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Impact of temperature on power density in closed-loop pressure retarded osmosis for grid storage

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ABSTRACT

Closed-loop pressure retarded osmosis (PRO) has been recently proposed as a means of transforming unusable forms of energy, such as waste heat, into valuable electricity. The process, which is also referred to as an osmotic heat engine (OHE), also enables a form of osmotic grid storage for intermittently available renewable energy sources, where available energy is stored as an osmotic potential and that energy is released via PRO when energy demand is high. The OHE has the potential to generate greater power than conventional open loop PRO because the draw solution can be engineered to have very high osmotic pressures, via enhanced temperature, solute concentration, or a combination of both. These variables change fluid properties and the performance of the membrane, which may or may not be beneficial to overall OHE operation. Using a custom-built, bench-top PRO system, a commercially available forward osmosis membrane from Hydration Technology Innovations™ (HTI) was evaluated for water flux and power density at two temperatures (20 °C and 40 °C) and three draw solution concentrations (0.5, 1.0, and 1.5 M sodium chloride) that are similar to temperatures and draw solution osmotic pressures capable in an osmotic heat engine. In general, power densities increased with the increasing draw solution concentration and system temperature. The highest observed power density (18.0 ± 2.3 W/m^2) was measured at 20.7 bar (300 psi) using a 1.5 M sodium chloride draw solution at a system temperature of 40 °C. Experimental data compared favorably to predicted performance using previously published governing equations for PRO water flux and power density.

1. Introduction

The adoption of many carbon-neutral renewable power technologies, such as solar or wind power, has been hindered by intermittent availability and intensity. Currently, these problems are being addressed by the development of grid storage techniques to capture excess power, permitting the distribution of energy during periods of high demand and energy storage during low demand periods. Batteries, compressed air, and water reservoirs have all been considered for grid storage applications, but each technology has drawbacks of either being prohibitively expensive or logistically difficult to implement [1,2].

With the advent of forward osmosis (FO) processes, a radically different concept for grid storage has emerged based on the concept of pressure retarded osmosis (PRO) [3–5]. In times of energy scarcity, a PRO membrane module can be run using a concentrated solution, known as the draw, and a dilute solution, known as the feed. The draw solution is pressurized, and when water naturally flows from the dilute stream into the concentrated stream, the volume of the draw increases and work is performed. This work can be used to turn a turbine and produce electricity. Energy from a secondary source, such as waste heat or geothermal energy, can be used continuously to recover the draw and feed solutions. If energy is not available, the solutions can be stored indefinitely until energy is available for recovery.

When energy is used to concentrate the draw solution, that energy is indefinitely stored in the form of an osmotic potential [6]. Depending on the properties of the chosen draw solute, the solute recovery method can vary widely. It can be multistage distillation or gas stripping for thermolytic solutes, or reverse osmosis and membrane distillation for non-volatile solutes [7]. For an osmotic *heat* engine, the energy used is thermal energy which can be used to strip a thermoytic solute *or* evaporate water to concentrate the solute. These concentrated draw solutions will not lose osmotic potential if properly stored, and the potential can be easily increased with additional solute [8]. These features overcome many limitations common with other grid storage methods. Furthermore, higher water flux in the PRO step will release more of the stored energy, leading to a more efficient overall process. This closed-loop energy conversion process illustrated in Fig. 1, is known as the osmotic heat engine (OHE) [9]. It is important to note that, in the case of the grid

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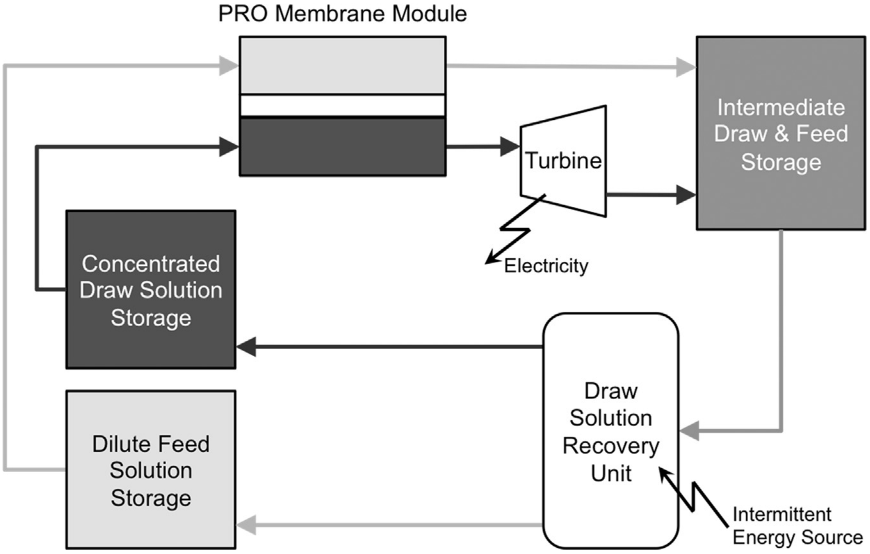

Fig. 1. Schematic for an osmotic heat engine used as part of an osmotic grid storage system. The draw solution recovery unit operates when energy is available, and the PRO membrane module operates when energy is in demand (pressure exchanger to maintain draw solution pressure is not shown).

storage option outlined in Fig. 1, the solute recovery system is only run to recover the draw and feed solutions when excess base-load power is available. In time of high energy demand, the solute recovery system is not run, and the stored feed and draw solutions are used by the PRO membrane element to generate power.

The OHE consists of three subsystems. The solute recycling system increases the draw solution concentration and its osmotic potential. The membrane process increases the extractable work of the draw solution through its dilution which converts osmotic potential to volume [16]. The third is the hydroturbine, which extracts work from the draw solution, and the work recovered from the hydroturbine can turn a generator to produce electrical energy. These subsystems are at various levels of development. The methods of draw solute recovery are generally conventional separations processes and are well developed for similar processes. Likewise, hydroturbines are well developed and understood technologies.

The membrane process, however, has only on rare occasions been demonstrated. Many of the "studies" were never published in the literature and only a handful of benchtop studies with flat sheet membrane coupons have been published. It is critical to analyze this part of the system under relevant PRO conditions, though, since the amount of energy released during this step is related directly to the energy generating capability of the integrated system.

We often characterize this system by considering the "membrane power density". This power (or work, W) is, reported in watts per square meter of membrane area, is the maximum power available to a hydroturbine. [10,11]. It can be calculated based on the following equation:

$$W = \eta J_w \Delta P \tag{1}$$

In this equation, η represents the turbine efficiency, which is often assumed to be 1 when simply evaluating membrane performance. When this equation is combined with the general water flux equation for FO, the maximum possible power density for any PRO process is generally determined as $A[(\Delta\pi^2)/4]$, where A is a membrane property known as the hydraulic permeance, and $\Delta\pi$ is the effective osmotic pressure gradient between the feed and draw solutions [12,13]. Therefore, assuming no mass transport limitations imposed by concentration polarization (CP) [14,15], peak power density is a function of both osmotic pressure and membrane permeance. While osmotic pressure will increase with draw solute concentration, both osmotic pressure and hydraulic permeance will increase with temperature. These parameters can be tightly controlled in OHE operation, which potentially yields power densities that are not possible using PRO with seawater as the draw solution, also known as open-loop PRO [16]. The manipulation of temperature and draw concentration beyond what may occur naturally can improve the viability of osmotic energy storage using membranes that had previously been considered not suitable for PRO due to their low power density.

This study was conducted to measure the water flux and power density produced by a commercial FO membrane operated under high-concentration and elevated-temperature conditions similar to those present in an OHE. In order to assess the accuracy of the experimental results, the data was then compared to predictions generated by an established model for PRO performance. We demonstrate that even membranes that are not specifically designed for PRO applications can still operate at high power density in conditions similar to that of an OHE. This finding is relevant to OHE development because, while high flux engineered osmosis membranes are currently reported in literature, there are currently no commercially available membranes or membrane module designed specifically for PRO applications. Being able to achieve high power density with less permeable but more commercially available membranes would enable the construction of a functional OHE.

2. Materials and methods

2.1. Materials and chemicals

The cellulose acetate (CA) membrane used in this study was provided by Hydration Technology Innovations (HTI™, Albany, OR). The membrane is asymmetric cellulose acetate mechanically supported by an integrated woven mesh support layer. These membranes have been used as a benchmark in prior studies of FO [17]. Water was provided by an Integral 10 water system (Millipore Corporation, Billerica, MA).

Sodium chloride was purchased from Fisher Scientific (Pittsburgh, PA). Sodium chloride was selected as the test draw solute for this study. While sodium chloride would not be an ideal solute in an actual OHE, this draw solute can still be thermally recovered by evaporation or physically recovered by reverse osmosis. Sodium chloride was also selected for this study because it is highly soluble and stable in water. Therefore, high draw solute osmotic pressures are possible at a wide range of concentrations