Desalination xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Kinetics and energetics trade-off in reverse osmosis desalination with different configurations

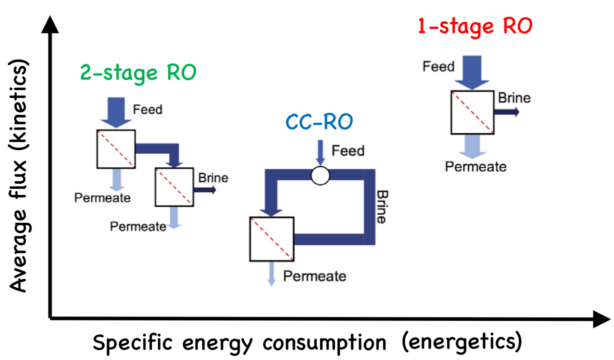
Shihong Lin [a,b,*], Menachem Elimelech [c]

[a] Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, TN 37235-1831, United States
[b] Department of Chemical and Biomolecular Engineering, Vanderbilt University, Nashville, TN 37235-1831, United States
[c] Department of Chemical and Environmental Engineering, Yale University, New Haven, CT 06520-8286, United States

HIGHLIGHTS

- Full scale RO process is constrained by the kinetics-energetics trade-off.
- This trade-off is reflected by the relation between water flux and specific energy.
- We quantify this relation for 1-stage, 2-stage, and closed-circuit RO.
- We compare the kinetics and energetics of three RO configurations.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 January 2016
Received in revised form 3 September 2016
Accepted 8 September 2016
Available online xxxx

Keywords:
Reverse osmosis
Desalination
Energy consumption
Trade-off analysis

ABSTRACT

Optimizing system design and operation of reverse osmosis (RO) systems requires an in-depth comprehension of the intrinsic tradeoff between RO mass transfer kinetics and energetics. In this study, we demonstrate that this critical trade-off can be quantified using the relationship between the average water flux and the specific energy consumption (SEC). We derive analytical expressions to quantify the average water flux and SEC for single stage, two stage, and closed circuit RO processes. These analytical expressions are useful for system design and operation optimization as they facilitate direct comparison of the kinetic and energetic efficiencies between RO processes with different operation conditions and system configurations. Finally, we compare the kinetics and energetics of the three system configurations using these analytical expressions and discuss their relative advantages and disadvantages in RO desalination.

1. Introduction

Desalination of seawater and brackish water is an increasingly important component in the portfolio of fresh water supply due to the ever-growing global water scarcity [1–3]. Among all existing desalination technologies, reverse osmosis (RO) is currently the dominant technology because of its technological maturity, operational reliability, and unparalleled energy efficiency [4,5]. Not only RO has replaced thermal distillation processes to become the technology of choice in seawater desalination, it also has grown significantly in other application areas such as municipal wastewater reuse [6–9], point-of-use water purification [10,11], and industrial water and wastewater treatment [12–15].

* Corresponding author.
E-mail address: shihong.lin@vanderbilt.edu (S. Lin).

http://dx.doi.org/10.1016/j.desal.2016.09.008
0011-9164/© 2016 Published by Elsevier B.V.

Energy-efficient RO and its large scale implementation were made possible mainly by the invention of thin-film composite membranes with dramatically enhanced water permeability and salt rejection [16–19], as well as the development of energy recovery devices that recoup the energy in the pressurized brine stream [20]. However, the development of RO has now reached a stage at which further innovations in membrane materials can only lead to marginal improvement in energy efficiency that is ultimately constrained by thermodynamics [3,21]. Consequently, future efforts to further drive down the energy consumption in RO should focus on (i) developing membrane materials [22–27] and operational strategies [28–36] for effective fouling mitigation, and (ii) optimizing RO operation by judicious selection of operational conditions and system configurations [37–43].

Conventional RO desalination systems have only one stage, i.e., they operate at a single constant pressure determined by the exit brine osmotic pressure at the target recovery rate [44]. Single stage constant pressure RO, though simple, has the intrinsic disadvantage of being energetically inefficient. The specific energy consumption (SEC), defined as the energy consumption per volume of desalinated water or permeate water, is relatively high for single stage RO due to the large driving force at the entrance of the pressure vessel (i.e., the first elements) which leads to a high degree of thermodynamic irreversibility. Innovations in system design and operation, such as multi-stage RO [39,43] or closed-circuit RO [43,45–47], can reduce the SEC by adjusting the applied hydraulic pressure to the be closer to the osmotic pressure of the remaining feed solution or brine.

Although energy consumption is an important aspect in desalination and thus usually the focal point in existing efforts for operation optimization [39,48], a more rational and holistic optimization should be performed with respect to the overall economics of the process, rather than energy consumption alone. The key to develop a rational optimization strategy lies in understanding the intrinsic trade-off between water flux and energy consumption; in other words, between process kinetics and energetics. Theoretically, faster mass transfer kinetics inevitably generate more entropy, leading to higher irreversible energy losses and thus lower energy efficiency [44,49]. Therefore, it is of paramount importance to acquire a quantitative understanding of such a trade-off in RO and to develop a sensible approach for economic optimization.

In this paper, we first briefly describe three major RO configurations: single stage RO (1-stage RO), two stage RO (2-stage RO), and closed-circuit RO (CC-RO). We then derive analytical expressions for the average water flux and SEC for these RO process configurations. Coupling the expressions for average water flux and SEC generates curves that quantify the trade-off between RO kinetics and energetics. With these trade-off curves, we systematically compare the energetics and kinetics for the different RO configurations with the goal of presenting a holistic picture of their relative advantages and disadvantages.

2. Description of RO configurations

In a 1-stage RO process, the feed water is separated in the membrane module into the desalinated permeate solution and the concentrated brine solution (Fig. 1A). Because the feed water only passes the module once, the minimum applied pressure required is the exit brine osmotic pressure, which is dependent on the water recovery rate. In practical operations, pressure is also applied in excess of the brine osmotic pressure to achieve a reasonable water flux. The very high driving force at the entrance of the module in a 1-stage RO process leads to a high degree of thermodynamic irreversibility and thus large SEC.

A 2-stage RO process operates by reusing the concentrated brine solution of the first stage as the feed solution of the second stage (Fig. 1B). Due to the different osmotic pressures of the effluent brine streams in each stage, different pressures can be applied in different stages to reduce the overall SEC. The staging in such a configuration is spatial and physical, i.e., there are two separate modules with two different applied pressures [43]. Theoretically, an RO process with such a configuration can be expanded to have any number of stages to achieve an even higher thermodynamic reversibility and lower SEC. However, the increased system complexity and capital cost render multiple-stage RO ($N > 2$) economically impractical. Therefore, only 2-stage RO will be considered in this study.

A CC-RO process, or semi-batch RO, is another approach to reduce the SEC by tailoring the applied pressure to the osmotic pressure of the remaining brine solution. In a CC-RO process, the effluent brine from a module is first mixed with the feed water to the system and then recirculated to the module as the influent (Fig. 3C). As the osmotic pressure in the closed circuit increases with water recovery, the applied pressure should be ramped up accordingly to maintain the driving force. Therefore, the staging in a CC-RO process is temporal and operational, i.e., there is only one physical module with one single applied pressure at any time, but the applied pressure can change over time [43,45]. A CC-RO can adopt many stages without increasing the complexity and capital cost of the system, and has thus been proposed as a highly promising technology to achieve high recovery with low energy consumption [45].

3. Development of the kinetics-energetics trade-off curves

In this section, we will derive the analytical equations required to quantify the kinetics-energetics trade-off in module scale RO

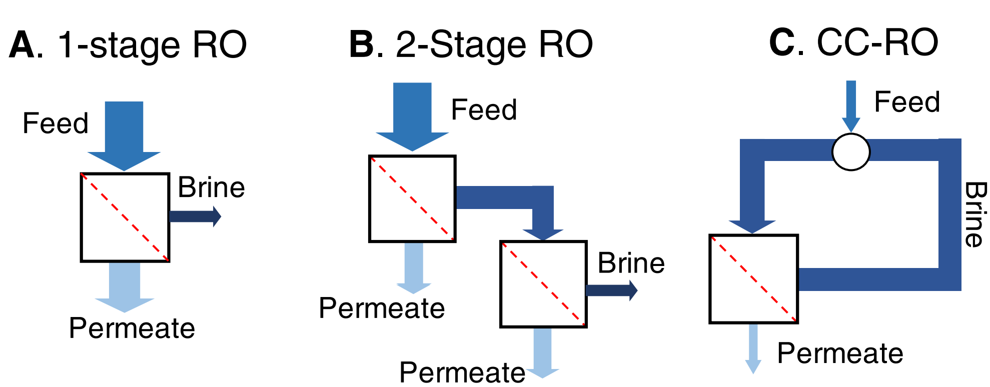


Fig. 1. (A) A single stage (1-stage) RO process in which the feed stream is separated into a concentrated brine stream and a desalinated permeate stream by the semi-permeable RO membrane in the module. (B) A two stage (2-stage) RO process in which the brine stream of the first stage is directed to the second stage as the feed stream; desalinated permeate water is collected from the permeate streams of both stages. (C) A closed-circuit (CC) RO process in which the brine of the module is sent back to the module as the influent after mixing with the feed solution; the brine concentration in the circuit increases over time as the rejected salts accumulate in the closed circuit.

Please cite this article as: S. Lin, M. Elimelech, Kinetics and energetics trade-off in reverse osmosis desalination with different configurations, Desalination (2016), http://dx.doi.org/10.1016/j.desal.2016.09.008