Power Generation Based on Pressure Retarded Osmosis: A Design and an Optimisation Study

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Abstract
A design procedure for an open system osmotic power generation plant utilising the salinity gradient between two liquid streams has been developed. Seawater (high salinity) as a draw solution and brackish water (low salinity) as a feed stream were selected. The high applied hydraulic pressure was substituted by implementing a pressure exchanger to reduce the energy consumption within the plant. The effect of the draw solution flow rate, the feed stream flow rate and the applied hydraulic pressure on the net power production, membrane area and specific energy consumption were examined. The calculations revealed that the optimised values of the draw solution flow rate, the feed flow rate and the applied hydraulic pressure were 35000Kg -20000Kg respectively. In addition, the optimal membrane area corresponding to the maximum net power production was 9608.789m².

Keywords: osmotic pressure, forward osmosis, pressure retarded osmosis

Introduction:
The increasing demand on energy due to global population and technological development, as well as to environmental problems, requires the identification of new energy resources. One of these resources is power production utilising a salinity gradient via Pressure Retarded Osmosis (PRO). This technique simply exploits a difference in salinity between salt water and fresh water, which appears as a difference in a chemical potential, to produce a high volume and a high pressure stream. The amount of fluid volume that can be obtained is dependent on a salt concentration in a salty stream, which qualifies by osmotic pressure. However, an increase in the osmotic pressure results an increase in the amount of the water or fluid flowing across a membrane. Accordingly, it is possible to harness the difference in salinity between the oceans and rivers or seas and rivers to produce electricity, which considerably assists in reducing the demand on fossil fuels.

Salinity gradient power, however, in addition to PRO, can be exploited by different technologies, for example, by reversed electrodialysis (RED), hydromatic generator and vapour compression [1]

Among these technologies, the PRO technique has received more attention. Sidney Loeb (1950) was the first scientist inventor of this process when he produced drinking water from seawater by using a high pressure pump. This process was hindered during the seventeenth of the nineteenth century due to the lack in producing a suitable membrane until1997, when Statkraft Norwegian Power Producer Company established a PRO plant to produce 25 kW electricity for the first time. Nevertheless, many studies took place before and after 1997. Norman [2] was the first investigator suggests a diagram of an osmotic energy converter, while the first experimental data for the PRO process was published during 1976 [3], utilising a hollow-fibre RO membranes. On the other hand, the concept of PRO, which suggested before by Lobe and Norman [4], has been proved by subsequent studies carried out [5,6,7]. In these investigations, the total output membrane power density obtained was lower than the expected values, based on the osmotic pressure difference across a membrane (1.56 to 3.27 W/m²). Furthermore, internal concentration polarization has been observed and its effect on the flux through the membrane and consequently on the PRO economic has been ensured. Lee [8] developed a theoretical reference model for PRO performance based on FO and RO experiments. Water flux and concentration polarization were researched. The mechanical efficiency of different theoretical PRO models was investigated quantitatively [9]. The possibility of using the PRO technique to produce electricity from the Great Salt Lake was investigated by Lobe [10,11] and he found the cost could be 0.15$/kWh. Seppala [12] demonstrated with evidence that a non-linear relationship controlled the transport of water and solute with osmotic and hydraulic pressures. A very high membrane power density (more than250 W/m²) and 16% Carnot efficiency has been found by McGinnis [13] when using ammonium-carbon dioxide as a draw solution. Sam [14] studied numerically the feasibility to produce electric power by PRO. Utilising a hydrodynamic mass transfer model, the real size membrane power output was about 40% less than the lab scale size. In addition the counter-current flow configuration produced more power than the concurrent by 15%. Remon [15] Elimelech [16] separately carried out an extensive review of osmotic power production by salinity gradient. The impact of different parameters on the power production capacity and the possible techniques which could be exploited were illustrated.
Theoretical part

In this paper, an optimisation study and a design procedure for a large scale open system osmotic power station has been developed utilising natural salinity and brackish water resources (sea and river). The effect of draw and feed mass flow rate as well as to the hydraulic pressure on the plant output power and the membrane power density have been researched.

Water flux across the membrane in PRO processes, \( J_w \), is usually represented by the following phenomenological relationship:

\[
J_w = A_w (\Delta \Pi - \Delta P)
\]  \hspace{1cm} (1)

Equation (1) shows that \( J_w \) is determined as the product of the system permeability to water, \( A_w \), and the net trans-membrane driving pressure, which is the net difference between the osmotic pressure, \( \Delta \Pi \), and the net hydraulic pressure, \( \Delta P \). The density of the power obtained from the PRO process, \( W \), can be estimated as the product from multiplying water flux by the hydraulic pressure \[17,18\]

\[
W = J_w \Delta P = A_w (\Delta \Pi - \Delta P) \Delta P
\]  \hspace{1cm} (2)

The power density of the membrane that is required to obtain a profitable PRO process was determined to be between 4 – 6 W/m\(^2\) [18]. A suggestion was made by another study [17], that the first derivative for equation (2) with respect to \( \Delta P \) assuming \( A_w \) as a constant may specify the maximum value for \( W \):

\[
W_{\text{max}} = A_w \frac{\Delta \Pi^2}{4}
\]  \hspace{1cm} (3)

Hence, from Eq. (2), it can be indicated that \( W_{\text{max}} \) which can be reached when \( \Delta P \) equals 0.5\( \Delta \Pi \). The \( \Delta P \) is normally estimated by assuming linear pressure drop alongside the OMU, i.e.:

\[
\Delta P = \frac{P_{\text{VDS-in}} + P_{\text{VDS-out}}}{2} - \frac{P_{\text{VFS-in}} + P_{\text{VFS-out}}}{2}
\]  \hspace{1cm} (4)

and similarly for \( \Delta \Pi \):

\[
\Delta \Pi = \frac{\Pi_{\text{VDS-in}} + \Pi_{\text{VDS-out}}}{2} - \frac{\Pi_{\text{VFS-in}} + \Pi_{\text{VFS-out}}}{2}
\]  \hspace{1cm} (5)

Where the subscripts VDS and VFS refer to the Draw Solution (the high concentration side) and the Feed Water (the low concentration side), respectively.

Mass balance

In commercial modules, where cross flow regimes are normally utilised, the concentrations change with membrane length. In processes that utilize co-current cross-flow modes, the lowest solution permeability may occur at the concentrated DS inlet position where the FW enters at its lowest concentration. As the concentration difference across the membrane continuously decreases, the solution permeability to water transfer continuously increases. Finally, many practical parameters and indices can be identified for the PRO process in an open hydro-osmotic power (HOP) plant. A material balance around the Osmotic Membrane Unit (OMU) gives the following:

\[
Q_{\text{VDS-out}} - Q_{\text{VDS-in}} = Q_{\text{w}} = Q_{\text{VFS-in}} - Q_{\text{VFS-out}}
\]

where \( Q \) is the volumetric flow rate and \( Q_w \) refers to the permeated water flow rate across the membrane.

Figure (A) Schematic representation for water flux and solute concentration across a pore of a symmetric membrane in the PRO process, (B) electrical analogy for the system resistance to water flux.
Osmosis Hydro-Power Plant:
The schematic diagram of the proposed Osmosis power plant via PRO technique can be shown in Fig. (1). It consists of three main components; membrane (1), hydro-turbine (unit no. 4) and pressure exchanger (unit no. 6) in addition to the other auxiliary units.

Seawater is pumped from the sea via a low pressure pump to a pre-treatment unit (unit no. 5), by a stream, (no. 13) for removal of suspension materials. This is used as a draw solution (stream no. 16) after it is pumped to the FO osmosis, then processed (unit no. 3) via a high pressure pump or pressure exchanger (unit no. 6) and low pressure pump (no. 7). Meanwhile, brackish water is received at the pre-treatment unit (unit no. 9) via a low pressure stream (stream no. 10). This stream is implemented as a feed to the FO process, where it is pumped via a low pressure pump (no. 8) via a stream (no. 11) to the FO unit (unit no. 2). According to the osmosis pressure difference between two streams (no. 2 and no. 3), permeation occurs from low osmotic pressure side (unit no. 2) to the high osmotic pressure side unit (no. 3). However, the salty stream is mitigated and leaves the FO unit with low salt concentration and high pressure via stream (no. 17). This stream (no. 17) is expanded at a hydro-turbine (unit no. 4) to produce electric power and depressurised and drawn outside the station (stream no. 20). Part of the high pressure stream (no. 17) is sent to the pressure exchanger (unit no. 6) via stream (no. 18). This, of course, helps to reduce power consumption through the plant which makes the process viable and economic. On the other hand, the low osmotic pressure stream (no.2) is concentrated and leaves the FO via stream (no. 12).

As shown in Fig.(1), the process exploits the open system technique to avoid the separation process, which definitely makes the process uneconomic and unviable. Furthermore, the availability of natural resources, especially in south of Iraq, helps the location of cheap and reliable additional energy sources.

Table 1: Review of PRO studies from the early days to the most recent Investigations , [19,20,21,22].

<table>
<thead>
<tr>
<th>Feed/Draw Solution</th>
<th>Membrane</th>
<th>Osmotic Pressure(bar)</th>
<th>Hydraulic Pressure (bar)</th>
<th>Power Density (W/m²)</th>
<th>Research Group/year</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshwater/Brine</td>
<td>Hollow Fiber seawater RO</td>
<td>25</td>
<td>12</td>
<td>0.35</td>
<td>Loeb et al.(1976)</td>
<td>[23]</td>
</tr>
<tr>
<td>Freshwater/Brine</td>
<td>FRL Composite seawater RO</td>
<td>101</td>
<td>19</td>
<td>1.56</td>
<td>Loeb, Mehta.(1979)</td>
<td>[24]</td>
</tr>
<tr>
<td>Freshwater/Brine</td>
<td>Hollow Fiber seawater RO</td>
<td>81</td>
<td>40</td>
<td>3.27</td>
<td>Mehta.(1978)</td>
<td>[25]</td>
</tr>
<tr>
<td>Freshwater/Brine</td>
<td>Hollow Fiber seawater RO</td>
<td>78</td>
<td>40</td>
<td>3.12</td>
<td>Mehta, Loeb (1979)</td>
<td>[26]</td>
</tr>
<tr>
<td>Freshwater/Brine</td>
<td>seawater spiral wound RO</td>
<td>28</td>
<td>11-16</td>
<td>1.6</td>
<td>Jellinek,&amp;Masuda (1981)</td>
<td>[27]</td>
</tr>
<tr>
<td>Freshwater/Brine(3.5%)</td>
<td>CA&amp; P&amp;P PBIL flat sheet seawater RO</td>
<td>28</td>
<td>12.5</td>
<td>1.55</td>
<td>Lee, Baker.(1980)</td>
<td>[28]</td>
</tr>
<tr>
<td>DI water /Brine (3.5 – 6%)</td>
<td>CTA flat sheet seawater FO (HTI)</td>
<td>27.6-48.8</td>
<td>9.7</td>
<td>2.7-5.1</td>
<td>Achilli et al. (2009)</td>
<td>[29]</td>
</tr>
<tr>
<td>Freshwater/Seawater</td>
<td>Lab TFC (flat sheet/hollow fiber) and CA seawater FO</td>
<td>26</td>
<td>10-13</td>
<td>1.3-3.5</td>
<td>Gerstandt et al. Statkraft (2008)</td>
<td>[30]</td>
</tr>
<tr>
<td>River water/Brine (3.5 –</td>
<td>TFC Hollow Fiber</td>
<td>24.6 - 49</td>
<td>4.7-47</td>
<td>2.8-11</td>
<td>Fane et al.(2011)</td>
<td>[31]</td>
</tr>
</tbody>
</table>
Optimization Procedure:
A design procedure has been developed based on mass balance to find the best conditions for making operation of the PRO plant smooth and economic. Many parameters affect the PRO performance; however, a computer program has been written to optimise them and make quantitative comparisons to specify the best values that give constant power production.

The first effective parameter is the membrane area. Fouling is a common problem which appears at PRO open system operation plant. However, decreasing the membrane area will considerably reduce fouling as well as reducing the capital cost. Figure (2) shows the variation of the membrane area with applied hydraulic pressure at a constant feed volumetric mass flow rate. An increased of the membrane area with increased applied hydraulic pressure can be clearly seen in the figure. The hydraulic pressure act practically as an additional resistance which impedes permeate or water flux from the feed side to the draw side. Therefore, for a constant output power, increasing the membrane area is a solution to overcome this obstacle. At the same time as, the membrane area is increased, the the feed side volumetric flow rate is increased at a constant applied hydraulic pressure. This could be justified reasonably by the implicit relationship that connects the feed side flow rate and the total flux, which reflects directly on the membrane area. The higher the feed side flow rate, the higher the flux subsequently increases the membrane area required. Meanwhile, a similar relationship can be shown between net power produced and the applied hydraulic pressure at a constant feed flow rate. Although the hydraulic pressure impacts negatively on the total permeate volume, it directly enhances the net power produced. The net power production at the hydraulic turbine, of course, depends on the total inlet turbine feed volume in addition to the applied hydraulic pressure value. On the other hand, at constant hydraulic pressure, the increase of the feed flow rate leads to an increase in the net power produced as a result of increasing the total volume permeating through the membrane. No considerable effect can be shown from the hydraulic pressure on the specific energy consumption value, where its value is still very low even at the maximum hydraulic pressure applied (Fig.(3)).

Similarly, studying the draw side effect on the PRO process revealed the same effect of the hydraulic pressure on the total membrane area, net power production and specific energy consumption as shown in Figs. (4, 5 &6) respectively.

<table>
<thead>
<tr>
<th>6%</th>
<th>seawater FO</th>
</tr>
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<tbody>
<tr>
<td>River water/ seawater (3.5%)</td>
<td>Cellulosic membrane, Hollow Fiber seawater RO</td>
</tr>
<tr>
<td></td>
<td>26</td>
</tr>
<tr>
<td>Freshwater/Brine (2M NaCl)</td>
<td>CTA commercial flat sheet seawater FO(HTI)</td>
</tr>
<tr>
<td>Wastewater(0.5M)/Brine (2M)</td>
<td>CTA commercial flat sheet seawater FO(HTI)</td>
</tr>
</tbody>
</table>

![Fig. 2: Membrane area versus applied hydraulic pressure](image1)

![Fig.3: Net power production versus applied hydraulic pressure](image2)
Fig. 4: Specific energy consumption versus applied hydraulic pressure.

Fig. 5: Membrane area versus applied hydraulic pressure for different draw solution flow rates.

Fig. 6: Net power production versus applied hydraulic pressure at different draw solution flow rates.

Fig. 7: Specific energy consumption versus applied hydraulic pressure at different draw solution flow rates.
Conclusions:
A theoretical design procedure for open system PRO plant is developed. According to the results the following conclusions can be made:
- Total membrane area increases when increasing the applied hydraulic pressure for both feed and draw side flow rates.
- Net power production increases with increased applied hydraulic pressure.
- Specific energy consumption increases when increasing applied hydraulic pressure and decreasing the volumetric flow rate of feed.

References:

Author