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Hybrid system of nanofiltration, reverse osmosis and evaporation to treat the brine of inland desalination plants

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ABSTRACT

This work is focused on the brine management of brackish water from desalination plants placed in inland areas. In inland areas the aquifers and other water resources present problems of pollution caused mainly by agricultural activities. In these areas, desalination plants are normally used to produce drinking-water from brackish water. However, the management of the concentrates generated by these plants is a big challenge due to the environmental problems of their disposal in the environment. One possible solution is the combination of membrane processes with low-cost evaporation technologies. This paper presents a theoretical analysis and preliminary experimental results for an innovative system to manage brines of desalination plants. The system treats sequentially the brine coming from a brackish water desalination plant in a nanofiltration stage (NF) and a natural evaporation process with absorbent surfaces. An osmosis stage (RO) treats the permeate from the NF stage. This hybrid system allows obtaining an additional water resource. The evaporation stage based on absorbent surfaces reduced land requirements by 90% in contrast with the land requirements in evaporation ponds.

Keywords: Nanofiltration; Reverse osmosis; Evaporation; Brine

1. Introduction

The application of membrane technologies to produce drinking-water and to reuse wastewater has increased in the last years owing to the problems of water scarcity and the deterioration of freshwater resources. In inland areas of dry countries, desalination plants are normally used to produce drinking-water from brackish water due to the fact that the aquifers and other freshwater resources present problems of pollution caused mainly by agricultural activities. However, these technologies involve the generation of a waste effluent that has to be managed.

The environmental problems of brine disposal in desalination inland plants are due to the high salinity of brine. High TDS makes the brine unsuitable for use in irrigation. Moreover, depending on wastewater source, brine can contain harmful substances for the environment. Several studies have proved the brine infiltration into aquifers and surrounding soils due to brine disposal [1]. From the economic point of view, the cost of brine disposal ranges from 5 to 33% of the total cost of desalination [2].

Therefore, brine disposal is an important problem in desalination facilities; especially in inland plants. Several disposal options are available for inland plants: disposal to wastewater systems, evaporation ponds, land applica-

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tion, injection into deep saline aquifers and zero-liquid discharge systems [3]. Sanitary sewer discharge of a small volume of concentrate usually represents a low cost disposal method with limited permission requirements. However, if the concentrate flow is too large or too saline, the desalination plant may not be able to use sewer disposal [4]. According to Mickley [5], deep well injection is not always possible due to the lack of suitable hydrogeological conditions and is not always feasible due to its high cost. Evaporation ponds require a large area and a suitable isolation to avoid aquifer pollution [6,7]. The management alternatives to treat these brines are currently focused on reducing brine volume to solid state. There are different treatments to reduce brine volume such as evaporation ponds, brine evaporators, evaporation with extended surfaces [8] and zero-liquid discharge technologies [9,10]. Among these technologies, natural evaporation is a cost-effective option in areas with a warm climate and high evaporation rates [11]. Nevertheless, in areas not far from the sea, like Mediterranean coast of Spain, the humidity of air can cause low evaporation rates (4 $L \cdot m^{-2} \cdot d^{-1}$) [12]; hence, it requires a large surface area per volume of concentrate.

Regarding evaporation systems, measurements of the water evaporation rate in still or moving air date back to the 20th century and many of theses studies have provided a wide variation in the measured data. Several studies have been focused on the effect of water salinity on the evaporation rate [11,13–16].

Ahmed et al. [7] proposed a formula for calculating the open surface area of evaporation pond:

$$A_{\mathrm{pond}} = \frac{V_{\mathrm{brine}}}{E} \cdot f_1 \tag{1}$$

where A_{pond} is the open surface area of evaporation pond (m^2), V_{brine} is the volume of brine ($m^3 \cdot d^{-1}$), E is the evaporation rate ($m \cdot d^{-1}$), and f_1 is a safety factor.

Furthermore, Brutsaert [17] developed a correlation to predict evaporation rate from a water surface:

$$E = k \cdot v \cdot (p_w - p_a) \tag{2}$$

$$k = 3.367 \cdot 10^{-9} \cdot A^{-0.05} \quad (4000 < A < 1.2 \times 10^8 \ \mathrm{m}^2) \tag{3}$$

$$k = 7.70 \cdot 10^{-9} \cdot A^{-0.066} \quad (0.1 < A < 6 \ \mathrm{m}^2) \tag{4}$$

where E is the evaporation rate ($mm \cdot d^{-1}$), v is the air velocity (in the same units as E), p_w and p_a are the vapour pressure of water and air respectively (mbar), k the mass transfer coefficient ($mbar^{-1}$) and A is the water surface area (m^2).

According to these expressions, the higher the surface area, the lower the evaporation rate from the water surface is. Hence, the evaporation pond requires a large area, but in contrast, the efficiency of evaporation ponds is reduced with the area. For this reason, a reduction in land requirements to evaporation would be suitable in order to improve the efficiency of evaporation.

Evaporation using arrays of wet surfaces can minimize land requirements. Evaporation rate of water from the wet surfaces can be expressed by:

$$e = h_m \cdot A \cdot (p_s - p_\infty) \tag{5}$$

where e is the mass transfer rate of water ($kg \cdot s^{-1}$), h_m is the mass convection coefficient ($kg \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$), A is the cross section area water–air, p_s is the vapour pressure of water in the air in contact with water surface and p_∞ is the vapour pressure of water in the bulk.

Consequently, the cross section area may be increased by using additional surfaces. The evaporation system was selected according to increase the cross section area air–brine.

This work is focused on a system to manage brines of desalination plants that consists of a membrane treatment following by evaporation treatment with additional wet surfaces. Fig. 1 describes the hybrid system to treat the brine of inland desalination plants. The system consists of a first nanofiltration stage (NF) to treat brine coming from a brackish water desalination plant with a suitable pretreatment by means of acidification and addition of antiscalants, a second stage of reverse osmosis (RO) to treat the NF permeate in order to obtain an additional water resource and a third stage of brine evaporation with an evaporation system developed by authors. The aim of the evaporation study is focused on comparing a novel evaporator structure against standard evaporation ponds with regard to land area used.

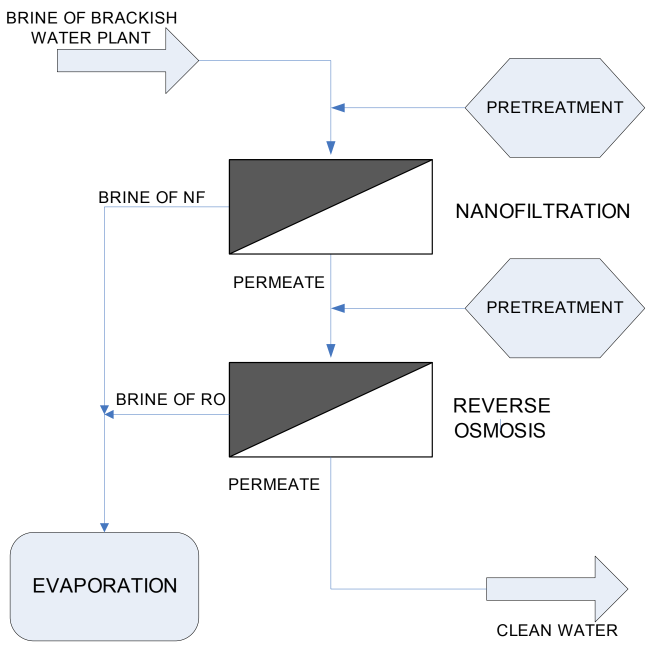

Fig. 1. Hybrid system to treat the brine of brackish water plants.

2. Experimental procedures

2.1. First stage: membrane treatment

The composition of the brine of a brackish water desalination plant used in the experiments is shown in Table 1. This brackish water desalination plant treats the water from a well by reversible electrodialysis system. The volume and the characteristics of the generated brine make unfeasible the disposal into municipal sewers.

Membrane experiments were carried out in a pilot plant for spiral-wound module membranes. For the NF experiments, a membrane module Filmtec-NF270 was used. Firstly, a pretreatment with HCl and antiscalants was carried out in order to avoid scaling. The NF permeate was treated by RO to study the possibility to obtain an additional water resource. These experiments were performed with a membrane module Hydranautics-ESPA1 in a pilot plant at low pressure (12 bar). Table 2 shows the characteristics of both membranes.

TDS rejection was measured by a conductimetric method and estimated by:

$$R = \frac{\Lambda_{\text{feed}} - \Lambda_{\text{permeate}}}{\Lambda_{\text{feed}}} \tag{6}$$

The concentrate of the NF and RO experiments were stored for the posterior evaporation treatment.

2.2. Second stage: evaporation system

The brine of NF and RO treatment was evaporated in a prototype that uses several parallel sheets of absorbent surfaces. The prototype can simulate the effect of natural wind by means of a fan and fixed nozzles. The absorbent surfaces allow reducing the land area required for evaporation (evaporation surface of 5.8 m^2 per m^2 of land). The absorbent surfaces are made of PVC. This material presents high mechanical resistance and low adherence to salts. The prototype has a brine reservoir or pond with an area of 0.24 m^2.

The array of absorbent surfaces was partially submerged in the pond during the time needed to wet completely the PVC surfaces (wetting time). When PVC surfaces were wetted, the array was taken out of pond and it was exposed to air during a fixed time (drying time). This sequence (wetting–drying–wetting) was repeated throughout the experiments.

Table 1
Brine composition

Parameter	Value
Potassium, mg·L^{-1}	5.2
Sodium, mg·L^{-1}	44.1
Magnesium, mg·L^{-1}	160.4
Calcium, mg·L^{-1}	563.1
Strontium, μg·L^{-1}	1139
Barium, μg·L^{-1}	248.6
Carbonate, mg·L^{-1}	1.1
Bicarbonate, mg·L^{-1}	730.8
Nitrate, mg·L^{-1}	345.6
Chloride, mg·L^{-1}	514.2
Fluoride, mg·L^{-1}	0.4
Sulfate, mg·L^{-1}	540.6
Silica, mg·L^{-1}	7.9
TDS, mg·L^{-1}	2917.4
pH	7.0
Temperature, °C	20.0

In order to study the efficiency of the system taking into account only the evaporation from absorbent surfaces, different operating conditions of drying time were studied (Table 3). The PVC surfaces were immersed in a pool of brine during 30 s and then they were exposed to air during different drying times. This action was repeated throughout the 24 h tests. The following parameters were monitored: conductivity of brine, relative humidity, brine temperature, air velocity and air temperature. All the experiments were carried out under winter Mediterranean climate conditions. With the aim to compare the effectiveness of the prototype, an evaporation pond was operated at the same time that the prototype. The evaporation pond consists of a brine reservoir with a surface area of 0.24 m^2. The evaporation rates from the pond were calculated from the volume evaporated using Eq. (7):

$$E = \frac{\Delta V}{A \cdot \Delta t} \tag{7}$$

where ΔV is the evaporated volume; A is the contact area brine–air of pond, and Δt is the time between the measure and the initial time.

Table 2
Membranes characteristics

Membrane	Manufacturer	Type	Effective area (m^2)	Rejection	Material
NF270	Filmtec	NF	2.6	High salt passage 97% (2000 ppm $MgSO_4$)	Composite polyamide
ESPA1	Hydranautics	RO	2.6	Ultra low pressure membrane 99.6% (1500 ppm NaCl)	Composite polyamide

Table 3
Plan of evaporation experiments

Test	Drying time (min)	v_{air}(m·s^{-1})
1	10	0.10
2	10	1.30
3	10	1.60
4	15	0.10
5	15	1.30
6	15	1.60
7	20	0.10
8	20	1.30
9	20	1.60

3. Results and discussion

3.1. Membrane treatment

In NF experiments, a pretreatment was required in order to avoid scaling. This pretreatment consisted of a strong acidification with HCl and the addition of antiscalants to ensure an LSI below zero.

The results of NF experiments showed a recovery of 40% without problems of scaling. It was observed that recoveries higher than 40% implied a sharp decrease of TDS rejection.

In all the experiments, the quality of the NF permeate was not enough to be used as drinking water, therefore, a RO treatment was required.

Regarding the RO system, a recovery of more than 70% was possible with the Hydranautics-ESPA1 membrane. The TDS rejection remained almost constant throughout all the experiments (> 99.0%) and it did not depend on recovery. Moreover, the RO permeate had enough quality to be used as drinking-water.

The low LSI value of NF permeate made possible to achieve a recovery higher than 70% in RO experiments.

In Table 4 the results of membrane treatment are shown.

Brine of NF and brine of RO treatment were managed together in the evaporation system with a brine volume proportion of 80% from NF and 20% from RO. With the membrane treatment brine volume was reduced by 30%. Therefore, this reduction involves a decrease in land requirements for evaporation.

Table 4
Results of membrane treatment

Membrane	Pressure (bar)	Recovery (%)	TDS rejection (%)
NF	8	40	50.0
RO	12	70	99.0

3.2. Evaporation experiments

The results (Fig. 2) showed that the evaporation rate was higher at lower drying times. In the case of drying times higher than 20 min, the absorbent surfaces were completely dried out; consequently salt deposits were formed over the absorbent surfaces. These deposits reduced the evaporation rate of the prototype.

The best prototype evaporation rates were obtained with a drying time of 10 min. The environmental conditions of the experiments (air velocity, air temperature, relative humidity and brine temperature) were measured throughout the tests. In all the experiments, relative humidity remained approximately constant with an average value of 45%. At the same time, air temperature did not have important changes so in all tests the average value was 16°C. Regarding brine reservoir, the temperature was 2°C below air temperature.

Therefore, air velocity was controlled and three different values were studied. First test was carried out in calm weather conditions (v < 0.2 m·s^{-1}), the second one with an average air velocity of 1.3 m·s^{-1} and the third one with 1.6 m·s^{-1}. In Figs. 3–5, evaporated volumes for the prototype and the evaporation pond are shown (the values are referred to the same land area: 0.24 m^2).

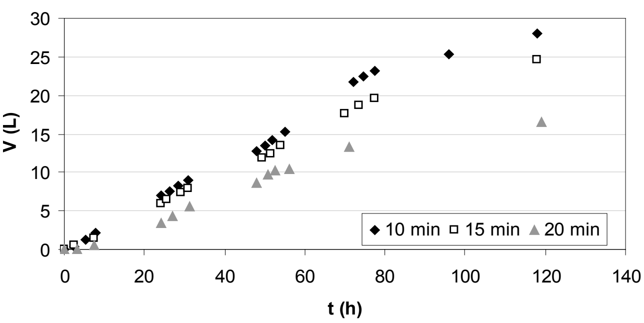

Fig. 2. Cumulative volume evaporated with different drying times (air velocity: 1.3 m·s^{-1}).

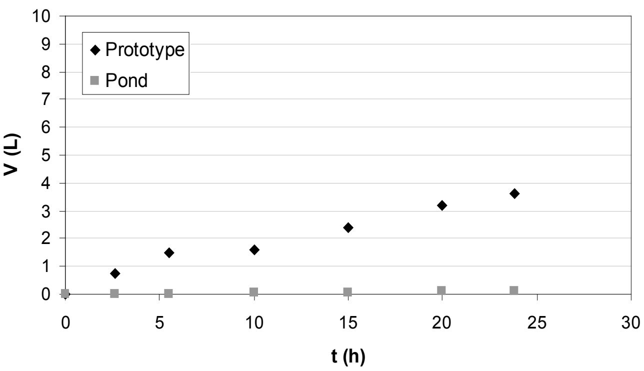

Fig. 3. Evaporated volume of the first experiment with a drying time of 10 min (air velocity: 0.1 m·s^{-1}, land area: 0.24 m^2).

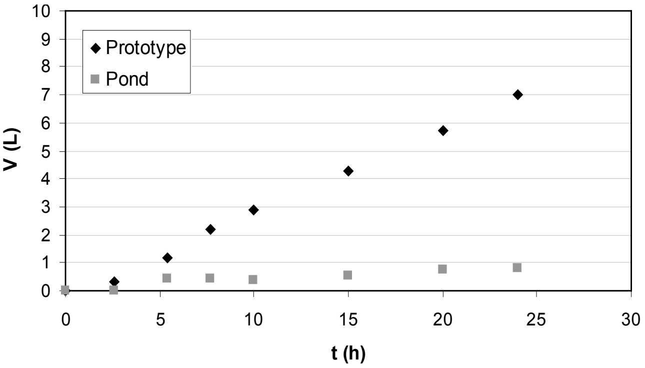

Fig. 4. Evaporated volume of the second experiment with a drying time of 10 min (air velocity: 1.3 m·s^{-1}, land area: 0.24 m^2).

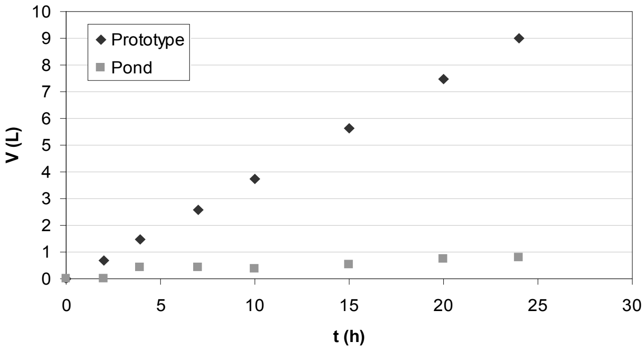

Fig. 5. Evaporated volume of the third experiment with a drying time of 10 min (air velocity: 1.6 m·s^{-1}, land area: 0.24 m^2).

The reservoir of the prototype and the evaporation pond have the same characteristics, and both were subjected at the same weather conditions. This way allows estimating the evaporation from PVC surfaces:

$$E_{\mathrm{prototype}} = E_{\mathrm{PVC}_{\mathrm{surfaces}}} + E_{\mathrm{Pond}} \tag{8}$$

In Table 5, a comparison between the contribution to evaporation rates of evaporation from pond and the evaporation from PVC surfaces is shown. The evaporation rates are expressed per square meter of land area. In all the tests, the contribution of the evaporation from the PVC surfaces was around 90%. Therefore, this prototype is able to reduce the land requirements to evaporate brines.

4. Conclusions

The results showed that NF and RO technologies are suitable to treat brine in order to reduce brine volume.

In all the NF experiments, a recovery of 40% was achieved without scaling problems. It was observed that higher recoveries than 40% implied a sharp decrease of the TDS rejection.

Furthermore, the RO experiments achieved a recovery higher than 70% with a TDS rejection of 99%.

This membrane treatment was able to achieve a brine volume reduction of 30%. Therefore, this reduction involves a decrease in land requirements for evaporation.

Regarding evaporation experiments, low drying times improved the operation of the prototype because of the salt deposits over the absorbent surfaces were negligible. The experimental results showed that the performance of the prototype evaporation system is ten times higher than natural evaporation with a drying time of 10 min. This evaporation rate implies a reduction higher than 90% with respect to the land requirements to treat the brine by natural evaporation.

As a conclusion, we can say that the combination of NF and RO with this new prototype is a promising solution for brine management.

Symbols

A — Contact area brine–air, m^2
E — Evaporation rate, L·m^{-2}·d^{-1}

Table 5
Contribution to evaporation rates of the evaporation from PVC surfaces and the evaporation from pond

Drying time (min)	v_{air} (m·s^{-1})	$E_{\mathrm{prototype}}$ (L·m^{-2}·d^{-1})	E_{pond} (L·m^{-2}·d^{-1})	Evaporation from PVC surfaces (%)	Evaporation from pond (%)
10	0.1	9.65	0.53	94.5	5.5
10	1.3	29.07	3.30	88.6	11.4
10	1.6	37.37	3.33	91.1	8.9
15	0.1	9.84	0.88	91.1	8.9
15	1.3	25.39	1.57	93.8	6.2
15	1.6	27.83	1.65	94.1	5.9
20	0.1	9.82	0.87	91.1	8.9
20	1.3	14.53	1.67	88.5	11.5
20	1.6	19.77	1.73	91.2	8.8

e — Mass transfer rate, $kg·s^{-1}$
h_m — Mass convection coefficient, $kg·s^{-1}·m^{-2}·Pa^{-1}$
k — Mass transfer coefficient, $mbar^{-1}$
LSI — Langelier Saturation Index
p — Water vapour pressure, Pa
R — Rejection
TDS — Total dissolved solids, $mg·L^{-1}$
V — Brine volume, L
v — Air velocity, $m·s^{-1}$
Λ — Conductivity, $mS·cm^{-1}$

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