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Evaluation of the recovery of osmotic energy in desalination plants by using pressure retarded osmosis

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ABSTRACT

The current paper explores the possibility of using pressure retarded osmosis (PRO) as part of the post-treatment of existing desalination plants: a membrane-based PRO system would be used to transform osmotic energy of the retentate into hydraulic pressure; this pressure is then used to generate electricity in a turbine. For this, a source of water with lower osmotic pressure would be needed: municipal or industrial wastewater, brackish water, etc. From the point of view of implementation, except for the PRO membranes, this additional PRO post-treatment uses a small number of additional components, which are similar to those already standards in desalination industry. A model of the process is developed, and some feasibility studies will be discussed, to evaluate the potential for varying mixing rates.

Keywords: Energy recovery; Desalination; Pressure retarded osmosis

1. Introduction

The salinity gradient power generation approach (SG, also called "Bluepower") is a renewable energy technique based on exploiting the chemical differences between liquids with different concentrations of salts [2,3]. It has been successfully developed at laboratory level during the last decades, with a pilot plant recently constructed by the main utility in Norway (Statkraft). This pilot plant has shown the feasibility of one of the proposed SG technologies such as the pressure retarded osmosis (PRO) technique [7]. Other test facilities, sometimes based on alternative operating principles, are being developed throughout the world: We can emphasize the pilot plant based on Reverse Electro Dialysis, which is being developed in the Netherlands by REDStack in collaboration with FUJI.

This paper concentrates on the use of SG techniques to recover osmotic energy from the retentate of desalination systems. Due to the high salinity of the retentate, this retentate is frequently mixed with other water sources (typically municipal wastewaters) to lower the salinity of the discharge. This mix generates a significant amount of energy, which can be recovered using SG technologies.

This paper is organized as follows: Section 2 describes briefly the material and methods of the PRO. Section 3 shows the mathematical modelling of the PRO vessel, and some results are shown in section 4. Finally, some conclusions are summarized in Section 5.

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2. Material and methods

The current work explores the possibility of using PRO within the posttreatment of desalination plants. The process operates as follows: the osmotic energy of the retentate draws water from a water source of lower osmotic energy through a specific membrane, generating hydraulic pressure; this pressure is then used to generate electricity in a turbine.

From the point of view of implementation, except for the PRO membranes, this additional PRO posttreatment uses a small number of additional components (pipes, sensors, and turbine), that are also similar to those already standard in desalination industry (see Fig. 1 how the studied PRO system would fit into a reverse-osmosis plant). Currently, the main difficulty of implementation is that novel membranes are needed, as the performance of standard RO membranes in this PRO applications are small, due to the different pressures and flow directions (for a discussion of the characteristics of the required membranes, see, e.g. [6,8]).

The models generally used to study the PRO process [1] are based on using a simple model that aggregates the flows (water and salts) through the membranes as scalar variables, taking into account the internal concentration polarization and the solute resistivity for diffusion within the porous layers. As it has already been pointed out by van der Zwan et al. [9], this gives a raw estimation of the flows through the membrane, based on a model described using partial–differential equations. Unfortunately, this 2D model is too complex for most studies, so in this paper following an approach previously used for RO systems [5], we first develop a one-dimensional model that considers the flows at different points of the membrane generated by variations in salinity along the membrane. This model is then used to study the process, evaluating the expected flows and the corresponding salinities for different mixing rates, which makes possible to evaluate the recovered energy.

3. Modelling

As it can be seen in Fig. 1, two streams are pumped to the recovery membranes:

(1) The rejected flow from the conventional energy recovery system (Q_r). This stream has some pressure (around 8 bar) and high salt concentration (around 65 kg/m^3 for seawater desalination plants).
(2) A feed water flow of the pretreated water (Q_f). This stream has low pressure (around 1 bar); the osmotic pressure of this water depends on the source used; and the worst case is assumed here, which is equivalent to the osmotic pressure of the seawater (around 35 kg/m^3 for seawater desalination plants).

Water mass balance of the reject flow is shown in Eq. (1), where the z direction corresponds to the direction of the stream, from the inlet to the outlet of the PRO system (see Fig. 2).

$$\frac{\partial Q_r}{\partial z} = +J \tag{1}$$

with $Q_r(0) = 1\ \mathrm{m}^3/\mathrm{h}$

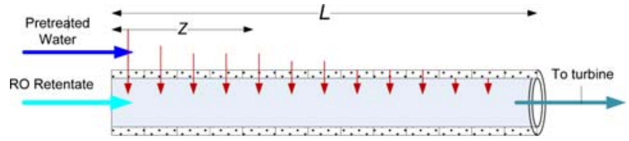

Fig. 2. Schematic diagram of water flow in membrane.

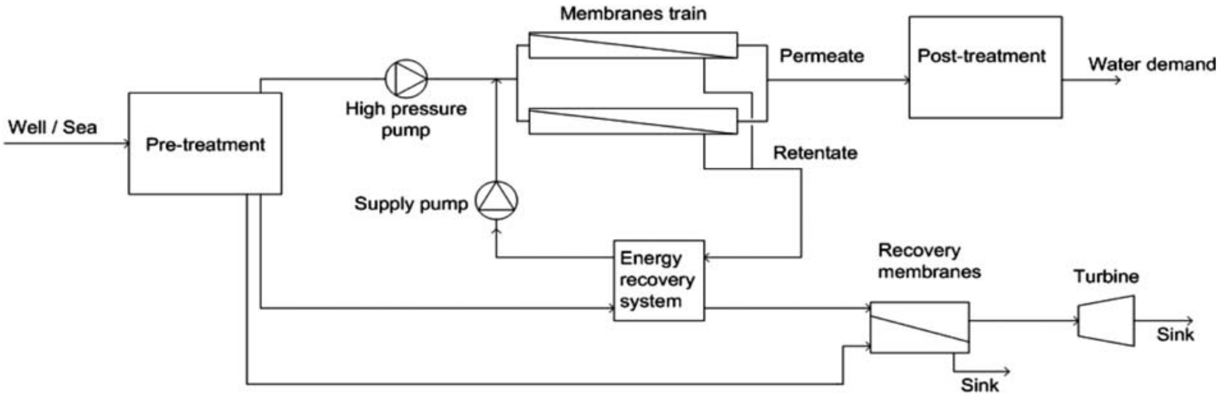

Fig. 1. Schematic diagram of reverse osmosis plant with pro module for recovering the osmotic energy.

where J means the water flux that crosses the membranes.

And water mass balance of the feed side is shown in Eq. (2):

$$\frac{\partial Q_{\mathrm{f}}}{\partial z} = -J \tag{2}$$

with $Q_{\mathrm{r}}(0) = r\mathrm{m}^3/\mathrm{h}$

where r means the ratio between the inlet feed flow and inlet reject flow. As it can be seen in next section, r takes values between 0.5 and 2.5.

$$r = \left.\frac{Q_f}{Q_r}\right|_{z=0} \tag{3}$$

The water flux that crosses the membrane can be calculated depending on the osmotic pressure between both sides of the recovery membranes:

$$J(z) = k \cdot \Delta\pi(z) \tag{4}$$

where $\Delta\pi$ means the osmotic pressure and k is a proportional parameter, which depends on the characteristics of the membranes.

Eqs. (5) and (6) show the salt mass balance for the feed and rejected side, respectively, where no flux of salt through the membrane has been assumed.

$$\frac{\partial C_{\mathrm{f}}}{\partial t} = \frac{1}{S_{\mathrm{f}}} \cdot \frac{\partial (Q_{\mathrm{f}} \cdot C_{\mathrm{f}})}{\partial z} \tag{5}$$

with $C_{\mathrm{f}}(0) \sim 35\,\mathrm{kg/m^3}$ for seawater desalination plants.

$$\frac{\partial C_{\mathrm{r}}}{\partial t} = \frac{1}{S_{\mathrm{r}}} \cdot \frac{\partial (Q_{\mathrm{r}} \cdot C_{\mathrm{r}})}{\partial z} \tag{6}$$

with $C_r(0) \sim 65\,\mathrm{kg/m^3}$ for seawater desalination plants.

Where S_f and S_r mean the cross section for the feed and reject side in the PRO system.

Osmotic pressure difference can be calculated by the Morse equation:

$$\Delta\pi(z) = i \cdot \sigma \cdot \frac{R \cdot T}{PM} \cdot \Delta C_{\mathrm{s}}(z) \tag{7}$$

where i means the van't Hoff factor ($i = 2$ for sodium chloride), σ means the reflection coefficient ($\sigma \sim 1$ for desalination), R means the gas constant, PM means the molecular weight of the salt, T means the temperature of the water, and ΔC_{s} means the difference between the salt concentration on the membrane surface in each side of the membrane (C_{fm}), as it can be seen in Fig. 2.

$$\Delta C_{\mathrm{s}} = C_{\mathrm{r}} - C_{\mathrm{fm}} \tag{8}$$

The C_{fm} is not able to be measured, but it can be easily estimated that applied a mass balance in the direction of the water flux (J). Typically, the ratio between the salt-concentration difference on the surfaces of the membranes, and is the bulks of the streams, is called polarization module, and represented by ϕ, as follows:

$$\phi = \frac{\Delta C_{\mathrm{s}}}{\Delta C} = \frac{C_{\mathrm{r}} - C_{\mathrm{fm}}}{C_{\mathrm{r}} - C_{\mathrm{fm}}} \tag{9}$$

Taking Eq. (9) into account, osmotic pressure can be calculated as follows:

$$\Delta\pi(z) = \phi \cdot i \cdot \sigma \cdot \frac{R \cdot T}{\mathrm{PM}} \cdot \Delta C(z) \tag{10}$$

At the end of the PRO system, the increase of pressure of the reject flow, caused by the osmotic pressure, can be calculated as follows:

$$\Delta P = \Delta\pi|_{z=0} - \Delta\pi|_{z=L} \tag{11}$$

where L is the length of the recovery membranes.

Finally, the power (W) that can be recovered from the PRO system, is calculated as follows:

$$W = \frac{1}{36} \cdot Q_{\mathrm{r}}|_{z=L} \cdot \Delta P \cdot \eta \tag{12}$$

where η means the energy efficiency.

4. Simulation

The mathematical model described in Section 3 was solved using a simulation environmental, parametrized using standard values. Some results are now discussed: Fig. 3 shows the salt concentration of the reject stream (C_{r}) and the feed stream (C_{f}), along the length of the membrane (from $z = 0$ to $z = L$), for a mixing rate of $r = 50\%$.

Notice that, in theory, the concentration difference would decrease until no more water flux is able to cross the membrane. Of course, in practice, some purge of feed water is used to facilitate cleaning and reduce the required membrane surface,

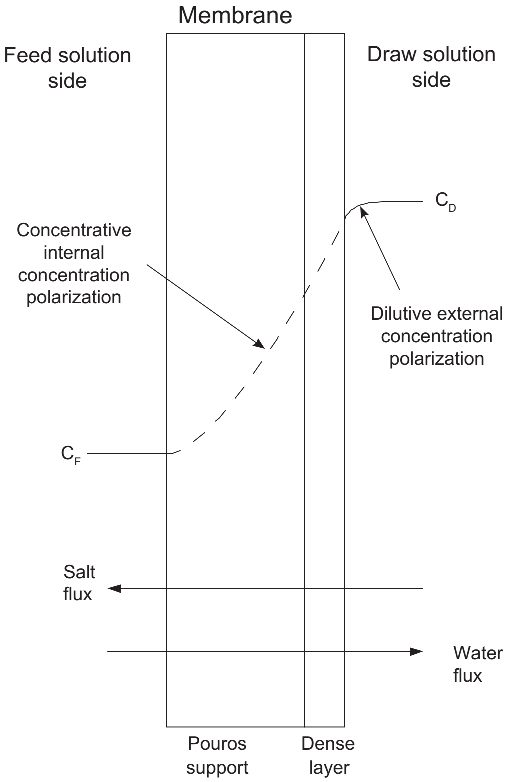

Fig. 3. Flows of water and salt at the membrane surface caused by variations of salinity.

so the practical length of the membrane is smaller than L.

The flow that crosses the membrane at different points is shown in Fig. 4. The ordinate axis of Fig. 4 represents the ratio between the water flux that cross the membrane and the inlet feed flow (%) $(100 \cdot J/Q_{f(z=L)})$. The total volume of water that has crossed the membrane is then proportional to the area below the curve.

Figs. 4 and 5 correspond to the results obtained for a mixing rate of $r = 50\%$. This mixing can be adjusted depending on the specific installation (available water flows and costs). Solving the mathematical model for different values of r makes possible to study the influence of this parameter. Figs. 6 and 7 show, respectively, the expected salt concentrations of the feed and reject flow, along the membrane. Fig. 8 shows the water flux that crosses the membrane.

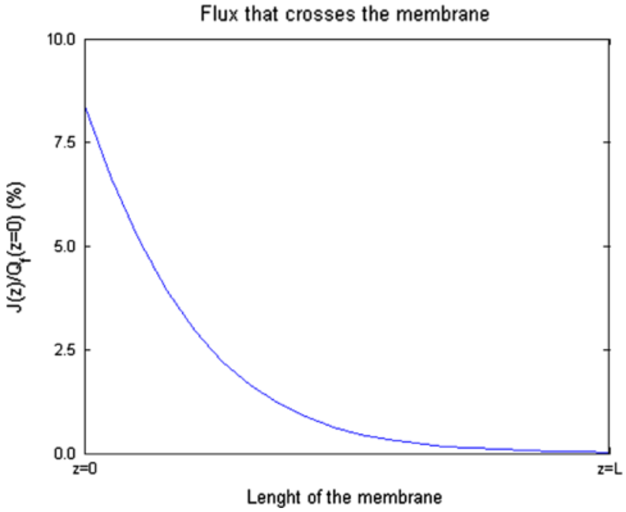

Fig. 5. Salt concentration of the reject (C_r) and the feed (C_f), along the recovery membrane.

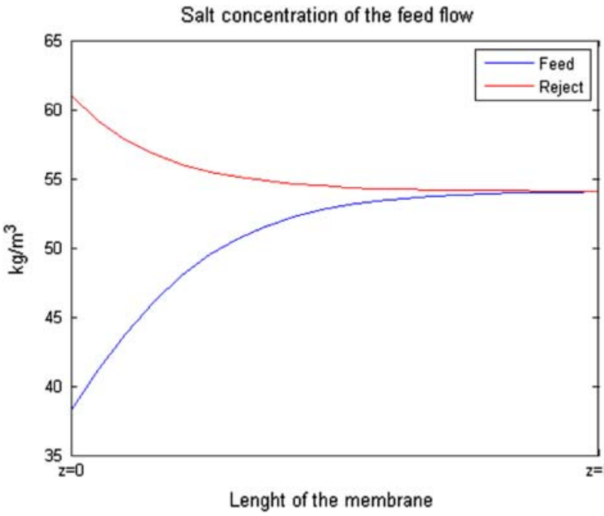

Fig. 4. Salt concentration of the reject (C_r) and the feed (C_f) along the recovery membrane.

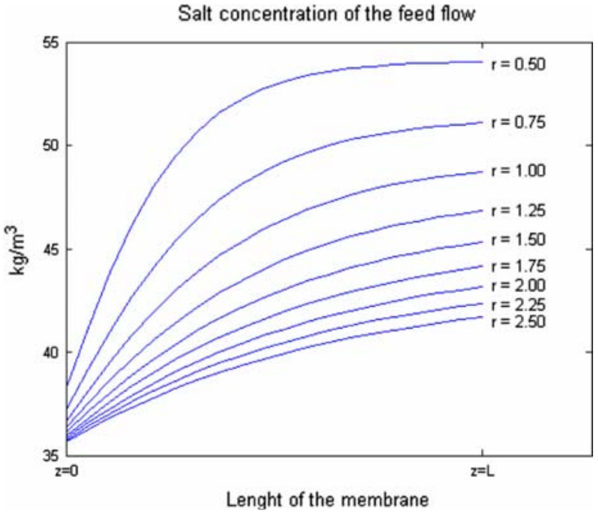

Fig. 6. Salt concentration of the feed flow (C_f) vs. the length of the membrane (z) for different values of r.

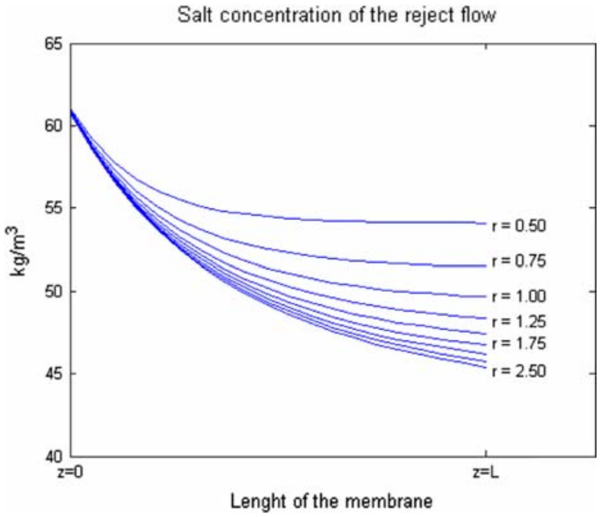

Fig. 7. Salt concentration of the reject flow (C_r) vs. the length of the membrane (z) for different values of r.

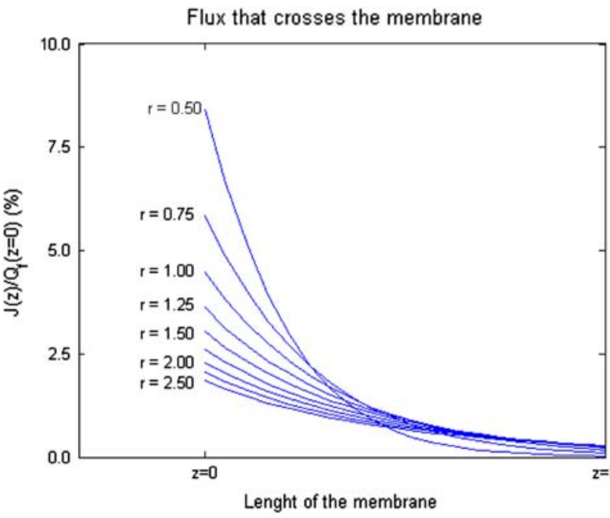

Fig. 8. Salt concentration of the reject flow (C_r) vs. the length of the membrane (z) for different values of r.

From these results, it is possible to estimate the expected power that can be recovered. For example, Fig. 9 depicts the maximum power energy recovery (W) that can be obtained for different values of r for a specific configuration. As a comparison, for these operating conditions the high pressure pump consumes around 2 kW, so around 50% of the energy consumed in the HP pump can be recovered. Notice that a maximum energy recovery takes place for values between 130 and 200%. To reduce the amount of water used, the lower value of 130% would be preferred.

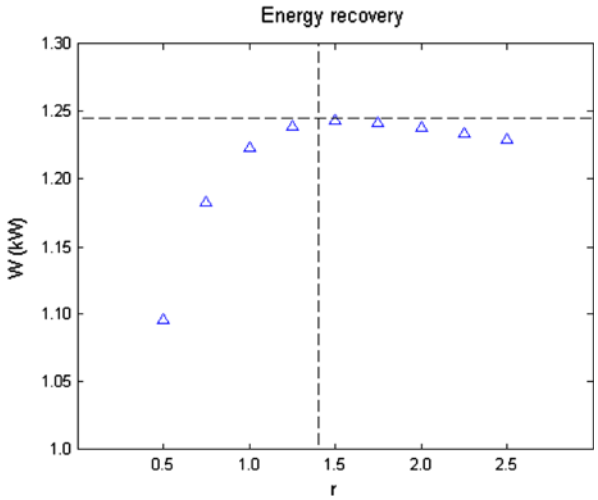

Fig. 9. Power recovery energy (W) vs. r.

5. Conclusions

Preliminary results of the capability of recovering osmotic energy from the reject of existing desalination plants are presented in this paper. Using a standard PRO post treatment, it might be possible to recover a significant percentage of the electrical power used in the desalination process and reduce the salinity of the discharge.

The process is studied by developing one-dimensional models that represent the osmosis process at different points of the membrane. These models are then simulated for varying values of the mixing rates. Results of section 4 showed that there is a significant recovery of the energy, but it is very important to design and operate the PRO system near its maximum efficiency point. For this, advanced control systems would be needed for the overall plant, as those discussed in Palacin et al. [4,5].

It has also been noticed that there is an additional degree of freedom in the design and operation of the PRO system. Of course the amount of produced energy will increase by using more pre-treated ("fresh") water, but this will increases the costs of pre treatment and PRO membranes, so the amount of feed water used should be carefully selected and controlled during the operation of the plant.

Symbols

C_f — salt concentration of the feed stream (m^3/h)
C_{fm} — salt concentration on the membrane surface at the side of the feed (m^3/h)
C_r — salt concentration of the rejected stream (m^3/h)
i — van't Hoff factor (–)
J — water flux that crosses the membrane (m/h)

k — ratio between the water flux and the osmotic pressure (m/(bar h))
L — length of the recovery membranes (m)
P — pressure (bar)
PM — salt molecular weight (kg/kmol)
Q_f — water volumetric flow ratio of the feed stream (m^3/h)
Q_r — water volumetric flow ratio of the reject stream (m^3/h)
R — gas constant ((bar m^3)/(kmol K))
r — ratio between the inlet feed flow and the reject feed flow (–)
S_f — cross section for the feed side (m^2)
S_r — cross section for the reject side (m^2)
T — temperature (K)
W — recovery power (kW)
σ — reflection coefficient (–)
ϕ — polarization module (–)
η — pressure recovery efficiency (–)
π — osmotic pressure (bar)

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