and electrode area) from any given feed flow-rate and inlet copper concentration, once working variables as transmembrane pressure, temperature and current density have been selected. Moreover, Williams equations that relate the cost of the main investment with these design parameters have also been successfully obtained.

Finally, the calculation of investment and operation costs for typical working conditions was also carried out. It was observed that increasing current density has a positive effect on reducing the final treatment costs. Moreover, it can be concluded that electrodeposition not only is an economically feasible alternative to carry out the polymer regeneration stage, but also it allows recovering the metal ion in its most valuable form, which can significantly reduce the treatment cost.

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