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Osmotically assisted reverse osmosis for high salinity brine treatment

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ABSTRACT

This work evaluates a novel osmotically assisted reverse osmosis (OARO) process for dewatering high salinity brines using readily available membranes and equipment. While traditional reverse osmosis processes are limited to treating brines with osmotic pressures below the membrane burst pressure, in OARO, the osmotic pressure difference across a membrane is reduced with a permeate side saline sweep. A series of OARO stages can be used to sequentially reduce the concentration of the feed until a traditional RO process can obtain fully desalinated water. This paper develops an OARO model to identify feasible operating conditions for this process and to estimate the water recovery and energy consumption across a range of brine feed concentrations. For a feed of 100–140 g/L sodium chloride, we estimate that the OARO process is capable of a 35–50% water recovery with an energy consumption of 6–19 kWh per m^3 of product water. The results suggest that an OARO dewatering process improves upon the recovery of reverse osmosis for high salinity brines and has a comparable or lower energy consumption than mechanical vapor compression.

1. Introduction

There is growing demand from the oil and gas, electric power, and industrial sectors for processes to desalinate high salinity brines with 50–350 g/L of total dissolved solids (TDS) [1–3]. Current brine dewatering techniques are expensive, energy intensive, or limited to low water recovery. There is an urgent need for new, scalable methods for concentrating brine prior to crystallization or disposal.

Current technologies for brine dewatering include both evaporative and non-evaporative approaches. The most common evaporative technologies include multi-stage flash distillation (MSF), multi-effect distillation (MED), membrane distillation (MD), and mechanical vapor compression (MVC) [4,5]. MSF, MED, and MD processes use thermal energy, commonly steam, which limits the practicality of these processes on field-deployable skids [1,4]. In contrast, the MVC process uses only electricity and is now widely adopted for dewatering high salinity brines in the oil and gas industry [1]. As an evaporative process, the energy consumption of MVC ranges from 11 to 25 kWh per m^3 of produced water, which is significantly greater than the theoretical minimum work of approximately 1–5 kWh per m^3 to dewater a brine with TDS of 35–150 g/L at 50% recovery [6].

By avoiding a phase change, non-evaporative membrane based technologies may reduce the energy intensity of desalination and brine dewatering processes. Reverse osmosis (RO), forward osmosis (FO), and pressure assisted forward osmosis (PAFO) offer several pathways for brine dewatering across a semi-permeable membrane [7–10]. Fig. 1A presents the set driving and retarding forces in membrane-based separation processes where positive water flux is defined as flow against the osmotic pressure difference from the feed side (f) to the permeate side (p) of the membrane. A positive hydraulic pressure difference ($P_f - P_p$, ΔP) drives water transport, while a negative ΔP retards water transport. In contrast, a positive osmotic pressure difference ($\pi_f - \pi_p$, $\Delta\pi$) retards water transport, while a negative $\Delta\pi$ drives water transport.

In RO, a positive hydraulic pressure difference ($+\Delta P$) drives water transport against the retarding force of a positive osmotic pressure difference ($+\Delta\pi$). In FO, there is a negligible hydraulic pressure difference ($\Delta P \approx 0$) and a highly concentrated draw solution establishes a negative osmotic pressure difference ($-\Delta\pi$) to drive water flux from the feed to the draw. In PAFO, a positive hydraulic pressure gradient is used to augment the negative osmotic gradient of FO ($+\Delta P$, $-\Delta\pi$). While not a separation process, pressure retarded osmosis (PRO) processes utilize the hydraulic pressure as a retarding force ($-\Delta P$) and the osmotic pressure as the driving force ($-\Delta\pi$). Of these membrane processes, only RO directly dewaters brines. FO and PAFO require a second process, most commonly a RO or thermal draw solute regenera-

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Nomenclature

Treatment technology

FO	forward osmosis
MD	membrane distillation
MED	multi-effect distillation
MSF	multi-stage flash distillation
MVC	mechanical vapor compression
OARO	osmotically assisted reverse osmosis
PAFO	pressure assisted forward osmosis
PRO	pressure retarded osmosis
RO	reverse osmosis

Variables

P	hydraulic pressure
ΔP	hydraulic pressure difference across the membrane
π	osmotic pressure
Δπ	osmotic pressure difference across the membrane
A	pure water permeability coefficient
J_w	water flux
i	number of dissociating ions
φ	osmotic coefficient
C	solute concentration
R	gas constant
T	temperature
k	feed mass transfer coefficient
K	solute resistivity for diffusion in the porous support

Subscripts

f	feed side
p	permeate side
s	sweep side
b	bulk
m	membrane surface

tion step, to produce a pure water permeate.

While non-evaporative membrane-based processes more closely approach the thermodynamic minimum of separation for seawater desalination, they are limited in their effectiveness for treating high salinity brines [11]. RO water recovery is limited for high salinity brines (> 50 g/L) because the hydraulic pressure cannot exceed the membrane burst pressure (membrane dependent, but typically about 70–80 bar) [7]. While ongoing research is focused on increasing this burst pressure, operating at ultra-high pressures may lead to severe compression of the polymer active layer and greater irreversible fouling. FO processes simply perform a salt exchange across a membrane, and thus do not dewater brines in the traditional sense without a second membrane, thermal, or solvent induced separations step.

Osmotically assisted reverse osmosis (OARO) is a non-evaporative, membrane-based process for high recovery, energy efficient desalination of high salinity brines [3,12–14]. OARO, like RO, uses hydraulic pressure to transport water across a semi-permeable membrane against the osmotic pressure difference between the feed and permeate (+ΔP, −Δπ). Unlike RO, where the permeate TDS approaches zero, OARO has a permeate-side saline sweep to reduce the osmotic pressure difference across the membrane. This modification enables water transport even when the osmotic pressure of the feed exceeds the burst pressure of the membrane. Therefore, OARO expands the maximum TDS from which water can be recovered from a hydraulic pressure driven membrane processes (Fig. 1B). When multiple OARO stages are linked in series, this process enables the recovery of freshwater from high salinity brines.

The present work explores the theoretical limits of OARO processes and quantifies key performance metrics. We develop a discrete model that includes concentration polarization effects, and we apply this model to estimate the water recovery and energy consumption of the OARO process. We also explore the decision space of the OARO process by varying inlet feed and sweep concentrations, the feed pressure, the number of OARO stages, and the membrane area. Additionally, we compare the performance of OARO to other electricity driven desalination technologies, MVC and RO. Finally, we discuss the limitations of our model and identify the critical research steps necessary to fully assess the technical and economic feasibility of the OARO process.

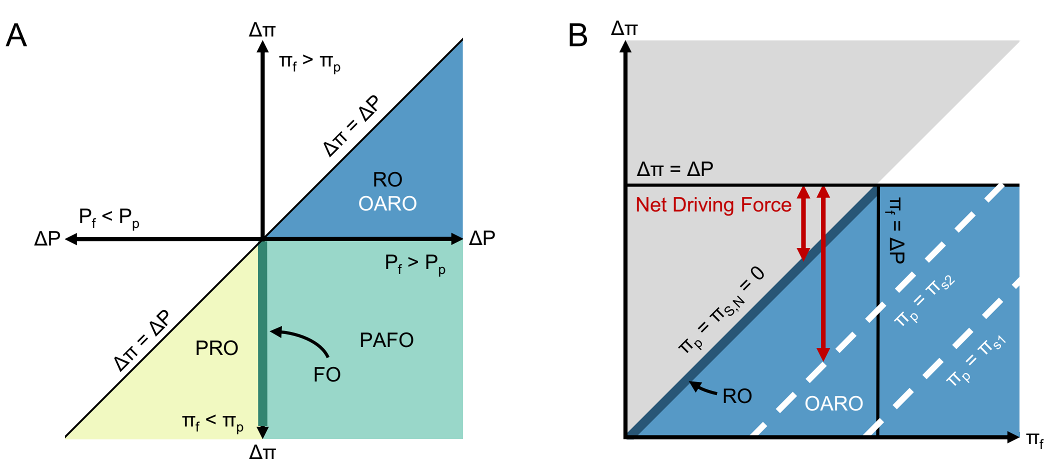

Fig. 1. A) Driving and retarding forces for reverse osmosis (RO), osmotically assisted reverse osmosis (OARO), forward osmosis (FO), pressure assisted forward osmosis (PAFO), and pressure retarded osmosis (PRO) membrane processes. We define the feed side (f) and permeate side (p) of the processes by the direction of the water flux (feed to permeate). Hydraulic pressure difference ($P_f - P_p$, ΔP) is a driving force when positive and is a retarding force when negative. Osmotic pressure difference ($\pi_f - \pi_p$, Δπ) is a retarding force when positive and is a driving force when negative. The white region is where the driving force is smaller than the retarding force, thereby changing the direction of water transport and inverting the definition of the feed side and permeate side. B) RO (dark blue line, $\pi_p = 0$) and OARO process region (blue) for two potential sweep concentrations (white dotted lines, $\pi_p = \pi_{s,1}$, $\pi_p = \pi_{s,2}$) at a constant applied hydraulic pressure difference (ΔP). The net driving force (ΔP − Δπ) of OARO is greater than the net driving force of RO with the same π_f. The grey region represents the infeasible case of π_p being negative. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)