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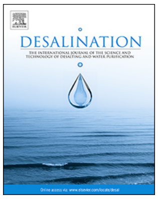

Split-feed counterflow reverse osmosis for brine concentration

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ABSTRACT

Brine concentration allows for increased recovery ratios in water treatment systems, reduction of waste volumes, and the production of minerals from saline brines. Existing methods of brine concentration, while robust, are often very energy intensive. Better efficiency may be possible using Counterflow Reverse Osmosis (CFRO), a membrane-based, pressure-driven brine concentration technology. The present work develops a model for CFRO. Using this model, a single CFRO module is simulated and its performance characterized. Exergy destruction within a single-stage system is analyzed, which provides insights for configuring and optimizing multistaged systems. Additionally, a parametric analysis of membrane parameters provides direction for the development of CFRO-specific membranes. Two existing configurations of CFRO are discussed, and compared with a new third configuration, split-feed CFRO, which is presented here for the first time. Split-feed CFRO systems are simulated and optimized to provide guidance for system design. A variety of multistage systems operating at a range of recovery ratios are simulated, and the results compared are with existing desalination and brine concentration technologies, showing the potential for improved recovery ratios and reduced energy consumption.

1. Introduction

Brine management is becoming an increasingly important step in a complete water processing operation. Increased regulation [1,2], environmental concerns [1,3-5], and cost saving opportunities are all factors that have led to the growing demand for brine concentration technologies that can help to make water recycling feasible, reduce waste volume [6,7], and in some cases recover value from brine streams [8]. Increased competition for clean water from a growing global population with agricultural and industrial needs, and additional stress on water supplies from climate change and changing diets has made access to clean water less secure and more expensive than in the past [9-11], trends which are not likely to change in the near future. All of these factors are leading to increased adoption of brine concentration technologies and increased recovery ratios for water treatment systems already in place.

Recovering water from low-concentration solutions (below 70 g/kg) is most commonly done using reverse osmosis (RO) because of its high efficiency, reliability, and technical maturity [12,13]. Although RO is the dominant desalination technology today, it suffers from several challenges when operating at higher concentrations: the system's maximum recovery ratio is limited by a combination of feed concentration and membrane limitations, and operation at high recovery results in inefficiency due to imbalances in driving force as well as an increased rate of fouling. Operating at high pressures, although offering a high theoretical energy efficiency [14], also requires more expensive pumps, pressure vessels, and pipes, increasing system capital costs. Some of these challenges are being addressed by new variations on standard RO technology, such as multi-stage RO, closed circuit RO, and batch RO [15-19], but some of these challenges, such as a recovery ratio limited by membrane properties and feed conditions, remain.

In extreme cases, where no liquid waste can be disposed of due to regulations or high disposal costs, zero liquid discharge (ZLD) or minimum liquid discharge processes are necessary. Because of the limitations of current RO systems, further treatment of high-concentration solutions has been performed mainly by evaporative methods, such as mechanical vapor compression (MVC) [2], which is inefficient and energy intensive. Several other technologies, including electrodialysis (ED), forward osmosis (FO), membrane distillation (MD), and hybrid MVC-RO have been proposed as alternatives to MVC for high salinity brine concentration applications. Each of these technologies has its own benefits and drawbacks, and it is unlikely that one technology will be the optimal choice for all use cases. While each of these technologies has been explored in depth in the literature [13,20-22], we consider another emerging brine concentration technology that could compete with these alternatives.

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Nomenclature

Acronyms

CFRO	counterflow reverse osmosis
COMRO	cascading osmotically mediated reverse osmosis
ECP	external concentration polarization
ED	electrodialysis
FO	forward osmosis
HPRO	high pressure reverse osmosis
ICP	internal concentration polarization
MD	membrane distillation
MVC	mechanical vapor compression
OARO	osmotically assisted reverse osmosis
RO	reverse osmosis
RR	recovery ratio [–]
SEC	specific energy consumption [kWh/m^3]
ZLD	zero liquid discharge

Symbols

A	membrane permeability [L/m^2-h-bar]
A_{mem}	membrane area [m^2]
B	membrane salt permeability [L/m^2-h]
$Flux_{CFRO}$	average flux of CFRO membranes [L/m^2-h]
g	Gibbs free energy [kJ/kg]
J_w	water flux [L/m^2-h]
$\dot{m}$	mass flow rate [kg/s]
P	hydraulic pressure [bar]
S	structural parameter [m]
$\dot{V}$	volumetric flow rate [m^3]
w	concentration [g/kg]

Subscripts

actual	sum total
bulk	in the bulk fluid
c	concentrate side
d	diluate side
ICP	due to internal concentration polarization
in	flowing into the system
max	maximum
mem	at the membrane-fluid interface
out	flowing out of the system
sup	at the active layer-support layer interface

Superscripts

N	number of stages

Greek

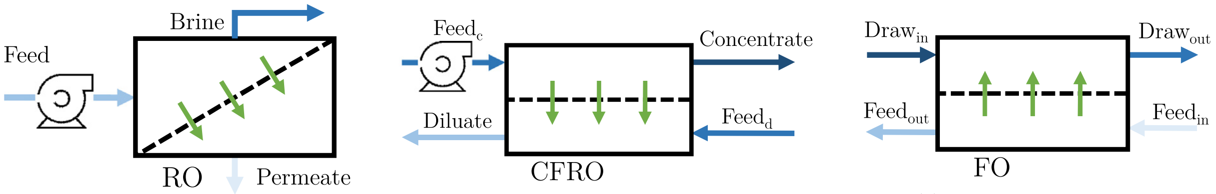
Δ	difference or change
δ	support layer thickness [m]
ε	support layer porosity [–]
η_{II}	isentropic (2nd law) efficiency [–]
$\sum$	sum
τ	membrane tortuosity [–]

Counterflow reverse osmosis (CFRO), which has also been called osmotically assisted reverse osmosis (OARO) [23] and cascading osmotically mediated reverse osmosis (COMRO) [24], has been shown to have the potential to be significantly more energy efficient than other brine concentration technologies, and also has the benefits of an increased operating range compared to RO. This is because CFRO's maximum recovery is not limited by the burst pressure of the RO membrane, as additional stages operating at low hydraulic pressure differences can be employed to increase the recovery ratio. Additionally, CFRO's ability to operate multiple stages at low hydraulic pressure differentials instead of a single stage at a much higher hydraulic pressure differential may reduce the propensity for fouling, which is another potential benefit of the technology [25].

2. Core technology

At its core, CFRO is a membrane-based, pressure driven brine concentration technology, which shares many properties with other membrane-based chemical separation technologies, such as RO and FO. Like RO, permeate flows from a stream of high concentration and high hydraulic pressure, across the membrane, to a stream of low concentration and low hydraulic pressure. However, unlike RO, CFRO employs two feed streams instead of one. The first feed stream, which we refer to as the concentrate stream, is analogous to the feed stream in an RO system. The concentrate stream is dewatered as permeate flows through the semi-permeable, salt-rejecting membrane, and leaves the module with a reduced mass flow rate and increased concentration. On the opposite side of the membrane is another saline feed stream, which we call the diluate stream. This stream is diluted as permeate flows through the membrane, and the stream leaves the module with increased mass flow rate and reduced concentration. Fig. 1 shows a comparison of single stages of RO, FO, and CFRO systems along with the equations that govern water flux through the membrane in each system.

Flow through the membrane in CFRO is governed by the familiar solution diffusion equation [26]



(a) Reverse osmosis
$J_w = A\,(P - \pi)$

(b) Counterflow reverse osmosis
$J_w = A(\Delta P - \Delta\pi)$

(c) Forward osmosis
$J_w = A\Delta\pi$

Fig. 1. Diagrams of reverse osmosis, counterflow reverse osmosis, and forward osmosis stages with the equations governing water flux through their membranes. The color intensity of the blue arrows indicates the solute concentration of the stream, while the green arrows show the direction of permeate flow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)