

Osmotic Power Plant: Process Innovation and Future Potential

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Abstract:

Osmotic power plant operating by Pressure Retarded Osmosis (PRO) is a promising technology for power generation from renewable resources. A wealth of literature has been published in PRO feasibility to replace conventional fossil fuel power plants. In this paper the PRO and the new innovative Dual Stage PRO process are briefly reviewed with the authors' insight on the future development and application of the PRO power plants.

Introduction:

Pressure retarded Osmosis (PRO) has been firstly proposed by Sydney Loeb [1] and it represents the energy of mixing a concentrated brine solution with a diluted solution. In practice, osmotic energy can be harvested by the PRO when concentrated and diluted solutions are separated by a selective semipermeable membrane that allows water movement but rejects most of the ionic species [2]. The concentrated solution (draw solution) is pressurized and pumped into the PRO membrane, which separates the draw solution from the diluted solution (feed solution). The osmotic pressure difference between the draw and feed solution induces fresh water movement across the membrane diluting the draw solution. The pressurized draw solution, then, goes to a special hydro-turbine system for power generation. Experimentally, the PRO process is a viable technology but most of the work was in a laboratory scale and few pilot plants have been carried out [3-5]. The advances in membrane technology has resolved the problem of finding a suitable PRO membrane that once has been an impediment for technology demonstration and testing in a field scale. Toyobo is one of the pioneering companies that have successfully manufactured and tested PRO membranes for a large scale pilot plant demonstration [6]. Hollow fiber FO membranes manufactured by Toyobo come with a large active area that reaches 700 m² and stands up to 30 bar feed pressure which make them suitable for handling a salinity gradient with 60 bar osmotic pressure difference. This was based on the assumption that power generation by the PRO process reaches a maximum amount at a hydraulic pressure equal to $\Delta P = \Delta\pi / 2$ [4]. Experimental work has also revealed the impact of membrane intrinsic properties on the performance of the PRO process [7]. Concentration of the feed solution and dilution of the draw solution, often termed as internal and external concentration polarizations, respectively, has been

experimentally measured and found to have a detrimental effect on the process performance [6-7]. Therefore, PRO membranes should be thin enough to reduce the effect of concentration polarization but strong enough to tolerate the hydraulic pressure on the draw solution side of the membrane. Finally, PRO membranes should have a relatively high rejection rate to ionic species to reduce reverse salt diffusion and ions transports from the draw and feed solutions, respectively.

Field Studies:

Few pilot plant studies have been attempted to demonstrate the feasibility of the PRO process in field conditions [8-9]. The first pilot plant was carried out by Statkraft Company (Norway) using seawater-fresh water salinity gradient resource [8]. Statkraft has incorporated a pressure exchanger on the draw solution flow in a featured design to reduce the operational energy of the PRO process [8]. Without the pressure exchanger, the PRO process becomes less energy-efficient. Field experiments have also revealed that the minimum power density, that is the energy generated per membrane unit area, should be more than 5 W/m² in order for the PRO process to be feasibly economic [8]. The pilot plant test lasted for 2 years before it has been shut down in 2011. Statkraft has not revealed the main reasons to call off experiments on the pilot plant but it has been thought it was due to the insufficient osmotic energy of the salinity gradient resource. Despite the unsatisfactory results from the Statkraft PRO plant, the field experiments have demonstrated the feasibility of power generation with the PRO process.

Recently, Mega-tone project has been carried out with Toyobo hollow fiber membranes using Reverse Osmosis (RO) brine-tertiary treated wastewater effluent salinity gradient resource [9]. The pilot plant study revealed the importance of feed water pretreatment to prevent membrane fouling. Initially, Microfiltration (MF) and RO process were performed for the treatment of tertiary treated wastewater but RO fouling has been observed. As such, the wastewater effluent was pretreated by the MF only and was found to be sufficient for the removal of fouling materials from the feed stream to the PRO process. PRO membrane fouling was further reduced by adding a forth port on the feed side of the membrane [10]. Mega-tone project successfully implemented the concept of osmotic power plant with an average power density of 10 W/m². This is almost double the threshold reported by the Statkraft Company and required for an economic PRO process.

Kim and co-workers [11] have tested a spiral wound membrane for power generation from seawater-river water salinity gradient resource. The spiral wound membrane has an axial and spiral flow paths, and net and tricot spacers for draw- and feed-solution streams, respectively. Draw solution pressurized to 9.8 bar before entering the PRO membrane. Water flux and maximum power density of the PRO membrane were 3.7 L/m²h and 1.0 W/m², respectively. The maximum power density achieved by the PRO process was only 20% of the threshold recommended by Statkraft Company for an economic osmotic power plant. This confirms the outcomes of the previous work by Statkraft Company and concluded that seawater-river water salinity gradient is an uneconomic source for power generation with the PRO process.

Advances in the PRO process:

Osmotically driven processes suffer from self-deficiencies due to the effects of diluted and concentrated concentration polarization taking place at the draw and feed solutions, respectively. As fresh water permeates across the membrane, the draw solution becomes more diluted while the feed solution gets more concentrated and hence reduces the osmotic pressure driving force across the membrane. The phenomenon of concentration polarization is inevitable in the PRO and FO processes and has detrimental effect on the process efficiency. Recently, Altaee et al, [12] proposed a dual stage PRO (DSPRO) process in an attempt to reduce the impact of concentration polarization and enhancing the performance of the osmotic power plant [12]. In practice, feed concentration in osmotically driven membrane processes tends to reduce the osmotic pressure gradient and water flux. Unlike pressure driven membrane processes in which concentration polarization occurs on the feed side, osmotically driven membrane processes suffer concentration polarization on both sides of the membrane. In the DSPRO process, the concentrated draw solution from the first stage of the PRO process is replaced with fresh draw solution for fresh water exchange with the already pressurized draw solution from the first stage [Figure 1]. Theoretical studies have shown that DSPRO process is able to increase the energy yield of the PRO process more than 18% [12]. Ignoring the membrane fouling issues, studies have shown that DSPRO process is more effective with feed solution of high concentration such seawater or RO brine. DSPRO does not require an extra high pressure pump on the draw solution since the pressurized draw solution from the first stage PRO process will be recycled to the second stage.

The second stage of the DSPRO process requires a small membrane area because the flow rate of the draw solution will be equal to the permeate flow in the first stage of the DSPRO process. A part of the pressurized draw solution equal to the initial flow rate of the draw solution is recycled to a pressure exchanger after leaving the first stage of the DSPRO process to exchange pressure with the draw solution as shown in Figure 1. Furthermore, the cost of PRO membrane has been brought down since Statkraft pilot plant demonstration. The cost of Toyobo hollow fiber PRO membrane, HP10 Series, is similar to that of the RO membrane. The membrane has an active area of 700 m² and stands 30 bar feed pressure which make it a good fit for many salinity gradient resources.

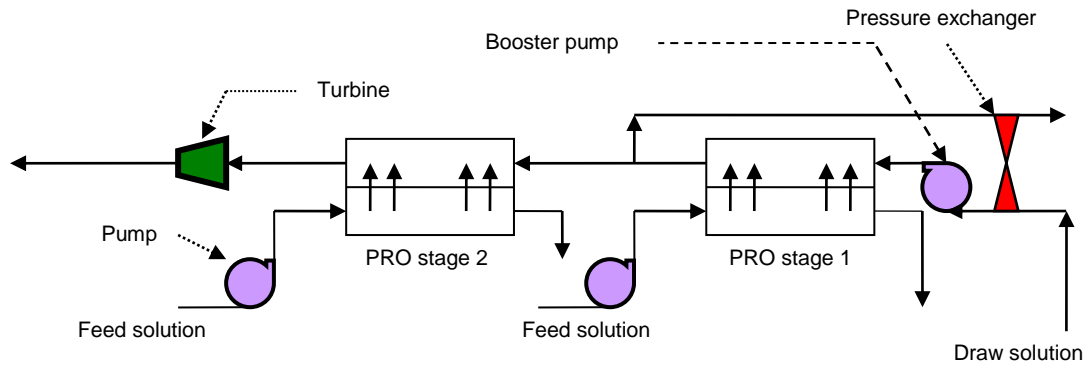


Figure 1: Schematic diagram of the Dual Stage Pressure Retarded Osmosis Plant

Conclusion:

Osmotic power plant is a new source of renewable energy that can be further developed for power generation. Despite the large number of laboratory scale studies, only few pilot plant tests were attempted. Power generation from a salinity gradient resource is highly affected by the concentration of feed and draw solutions and the characteristics of the PRO membrane. PRO membranes are commercially available and can be ordered from Toyobo or Toray at a competitive price to the RO membranes. Experimental work also revealed that DSPRO process is able to enhance the performance of the PRO process by reducing the effect of concentration polarization at the feed side. More pilot plant studies are required to demonstrate the advantages of DSPRO process. This will encourage more research and investment on the osmosis power plant as a replacement to the conventional fossil fuel powered power plants.

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