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Can batch or semi-batch processes save energy in reverse-osmosis desalination?

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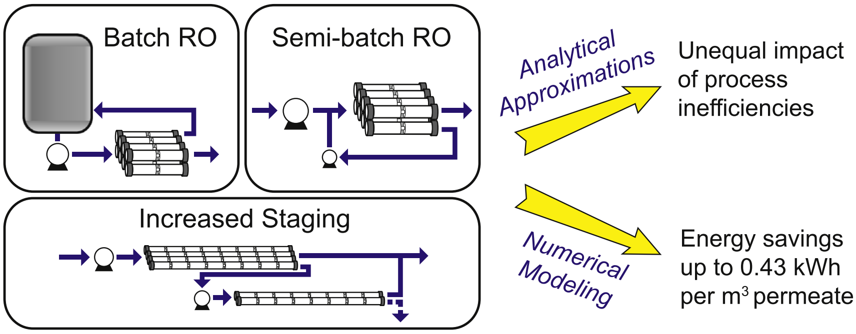
HIGHLIGHTS

- Batch-like processes yield similar energy savings as staging with energy recovery.
- Semi-batch RO and two-stage RO show similar promise for seawater RO.
- A practical batch RO process shows promise for high recovery brackish water RO.
- Process inefficiencies hinder batch-like processes more than staged processes.
- Capital cost and process robustness should be considered in addition to energy use.

GRAPHICAL ABSTRACT



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ABSTRACT

Energy savings in reverse osmosis (RO) are highly constrained by the design of conventional processes, for which the minimum practical energy of desalination substantially exceeds the thermodynamic minimum. Batch processes can theoretically approach the thermodynamic minimum, suggesting the possibility for further energy savings. In this study, we aim to quantify what energy reductions may be possible for batch-like processes when process inefficiencies such as frictional losses and concentration polarization are included. We first introduce a practical batch process that utilizes energy recovery devices and an unpressurized feed tank. We also consider a less practical pressurized-tank scenario, as well as semi-batch (closed-circuit) RO. We then derive analytical approximations and conduct numerical modeling to compare the energy requirements of batch, semi-batch, and staged RO processes under realistic conditions. Through this analysis, we find that practical batch-like processes and processes with increased staging offer comparable and significant energy savings. For example, semi-batch RO and two-stage RO would save 13% and 15% energy, respectively, over one-stage seawater RO at 50% recovery. We conclude with a discussion of other important factors, such as capital costs and process robustness and flexibility, that will affect the implementation of batch, semi-batch, and staged processes.

1. Introduction

With the need to alleviate water scarcity in water-stressed regions around the world, desalination of saline waters such as seawater and brackish groundwater has become an increasingly important and widespread technology [1,2]. Membrane-based desalination, particularly

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reverse osmosis (RO), makes up the vast majority of new installations, largely owing to its high energy efficiency and low operating costs relative to thermal desalination [3]. The cost and energy requirements for RO have decreased considerably over the last few decades. For example, in seawater RO (SWRO), the specific energy (i.e., the amount of energy required per volume of permeate) in the desalination stage has decreased from over 15 kWh m^{-3} in 1970 to around 2 kWh m^{-3} today [2]. This decrease in specific energy stems from the advent of highly permeable thin-film composite membranes, the increased efficiency of pumps, and the use of high-efficiency energy recovery devices (ERDs) to recover hydraulic energy from the high-pressure brine [2,3]. Despite the substantial progress, energy remains an important consideration; energy usage can still be up to 50% of a SWRO facility's operation and maintenance costs [3].

The energy consumption in brackish water RO (BWRO) is typically lower than SWRO and considerably more variable, as the total dissolved solids (TDS) content of brackish groundwater varies over a wide range (1000–10,000 ppm) from site to site [3,4]. While energy consumption is a relatively low concern for low-salinity feed water, brackish feed streams with greater salinity can require substantial energy consumption, especially when operated at high recoveries. In addition, there is often a strong driver to maximize recovery due to concerns over disposal of the high concentration brine, especially for inland locations [3,4]. Despite this driver, achieving high recoveries is often technically challenging due to the sharp increase in concentration factor (i.e., the brine solute concentration divided by the feed concentration) at very high recoveries, which can lead to scaling and sharply increased osmotic pressure. Hence, there is a need to develop processes that can achieve very high recoveries in a robust and efficient manner.

RO is also increasingly applied for the treatment of municipal and industrial wastewaters [5]. Salinities are relatively low in municipal wastewater, typically < 1000 ppm TDS [6], and require relatively low energy for RO treatment. In contrast, industrial wastewaters, such as wastewaters from the chemical, pharmaceutical, and power industries, can vary much more broadly in solution composition and can have more stringent treatment goals. In the most extreme example, some plants must operate zero liquid discharge (ZLD) schemes because of waste disposal concerns [7,8]. ZLD processes invariably consume large amounts of energy due to the need to separate all of the water from solids. As the most efficient desalination technology available, RO will play a large role in ZLD schemes and will need to be operated at very high recoveries as efficiently as possible.

Owing to the ever-increasing desalination capacity of RO facilities, further improvements in energy consumption would have considerable impact. Energy savings from further membrane advances will be rather limited, as increased membrane water permeability above currently achieved levels (2–3 L m^{-2} h^{-1} bar^{-1} for SWRO) would have only a minor impact [9]. Recent modeling studies indicate that even a large increase in the membrane water permeability coefficient from 2 to 10 L m^{-2} h^{-1} bar^{-1} would yield at best a 4% decrease in energy consumption for SWRO [9]. This limited decrease is partly due to the energetics being highly constrained by conventional, one-stage operation in SWRO [10]. Current energy requirements (~2 kWh m^{-3}) already approach the practical minimum specific energy for conventional, one-stage SWRO, which is approximately 1.6 kWh m^{-3} for 35,000 ppm seawater at a recovery of 50% [2].

For further energy savings in the desalination stage of RO, improved process design may offer considerable benefits. Particularly interesting are batch processes and processes with increased stages, which theoretically can approach the thermodynamic minimum energy of separation [11–13]. While these processes are promising, their energy requirements are largely unclear. Previous analyses neglected process inefficiencies [11–13], which are critical for an accurate comparison of the various process configurations. A rigorous quantitative analysis of the energetic requirements of the various RO configurations is clearly needed.

In this study, we quantitatively compare the energy of the desalination stage for batch and semi-batch RO processes with conventional RO processes and RO processes with increased staging. We first introduce the considered process configurations, highlighting particularly important components. We then discuss the minimum energies theoretically possible to illustrate the fundamental constraints stemming from each configuration. After establishing the intrinsic minimum energy requirements, we derive analytical approximations to gain insight into how realistic process inefficiencies, such as frictional pressure loss, affect the total energy efficiency for each configuration. Next, we rigorously compare the energetic requirements of the different processes using module-scale, numerical modeling. Lastly, we discuss other factors such as capital costs, operational experience, and process robustness that may distinguish the different process configurations.

2. Considered process configurations

2.1. Staged reverse osmosis

In current desalination facilities, both SWRO and BWRO are operated in a once-through fashion, meaning the concentrated brine is disposed of without recycle after passing through the membrane modules. SWRO is typically operated in a single stage (Fig. 1A) with recoveries of 35–50% [3]. ERDs are crucial in SWRO for decreasing energy usage by recovering energy from the high-pressure brine [14]. Essentially all new SWRO plants employ ERDs, typically isobaric work exchangers such as the DWEER device from Flowserve Corporation (Irving, TX) and the PX Pressure Exchanger from Energy Recovery Inc. (San Leandro, CA), each of which can recover energy from the brine at efficiencies up to 98% [3,15–17]. While ERDs have markedly decreased the energy

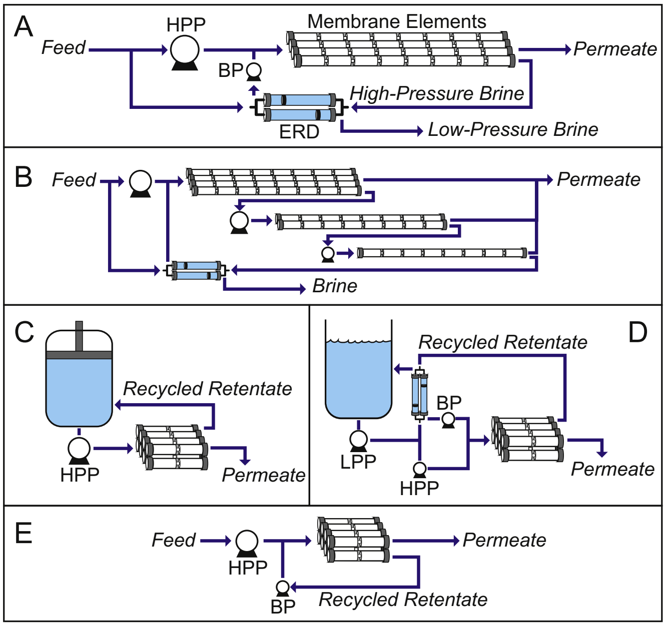

Fig. 1. Simplified reverse-osmosis (RO) process designs considered in this study: (A) one-stage RO, (B) multi-stage RO, (C) relatively impractical batch RO process that utilizes a pressurized feed tank and can be considered ideal from an energetics perspective as the energy of the brine is fully retained, (D) relatively practical batch RO process utilizing energy recovery devices (ERDs) and an unpressurized feed tank, and (E) semi-batch RO process commonly known as closed-circuit desalination. ERDs are illustrated as the isobaric work exchanger DWEER device (Flowserve Corp., Irving, TX), but may take other forms as well. In (B), three-stage RO is depicted in the most energy-efficient form, i.e., with inter-stage booster pumps and an ERD. A similar diagram would apply for less efficient variations, in which the ERD and/or inter-stage booster pumps would not be employed. In (C), a variable-volume tank is depicted to maintain pressure within the tank. A pressurized headspace would be another alternative. In the transient processes (C–E), only the concentration cycle is shown. Valves are not shown in any of the diagrams. HPP: high-pressure pump; BP: booster pump; LPP: low-pressure pump.