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# Defluoridation of Moroccan Groundwater by Nanofiltration and Electrodialysis: Performances and Cost Comparison

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**Abstract:** Fluoride contamination of groundwater has become of increasing worldwide concern. With the decrease in water resources, especially underground water and the frequent excess of fluoride observed these last decades, dilution became an ineffective solution. So to prevent this situation, the National Office of Potable Water (ONEP) in Morocco, has initiated studies to investigate remedial options. The study on the comparison of the performance of electrodialysis and nanofiltration in fluoride removal from Moroccan groundwater was started six years ago using two pilot plants. This study confirms the performances of the two technologies in the fluoride reduction and shows that these performances are comparable. A preliminary economical comparison is carried out. The investment and operating costs have been estimated for the two technologies on the basis of two different adopted models. The results of the two models are discussed and compared with industrial realities.

**Key words:** Fluoride · Nanofiltration · Electrodialysis · Membrane · Cost · Comparison

## INTRODUCTION

Most ground waters in the world have a low or acceptable concentration of fluoride (<1.5 mg/l) [1]. In groundwater, the natural concentration of fluoride depends on the geological, chemical and physical characteristics of the aquifer, the porosity and acidity of the soil and rocks, the temperature, the action of other chemical elements and the depth of wells. Due to these variables, the fluoride concentrations in groundwater can range from less than 1 mg/l to more than 35 mg/l.

The benefit and harmful impacts on health from long-term consumption of drinking water with a high or low fluoride concentration are summarized in Table 1 [2, 3]. To prevent these adverse effects, the World Health Organization fixed the maximum acceptable concentration of fluoride ions in drinking water as 1.5 mg/l [3]. These standards were adopted in Morocco.

The total number of people affected is not known, but it is estimated that tens of millions in the world are affected. A study by UNICEF shows that fluorosis is endemic in at least 27 countries across the globe [1]. These countries are: Algeria, Argentina, Australia, Bangladesh, China, Egypt, Ethiopia, India, Iran, Iraq, Japan, Jordan, Kenya, Libya, Mexico, Morocco, New Zealand, Palestine, Pakistan, Senegal, Sri Lanka, Syria, Tanzania, Thailand, Turkey, Uganda and the United Arab Emirates. In Australia, the fluoride concentration recorded in a water body near the Indulkana region was 13 mg/l. However, it is not used for human consumption [4]. In 1993, 15 of India's 32 states were identified as endemic for fluorosis [5].

The fluoride content in many regions of Morocco significantly exceeds acceptable standards. In the plateau of Benguerir (centre of Morocco) where the work was conducted, harmful dental fluorosis is widespread among the population supplied directly from wells. The fluoride contamination in this region is attributed essentially to the phosphate deposit.

Until today, the National Office of Drinking Water (ONEP Co.) in Morocco has proceeded to dilute fluorides to avoid the frequent seasonal excesses. With the decrease in water resources, especially underground water and the frequent excess of fluoride observed these last decades, the dilution solution becomes unattainable in the short term.

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Table 1: Health impacts from long-term use of high or low fluoride concentration in drinking water

| Fluoride concentration (mg/l) | Effect on health |
|---|---|
| <0.5 | Dental caries |
| 0.5–1.5 | Promotes dental health |
| 1.5–4 | Dental fluorosis |
| >4 | Dental and skeletal fluorosis |

Since three years ago, the ONEP Co. in collaboration with Ibn Tofail University has conducted studies to remove excessive fluoride from drinking water using membrane processes especially ED and NF which appear to be the best processes for removal of fluorides from equilibrated underground water due to their high and specific membrane selectivity [6].

In previous works, results concerning the technical performances of these technologies were separately shown [7, 8, 9]. This study confirms the performances of the two technologies in the fluoride reduction and compares them briefly. A preliminary economical comparison of the two technologies is carried out on the basis of two different adopted models. The results of the two models are discussed and compared with industrial realities.

**Economic Evaluation:** Cost of each membrane separation system is definitely varied and depends on production capacity, type of treatment, design criteria, climate condition, characteristics of land and building, etc. Most of the cost models were established on the basis of project data and tender provided by supplier and vendor.

As for all the other membrane processes, the economic evaluation of the cost of a produced cubic meter requires the calculation of the investment cost and the operating cost.

**Nanofiltration:** For nanofiltration, the investment cost and operating cost were estimated from the Verberne and Wouters model [10]. This model is based on the project practical data and tender from suppliers. The same cost model was used by van der Bruggen *et al*. [11] and Nora'Aini Ali *et al*. [12]. Table 2 gives the data and details of the adopted model [11]. Figure 1 shows the different steps to estimate the capital and operating costs. The input requirements for this model are given in Table 3.

**Electrodialysis:** The calculation of the capital cost in the case of the ED, requires the calculation of the power and the membrane surface. Figure 2 shows the stage to estimate the capital cost.

For electrodialysis, the model used to calculate the power and membrane requirement surface, is designed from a paper presented by Thomas D. Wolfe of HPD Inc. at the American Water Works Association meeting in August, 1993 and presented in a report of the U.S. Department of the Interior in 1999 [13]. If the desalination ratio (Input TDS/Output TDS) is less than 3.6, the model gives a good estimate of power and membrane requirements. This is our case, the input requirements for this model are given in Table 4.

Table 2: Data and details of the adopted nanofiltration model [11]

| Capital cost items |
|---|
| $Q_F$ = flow rate, $n$ = number of membrane modules |
| (i) Civil investment cost: for instance, a building where installation of membrane system is be positioned. Depreciation period is 30 years. |
| $C_{civil} = 862 \times Q_F + 1239 \times n$ |
| (ii) Mechanical engineering costs: for pumps, filters, piping, etc. Depreciation period is 15 years |
| $C_{mech} = 3608 \times Q_F^{0.85} + 908 \times n$ |
| (iii) Electrotechnical costs: for energy supply, control engineering and all electronic components |
| $C_{electro} = 1.4 \times 10^6 + 54 \times P \times Q_F$ |
| (iv) Membrane investment costs: for membrane installation. The membrane lifetime is taken as 5 years. It was assumed that one membrane module costs about 1000£ $C_{membrane} = 1000 \times n$ |
| **Operating cost items** |
| (i) Depreciation costs: depreciation rate upon investment cost. The investments are linearly depreciated and interest neglected |
| (ii) Energy cost: energy required to pump the feed stream into membrane system. It is assumed that membrane system uses 40 Wh/m$^3$ for each m$^3$ feeding and feeding pressure (bar). An electric cost is estimated as 0.10 £/kWh |
| (iii) Chemical cost: cost needed by a total of chemical materials which be filtered. This cost is used as 0.023 £/m$^3$ |
| (iv) Maintenance cost: 2% of the total investment costs |
| (v) Quality control cost: 2% of the total investment costs |
| (vi) Operation of installation: 2% of the total investment costs |

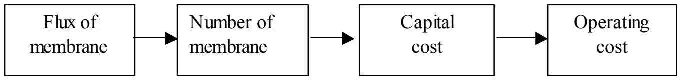


Fig. 1: Different steps to estimate the capital and operating cost

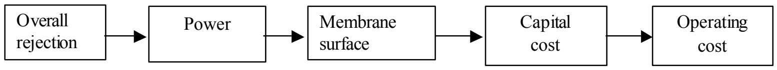


Fig. 2: Different steps to estimate the capital and operating cost

Table 3: The input requirements for this model

| The input requirements | Parameter |
|---|---|
| Number of membrane modules | n |
| Flow rate | l/h |
| Percent recovery | % |
| Cost of electricity | US$/kWh |

Table 4: The input requirements for this model

| Input requirements | Parameter |
|---|---|
| Feed and product TDS | mg/L |
| Average equivalent weight | g/eq |
| Flow rate | l/h |
| Percent recovery | % |
| Cost of electricity | US $/kWh |
| Membrane cost | US $/m$^2$ |

Capital cost of electrodialysis is determined by multiplying the membrane cost by the construction factor. The construction factor used here is 1.65. This value was arrived at by adjusting the membrane operation variables till the electrical and membrane requirements matched those listed in a cost estimate by Pittner in 1993 [13] and then multiplying by an appropriate construction factor so that the costs matched also.

To estimate the operating and maintenance cost in the case of ED, the same data as for the NF (Table 2) are adopted except for the following parameters: depreciation periods are 15 years for civil investments, for mechanical engineering and electrotechnical engineering and for membrane investments, maintenance cost are 5% of the total investment costs and the energy required to pump is assumed that membrane system uses 0.4 kWh/m$^3$. The electrical energy cost is estimated as 0.10 US $/kWh.

## MATERIALS AND METHODS

The electrodialysis operations were carried out in a pilot plant supplied by Eurodia Co and already described [7,14,15] (Figure 3). The pilot plant was equipped with the following membranes: NEOSEPTA ACS as anionic exchange membrane and NEOSEPTA CMX-Sb as cationic exchange membrane, all manufactured by Tokuyama Corp.

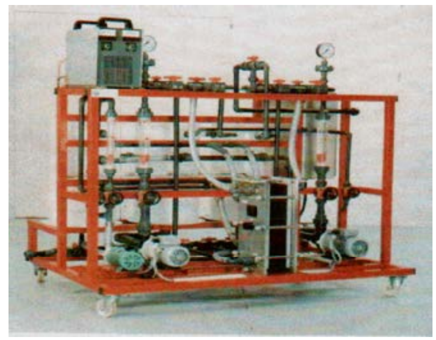

Fig. 3: Electrodialysis pilot plant

Fig. 4: Nanofiltration pilot plant

The best fluoride selectivity and the best sulphate rejection of the ACS membrane were demonstrated in a previous work [7]. The ED operations were conduced in a continuous mode with inverting polarity each 20 min.

The raw water circulates in dilute and concentrate streams. In the rinse, a solution of sulfamic acid was used to avoid among others the following disadvantages: precipitation of salts, emission of $Cl_2$, rapid corrosion of electrode [7, 14].

The nanofiltration experiments were performed on NF/ RO pilot plant supplied by TIA Company (Technologies Industrielles Appliquées, France) and already described [8-9] (Figure 4).

The pilot plant is equipped with two spiral wound modules of the commercial Filmtec membrane NF270, manufactured by Dow Chemical Corp. In a previous work the good performances of this membrane in fluoride removal have been shown [9].

Table 5: Characteristics of the untreated water.

| Temperature °C | 29 |
|---|---|
| Conductivity µS/cm | 1492 |
| pH | 7.41 |
| pHs | 7.80 |
| TH °F | 44.2 |
| TA °F | 0 |
| TAC °F | 32 |
| $Ca^{2+}$ ppm | 108 |
| $Mg^{2+}$ ppm | 38.5 |
| $NO_3^-$ ppm | 20 |
| $Cl^-$ ppm | 560 |
| $F^-$ ppm | 2.32 |
| $SO_4^{2-}$ ppm | 116 |
| Langelier Index | 0.39 |

$$IR\% = \left( \frac{[\text{Ion}]_{t=0} - [\text{Ion}]_t}{[\text{Ion}]_{t=0}} \right) \times 100$$

$$OR\% = \left( \frac{[\text{TDS}]_{t=0} - [\text{TDS}]_t}{[\text{TDS}]_{t=0}} \right) \times 100$$

For both ED and NF, experiments were performed at 29°C. Samples of permeate were collected and the water parameters were determined analytically following standard methods previously described [12]. Some other parameters were followed such as ion rejection (IR) and the overall rejection (OR):

The fluoride removal operations were conducted on a groundwater of N'zalat Laadem in the centre of Morocco. The analytical results of the untreated water are shown in Table 5.

## RESULTS AND DISCUSSION

In previous works, the technical performances of electrodialysis and nanofiltration were separately demonstrated [7, 8, 9] and the optimal operating conditions were determined for various commercial membranes. This study confirms and compares briefly the performances of the two technologies. The concerned membranes are the Neosepta ACS/CMX-Sb couple for ED and NF 270 80 40 for NF.

A preliminary economical comparison is carried out. The investment and operating costs have been estimated for the two technologies on the basis of two different adopted models. The results of the two models are discussed and compared with industrial realities.

**Performances of ED and NF in Fluoride Removal:** For electrodialysis operation, Fig. 5 shows the variations with overall rejection of fluoride content and conductivity.

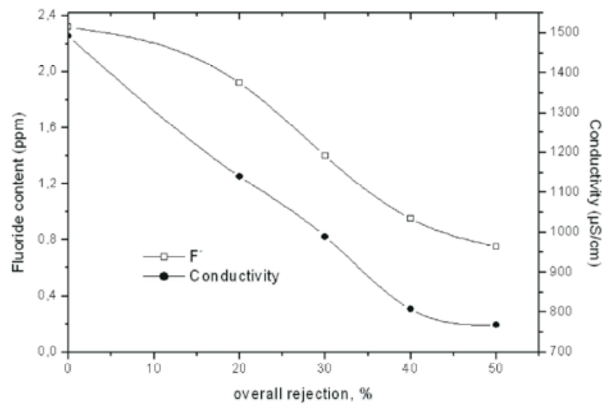


Fig. 5: Variation with overall rejection of fluoride content and conductivity

Characteristics of the treated water at different overall rejection are given in Table 6.

The fluoride content in the treated water decreases linearly with the OR. The maximum admissible of fluoride was reached at 30% of OR. At 40% of OR the fluoride content reaches the recommended value of 1ppm.

Results in Table 6 show that the quality of the obtained water is satisfactory according to Moroccan standards, except for 20% of OR. At this OR, the fluoride content exceeds the standards

For nanofiltration operations, Table 7 gives the mean fluxes, overall rejections, fluoride rejections and the other parameters of the treated water. The applied pressure was 5, 10 and 15 bars. The total recovery rates for the two modules were of 42%, 54% and 62%.

Results in Table 7 show that the obtained water qualities were satisfactory according to the Moroccan standards.

These results show that NF and ED present excellent performances to reduce fluoride content in groundwater. These performances are practically the same for these two technologies. On the basis of our running conditions and on these results, one can recommend that NF can be designed for a treatment of part of the total well capacity and a subsequent mixing of the permeate with untreated water, while ED can be designed for a treatment of the total well capacity.

**Preliminary Economic Evaluation:** The investment and operating costs of ED and NF were estimated from the models described in the introduction part. The desired production is of 100 $m^3$/h, corresponding to a large plant of a 2400$m^3$/day and to a water consumption for 50.000 capita following the Moroccan considerations.

Table 6: Results of analysis of water treated at different overall rejection

| | Overall rejection | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 20% | | 30% | | 40% | | 50% | |
| Parameter | [ ] | R (%) | [ ] | R (%) | [ ] | R (%) | [ ] | R (%) |
| Voltage, V | 6 | - | 13 | - | 20 | - | 24 | - |
| Current, A | 1.6 | - | 2.4 | - | 3.37 | - | 3.75 | - |
| pH | 8.0 | - | 7.77 | - | 7.77 | - | 7.82 | - |
| Conductivity, μS/cm | 1140 | 20 | 989 | 30 | 807 | 40 | 768 | 50 |
| TH, °F | 31 | 29.8 | 24 | 45.7 | 18.4 | 58.3 | 15.9 | 64.0 |
| TAC, °F | 27 | 15.6 | 20 | 37.5 | 19 | 40.6 | 14 | 56.2 |
| $Ca^{2+}$, ppm | 94.5 | 12.5 | 63.5 | 41.2 | 44.5 | 58.7 | 31.5 | 71.2 |
| $F^-$, ppm | 1.92 | 17.42 | 1.4 | 39.65 | 0.95 | 59.05 | 0.75 | 67.67 |
| $NO_3^-$, ppm | 15.6 | 22 | 14 | 30 | 12.4 | 38 | 9.6 | 52 |
| $Cl^-$, ppm | 476 | 15 | 368 | 34.2 | 279 | 50.1 | 203 | 63.7 |
| $SO_4^{2-}$, ppm | 108 | 6.5 | 102 | 11.7 | 96 | 17 | 90 | 21.7 |

Table 8: Data for economic evaluation.

| Nanofiltration cost | | Electrodialysis cost | |
|---|---|---|---|
| The input requirements | Parameter | The input requirements | Parameter |
| Membrane | NF270 8040 | Couple of membranes | ACS/CMX sb |
| Pressure | 5, 10, 15 bars | Feed water TDS | 1120 mg/l |
| Number of module | n | product water TDS | 741, 605, 576 mg/l |
| Flow rate | 100 $m^3$/h | Average equivalent weight | 26.8 g/eq |
| Percent recovery | 90% | Flow rate | 100 $m^3$/h |
| Cost of electricity | 0.1$/kWh | Percent recovery | 94 % |
| | | Cost of electricity | 0.1 $/kWh |
| | | Cost of Membrane | 100 $/$m^2$ |

Table 9: Capital and operating costs per cubic meter for the two processes.

| Nanofiltration | | | | Electrodialysis | | | |
|---|---|---|---|---|---|---|---|
| Applied pressure (bar) | Number of membranes | Capital cost ($) | Operating cost ($/m3) | Overall rejection (%) | Number of compartments | Capital cost ($) | Operating cost ($/m3) |
| 5 | 56 | 1,915,220 | 0.198 | 30 | 614 | 81,355 | 0.070 |
| 10 | 34 | 1,920,014 | 0.22 | 40 | 877 | 116,202 | 0.073 |
| 15 | 25 | 1,883,897 | 0.24 | 50 | 957 | 126,802 | 0.074 |

Table 10: Technical comparison of nanofiltration and electrodialysis,

| Process | Advantages | Disadvantages |
|---|---|---|
| Electrodialysis | - Inexpensive pre and post treatment, | - Only separation of Ionic components. |
| | - Flexible (seasonal operation), | - Potential formation of $H_2$ in the electrode rinse |
| | - Low chemical demand, | - Specific power consumption for Pumping |
| | - High water recovery. | - Necessity of concentrate treatment |
| Nanofitration | - Sample design, | - Scaling by silica is possible |
| | - Easy membrane exchange, | - Very sensitive against scaling |
| | - Rejection of suspended particles and organic compounds. | - Less flexible than ED |
| | - Low chemical demand. | - Necessity of brine treatment |

For ED, the selected couple of membranes for this installation was NEOSEPTA ACS/CMX-Sb with industrial dimensions of 50 cm X 50 cm. For nanofiltration, the chosen membrane was NF270 8040. Table 8 gives the required data for the adopted models. Table 9 gives the capital and operating costs for the two processes.

The preliminary economic evaluation calculated on the basis of two different models shows a capital and operating cost largely higher for NF than for ED. Practically and experimentally, the costs of the two technologies must be close. Moreover the NF capital and operating costs appear excessive with regard to ED and to the reality, while the ED operating costs appear much lower than reality. The difference can be attributed to the adopted models. We think that the ED model expresses better the reality of the investment cost than the NF model. The NF module does not take into account the industrial reality such as the tubular configuration of the membrane modules which certainly will decrease the costs. Moreover the data of both models are completely different. However the two models seem too simplified with regard to the experimental realities.

## CONCLUSION

Fluoride removal by nanofiltration and electrodialysis was conducted on a ground water using two pilot plants. This study confirms the performances of the two technologies in the fluoride reduction. These performances are comparable. A drinking water with outstanding quality can be easily produced by these two technologies. The investment and operating costs have been estimated for the two technologies on the basis of two different adopted models. The adopted model for NF shows more deficiency with regard the reality than that of ED. However the two models seem too greatly simplified with regard to the industrial realities.

Technically, ED has the advantage of flexibility with respect to the seasonal variation of fluoride content. The final salt concentration can be adjusted easily, if required, which is less evident for the NF process. Among the advantages of NF compared to ED is its simplicity which is of special imxportance for small scale applications. Table 10 gives a summary comparison between the two technologies.

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