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Economic Viability Analysis on Seawater Desalination by Electrodialysis as an Alternative for Water Potabilization in Pueblo Viejo, Colombia

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This study presents an economic cost evaluation on seawater desalination using an electrodialysis system operating continuously in stages. The physical configuration is evaluated for treating seawater in Pueblo Viejo, Colombia. A phenomenological model is implemented to determine investment and operational costs based on cell thickness, removal efficiency, membranes and flow velocity analysis. Simulation results show that the total costs decrease more than 50% when the cell thickness is increased. However, cost increases when velocity is increased due to the influence in retention time. Economic viability analysis indicates that the total costs in optimal conditions are equivalent to almost three times the cost associated to conventional treatment. It is, however, competitive with others desalination systems.

1. Introduction

Colombia is a country with problems of drinking water in some coastal areas due to fresh water scarcity. The regions with the greatest vulnerability to drinking water supply are concentrated in the Andean region, the Atlantic coast and San Andres island. Pueblo Viejo is a small town located in the Magdalena Department (Atlantic coast). It covers an area of about 678 km^2 and its population is around 30,000. Currently the municipality does not have enough water supply systems. For this reason, drinking water is constantly being distributed by tanks. To increase its water demand, it is necessary to look for water desalination alternatives like electrodialysis (ED) which consists in a treatment with ion-permeable membranes at a relatively lower pressure (Strathmann, 2004). These systems are useful in remote areas with access to saline aquifers or coastal areas. But they usually have a disadvantage, their higher costs. Thus, to minimize ED cost, it is possible to carry out an optimization study. This work analyzes variables like velocity, cell thickness and type of membrane using a mathematical model based on Lee et al. (2002) to find optimal conditions for making the Electrodialysis an alternative feasible in this region.

2. Mathematical Model

The simulation is performed in MATLAB for an ED system that operates continuously in stages without recycling (Figure 1) to separate NaCl from seawater, obtaining two flows, a concentrate and a diluted. The diluted flow is used as drinking water. Mathematical model is based on Lee et al. (2002) and Vargas, Guardani (2011) where mass transfer depends on fluxes caused by migration of cations and anions in the z-direction and convection of the solution in the *x*-direction across the membranes as it is shown in Figure 2 (Bird et al., 2007; Gnusin, 2004):

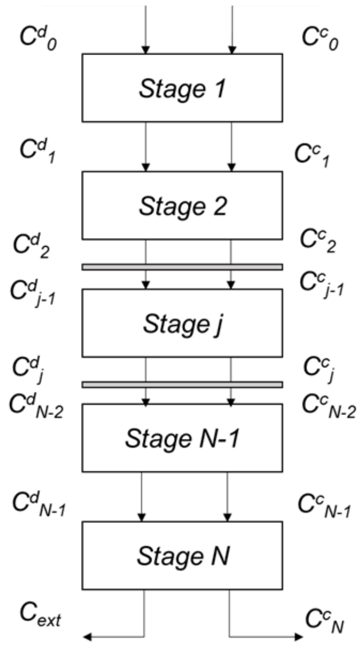

Figure 1. Electrodialysis System operating in N stages

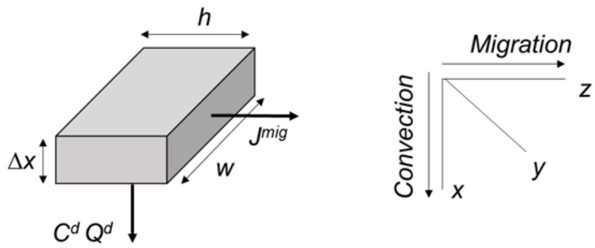

Figure 2. Differential volume to analyze the diluted flow across the ED system

The variation of the concentration, $d^{\Delta}C$, throughout dx, is defined as:

$$dC^{d} = -dC^{c} = d^{\Delta}C = \frac{\Im\, E_{cell}\, w}{Z_c v_c \left(\frac{h}{\kappa^c} + \frac{h}{\kappa^d} + R^{am} + R^{cm} \right) F Q_{cell}}\, dx \tag{1}$$

The boundary conditions for stage j is:

$$x = 0;\ d^{\Delta}C = 0$$
$$x = L_j;\ d^{\Delta}C = dC^{d}{}_{j-1} - dC^{d}{}_{j} \tag{2}$$

for a total length; L_T; equal to:

$$L_T = \sum_{j=1}^{N} L_j \tag{3}$$

where N is the total number of stages necessary to arrive at the concentration, C_{ext}, equivalent to the maximum concentration permitted by environmental and health policies for drinking water.

Here, E_{cell} is the electrical potential applied in each cell pair, $\Im$ is the process efficiency, w is the cell width and h is the cell thickness, and R^{am} are R^{cm} the anionic and cationic membrane resistances, respectively. F is the Faraday constant, Q_{cell} is the flow rate across the single cell in stage j, Z_c is the valence, v_c is a stoichiometric constant. The specific conductance κ of the solution is calculated as a function of the salt concentration (Horvath, 1985):

$$\kappa = \Lambda_e C^i \qquad for\ \ i = d\ ou\ c \tag{4}$$

where Λ_e is the specific conductance calculated from *Osanger* or *Stokes* equation (Holvarth, 1985).

Total cost per meter of water treated is expressed as a sum of the operational, C^{OP}, and investment cost, C^{INV}:

$$C^{TOTAL}\left(\frac{\$}{m^3}\right) = C^{OP} + C^{INV} \tag{5}$$

The cost of investment, C^{INV}, is related to the cost of membrane, C^M, with respect to its effective total area, A_T $(2\ L_T\, w\ N)$, (Nikonenko et al., 1999):

$$C^{INV} = C^M\left[\frac{A_T(n+1)}{Q\ t_{year}\ t_{max}}\right] \tag{6}$$

Here, n is the number of membrane replacements during t_{year}, Q is the production rate and t_{max} is the number of years of operation of the ED system.
The operational cost, C^{OP}, is a function of the energy costs for pumping, $C_{Bomb\ T}$, and cell current, C_{ED}:

$$C^{OP} = C_{ED} + C_{Bomb\ T} \tag{7}$$

3. Results

The economic analysis was carried out in an ED system for producing desalinated water. The initial conditions and water characteristics are presented in Table 1:

Table 1. Initial conditions for the seawater treatment using an Electrodialysis System

Symbol	Units	Value	Symbol	Units	Value
C^d_o, C^c_o	mg/L	1000	Q	m^3/d	13301
C_{ext}	mg/L	42	h	m	0.0004
v_c	-	1	w	m	1.02
Z		1	L_j	m	1.27
F	C/kmol	96485339,9	N	-	5
$\Im$	-	0.9	E_{cell}	V	0.1
Q_{cell}	m^3/d	3.73×10^{-5}			

Resistance membranes are determined from different membranes presented in Table 2:

Table 2. Characteristics of cationic (C) and anionic (A) membranes

Membrane	IONAC.		IONAC		AMBERPLEX		NEPTON		NEOSEPTA		PERMAPLEX		PERMUTIT	
Type	C	A	C	A	C	A	C	A	C	A	C	A	C	A
Resistance ($W\ cm^2$)	9.1	10.1	9.6	10.5	40.0	60.0	6.0	12.0	3.2	4.7	25.0	60.0	8.0	8.0

3.1 Efficiency analysis of ED system

To analyze the desalination system in Pueblo Viejo, it is assumed an input concentration of 1 g/L, considering that it has been already removed salt in previous processes for preventing fouling formation and damage in the membrane (Vargas 2010). For drinking water, according to health policy in Colombia (Ministerio de Ambiente, 2007) and international organizations such as U.S. Environmental Protection Agency (EPA) (2003), the maximum concentrations recommended are 25 mg/L of sodium and 20 mg/L of chlorides; where in terms of salt concentration it is approximately 42 mg/L NaCl in water.

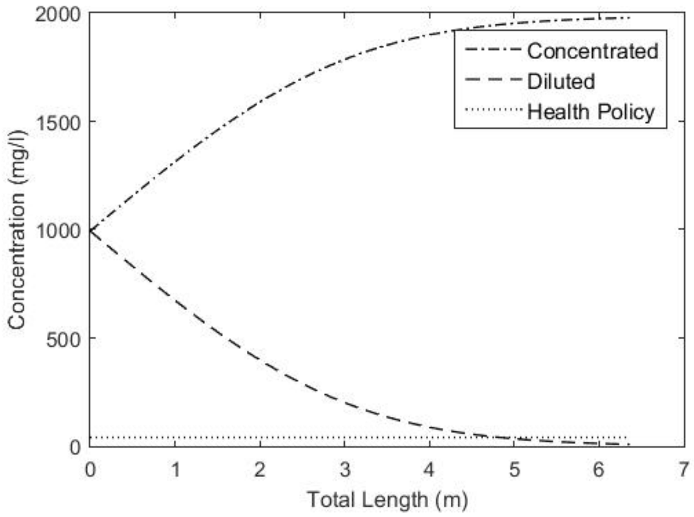

Figure 3. Diluted and Concentrated flows profile throughout the ED system.

As can be seen from Figure 3, concentration profile of NaCl in the diluted stream through the length of the system reaches concentrations below 40 mg/L (around 22 mg/L). It means that the output concentration is suitable for human consumption; with an efficiency of 98% of salt removal employing 5 stages and an electric potential per cell of 0.1 V where for finishing the process it is necessary to add only a disinfection system after the desalination system.

3.2 Resistance Membranes effect

Operational costs of desalination per day for supplying water to the inhabitants of Pueblo Viejo vary according to the type of membrane. As is shown in Figure 4, using the membrane AMBERPLEX obtains the highest cost, whereas with the NEOSEPTA membrane obtains the lowest cost. The difference is around $90 dollars per day, in other words, a saving of $2700 dollars per month for this population. This due to the variation in electrical resistance of the membranes. Despite the fact that effective area of membranes is the same in all cases; the electric potential increases as the resistances membranes grow, directly affecting the energy consumption, which has a consequence of an increment in the operational costs.

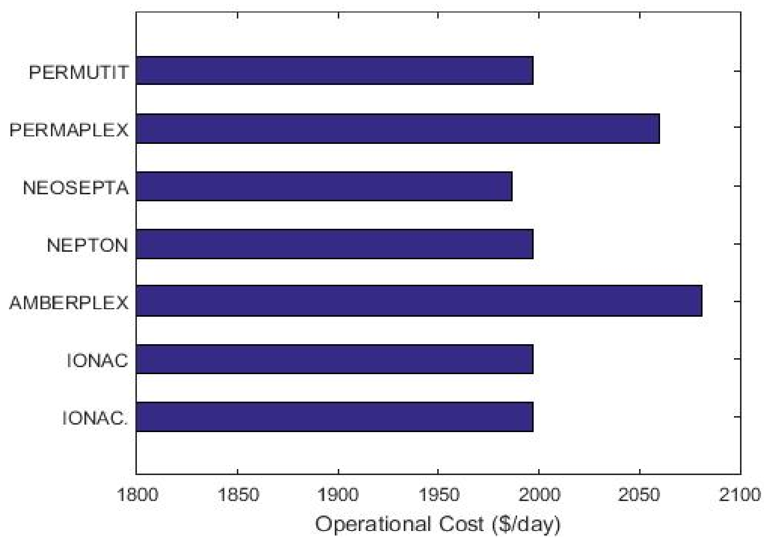

Figure 4. Cost comparison of operational costs using different types of membranes

3.3 Linear Velocity Effect

The linear velocity across the system is another variable of interest in an ED design. Figure 5 shows the decrease in investment cost because total area reduces when the velocity increases for maintaining the same production capacity. The behavior is reversed for the operational cost due to the increase in the pumping cost. In addition, the low residence time is compensated with an increment of the electric potential applied, meaning a higher energy cost. It can be observed that the optimal cost is reached with a velocity of 0.08 m/s. It is approximately 0.33 dollars per cubic meter, equivalent to three times the total cost for traditional systems.

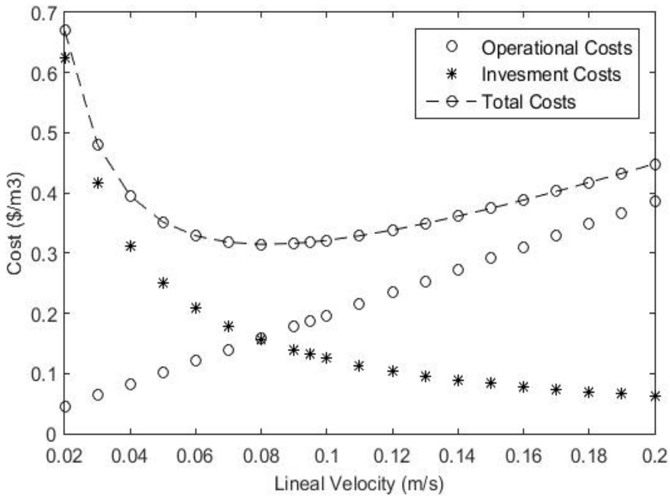

Figure 5. Linear velocity effect in the total cost of an ED systems for Pueblo Viejo, Colombia

3.4 Cell thickness Effect

The cell thickness is a part of the ED system that can be adjusted with the suppliers. Its effect is directly related to the variation of the solutions resistance, the flow through each compartment and the cell pairs number in each stage. As it is shown in the Figure 6, when the cell thickness is extended, the investment cost falls. This is because the growth in the residence time decreases the membrane pairs required. The effect of the solutions resistance is observed in the slight increase in energy costs from 0.5mm. The maximum value adopted for this variable depends on the configurations available in the market.

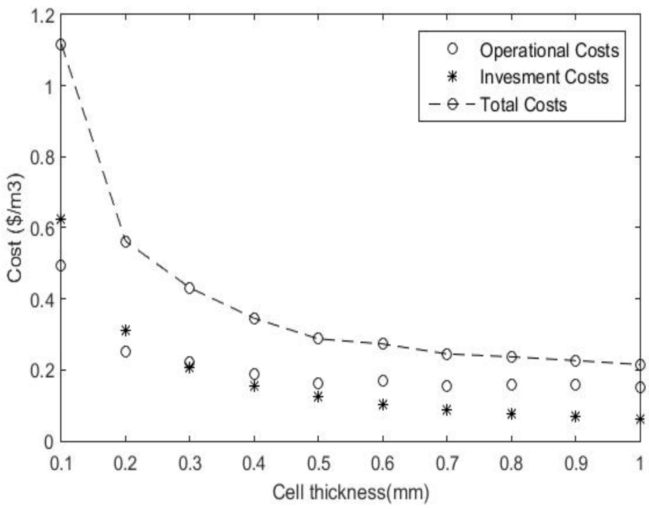

Figure 6. Cell thickness effect in the total cost of an ED systems for Pueblo Viejo, Colombia

4. Conclusions

The present study was based on a simplified mathematical model focused on the transport mass analysis and physical properties of the ED system for obtaining high levels of salt removal. In the case of cell thickness effect, the influence on investment costs is clearly defined. The optimal cost depends on the geometric characteristics of the spacers available in the market. In the same way, it is possible to see how the linear velocity affects the total costs. After a certain point, the energy cost becomes more influential on the total cost.

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