Journal of Membrane Science 503 (2016) 132–147

Contents lists available at ScienceDirect

Journal of Membrane Science

journal homepage: www.elsevier.com/locate/memsci

Gross vs. net energy: Towards a rational framework for assessing the practical viability of pressure retarded osmosis

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ARTICLE INFO

Article history:
Received 31 July 2015
Received in revised form
23 October 2015
Accepted 15 November 2015
Available online 2 December 2015

Keywords:
Pressure retarded osmosis
Sustainable energy generation
System analysis

ABSTRACT

Although significant technological advances have been made in recent years on pressure retarded osmosis (PRO), its practical viability remains unclear as few studies have been conducted at an integrated system level to quantify the potential of net energy output. In this study, we develop a framework to assess the net energy output of a PRO system by first quantifying the gross energy output via solving the mass transfer equations for a full-scale PRO module, and then incorporating the major energy losses from pretreatment, flow circulation, and inefficient energy recovery. We also propose a novel concept called net membrane power density that is strongly relevant to the capital cost of a PRO system. Finally, we describe an approach, based on the quantifiable specific net energy and net membrane power density, for assessing the economic viability of a PRO system. Albeit using seawater/river water PRO as the context for illustrating our approach, the assessment framework developed is universally applicable to PRO systems with any solution pairing. The results from this study clearly show the impacts of various parameters on the practical performance of a PRO system, thereby providing important guidance to the improvement of its design and operation.

1. Introduction

Advancing renewable energy technologies is critical to the development of a sustainable energy portfolio for mitigating air pollution and climate change [1–4]. Towards this goal, a variety of technologies for harnessing renewable energy sources, such as wind, solar, ocean wave and geothermal energy, have been extensively investigated [5,6]. Recently, natural salinity gradient has also been identified as a potential source of energy with appreciable estimated global power of 1.4 to 2.6 TW from simply mixing seawater and river water [7,8]. In addition to its sizable amount in the global scale, the volume energy density of salinity gradient energy also seems to be substantial: simple thermodynamic calculation based on Gibbs' free energy of mixing suggests that the salinity gradient energy released from a cubic meter of fresh water mixing with the ocean is equivalent to a hydraulic water head of ~290 meters (i.e. ~0.8 kW h). The volume power density can be even higher with other sources of salinity gradient, such as those from mixing wastewater with reverse osmosis (RO) brine solution [9] and from mixing seawater with water from the Dead Sea [10,11].

Among the several technologies developed to harvest salinity gradient energy, including pressure retarded osmosis (PRO) [10,12,13], reverse electrodialysis [14,15], and capacitive mixing [16,17], PRO is the most studied process due to its superior energy efficiency and high power density [18], as well as its compatibility with highly salty solutions [19]. In a PRO process, the osmotic pressure difference between the high-salinity draw solution (e.g. seawater) and the low-salinity feed solution (e.g. fresh water) drives the water molecules in the feed solution to permeate through a semipermeable membrane to expand the volume of the draw solution with an applied hydraulic pressure lower than the osmotic pressure difference. A hydraulic turbine is used to extract the energy embedded in the expanded volume of the pressurized draw stream [20–22].

While most early studies on PRO investigated either the membrane materials or the local mass transfer kinetics [12,23], recent studies have identified the critical importance of analyzing the thermodynamics and energy efficiency of a full scale PRO system [24–29]. In fact, even though the technological feasibility of PRO has been demonstrated, the practical or economic viability of this seemingly promising technology remains challenging to determine [30]. Here, practical viability refers to the ability to generate any net energy after accounting for other energy inputs and

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http://dx.doi.org/10.1016/j.memsci.2015.11.035
0376-7388/

losses, whereas economic viability associates with the economic competitiveness of the process as compared to other sustainable or conventional energy generation technologies. For example, energy generation via controlled nuclear fusion has been proven technologically feasible but is so far practically non-viable due to large amount of energy required to initiate and contain a fusion reaction [31].

Existing system-scale analyses on the energy efficiency of a PRO system typically use gross energy output as the evaluation metric [24–29]. However, gross energy output alone does not suffice to assess the practical viability of a PRO process due to the presence of non-negligible parasitic energy losses in a PRO system, such as those from pretreatment, flow circulation (i.e. pressure drop) and inefficient energy recovery [11,12,30]. Not only does the existence of these energy losses reduce the net energy extractable from the system, it also affects the optimal operation conditions due to the dependences of these energy losses on the operation conditions. Therefore, it is of paramount importance to account for the parasitic energy losses in assessing and optimizing the energy efficiency of a PRO system.

In this study, we develop a framework to evaluate the specific *net* energy (w_N) output of PRO taking into account various parasitic energy losses associated with the process. We first rationalize the method for normalizing the energy output and identify the most sensible metric to incorporate various energy losses. By solving the mass transfer equations in a counter-current module, we quantify the specific gross energy output normalized by the feed solution volume. We then evaluate the parasitic energy losses due to uptake and pretreatments, pressure drop in the module, and inefficient energy recovery in the pressure exchanger. Combining the specific gross energy output and the specific energy losses leads to the specific net energy output of the system. In addition, we analyze net membrane power density that dictates the system scale. Finally, we briefly discuss the implications of this performance assessment framework and future research needs towards a confident evaluation of the practical and economic viability of PRO.

2. Identifying the sensible metric for energy efficiency evaluation

For optimizing PRO system design and operation, it is critical to use a sensible metric to evaluate the energy output, or in other words, to select a reasonable method for normalization. Normalization is essential for fair comparisons between different systems and different operations independent of their absolute scales. Many previous studies chose to normalize the gross energy output by the volume of the feed solution (i.e. the low concentration solution), with the justification that the feed solution is the scarce resource for seawater/river water PRO [24,32].

Using such an evaluation metric leads to a particularly promising conclusion suggesting a gross energy density close to 0.8 kW h m^{-3} from mixing river water and seawater [8]. Realizing this theoretical maximum energy output per feed volume using PRO is, however, impractical, as it requires the ratio between feed and draw volumes to approach zero and the applied hydraulic pressure to approach the osmotic pressure of the draw solution (i.e. zero driving force, infinite membrane area) [24]. Since there are economic and energy costs that scale with the volume of the draw solution [15], normalizing gross energy output by the feed volume seems to provide a poor rationale for optimizing the flow ratio and the applied pressure—the two important operation parameters in a practical PRO system [25].

Recent studies have attempted to provide a more reasonable evaluation metric by normalizing the gross energy output using the total volume of the feed and draw solutions combined, with the argument that both the feed and draw solutions require economic and energy costs for uptake, pretreatment, and flow circulation along the module [15,25,26,29,30]. Such a normalization method based on total solution volume leads to convenient optimization of the operation conditions in PRO, resulting in analytical expressions for the optimal applied hydraulic pressure and flow rate ratio between the feed and draw streams for different system configurations [25].

However, an important limitation for normalizing gross energy by total volume is the implicit assumption that the feed and the draw solutions are equally “valuable” to energy production [15], which is unnecessarily the case. It is probable to improve this approach by assigning different “weights” to the feed and draw streams based on their relative “values” when calculating the weighted total volume. However, such a value assignment is ambiguous as the relative “values” of the feed and draw streams are also dependent on the operation conditions (e.g. applied hydraulic pressure). Furthermore, because gross energy output is always positive, any evaluation approach based on gross energy cannot yield explicit information regarding the practical viability of the process (i.e. whether net energy can be generated).

In this study, we further rationalize the metric of energy efficiency evaluation to facilitate a more judicious optimization of parameters for system design and operation. Thoughtful considerations on the contributions of different parasitic energy losses suggest that it is most reasonable to carry out system analysis based on the *net energy output per feed volume*, which we define in the following discussion as the *specific net energy,* w_N. By understanding how each energetic loss scales with the flow rates of the feed and draw streams, respectively, we can incorporate into w_N all the energetic losses contributed by the feed and the draw streams and provide an unambiguous approach for system and operation optimization.

To facilitate our discussion, let us first briefly review the energy and mass balances in an engineered PRO system. Fig. 1 shows a simple schematic diagram of a typical one-stage PRO system which includes the following major components: a PRO membrane module, an energy recovery device (e.g. pressure exchanger, PX), pretreatment processes for the feed and draw streams, and a hydro-turbine for energy generation. We note that auxiliary components such as booster pumps are neglected in the figure. The streams are either pressurized to ΔP (the dark blue streams) or unpressurized (the light blue streams). The flow rates of different streams passing through these components are shown in schematic diagram.

We identify the major parasitic energy consumption in the system shown in Fig. 1, which include those from pressure drop and the inefficient energy recovery in the pressure exchanger, as well as those needed for pretreating the draw and feed solutions. The output energy is generated in the hydro-turbine. The energy balance is illustrated in the bar chart presented in Fig. 1, which suggests that the net energy output is simply the difference between the gross energy output and the sum of the parasitic energy losses. It should be again emphasized that all these energy outputs and losses will be normalized by the feed flow rate, Q_F, during the energy balance calculation, as will be elaborated below.

Fig. 2 gives an illustrative overview about how w_N can be obtained. We start from calculating the *specific gross energy,* w_G, defined as the gross energy output per volume of the feed solution, without taking into account any parasitic loss (Fig. 2A). It is clear that w_G is a function of the ratio between the draw and feed volumes, ϕ. Because volume ratio is equivalent to flowrate ratio, ϕ can also be interpreted as the initial flow rate ratio between the draw and feed streams. We note that w_G is also a function of several other variables such as the applied hydraulic pressure, ΔP,