Desalination 380 (2016) 85–92

Contents lists available at ScienceDirect

Desalination

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

Performance analysis of reverse osmosis, membrane distillation, and pressure-retarded osmosis hybrid processes

Jihye Kim [a], Minkyu Park [b], Ho Kyong Shon [c], Joon Ha Kim [a,d,e,]*

[a] School of Environmental Science and Engineering, Gwangju Institute of Science and Technology (GIST), Gwangju 500–712, Korea
[b] Department of Chemical and Environmental Engineering, University of Arizona, Tucson, AZ 85721, USA
[c] School of Civil and Environmental Engineering, University of Technology, Sydney, Post Box 129, Broadway, New South Wales 2007, Australia
[d] Sustainable Water Resource Technology Center, GIST, Gwangju 500–712, Korea
[e] Center for Seawater Desalination Plant, GIST, Gwangju 500-712, Korea

HIGHLIGHTS

- The performances of the RO–MD–PRO hybrid processes were evaluated using numerical approaches.
- The brine division ratio (BDR) positively influences the efficiency of the hybrid process.
- The supply cost of the MD heat source plays a crucial role in determining the total efficiency.
- The RO–MD–PRO hybrid process outperforms stand-alone RO in terms of reducing both the SEC and environmental footprint.

ARTICLE INFO

Article history:
Received 9 June 2015
Received in revised form 18 November 2015
Accepted 20 November 2015
Available online 11 December 2015

Keywords:
Reverse osmosis (RO)
Membrane distillation (MD)
Pressure-retarded osmosis (PRO)
RO–MD–PRO hybrid process
Performance analysis

ABSTRACT

A performance analysis of a tri-combined process that consists of reverse osmosis (RO), membrane distillation (MD), and pressure-retarded osmosis (PRO) was conducted by using numerical approaches in order to evaluate its feasibility. In the hybrid process, the RO brine is partially used as the MD feed solution, and the concentrated MD brine is then mixed with the rest of the RO brine to be considered as the PRO draw solution. Here, the brine division ratio, incoming flow rate of RO, dimensions of the MD and PRO processes, and the supply cost of the MD heat source were considered as influential parameters. Previously validated process models were employed and the specific energy consumption (SEC) was calculated to examine the performance of the RO–MD–PRO hybrid process. The simulation results confirmed that the RO–MD–PRO hybrid process could outperform stand-alone RO in terms of reducing the SEC and the environmental footprint by dilution of the RO brine in locations where free or low-cost thermal energy can be exploited. Despite the need for further investigations and pilot-tests to determine its commercial practicability, this study provides insights into future directions for water and energy nexus processes for energy efficient desalination.

1. Introduction

Demands for water and energy are dramatically increasing in both developing and industrialized countries. People in developing countries suffer from a lack of access to safe drinking water and sustenance energy sources, whereas those in industrialized countries consume resources more to meet increasing standards of living [1,2]. To relieve these water and energy scarcity issues, water and energy nexus processes, i.e., the co-generation of water and energy, have received increased attention [3]. As examples, Hosseini et al. [4] analyzed a combined gas turbine and multi stage flash (MSF) desalination system in terms of exergetic, economical, and environmental aspects, and Avrin et al. [5] compared the applicability of coal-desalination and nuclear-desalination in China. However, despite the increase in research activities into water-energy nexus processes, further developments that consider sustainable and environmental impacts are still required. In particular, a combination of pressure-retarded osmosis (PRO) and membrane distillation (MD) is thought to be a favorable candidate as a water-energy nexus process. A recent publication by Han et al. [6] for instance, experimentally investigated the performance of PRO-D hybrid process through a lab-scale system.

Investigations into PRO have resumed over the last decade due to advances in membrane technology, and have received considerable attention as a salinity gradient power (SGP) process [7]. The driving force of PRO is the chemical potential difference between a low-saline feed solution and a high-saline draw solution. Specifically, water transfers from the feed side to the draw side due to osmosis phenomena, with

---

* Corresponding author at: School of Environmental Science and Engineering, Gwangju Institute of Science and Technology (GIST), Gwangju 500-712, Korea.
E-mail address: joonkim@gist.ac.kr (J.H. Kim).

http://dx.doi.org/10.1016/j.desal.2015.11.019
0011-9164/

the increased volumetric flow used to run a turbine to generate power [8]. PRO is mostly regarded as an environmental-friendly and sustainable energy production process that uses seawater or concentrated seawater (i.e., brine from reverse osmosis (RO)) as the draw solution, while river water or wastewater effluent is used as the feed solution [9,10]. The fact that there are no carbon dioxide emissions and that there is less periodicity to the weather conditions make this process even more attractive [11].

In the field of desalination, MD is another process that has re-emerged in recent research, as it has the benefits of both thermal and membrane technologies. In MD, water vapor is transferred to the permeate side through a microporous hydrophobic membrane because of the vapor pressure difference. There are four types of MD configurations, categorized according to the method for activating the vapor pressure difference: direct contact MD (DCMD), air gap MD (AGMD), vacuum MD (VMD), and sweep gas MD (SGMD) [12]. The advantages of MD include the rejection rate, which theoretically reaches 100% [13], and more importantly the potential to utilize the highly concentrated water. The performance of MD is not highly affected by the concentration of the feed water, unlike other desalination processes [14], which makes it possible to use MD in the treatment of high-salinity water, such as RO brine and shale gas wastewater.

In this context, a research project entitled 'Global MVP' (M for MD, V for valuable resource recovery, and P for PRO; hereafter GMVP) was launched in Korea, planning to construct an RO–MD–PRO hybrid pilot plant. Here, RO, a proven and widely used technology, plays the main role to produce potable water, and MD then supports the water production while PRO is used as an energy generation or recovery process. In fact, a similar project, the 'Mega-ton water system' has been conducted in Japan [15]. A prototype PRO plant hybridized with RO was subsequently constructed and operated by utilizing the RO brine as the draw solution and wastewater effluent as the feed solution. Since the utilization of MD is the biggest distinction between these two projects in terms of process schemes, the design optimization of RO, MD, and PRO use can be a critical issue.

The objective of this study is to investigate the commercial feasibility of the RO–MD–PRO hybrid process by using a numerical approach. As a scenario study, the concept of the GMVP project was adopted such that RO is the first process in the system, and is followed by MD and PRO in consecutive order. Previously validated RO, MD, and PRO numerical models were applied and combined in order to evaluate the performance of the hybrid process; the efficiency was then calculated in terms of the specific energy consumption (SEC). The effects of the division ratio of the concentrated RO brine (i.e., the brine division ratio; BDR), the plant dimension ratio of MD and PRO to RO, and the supply cost of the MD heat source were importantly considered in this study in order to explore the cost-effective design of this hybrid process.

2. Materials and methods

2.1. RO–MD–PRO hybrid process

Fig. 1 illustrates the schematic of the RO–MD–PRO hybrid process. First, seawater flows into the RO membrane as a feed water, and a certain amount of the concentrated RO brine is then utilized as the MD feed solution in order to achieve higher recovery of water. Here, the same amount of produced water from RO flows into the other side of MD membrane as a permeate solution. Finally, the concentrated MD brine and the rest of the RO brine are mixed and supplied to the PRO process as the draw solution. Pressure exchanger (PX) are utilized for both RO and PRO processes, at which to recover the RO brine pressure and also to restore the remained pressure of PRO draw solution. In this process, the division ratio of the RO brine is critical, i.e., the brine division ratio (BDR), and consists of the flow rate of the MD feed solution (denoted as x) and that of RO brine (denoted as y) (see Eq. (1)). In Fig. 1, $\dot{W}_{pump,RO}$, $\dot{W}_{heat,MD}$, $\dot{W}_{pump,PRO}$, and $\dot{W}_{p,PRO}$ indicate the rate of work done by the RO pump, MD heater, and PRO pump, and the energy generated by PRO, respectively. In addition, $Q_{p,RO}$ and $Q_{p,MD}$ are the volumetric flow rates of the RO and MD water production. The relationship among the terms will be described in detail in the following section. In the hybrid process, it is assumed that secondary wastewater effluent is used as the PRO feed solution [10], and the energy generated by PRO supports the operation of the hybrid process such that the total energy consumption can be decreased. In addition, from the four MD configurations, DCMD is applied due to its simplicity and frequent appearances in literature [14,16].

$$\text{Brine division ratio (BDR)} = \frac{\text{Flow rate of MD feed solution } (Q_{f,MD})}{\text{Flow rate of RO brine } (Q_{b,RO})} \tag{1}$$

2.2. RO model

Water in RO is transported through a semi-permeable membrane because the hydraulic pressure is higher than the osmotic pressure, which can be explained by the solution diffusion model [17]:

$$v_w = A(\Delta P_{RO}(x) - \Delta\pi_{RO}(x)) \tag{2}$$

where v_w is the permeate flux, A is the water permeability coefficient, ΔP_{RO} is the hydraulic pressure applied in RO, and $\Delta\pi_{RO}$ is the osmotic

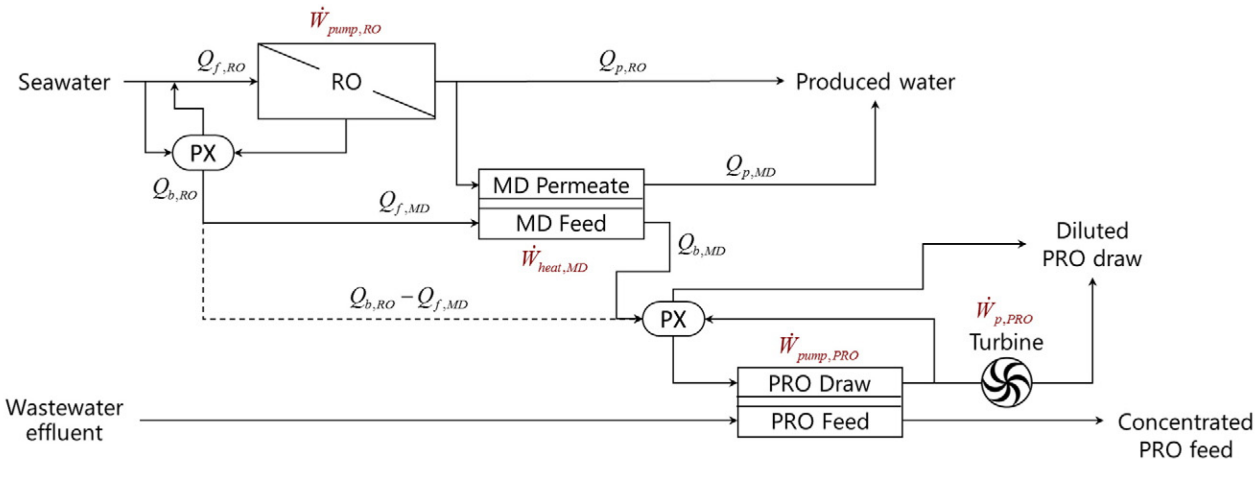

Fig. 1. Schematic of RO–MD–PRO hybrid process with seawater as the RO feed water and wastewater effluent as the PRO feed solution.