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A simulation study with a new performance index for pressure-retarded osmosis processes hybridized with seawater reverse osmosis and membrane distillation

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ABSTRACT

Despite many kinds of research on pressure-retarded osmosis (PRO), feasibility studies for PRO are still insufficient. To provide a better understanding of PRO-hybridized processes, an energy efficiency analysis should reflect the hybridization features of three processes, including PRO, seawater reverse osmosis (SWRO), and membrane distillation (MD). To this end, a new dimensionless (i.e., unitless or scale-free) performance index is proposed to facilitate a fair comparison of energy efficiency between SWRO-PRO and SWRO-MD-PRO. The new performance index physically implies a ratio of the total energy recovered by PRO to the total energy consumed by SWRO and MD. The performances of hybridized processes were estimated with the new index and compared to each other after running several simulations. The simulation results showed that SWRO-MD-PRO generally has a higher energy efficiency than SWRO-PRO if an inexpensive heat source, such as waste heat, is used. However, the energy efficiencies of both PRO-hybridized processes were different according to the simulation conditions. Therefore, it can be concluded that energy optimization for PRO-hybridized processes should be conducted differently than for SWRO. The results from this study are expected to play a key role in providing a new roadmap for PRO-hybridized process research.

1. Introduction

Greenhouse gas (GHG) emissions and global warming are by far the most controversial issues of the twenty-first century. Countries around the globe have continually tried to find an optimal solution that can satisfy each country, resulting in various important outcomes such as the so-called Paris Agreement [1, 2]. Such efforts are leading the world into a new climate regime that will implement urgent actions to reduce the magnitude of GHG emissions. However, shifting a national industrial structure to an environmentally sound one is almost impossible, so most developed countries are seeking solutions that can decrease GHG emissions.

In this context, pressure-retarded osmosis (PRO) is being recognized as an excellent alternative to conventional energy generation processes since it gives off no carbon-related compounds, at least in theory. PRO utilizes a higher-concentration solution (e.g., seawater) and a lower-concentration solution (e.g., treated wastewater) to generate energy by letting the solutions mix. When first invented, PRO was thought of as an impractical technology because of the poor performance of membranes at the time, but it was rediscovered in the 2000s and started to be investigated again thanks to great advances in membrane technology [3, 4].

Encouraged by previous research, the Norwegian company Statkraft constructed a PRO pilot plant for the first time ever in 2009 [5, 6]. After the construction of the pilot plant, many countries, inspired by Statkraft, started to use PRO and began nationwide projects. The global MVP project from the Republic of Korea and the Megaton project from Japan are representative cases [7–9]. Those projects produced many valuable results that contributed to the progress of PRO. However, the viability of PRO is still controversial due to its productivity limits, which can be predicted through thermodynamic analysis [10–14]. Many researchers claim that using stand-alone PRO with status quo technology makes it hard to secure enough energy to reach a break-even point. To overcome such an obstacle, many new research approaches have been attempted recently. Accordingly, research on PRO can be grouped into three categories: thermodynamics [10–17], new membrane modules for PRO

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[18–21], and the hybridization of the process [22–29].

Although these three categories may seem independent, they are deeply interconnected. Both membrane modules and process hybridization are directly linked to the problem of a conventional PRO index, power density (*PD*). *PD* has served as a performance index of stand-alone PRO and is regarded as reflecting the quality of PRO membrane module technology. However, *PD* currently has two significant problems. The first is the way that the *PD* value plummets in a large-scale membrane module case. Although the value of *PD* with lab-scale PRO membranes has increased rapidly, thanks to vigorous research, *PD* still shows a much lower value in large-scale membrane modules [30]. Therefore, significant research is still required to clarify the reasons for such a decline. Furthermore, the quantities of *PD* resulting from the membrane module performance tests are inconsistent, so the performance of the large-scale PRO modules is not yet fully known. The second problem concerns the incompatibility of energy units between the subunit processes within PRO-hybridized processes. The energy unit of seawater reverse osmosis (SWRO) and membrane distillation (MD) is based on a terminology called "specific energy" (hereafter, energy units for SWRO and MD are denoted as *SEC*, which stands for "specific energy consumption"), while PRO utilizes *PD* as the main performance index. These two units differ not just in their names, but in their physical implications [31, 32]. In spite of many attempts to assess the feasibility of the PRO process, research has not yet been conducted to deal with the large-scale model problem and the hybridization problem simultaneously.

Therefore, in this study, a new dimensionless performance index uniquely targeting the PRO-hybridized processes is proposed, and an analysis of the PRO-hybridized processes is performed with the new index. In order to investigate the potential of the PRO-hybridized processes, the performances of two types of PRO-hybridized processes, the SWRO-PRO and SWRO-MD-PRO processes, were compared. Although SWRO-MD-PRO is not currently a popular PRO-hybridized process configuration, it has the potential to phenomenally enhance the performance of PRO, as MD processing causes not only the concentration but also the temperature of brine to increase [33, 34]. In addition, the effects of the parameters of the subunit processes on the performance of PRO-basis processes were scrutinized. The objective of this study is to overcome a strong tendency to rely on the optimal parameters of stand-alone SWRO and reorient the future direction of studies concerned with PRO-hybridized processes.

2. Materials and methods

2.1. Configurations of PRO-hybridized processes

Fig. 1a and b represent the configurations of SWRO-PRO- and SWRO-MD-PRO-hybridized processes, respectively. Both processes employ energy circulation systems. That is, the energy generated by PRO is transferred to the seawater influent. Hence, a pressure exchanger (PX) plays a key role in each hybridized process. In reviewing the function of an energy circulation system with PXs, it can be observed that: (1) the brine of SWRO enters PX1 and partially conveys the hydraulic pressure to the seawater influent; (2) unpressurized SWRO brine enters PRO (Fig. 1a) or MD (Fig. 1b); (3) the draw solution in PRO gains thermodynamic energy (Fig. 1a), or exiting MD brine is repressurized by PX1 and enters PRO (Fig. 1b); and (4) lastly, the draw solution, which possesses energy, enters PX2, conveys the energy to the seawater influent, and is disposed of (Fig. 1a and b). As shown in many previous studies, the efficiency of PX, η_E, has very high efficiency, ranging from 95% to 97%. However, the efficiencies of the PXs in the current study should be selected differently for each hybridized process due to their distinct purposes. The PXs in Fig. 1 essentially convey the pressure from the SWRO brine to the seawater influent. However, the brine exiting from PX1 still must possess enough pressure to operate PRO. Therefore, the amount of pressure conveyed to the seawater influent at PX1 should be much lower than in the conventional case. This implies that the real efficiency of PX1's impact on SWRO is not as high as the efficiency of conventional PX, although the energy transfer efficiency of the PX itself does not change. Therefore, the partial efficiency of the PX for SWRO should be estimated as.

$$\eta_{PX1,RO} = \eta_{PX1}\left[1 - \left(\frac{\Delta P * Q_{ds,in}}{\pi_{b,RO} * Q_{b,RO}}\right)\right] \quad (1)$$

Here, $\eta_{PX1,\ RO}$ is the real efficiency of PX1 for SWRO; η_{PX1} is the energy transfer efficiency of PX1; ΔP is the external hydraulic pressure of PRO; $\pi_{b,\ RO}$ is the osmotic pressure of SWRO brine; $Q_{ds,\ in}$ is the entering flowrate of PRO draw solution; and $Q_{b,\ RO}$ is the volumetric flow rate of SWRO brine. In contrast, the efficiency of PX2 can be applied as is. Therefore, the energy of the seawater influent conveyed via PX2 can be well-transferred compared to that conveyed via PX1. Hereafter, the efficiencies of PX1 and PX2 are distinguished according to their suitable usages, and PX2 is fixed at 97% to facilitate the best performance of the hybridized processes.

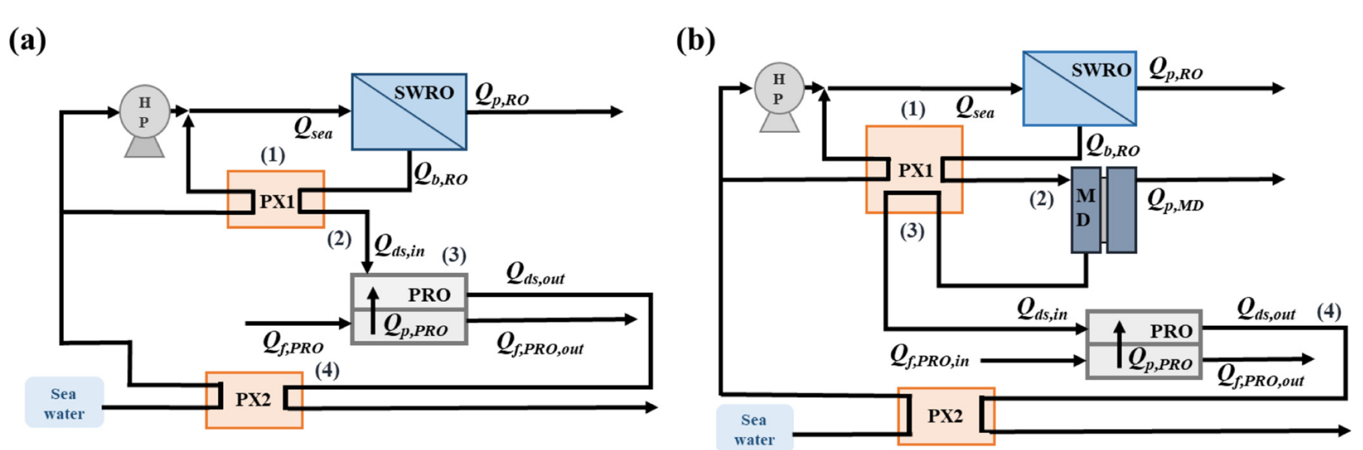

Fig. 1. Configurations of the (a) SWRO-PRO- and (b) SWRO-MD-PRO-hybridized processes implemented in the current study. HP and PX are a high-pressure pump and a pressure exchanger, respectively; *Q* indicates the volumetric rate of solution; the subscripts *p*, *b*, and *f* indicate the "permeate," "brine," and "feed," respectively.