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Pressure retarded osmosis from hypersaline sources — A review

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HIGHLIGHTS

- We review the use of high salinity solutions in PRO.
- Experimental results are reviewed and an overview of hypersaline resources is made.
- Using hypersaline solutions it is possible to achieve cost effective power densities.
- Hypersaline resources are widespread and offer possibilities for small compact PRO systems.
- Eight areas of future research are identified some of which are specific to hypersaline PRO.

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ABSTRACT

Salinity gradient power has been identified as a promising new renewable energy technology, but previous attempts to commercialize the technology have failed due to low energy densities and power densities when using seawater as the saline water. One way to overcome these challenges is to use concentrated saline waters, in this context termed hypersaline waters. Hypersaline waters have higher energy densities and very high power densities are possible. Use of desalination brines has already shown promising results in pilot scale, and solutions of higher salinity may offer a potential route for commercialization. The scope of this paper is to review the existing knowledge on the use of hypersaline waters in the salinity gradient process, pressure retarded osmosis. Although only few papers have had the specific aim of investigating hypersaline waters, concentrated solutions have been used in many papers. In this review, the experiences gained from these experiments are collected and used to evaluate both the potential and challenges of using hypersaline waters. In the second part of the review, an overview is made of where hypersaline resources can be found. Finally, we provide an outlook for hypersaline based salinity gradient energy and point to the areas that require further research.

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1. Introduction

Pressure retarded osmosis (PRO) as a concept has been available since 1975, when the term was coined by membrane pioneer Sidney Loeb [1]. However, the technology has yet to be realized on a commercial basis. In 2009 a serious attempt at commercializing PRO was made by the Norwegian energy company, Statkraft. They constructed a PRO plant based on mixing of river water and seawater, but to the shock of the PRO community, Statkraft had to shelve the project in 2013 due to the company's assessment that [2]:

> "*The technology will not be sufficiently developed to become competitive within the foreseeable future*".

At the same time, serious doubt has been cast on the potential of river water/seawater schemes. Lin et al. calculated that only 75% of the thermodynamic potential could be reached, giving a specific energy density of 0.192 kWh per cubic meter mixture, which would leave little energy to the pre-treatment and pumping required to run the process [3]. A second barrier has been the number of watt that can be generated per membrane area, also known as the power density, which determines the overall size of the PRO plant and the capital costs. Statkraft assessed that for a PRO facility to reach an economic break-even point, a power density of 5 W/m^2 was necessary, but in their pilot tests they could only reach 1 W/m^2 with commercially available membranes [4,5].

Since then the 5 W/m^2 has been the focal number for PRO research, with studies investigating how this number can be reached and surpassed. In general, there are two ways to do this.

1. Improvements of the osmotic membranes
2. Use of high salinity draw solutions instead of seawater

In the scientific literature, improving the efficiency of membranes has attracted significant attention and several studies have reported membranes exceeding the 5 W/m^2. Simultaneously, at the commercial level, several companies such as Porifera Inc. and Aquaporin A/S are introducing osmotic membranes, based on technologies that could lead to the high flux membranes that are required to reach the 5 W/m^2 and studies have already reported the Porifera membranes to be able to exceed the 5 W/m^2 under laboratory conditions [6]. Less focus has been on the use of high salinity solutions, although these may allow already existing commercial membranes to reach the 5 W/m^2 power density. High salinity solutions would also have higher energy densities, and processes based on these could therefore be less sensitive to the parasitic energy consumption of pumping and pretreatment. Finally, use of highly saline solutions would allow for more flexible and varied process designs, which could make it easier to find applications.

Looking back, the early days of PRO were highly characterized by several studies on the use of high salinity solutions. In the same Science publication in which he coined the term "pressure retarded osmosis", Sidney Loeb suggested the use of water from the Dead Sea [1] and further continued the considerations in two publications [7,8]. Later in 1978, Wick and Isaac contemplated the use of salt domes along the US East coast and had discussions with Williams that extended into 1979 [9,10]. In 1981 Lee et al. developed a model to describe the PRO process and found that with current membranes, seawater was not economically viable for PRO but that use of brines could make the technology competitive with other energy technologies [11]. When focus returned to PRO around the change of the millennium after having been through a period of very low research activity since the initial spike in the 70s [12], Sidney Loeb continued his interest in high salinity waters and produced further work on the use of water from the Dead Sea and the Great Salt Lakes [13,14]. Shifting focus towards use of high salinity solutions could as such be considered as returning to the roots of PRO.

Solutions with higher salinity than seawater are called hypersaline and the use of these types of solutions could potentially open a route for making PRO commercially attractive. Although few publications have specifically used the term "hypersaline" in the explosion of PRO studies that has occurred since the turn of the century, many studies have included solutions with salinities greater than seawater in their investigations and in this review the aim is to collect these experiences and put them into the context of hypersaline PRO. Furthermore, the review examines where hypersaline solutions can be found. The biggest advantage of seawater is it general availability and for hypersaline PRO to gain interest, there needs to be more than just specialized niche applications.

2. Hypersaline PRO theory

To start examining the use of hypersaline solutions, the specific meaning must be determined. Hammer defined hypersaline waters as having a salinity > 5 wt/wt% [15]. Within PRO research the lower limit of salinity of the hypersaline region could be said to be 6 wt% ($\approx$1 M NaCl), as this is the typical concentration found in desalination brines, which are the most common type of water used in studies that focus on waters with higher salinities. The upper limit is the solubility, which for NaCl is 26 wt/wt% at 25 °C [16]. In real hypersaline waters, a mixture of salts may be present, which increases the potential salinity to 33–35 wt/wt% [17,18] and by using engineered solutions, concentrations up to 59% (7.6 M) have been reported [19,20].