

Energy-efficient seawater desalination and wastewater treatment using osmotically driven membrane processes



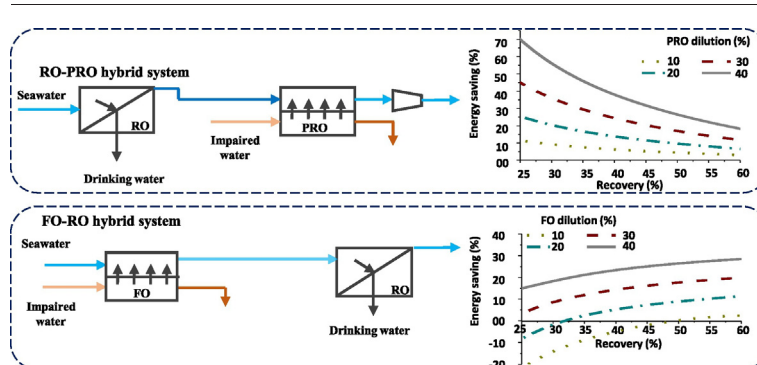
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HIGHLIGHTS

- Hollow fiber module based RO-PRO and FO-RO hybrid systems are modeled, assessed and optimized.
- The model of an axial-flow hollow fiber module for PRO and FO is validated.
- The hybrid systems with zero discharge of seawater are also investigated.
- The energy saving in RO-PRO system decreases with increasing the RO recovery.
- FO-RO system can be economically more feasible for the higher RO recoveries.

GRAPHICAL ABSTRACT



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ABSTRACT

The osmotically driven membrane process, such as pressure-retarded osmosis (PRO) or forward osmosis (FO), assisted reverse osmosis (RO) hybrid systems are investigated for low-energy cost seawater desalination and wastewater treatment, and the simultaneous RO brine (or RO concentrates) management. Unlike the earlier studies, the hollow fiber types of modules are used in these hybrid systems. For commercialization of the hybrid systems, a big concern is that how much energy per unit product (i.e., specific energy) can be saved due to the hybrid systems as compared to the most preferred conventional RO technique. For this, the generalized mathematical models for an axial-flow and a radial-flow hollow fiber module are developed in the current study. These models are applicable to evaluate all PRO, FO, and RO processes. For an RO recovery of 50% and FO/PRO dilution of 40%, it is found that around 25% specific energy saving may be realized in both the hybrid systems as compared to the conventional RO system at studied operating conditions. Interestingly, the results also reveal that as the RO recovery increases, the specific energy saving increases for the FO-RO hybrid system but decreases for the RO-PRO hybrid system.

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1. Introduction

The attention on the seawater desalination is nowadays growing in the water-stressed regions to enhance fresh water supply [1]. Reverse

osmosis (RO) is currently the one of the most preferred seawater desalination technology [2–5]. This is because of the introduction of high-efficiency pumps and energy-recovery devices (ERDs) have reduced the energy requirements in RO by about 60% from over 7 kWh/m³ to <2.5 kWh/m³ [6]. However, desalination using the RO technique still remains an energy-intensive process [1,4,6]. In addition, the discharge of remaining high-salinity RO brine solution directly into water bodies

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Nomenclature

J_v	Volumetric permeate flux through membrane ($\text{m}^3/\text{m}^2 \text{ s}$)
L_p	Hydraulic permeability ($\text{m}^3/\text{m}^2 \text{ s Pa}$)
B	Solute permeability (m/s)
K	Solute Resistivity (s/m)
k	Mass transfer coefficient (m/s)
ka and kb	Mass-transfer-coefficient correlation constants
R_g	Gas constant ($\text{m}^3 \text{ Pa/K kmol}$)
T	Temperature (K)
M_W	Molecular weight (kg/kmol)
C_{Dm}, C_{Fm}	Concentration of draw solution and feed solution at the active layer surface of membrane, respectively (g/L)
P_D, P_F	Hydraulic pressure of draw solution and feed solution, respectively (Pa)
J_s	Salt flux ($\text{kg/m}^2 \text{ s}$)
C_{Db}, C_{Fb}	Concentration in the bulk of draw solution and feed solution, respectively (g/L)
V_D, V_F	Velocity of draw solution and feed solution, respectively (m/s)
z	Axial coordinate
r	Radial coordinate
D_o	Shell diameter (m)
D_i	Center tube diameter (m)
d_o	Fiber outer diameter (m)
d_i	Fiber inner diameter (m)
l	Fiber effective length (m)
l_m	Module length (m)
W	Number of wound of hollow fiber
$Q_{D in}, Q_{F in}$	Inlet flow rate of draw solution and feed solution, respectively (m^3/s)
$Q_{D out}, Q_{F out}$	Outlet flow rate of draw solution and feed solution, respectively (m^3/s)
N	Number of fibers
$C_{D in}, C_{F in}$	Inlet concentration of draw solution and feed solution, respectively (g/L)
$C_{D out}, C_{F out}$	Outlet concentration of draw solution and feed solution, respectively (g/L)
A_{RO}	Area of reverse osmosis (m^2)
A_{FO}	Area of forward osmosis (m^2)
A_{PRO}	Area of pressure retarded osmosis (m^2)
d_p	Diameter of Particle (m)
$DECP$	Dilutive external concentration polarization
$CECP$	Concentrative external concentration polarization
$DICP$	Dilutive internal concentration polarization
$CICP$	Concentrative internal concentration polarization
RO	Reverse osmosis
FO	Forward osmosis
PRO	Pressure retarded osmosis
$TFC-HF$	Thin film composite-hollow fiber
$CTA-HF$	Cellulose triacetate-hollow fiber
SES_{RO-PRO}	Specific energy saving in RO-PRO hybrid system
SEP_{PRO}	Specific energy production by PRO system (kWh/m^3)
SEC_{RO}	Specific energy consumption in RO system (kWh/m^3)
R	Salt (NaCl) rejection
π_F	Feed solution osmotic pressure (Pa)
E_{ERD}	Efficiency of energy recovery device
E_p	Pump efficiency
$Q_{P PRO}$	PRO permeate flow rate (m^3/s)
$P_{D in}, P_{F in}$	Inlet hydraulic pressure of draw solution and feed solution, respectively (Pa)
$P_{D out}, P_{F out}$	Outlet hydraulic pressure of draw solution and feed solution, respectively (Pa)
$Q_{P RO}$	RO permeate flow rate (m^3/s)

SES_{FO-RO}	Specific energy saving in FO-RO hybrid system
SEC_{FO-RO}	Specific energy consumption in FO-RO hybrid system (kWh/m^3)
J_{pexp}	Experimental permeate flux (LMH)
$J_{p the}$	Theoretical permeate flux (LMH)
ΔP	Hydraulic pressure difference across the membrane (bar)

Greek letters

σ	Reflection coefficient
ν	Ionization number
μ	Viscosity ($\text{kg/m}^2 \text{ s}$)
ε	Module porosity
$\emptyset$	RO system recovery

poses huge environmental concerns with a grave danger to the marine life [7,8]. A plausible solution to address all these problems may be the integration of the RO seawater desalination with osmotically driven membrane process, such as pressure-retarded osmosis or forward osmosis, in a hybrid system.

The traditional osmosis process is recognized as forward osmosis (FO) [9–13]. In this process, permeation of water from a feed (or low-salinity) solution to a draw (or high-salinity) solution takes place through a semi-permeable membrane due to a concentration difference between these two solutions. The pressure-retarded osmosis (PRO) is almost similar to the FO; the only difference is that the draw solution is partially pressurized to a constant value that is less than the osmotic pressure difference across the membrane. The increased high-pressurized volumetric flow rate due to permeation across the membrane in the draw side is directed to a turbine for generating power [14–16]. The model impaired water like industrial wastewater, and wastewater effluents are often considered as the feed solution along with the model seawater/RO brine as the draw solution in the earlier studies on FO and PRO [17–19].

In FO-RO hybrid system, the FO process is used to mitigate the concentration/osmotic pressure of the highly concentrated RO feed solution [19] and thus, saving the specific energy consumption by minimizing the applied hydraulic pressure requirement in RO. On the other hand, in RO-PRO hybrid system, the power produced by PRO is used to save the specific energy consumption in the RO seawater desalination [4]. The hybrid systems are described in detail in the next theory section. Recently, the pilot plant of the RO-PRO hybrid system is constructed in Japan. The specific energy saving in this plant, as compared to the conventional RO system, is around 10% and can be further enhanced by improving the PRO membranes [14].

The usage of FO/PRO with RO may be economically less feasible, if the concentration of draw-side solution is much lower than that of the seawater (0.5–1.0 M) like brackish water. This is because a sufficient driving force across the membrane may not be obtained to produce power in PRO or to extract water from feed solution in FO. On the contrary, if the concentration of draw solution is higher than that of seawater, these hybrid systems would be economically more feasible due to the increased driving force across the membrane [4,13,16,19,20].

Only a few researchers [4,5,20,21] have proposed the usage of PRO in combination with RO for the low-energy cost seawater desalination and wastewater treatment, and simultaneous brine management. The performance of the combinations of PRO with RO has been earlier examined by using the spiral wound modules in the hybrid systems [4,20]. The knowledge to design the RO-PRO as well as the FO-RO hybrid systems using the hollow fiber modules is still limited. Currently, spiral wound module is the most mature design for FO and PRO application. The commercial spiral wound modules made by Hydration Technologies Inc. (HTI) are already available for FO/PRO processes [22]. The

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