The potential for power production from salinity gradients by pressure retarded osmosis

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A B S T R A C T

A large amount of potential renewable energy can be extracted from the mixing of freshwater and seawater. Two membrane processes can be used to extract this energy, namely pressure retarded osmosis (PRO) and reverse electrodialysis. Both processes need membranes that are similar to the ones used to perform reverse osmosis and electrodialysis. So far neither of the processes has been optimally designed. In the present study PRO has been analysed for potential power production. It appears that PRO exhibits a significant potential for power production and future developments may further improve this. A specific power in the order of 5 W/m² of membrane seems possible and approximately 40 per cent of the potential mixing energy of freshwater with infinite amount of seawater can be converted to mechanical energy. This article aims to describe the PRO process and to develop guidelines for the development of membranes that are suitable for PRO. Furthermore, some experimental results from laboratory measurements are included both to verify the model and to show present state of membrane development.

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1. Introduction

The principle of salinity power is the exploitation of the mixing entropy between two solutions of different salinities, in the context of this article freshwater and seawater. Two membrane processes of technical interest can be used to extract this power, reverse electrodialysis (RED) and pressure retarded osmosis (PRO). Energy extracted by PRO is here called as osmotic power. Both processes were discussed by Post et al. [1]. They concluded that RED appears to be the most efficient method to extract some of the potential mixing energy of freshwater and seawater. This article presents a novel and detailed analysis of PRO based on a model that includes concentration polarisation on the membrane surfaces and in the interior of the support membrane for realistic operating conditions of a membrane module. The results from the analyses lead to conclusions that are different to the ones made by Post et al. [1] as PRO appears to be significantly more efficient with respect to specific power than the 1 W/m² membrane area indicated by them.

Salinity power is completely renewable and less periodic than other renewable sources like wind and solar energy. No significant operational hazards are known. Salinity power is potentially one of the largest sources of renewable energy on earth. Further, salinity power production is clean and there are no significant emissions to the atmosphere like CO₂ and low emissions to water. These features justify the interest in salinity power that has emerged in recent years. Skilhagen et al. [2] summarise some recent efforts towards the development of osmotic power.

A review of previous studies reveals that many estimates of the potential for salinity power production were done for conditions that are necessarily not realistic today, in positive as well as negative senses. In these studies, energy costs from about 0.015$/kWh [3] to about 0.15–0.30$/kWh [4] were indicated. Some early negative conclusions were made based on measurements of RO membranes and not membranes adapted to osmosis. Such membranes are not expected to perform well in PRO as different requirements to the membrane structure have to be met for the two processes. Only limited efforts to optimise membranes for PRO are mentioned in the literature. Some challenges to PRO membranes are discussed by McCutcheon and Elimelech [5].

It has been previously proposed to construct an osmotic power plant 120 m below sea level to avoid power loss in the high pressure seawater pump [6]. Today modern pressure exchangers with increased efficiency exist that may improve the efficiency also for ground level plants.

The worldwide salinity power potential, estimated from [7,8], may correspond to about half the potential for conventional hydropower. In Norway the present technical potential of osmotic power is estimated at up to 12 TWh/year, equivalent to 10 per cent of current power consumption in the country. In Europe the equivalent potential is estimated at 170 TWh/year while the global potential is in the order of 1650 TWh/year. Capital cost for an osmotic power plant will be relatively high when compared to wind power.
However, an osmotic power plant can be designed to operate at full capacity almost continuously. This may reduce the PRO energy cost to an attractive level. Estimates made in the present study by the Norwegian power company Statkraft show that osmotic power generation may be developed to be cost competitive with other renewable power sources such as wind power and biomass.

PRO membranes should have many of the features of the present membranes made for reverse osmosis (RO) and ultrafiltration (UF). The estimated value of the yearly market for PRO membranes is significantly larger than the present RO and UF markets, even for a modest exploitation of the power potential. This illustrates the large market potential for the production of membranes, which would require a significant increase in the global membrane production capacity. A lower cost per square meter of membrane must be realised for PRO membranes compared to the present RO membranes, however.

2. Mixing of freshwater and seawater

Freshwater that flows into the sea is mixed irreversibly with seawater. The enthalpy of mixing for these fluids is close to 0. The temperature in the mixing zone will depend on the temperature of the freshwater, the seawater temperature and the effective mixing volumes. If the mixing process is performed in a reversible manner in a device constructed specifically for the purpose, work can be extracted. The change in Gibbs free energy for mixing 1 mol of freshwater with an infinite amount of seawater can be expressed by

\[ \Delta G_{\text{mix}} = RT \ln x_{\text{H}_2\text{O}} \]  

assuming ideal fluids [9] and where \( x_{\text{H}_2\text{O}} \) is the mole fraction of water in the seawater. Seawater has the same osmoticity as a solution of 32 g NaCl/l. In this solution the concentrations of NaCl and water are 0.549 (1.1 equiv. of ions) and 54.92 mol/l, respectively. At 20 °C the values given above inserted into Eq. (1) gives \( \Delta G_{\text{mix}} = -48.1 \text{J/mol or } -2.7 \text{kJ/kg freshwater.} \) This amount of energy can be extracted as work in a device that mixes freshwater and saltwater reversibly. With a molar volume of water of 18 \( \times \) 10\(^{-6} \) m\(^3\)/mol this corresponds to an osmotic pressure of 26.7 bar (ideal solution).

The mixing process of freshwater and seawater will be close to adiabatic, i.e. there is no heat exchange with the surroundings (\( dq = 0 \)). Since the enthalpy of mixing is close to 0 and work (\( dw \)) is extracted from the process, the law of energy conservation gives

\[ dE = c_p \, dT = dq + dw = dw \]  

where \( dE \) is the change in internal energy and \( c_p \) is the heat capacity of the system. Extraction of work from the mixing process will result in a cooling of the mixture according to Eq. (2). Assume that, e.g. 1 mol of freshwater is mixed with 3 mol of seawater. Less than 48.1 J can be extracted from the process. With a heat capacity of 4.18 J/g the close to 72 g diluted seawater (4 mol) will be cooled by less than 0.17 °C. In a process optimised for energy production less than half of the reversible work will be taken out and the corresponding mixture thus will be cooled less than 0.08 °C.

3. The PRO process

3.1. Model description

In order to facilitate a working PRO process the membrane must be configured in modules like in RO, either in a spiral, fibre or in other forms. An essential feature of the PRO module is the flow of the two water phases along both opposite surfaces of the membrane, called cross-flow in membrane filtration terminology. This is different from RO where there is cross-flow all through the module on the saltwater side of the membrane only. A section of a membrane in PRO operation is illustrated in Fig. 1.

The osmotic process in PRO occurs in the thin semi-permeable skin layer of the membrane. The mass transport through the rest of the membrane is dominated by hydraulic flow. This is evident from the pore dimensions, which are large enough for the continuum theory to apply (Gad-el-Hak [10]).

The present article aims to describe the PRO process in detail in order to understand how it can be optimised. The ideal osmotic process can be described by the thermodynamic equations for the water and salt fluxes. Our experimental results indicate that no significant corrections for non-ideal behaviour are necessary. In these experiments a significant number of membrane samples have been used, both commercial RO type and experimental samples made as part of the investigation. The simplest forms of these equations are

\[ J_w = A \cdot (\Delta p - \Delta \pi) \]  

and

\[ J_s = B \cdot \Delta c_s \]  

Accordingly the water flux, \( J_w \), is proportional to the water permeability, \( A \), and the difference between the osmotic pressure difference, \( \Delta \pi \), and the hydraulic pressure difference, \( \Delta p \), across the membrane skin. The salt flux, \( J_s \), is proportional to the salt permeability, \( B \), and the salt concentration difference across the skin, \( \Delta c_s \). The equations are valid for the skin only and describe diffusive transport of water and salt through the skin material. The porous structures in the membrane, corresponding to the support membrane in TFC types (thin film composite), mainly serve to support the skin mechanically. The presence of these structures reduces the efficiency of the membrane in PRO, as will be shown below.

No skin is perfectly semi-permeable and some salt will diffuse through the skin. With saltwater on the skin side of the membrane this salt will diffuse into the porous substructure toward the freshwater, and the salt concentration will thus increase on the freshwater side downstream in the module. The net salt transport in the porous structure is equal to this diffusion minus the salt flux coupled to the osmotic water flux in opposite directions. For salt to escape out of the structure a concentration gradient will develop and consequently concentration polarisation will arise within the porous structure.

The porous structure can be described by its average thickness, \( x \), the porosity, \( \phi \), the tortuosity, \( \tau \), and the pore length, \( l_p \). The exact definition of tortuosity is dependent on which geometrical model is considered; see Bear [11, p. 111]. With a model of diffusion and hydraulic flow in tilting or zigzag pores the tortuosity is \( \tau = (l_p/x)^2 \) and the water velocity in the pores is \( v_p = J_w / l_p / \phi / x \). From Eq. (4) and a mass balance through the membrane a relation can be found for the steady state transport of salt through the skin and the porous
structures:
\[
B \cdot \Delta c_t = \frac{x \cdot \phi}{l_p} \left( D \frac{dc}{dt_p} - \nu \cdot c \right) = \frac{x \cdot \phi}{l_p} \left( D \frac{dc}{dt_p} - J_w \cdot \frac{I_p}{\phi} \cdot c \right)
\]
\[
= \frac{\phi \cdot D}{\tau} \frac{dc}{dx} - J_w \cdot c
\]
\[(5)\]

Here \( \Delta c_t \) is the salt concentration difference across the skin and \( D \) is the salt diffusion coefficient.

Eq. (5) can be developed into expressions for the concentration differences across the skin in terms of the concentrations at the outer surfaces of the membrane. For either case, with seawater facing the skin side or the porous side of the membrane, the expressions have the form:
\[
\Delta c_{skin} = \frac{c_{m1} - c_{m2} \cdot e^{E1}}{1 + \left( \frac{B}{J_w} \right) \cdot e^{E1} - 1}
\]
\[(6)\]

where the exponent \( E1 \) has the form
\[
E1 = \frac{\tau \cdot J_w}{\phi \cdot D} = \frac{\tau \cdot J_w}{D
\]
\[(7)\]

It appears that the osmotic efficiency of the membrane itself can be described entirely by the values of \( A \) and \( B \) of the skin and one single parameter for the porous structure \( S \). This parameter is called the structure parameter and is defined by the tortuosity, \( \tau \), thickness, \( x \), and porosity, \( \phi \), of the porous structure, as shown in Eq. (8). \( S \) has the dimension of length and appears as an apparent stagnant film thickness.

\[
S = \frac{\tau \cdot x}{\phi}
\]
\[(8)\]

The concentrations on the membrane surfaces, \( c_{m1} \) and \( c_{m2} \), can be found from a two-dimensional model similar to the classical solution for membrane channels described in several publications, like [12,13]. The surface concentrations on the membrane in cross-flow operation is influenced by the water and salt fluxes through the membrane and a number of external variables like cross-flow water velocity, \( u \), channel dimensions and the distances from the inlets to the channels, \( l \). The direction of the fluxes will be different from UF and RO:

\[
\frac{\partial c}{\partial y} + J_w \frac{\partial c}{\partial y} = D \frac{\partial^2 c}{\partial y^2}
\]
\[(9)\]

Here \( y \) is the distance from the membrane surface. This equation is valid for the seawater channel. In the freshwater channel the flux term has opposite sign. Both \( u \) and \( J_w \) are functions of \( y \) as well as \( l \). The functions of \( y \) are included explicitly in the detailed integration whereas the dependence on \( l \) is taken care of by the numeric integration in the \( y \) direction by stepwise changes based on the mass balance. The values of \( u \) and \( J_w \) are assumed to be constant within very small segments of \( l \).

The general solution of the differential equations is
\[
c = c_{m1} \pm \frac{1}{D} \left( B \cdot \Delta c_{skin} + J \cdot c_{m1} \right) \int_0^y e^{E} \, dy
\]
\[(10)\]

This can be solved for the concentration on the membrane surface:
\[
c_{m1} = \frac{c_0 \pm \left( \frac{(B \cdot \Delta c_{skin})}{D} \right) \int_0^y e^{E2} \, dy}{1 \pm \left( \frac{J_w}{D} \right) \int_0^y e^{E2} \, dy}
\]
\[(11)\]

where the exponents \( E2 \) have the form
\[
E2 = -\frac{u_0}{\frac{3}{2} \cdot \nu \cdot l \cdot D} \cdot x^3 \pm \frac{J_w}{D} \cdot y
\]
\[(12)\]

where \( c_m \) are the concentrations on the membrane surfaces toward either of the cross-flow streams and \( c_0 \) are the concentrations in the centre of the either of the two cross-flow channels containing freshwater or seawater. \( u_0 \) is the bulk flow velocity of either of the cross-flow channels. The various forms of the equations give concentrations that are valid with seawater on the skin side or on the porous side, respectively.

Eqs. (6), (7), (11) and (12) feature a complete solution for modelling full scale performance of membrane modules. The inside of the membrane (skin and porous structure) and the cross-flow channels are modelled separately by these equations and the two models are connected through common conditions on the membrane surface, namely \( J_w \) and the salt concentrations, \( c_{m1} \) and \( c_{m2} \). The value of \( u \) is zero at the surface. This defines the common boundary conditions for the two models and can be applied in iterative calculations. The conditions along the full length of the membrane change because the cross-flow velocities change and the seawater is gradually diluted, and also because concentration polarisation increases. The cross-flow velocity profiles must be adapted to the module form at hand. Spacers in spiral modules are a challenge, but can be assessed using assumed velocity patterns in such modules according to [14]. Models have been formulated for spiral and fibre modules and inside and outside axial and radial flow in fibre modules.

### 3.2. Modelling PRO experiments

The models described above can also be applied for the analysis of PRO experiments. An apparatus has been built that uses 65 cm² of sheet membranes in a small cell to do PRO experiments with actual cross-flow along the membrane surfaces. The cell uses the same type of spacers that are used in spiral RO modules. The apparatus is equipped with common precision instruments to measure and control the saltwater and freshwater pressure and pressure drop along the spacers. Piping is stainless steel and reinforced tubing. The cell was constructed as part of this study. It was made of a stainless steel flat sheet design of similar construction as used in most institutes working with RO experiments. The main difference is that cross-flow is possible on both sides of the membrane. A simplified sketch of the equipment is shown in Fig. 2. A reservoir in the saltwater loop is not shown.

With this apparatus it is possible to run PRO experiments for more than 1 day without interruption. The saltwater pressure is maintained constant in PRO operation by a backpressure valve and the fluxes are measured by balances. Further, a pressure system, not shown in the figure, makes it possible to run continuous hysteresis of PRO-RO by adjusting the pressures on both sides of the membrane.

Several smaller apparatuses using stirred cells instead of the cross-flow cell shown in the figure have also been used. These smaller cells are in principle similar to the equipment used by Lee et
al. [4] and experimental data are logged as for the cross-flow apparatus. Glass cells made for osmotic flow measurements at ambient pressure have open membrane areas of 1.2 cm² in the plate that separates the two half cells. A cell made of Hastelloy C for PRO measurements can use membranes with effective areas of either 7 or approximately 0.5 cm². The largest area requires a mechanical support of the membrane that significantly increases the effective diffusion length of the transport system. Without a mechanical support an aperture in the metal plate that separates the two half cells is only 7 mm. Due to bulging of the unsupported membrane the area is increased to approximately 0.5 cm². Examples of measurements both in an osmotic flow cell and in the PRO cell without mechanical support of the membrane are shown below.

By fitting the measured water and salt fluxes to the models described above, a wide range of combinations of permeability values (A and B) and structure properties (S) can be screened. The best fit values of A and B usually will be close to the values that easily can be measured in RO operation with the same membrane or calculated from the manufacturers’ specification for the RO membrane types.

Exact film thicknesses for concentration polarisation are not a feature of the complete model, but apparent film thickness can be calculated as if a stagnant film model was applied (Mulder [15]), called the film model. Film thickness is a subtle parameter, but facilitates a convenient method for quick calculations of approximate results. Common average apparent film thicknesses according to the film model through a membrane module have been calculated using the models described above.

### 3.3. Experimental results

Results from an experiment with a commercial CA (cellulose acetate, SS10 from Osmonics) RO sheet membrane are shown in Fig. 3. For most modelling of experimental results the calculation (the line in the graph) has been derived using an apparent film thickness, which provides acceptable accuracy in this case. The polarisation inside the membrane is significant, however, and is included in the modelling.

The figure clearly shows that our model describes the experimental results closely. The values of A, B and S shown in the box in the graph are the values that gave the best fit for the curve that was calculated with our model. The values of A and B are very close to the values that can be calculated from the manufacturers’ performance specification in RO operation. The value of S is 2.5 mm, which is more than 10 times the membrane thickness. Therefore the value of \( \frac{\tau}{\phi} \) must be more than 10, see Eq. (7). This is typical for commercial CA RO membranes.

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**Fig. 4.** Power and flux measured in a PRO experiment with a naked CA membrane at 23.5 g/l.

Provided that PRO experiments are done with several different conditions during the experiment, like various saltwater pressures, it is not necessary to do a PRO-RO experiment in order to find A, B and S. Fig. 4 shows the direct results from a cross-flow PRO experiment with an experimental flat sheet CA membrane made without fabric reinforcement (naked) for the present study. The membrane was operated at a salt concentration difference between the bulk flows of 23.5 g/l.

The figure shows the water flux and the power yield, expressed as the product of water flux and hydraulic pressure in saltwater channel. It can be seen that the maximum obtainable pressure with this salt concentration was 16 bar and the specific power was 1.6 W/m². The expected average salt concentration in a power plant module would be approximately 28 g/l, which would increase the specific power to approximately 2.1 W/m².

From several experiments with membrane types similar to those used for the results in Figs. 3 and 4 it was found that the value of S is approximately 2.5 mm with backing fabric and close to 1 mm without the backing. The backing obviously adds approximately 1.5 mm to the value of S. This is in agreement with the structure and thickness of the backing material.

CA membranes behave well, as illustrated in the figures above. But their semi-permeable properties are inferior to TFC membranes, as is well known for application in RO. It has been observed from experiments with commercial TFC types for RO that these membranes have inherent properties that make them less efficient in PRO. This was already noted in early experiments with PRO by Lee et al. [4]. Therefore, in order to realise their full PRO performance they need to be redesigned. So far the development of TFC membranes has improved the measured performance significantly compared to commercial RO types.

Example of measurements on a sample of an experimental TFC membrane made in the present study (by GKSS Forschungszentrum, Geesthacht, Germany) is shown in Fig. 5. The left picture shows results from two osmotic flow measurements using a glass cell (1.2 cm² area) where transferred mass to/from both half cells are shown as function of time. In one experiment the saltwater (27.0 g/l NaCl) faced the skin side of the membrane. In the other experiment the saltwater (26.9 g/l NaCl) faced the support side of the membrane. As seen in the figure the graphs that show the absolute values of the mass changes in the two half cells (each half cell was connected to a fluid reservoir placed on balances) overlap, closing the mass balances of the experiments. The transfer of salt was also measured. From the measured water and salt fluxes the values of A, B and S for the membrane were determined to 7.1 × 10⁻¹² m²/Pa s, 1.1 × 10⁻⁷ m/s and 0.67 mm, respectively. The value of the water permeability was confirmed by hydraulic flow measurements.
The right hand picture in Fig. 5 shows the results from PRO measurements for the same membrane using freely suspension giving a very small effective membrane area (0.5 cm²). The thin lines represent measured water flux and specific power as functions of the pressure on the saltwater side. The saltwater concentration on the skin side of the membrane was 30.6 g/l NaCl at start of the PRO measurements. The thick lines in the figure represent modelled water flux and specific power as function of pressure using the membrane parameters given above. All measurements were made at 20°C.

Fig. 5 (right) shows that it was possible to extract approximately 2.7 W/m² from this TFC membrane, compared with typically less than 0.1 W/m² for most commercial RO types tested. The calculated water flux to the right in the figure is the time derivative of a similar transferred mass vs. time relationship as shown to the left. Due to the low membrane area the mass transfer is relatively low and there is some scattering in the calculated flux. However, the trend in the measurements is clear, the flux–pressure relationship follows a almost linear decline from the initial flux at zero pressure to zero flux at an effective osmotic pressure of 20.6 bar. Experimental factors that could have biased the measurements would be related to leakage of saltwater from the pressurised half cell, either out to the surroundings or around the membrane suspension back to the half cell with freshwater. Both cases would have resulted in a lower calculated water flux through the membrane than the real flux. The results shown in Fig. 5 (right) are in this respect conservative. During the PRO mode measurements the mass transfer is calculated based on change in mass of a water reservoir connected to the freshwater (low pressure) side only.

It can also be noticed that due to the membrane suspension in the plate that separates the half cells the boundary layer on the membrane surface will be significantly thicker as compared to the conditions during cross-flow in a module. The performance of the membrane is thus reduced compared to what could be expected in a module at otherwise identical conditions.

Development membranes made in this project have for practical reasons often been made in small formats which do not allow testing in the cross-flow cell. However, in several cases where available membrane types have allowed measurements both in the cross-flow cell (65 cm²) and in small cells confirm the reliability of the measurements with small membrane samples.

Further development is needed in order to extract enough power using flat sheet TFC membranes to make them acceptable for PRO. The values of all the three critical membrane parameters should be improved and structural issues related to the membranes must still be resolved.

4. Preferred PRO membrane and process properties

4.1. Suitable membranes

As mentioned the basic parameters that characterise the membrane are A, B and S. The value of A appears indirectly in the equations through its influence on the water flux, \( J_w \). In Fig. 6 a series of calculations are presented using the film model. In the figure the potential power yield for three different membranes is shown. The A-values range from \( 3 \times 10^{-12} \) to \( 2 \times 10^{-11} \) m/Pa s and B varies from \( 10^{-8} \) to \( 10^{-7} \) m/s, which represents typical commercial RO membranes (ULP = ultra low pressure type; HR = high rejection type).

The salt concentration difference between the bulk flows of freshwater and seawater used in calculation of the graph was 28 g/l. This is the expected average in a membrane module where gradual dilution of the seawater occurs and based on estimates from plant designs and costs (see below). Further, the average film thickness
was set to 30 μm which is a common average value calculated for spiral modules using the complete model. The calculated results are specific membrane power as a function of $S$. The effects of increased salt concentration in the freshwater because of transmembrane diffusion and the energy loss due to cross-flow losses have not been included in the calculations. However, these losses are relatively low for membranes with high salt rejection and well-designed modules.

The figure shows that the value of $S$ is very important for the power yield. Values below 1 mm are needed for acceptable power production. Experiments with a large number of commercial RO membranes show that the $S$ values in these membranes are much larger. This is indicated on the top of Fig. 6. It has been found that it is possible to make membranes with a modified structure that have values of $S$ in the order of 0.5 mm, or even lower. In that case the potential power production from the membrane can be higher than 6 W/m². A possible compression of the membrane during PRO will increase the value of $S$ and is a factor that must be taken into account during membrane development.

### 4.2. Process properties

In order to estimate the power that could be extracted from hypothetical PRO power plants in the future, suitable and realistic membrane and plant properties should be chosen. Our experiments have shown that skin permeability values, $A$ and $B$, already realised in present RO can be sufficient for PRO as well. Experimental PRO membrane samples have been made that have values of $S$ close to 0.5 mm. This has been verified in our experiments and is also seem realistic from evaluation of SEM pictures of the porous membrane structures. Plant efficiency estimates in this study have shown that a feed volume ratio between seawater and freshwater of approximately 2 appear to be close to optimal, resulting in an average salt concentration in the module of approximately 28 g/l. Table 1 summarise actual values of some essential parameter for efficiency estimates.

If these conditions are met we can, according to model calculations, expect a net specific power production of slightly above 5 W/m² from a membrane module of a spiral type. Details in the calculations reveal that with counter-current cross-flow the local power yield at maximum module power varies through the module from 4 to 6.3 W/m² because of seawater dilution and concentration polarisation. Estimates for losses in the plant indicate that the net power from the plant will be in the order of 1 W/m² lower than the values given in Fig. 6.

Fig. 7 shows a sketch of the plant layout that was been chosen for the study. Central in the plant is the membrane modules and the pressure exchanger that minimise the losses for seawater pumping. A complete analysis of the plant performance necessitates the involvement of a significant number of variables, including the basic properties of the membrane, the physical dimensions of the module, the operation conditions as well as the water characteristics. But the present model makes it possible to simulate a wide range of variable values for the purpose of optimisation.

For spiral modules it appears that dimensions that are common in RO dimensions could be suitable for PRO as well. Furthermore, simulations show that the power yield from a module is similar for co- and counter-current cross-flow; although counter-current flow gives more even flux values along the module. Because higher flux increases the fouling potential, counter-current is the preferred choice. Similar analyses are presently being performed for fibre modules.

### 4.3. Energy recovery

Maximum specific power is obtained at a hydraulic pressure of about 50 per cent of the effective osmotic pressure as also seen in the experiments shown in Figs. 4 and 5. If the pressure is increased by restricting the brackish water outlet, the flux decreases, but the power production does not decrease proportionally. Because of lower flux, the power produced in relation to the freshwater feed increases. This is illustrated in Fig. 8. The figure shows the membrane power, the water flux and the energy recovery. The latter is the amount of energy that is recovered by the mixing process relative to the theoretical maximum amount of energy from mixing of freshwater with infinite amounts of seawater. It can be seen that the recovery is between 30 and 40 per cent at maximum specific power, but approaches 65 per cent with very low water flux. The maximum obtainable pressure in this illustration is assumed to be 22 bar. The reasons for the recovery not being 100 per cent at close to zero water flux are that only 80 per cent of the freshwater feed is transported through the membrane and that the osmotic pressure is reduced by dilution of the seawater downstream in the membrane module.

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical parameters used in the PRO calculations in this study.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water permeability, $A$</td>
<td>$10^{-11}$ m²/Pa s</td>
<td>Exists in RO membranes</td>
</tr>
<tr>
<td>Salt permeability, $B$</td>
<td>$3 \times 10^{-5}$ m/s</td>
<td>Exists in RO membranes</td>
</tr>
<tr>
<td>Value of the structure parameter, $S$</td>
<td>0.00004 m</td>
<td>Verified in experimental membranes</td>
</tr>
<tr>
<td>Thickness of stagnant films, when applied</td>
<td>0.00003 m</td>
<td>Modelled</td>
</tr>
<tr>
<td>Channel thicknesses (in spiral type module)</td>
<td>0.0005 m</td>
<td>Best compromise</td>
</tr>
<tr>
<td>Process temperature</td>
<td>8 °C</td>
<td>As actual</td>
</tr>
<tr>
<td>Inlet concentration of NaCl in seawater</td>
<td>32 g/l</td>
<td>Equivalent to real ocean water</td>
</tr>
<tr>
<td>Volumetric inlet ratio saltwater/freshwater</td>
<td>2</td>
<td>Close to optimum</td>
</tr>
<tr>
<td>Freshwater utilisation</td>
<td>80 per cent</td>
<td>Maximum to avoid fouling</td>
</tr>
</tbody>
</table>

Fig. 8. Calculated membrane power, flux and energy recovery with PRO, using the membrane specified in Table 1 and 80 per cent freshwater utilisation. Average salt concentration is 28 g/l and assumed maximum osmotic pressure is 22 bar.
5. Discussion

There is a series of practical limitations related to the possible performance of industrial membranes, such as concentration polarisation, fouling, etc. However, several studies have been published on osmosis and PRO experiments with RO membranes, e.g. in [4,6], where the results on membrane fluxes are in general agreement with the results in this study. Few in-depth studies have, however, focused on the actual power output that can be obtained from PRO power plants and energy recovery. Post et al. [1] made some calculations and concluded that only 1 W/m² or less can be expected from PRO plants using seawater and freshwater. Their conclusions were based on osmotic membranes with water permeabilities significantly less than existing commercial RO membranes. This figure is also less than the 2.7 W/m² specific power that as been measured in laboratory experiments.

The present analyses show that the specific power in PRO may approach high values (cf. Fig. 6). The best RO membranes on the market today probably already have skins with the necessary semi-permeable properties, but the structure parameters are far too high. An integrated PRO membrane must be tailor-made using an improved support membrane having a low S value in a manner that does not impair the osmotic properties of the skin. Large steps have been taken towards reaching this goal but further progress is needed in order to make membranes that will be useful for commercial osmotic power production.

Theoretical modelling supported by experimental work indicates that it may be possible to develop membranes that yield 5 W/m², or even higher if a breakthrough in membrane development occurs. In an optimised osmotic power plant this figure would be reduced by approximately 1 W/m² due to various losses in the total process. The resulting net power gives a realistic perspective for seawater/freshwater PRO. Post et al. [1] indicated a specific power in the order of 2.5 W/m² for an optimised RED.

In Section 2 it was shown that the maximum extractable energy from mixing of seawater and freshwater is 2.67 MJ/m³ of freshwater at 20 °C. This is a relevant quantity to use as reference for plant efficiency because it is the available amount of freshwater that will limit the power production potential. While there is normally no restriction on the amount of seawater available, the energy and costs needed to handle it will limit the flow to approximately twice the freshwater flow. The freshwater utilisation in PRO should normally not exceed 80 per cent in order to reduce fouling, since all natural freshwater feeds will contain some fouling components.

The PRO calculations are made for a feed of salt free freshwater (most Norwegian surface waters contain less than 0.1 g/l salt) and seawater. In the example of Fig. 8 it is shown that 40 per cent of the potential mixing energy or approximately 1 MW/(m³ s) can be recovered at a pressure slightly above optimum power production (5 W/m²). Actually a PRO plant may be operated with higher recovery than 1 MW/(m³ s) in periods of freshwater shortage, but then with reduced specific power. However, due to the operating characteristics of a PRO plant the output will for example only be reduced by 9 per cent when the freshwater feed is reduced by 25 per cent. If future improved membranes (e.g. based on nanotubes) can improve the water permeability and still keep the salt permeability low, the mixing process in PRO can be made more reversible using even higher pressures in the seawater (well above the pressure for maximum specific power).

In order to compare the feasibility of PRO and OED for power production the cost and service time of membranes, the energy losses in the plant and construction costs are important parameters. It is not possible to assess the future cost of membranes since commercial utilisation of salinity power will allow cost reductions through economy of scale. Nevertheless it is difficult to envisage that the cost of 1 m² membrane for PRO will be higher than 1 m² of membrane pair for RED. The power loss for a large and well-designed PRO plant will be in the order of 1 W/m² installed membrane. A similar figure for a RED plant has not been found.

The evaluations of the PRO process were based on an essentially salt free freshwater feed. The efficiency of the PRO process will be reduced if the freshwater feed contains significant amounts of salt. In this respect the RED process offers an advantage over PRO since some salt in the freshwater is needed to improve the performance. If this salt is not naturally present in the freshwater feed some seawater has to be added. In order to prevent fouling of the membrane stacks, the both processes will have requirements regarding the quality of the feed fluids.

6. Conclusions

An analysis of the PRO processes for energy production from mixing of freshwater and seawater has been performed at realistic conditions for physical plant operation. The specific energy production and the utilisation of the freshwater feed for the PRO process have been analysed. The model has been used to analyse laboratory experiments.

If the semi-permeable properties of the best commercial RO membranes can be realised in membranes optimised for PRO, a specific power in the order of 5 W/m² membrane appears to be realistic when the various loss factors are not considered. The total power losses in a large and optimised PRO plant are estimated to be in the order of 1 W/m². A freshwater utilisation efficiency of 1 MW/(m³ s) or approximately 40 per cent of the maximum mixing energy of freshwater with infinite amounts of seawater can be obtained. These performances may be further improved if new membrane types are developed that allow the process to operate more reversibly at higher seawater pressures.

Present RO membranes have the semi-permeable properties that are needed to reach the high performance. The structure parameter must be reduced to values in the order of 0.5 mm or less to obtain specific power of 5 W/m² or higher. In order to reduce the structure parameter new membranes specially designed for PRO must be developed.

A specific power in the order of 2.7 W/m² has been measured for a small sample of development membrane in a stirred two chamber PRO cell.

List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>water permeability (m/Pa s)</td>
</tr>
<tr>
<td>B</td>
<td>salt permeability (m/s)</td>
</tr>
<tr>
<td>c</td>
<td>concentration (g/l or mol/l)</td>
</tr>
<tr>
<td>D</td>
<td>coefficient of Brownian diffusion for salt (m²/s)</td>
</tr>
<tr>
<td>E</td>
<td>energy (J)</td>
</tr>
<tr>
<td>ΔG&lt;sub&gt;mix&lt;/sub&gt;</td>
<td>Gibbs free energy of mixing (J)</td>
</tr>
<tr>
<td>h</td>
<td>half-height of cross-flow channel (m)</td>
</tr>
<tr>
<td>J&lt;sub&gt;w&lt;/sub&gt;</td>
<td>water flux (m/s)</td>
</tr>
<tr>
<td>J&lt;sub&gt;s&lt;/sub&gt;</td>
<td>salt flux (mol/m² s or g/m² s)</td>
</tr>
<tr>
<td>L&lt;sub&gt;p&lt;/sub&gt;</td>
<td>pore length (m)</td>
</tr>
<tr>
<td>l</td>
<td>distance from membrane channel inlet (m)</td>
</tr>
<tr>
<td>q</td>
<td>heat energy (J)</td>
</tr>
<tr>
<td>R</td>
<td>gas constant (8.314 J/mol K)</td>
</tr>
<tr>
<td>T</td>
<td>absolute temperature (K)</td>
</tr>
<tr>
<td>u</td>
<td>general local cross-flow velocity (m/s)</td>
</tr>
<tr>
<td>u&lt;sub&gt;0&lt;/sub&gt;</td>
<td>bulk cross-flow velocity (m/s)</td>
</tr>
<tr>
<td>v&lt;sub&gt;p&lt;/sub&gt;</td>
<td>pore flow velocity (m/s)</td>
</tr>
<tr>
<td>w</td>
<td>work energy (J)</td>
</tr>
<tr>
<td>x</td>
<td>distance from the channel inlet (m)</td>
</tr>
<tr>
<td>x&lt;sub&gt;i&lt;/sub&gt;</td>
<td>mole fraction of component i</td>
</tr>
<tr>
<td>y</td>
<td>distance from the membrane surface (m)</td>
</tr>
<tr>
<td>φ</td>
<td>porosity</td>
</tr>
</tbody>
</table>
\[ \pi \quad \text{osmotic pressure (Pa or bar)} \]

\[ \tau \quad \text{tortuosity} \]

**Subscripts**
- \( b \): bulk water phase
- \( i \): species \( i \)
- \( m \): membrane
- \( m_1, m_2 \): membrane surfaces 1 and 2
- \( \text{skin} \): membrane skin
- \( S \): salt
- \( w \): water

**References**


