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Synthesis of integrated membrane desalination and salt production networks

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HIGHLIGHTS

- First systematic conceptual design approach for integrated desalination and salt production processes
- Superstructure representation captures large numbers of design alternatives.
- Structural optimization yields low cost design options.
- Results highlight the benefits of integrated designs towards lower water production costs.

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ABSTRACT

The development of desalination processes that are coupled with simultaneous salt production opportunities are increasingly receiving attention by the scientific community. This work is the first to propose a superstructure-based optimization approach that enables a systematic identification of high performance designs for such systems. The approach considers hybrid seawater reverse osmosis (SWRO) and nanofiltration (NF) membrane desalination together with salt production processes (SPPs). The proposed mathematical formulation has been developed based on a membrane superstructure, which mainly consists of SWRO, NF, and SPP as its primary synthesis units. The various connectivity options between synthesis units has also been explored in this work. For instance, SWRO and NF membranes follow slightly different connectivity patterns due to NF membrane's lower rejections for monovalent ions. The objective function identifies the minimum cost network embedded in the superstructure. The proposed method is illustrated with an example involving SWRO and NF membrane units as well as two different SPP options. The example highlights potential savings in water production cost as a consequence of salt value extraction. It further illustrates the benefits of integrated design of membrane desalination systems coupled with salt production processes over sequential designs of desalination processes followed by end-of-pipe salt production.

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1. Introduction

Membrane-based desalination processes using seawater reverse osmosis (SWRO) technology have become the most widely applied. Many alternatives exist for SWRO membrane unit configurations or networks which need to be explored in design. Over the past decades, a number of superstructure optimization methods have been proposed to support the systematic identification of optimal SWRO membrane networks. A superstructure representation consists of all possible connections between SWRO units, from which the best performing design is extracted subject to process constraints [1]. Since the pioneering work by El-Halwagi [2], many refined approaches have been proposed to synthesize membrane desalination networks [1,3–6]. These approaches have long modelled seawater as a two component mixture of water and salt (TDS). Recent work has overcome this major limitation and considered water quality in detail by accounting for major ions present in seawater [7], which was then followed by additional efforts that enable the selection of different RO membrane types [8].

Besides the constant drive to reduce cost of desalinated water, an emerging concern with seawater desalination is the potentially negative impact on the marine environment from brine discharges [9]. Several brine treatment processes such as technologies with improved water recovery and technologies for the production of mineral salts from brines have been proposed to achieve reductions in brine discharge [10]. Salts that could be produced from brines can have considerable value. An initial analysis that considers the major ions contained in seawater has shown that the theoretical value of salts that could be

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produced per m^3 of seawater can amount to about 20 times the cost of one cubic meter of desalinated water (see Supplementary information). The technologies that have been considered for the production of different salts from desalination brines include crystallization or softening using chemicals such as lime and soda ash [10,11].

The performance of a salt production process depends on feed composition. While significant emphasis has been placed on researching salt production processes and designing desalination plants, the integration of the two processing tasks has received comparatively little attention. Unlike in the case of SWRO desalination processes, there exists no superstructure-based optimal design approach for such systems. Conventionally, salt production processes are placed downstream, yielding a process configuration consisting of a desalination plant with end-of pipe treatment to produce salts [12]. In contrast, the salt production processes may be more tightly integrated with the SWRO membrane network design to enable the routing of intermediate water quality streams to the salt production processes, which may enable better extraction of value. This work is a first attempt to the development of a superstructure representation for integrated membrane desalination and salt production systems. The work also addresses a current gap in membrane desalination networks synthesis by enabling the optimization of hybrid superstructures containing both SWRO and nanofiltration (NF) membrane units. While SWRO membranes have very high rejections for all ions, NF membranes offer higher rejections for bivalent ions over monovalent ions. The inclusion of NF modules provides additional control over the concentration of the different ions in intermediate streams that may be routed to salt production processing steps. The objective of this work is to develop a superstructure based optimization approach for hybrid SWRO-NF membrane and SPP systems. The following section presents the proposed superstructure approach in detail, followed by an illustrative case study.

2. Synthesis units and superstructure

The proposed approach is based on superstructure networks that embed the possible combinations of membranes and salt production processes as a basis for optimization. It builds upon earlier work on SWRO membrane network synthesis [1,7]. The superstructures are constructed from basic building blocks termed 'synthesis units' as described below.

2.1. SWRO and NF synthesis units

The work adopts the SWRO synthesis unit from Alnouri and Linke [7]. A SWRO unit receives a pressurized feed stream from a mixer and produces two product streams, a lean (permeate stream) and a concentrate stream. Each product stream is associated with a splitter. A SWRO synthesis unit contains SWRO elements and is modelled based on data available from commercial membrane element simulators [13]. Hence, the performance of commercially available membranes may be captured while enabling design optimization [7]. The NF synthesis unit is structured and modelled following the SWRO synthesis unit. The difference between the two units is the membrane performance in terms of flux and ion rejection. Both NF and SWRO synthesis units with feed mixers and product stream splitters are shown in Fig. 1.

2.2. Salt production process (SPP) synthesis unit

A salt production process receives a saline feed stream and converts it into salt, in addition to 3 different forms of water streams: (1) purified water, (2) brine reject, and (3) water losses. Additionally, desired salt streams may involve heat, power and salt inputs, e.g. for softening. The SPP unit is conceptually represented using a single-input multiple-output model as shown in Fig. 1. In this work, we consider that one SPP unit produces only one salt. Future work may consider processes that co-produce multiple salts.

2.3. Superstructure connectivity

A superstructure includes all possible connections amongst the synthesis units present in the superstructure. In this work, we follow the work by Alnouri and Linke [1] and construct a 'lean' superstructure, so as to allow the elimination of underperforming connectivity options beforehand. The lean SWRO-NF-SPP superstructure connectivity has been carried out as follows:

- Feed connectivity: seawater feed connects to all SWRO and NF synthesis units, as well as the network product water mixer (as a bypass stream). Seawater feed is not allowed into the network brine mixer product, to prevent any unused pretreated feed from being discarded.
- SWRO permeate connectivity: a permeate stream leaving a SWRO synthesis unit may be connected based on the same criteria provided by Alnouri and Linke [7]. However, this type of stream is not allowed into an SPP synthesis unit, due to the low concentration of ions.
- SWRO brine connectivity: a concentrate stream leaving a SWRO synthesis unit may be connected to all other SWRO units in the network, to the network brine mixer, and to all SPP units. High salinity RO brine is not connected to the same RO membrane feed and the product water mixer to avoid increasing the concentration of the low salinity feed and product water respectively.
- NF permeate connectivity: a permeate stream leaving an NF synthesis unit is connected to all SWRO, NF and SPP synthesis units, the product water mixer and the network brine mixer. Since the overall salt rejection of NF membranes is not as high as RO membranes [14], NF permeate streams of higher salt concentrations than product water quality that are not required for further desalination or salt extraction, can be sent to the network brine mixer. As in the case of SWRO, NF permeate streams are not connected to the feed mixer of same NF unit.
- NF brine connectivity: a concentrate stream leaving an NF synthesis unit is connected to all SWRO, NF and SPP synthesis units, and the network brine mixer. NF brine streams are also not connected to the feed mixer of same NF unit, due to the same reasoning that was provided for SWRO unit connectivity.
- SPP connectivity: the composition of outlet streams from SPPs depends on the specific performance of the specific SPP. In the general case, all outlet streams from an SPP synthesis unit are connected to all other SPP units, SWRO and NF units, the product water mixer and the network brine mixer.

An example of a superstructure consisting of four membranes, two SWRO, two NF and two SPP synthesis units is illustrated in Fig. 2.

3. Optimization model

The mathematical formulation of the problem described above is based on the following sets:

I {i = 1,2, …, Ni| I is a set of ionic species in a water stream}
J {j = 1,2, …, Nm| J is a set of membrane units in the superstructure}
S {s = 1,2, …, Ns| S is a set of SPPs in the superstructure}
K_S {k = 1,2, …, Nk| K is a set of salts fed to SPP 's'}

The superstructure contains synthesis unit building blocks as described above. Splitters and mixers are used to connect the streams between these three units. Splitters divide and distribute streams to different destinations while mixers receive and mix streams from different splitters to produce one exit stream [1]. Splitters are associated with the seawater feed, every membrane and SPP outlet stream. Mixers are associated with the feed streams of every membrane, SPP, and network outlet streams (such as product water, network brine and lost water). The lost water outlet mixer receives streams of evaporated water from

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