

MAKING DESALINATION AN ENERGY EFFICIENT ALTERNATIVE

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ABSTRACT

Desalination of seawater, brackish ground water, and even wastewater, has become a major tool in meeting the world's growing water demand, but energy intensity remains high and more efficient systems are needed. The tools of heat and mass transfer, and of thermal system systems engineering are directly applicable. This lecture discusses design analogies between desalination systems and thermal power systems, with a focus on reverse osmosis systems. Entropy generation minimization is shown to be the major aim in energy efficient design. Analogies between heat exchangers and osmotic mass exchangers are developed. The potential use of ultrapermeable membranes to reduce system size or energy consumption is considered. The impact of concentration polarization, analogous to incondensable gases in heat exchangers and dependent upon mass transfer coefficients, is shown to be controlling in system performance. Finally, the role of varying mass flow rates in membrane feed channels is examined using analogy to heat transfer and a superposition technique, showing how mass transfer coefficients can be accurately modeled in these systems.

KEYWORDS: Desalination, Mass transfer, Convection, Phase change, Heat and mass exchangers, Analogies, Reverse osmosis, Membrane permeability, Mass transfer units

1. INTRODUCTION

Desalination has been deployed worldwide to expand the supply of freshwater, especially for coastal populations, and its use has been increasing rapidly, now exceeding 86 ML/day of installed capacity [1]. The technology has also improved steadily over recent decades, especially for reverse osmosis (RO) membrane systems for which energy consumption has dropped by a factor of eight since 1970 [2]. But concerns remain about the energy requirements of desalination. Significant research is now being directed at understanding the causes of energy inefficiency in various desalination processes; and, for both thermal and membrane-based systems, many concepts from thermal engineering can be directly adapted to improve the performance of desalination systems. In this talk, I highlight areas where thermal engineering is directly applicable to today's challenges in desalination system design.

2. THERMODYNAMIC EFFICIENCY AND ENTROPY GENERATION

Desalination is the process of separating freshwater (A) from saline water (B), usually creating a more saline brine (C) in the process. Work (either mechanical power or as the exergy of heat from a higher temperature source) is required to effect the separation, and direct application of the first and second laws of thermodynamics shows that the rate of work required is:

$$\dot{W} = \dot{N}_A G_A + \dot{N}_C G_C - \dot{N}_B G_B + T_0 \dot{S}_{gen} \quad (1)$$

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where $G = H - TS$ is the Gibbs energy per mole of stream and \dot{N} is the molar flow rate. When the entropy generation rate, \dot{S}_{gen} , is zero, the work requirements are minimized. For this reversible case, separating 50% of the water from typical seawater requires about 1 kWh_e/m³ of fresh water produced. Practical reverse osmosis systems today operate below 3 kWh_e/m³, with some demonstration technology being slightly under 2 kWh_e/m³; but auxiliary processes such as intake pumping and pretreatment can add 1 kWh_e/m³ to the overall energy requirement.

Equation (1) shows that the design of effective desalination processes requires a clear appreciation of the causes of entropy production (and, more broadly, exergetic processes) in the system [3]. Essential concepts from thermal design apply very directly: minimize the temperature and concentration differences through which heat and mass are transferred [4]; balance opposing streams in exchangers to help maintain minimal temperature and concentration differences [5, 6, 7]; maximize the heat and mass transfer rates associated with these small difference in order to have compact, low capex, equipment [8, 9]; use multiple stages in processes that involve transport against a fixed point condition, such as a saturation temperature [10, 11]; and recover the exergy associated with condensation to drive further evaporation at lower temperatures [9, 10, 11, 12]. In short, the heat transfer and thermal engineering communities understand the techniques required in desalination system design very thoroughly.

Today's desalination plants have come to be dominated by a pressure-driven membrane separation (reverse osmosis), for the reason that it is primary a mechanical process that has more favourable entropy generation and cost characteristics than are possible with most thermal systems (low \dot{S}_{gen} in a thermal system requires large, low temperature difference heat exchangers, which are expensive or impractical). However, membrane separations can be studied by direct analogy to heat exchangers; and when that is understood, the required design characteristics are clear.

3. OSMOTIC MASS EXCHANGERS BY ANALOGY TO HEAT EXCHANGERS

Osmotic mass exchangers use a semipermeable membrane to separate water from salts. The membranes operate on the basis of Donnan exclusion, with charged polyamide surface layers that reject salts while admitting water [13, 14]. By pressurizing a saline feed stream on one side of the membrane, the Gibbs energy of water on the saline side is raised above that of a fresh water draw stream on the opposing side, reversing the direction of osmosis and causing water to diffuse through the membrane to the fresh side. The process may be described simply [15] using a membrane permeability coefficient A , and considering the differences in hydraulic and osmotic pressures, P and π , respectively, to write the mass flux from feed to draw stream as:

$$\dot{m}_p'' = A \{ [\pi_d(x) - \pi_f(x)] - [P_d(x) - P_f(x)] \} \quad (2)$$

We can immediately see the analogy to the heat transfer from the hot to the cold stream of a heat exchanger

$$\dot{Q}'' = U [T_h(x) - T_c(x)] \quad (3)$$

which leads to the famous ϵ -NTU method of sizing and rating heat exchangers [16]:

$$\frac{U \cdot A_s}{\underbrace{C_{\min}}_{NTU}} = \text{fn} \left[\frac{\dot{Q}_{\text{actual}}}{\underbrace{\dot{Q}(NTU \rightarrow \infty)}_{\epsilon}}, \frac{(\dot{m}c_p)_{\min}}{\underbrace{(\dot{m}c_p)_{\max}}_{C^*}} \right] \quad (4)$$

Banchik, Sharqawy, and Lienhard, in a series of papers, have exploited this analogy in detail for reverse osmosis, pressure retarded osmosis, and other systems to develop the analogous framing for osmotic mass exchangers. For the case of reverse osmosis [17], they define the “number of mass transfer units”, or MTU, as follows:

$$\underbrace{\frac{A \cdot A_m \cdot \Delta P}{\dot{m}_{f, \text{in}}}}_{MTU} = \text{fn} \left[\underbrace{\frac{RR_{\text{actual}}}{RR(MTU \rightarrow \infty)}}_{\varepsilon}, \underbrace{\frac{\pi_{f, \text{in}}}{\Delta P}}_{SR_f} \right] \quad (5)$$

where RR is the water recovery ratio and A_m is the membrane area required. Figure 1 illustrates this analogy.

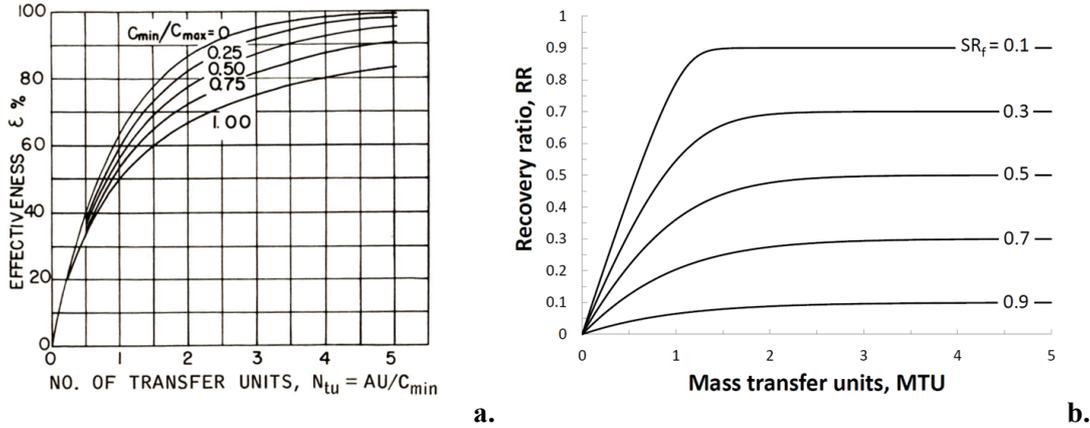


Fig. 1 Analogy between: (a) heat exchangers [16]; and (b) reverse osmosis mass exchangers [17].

Major differences between heat exchangers and osmotic mass exchangers do arise, however, from two factors:

1. The mass flow rate in the feed channels of a mass exchanger declines as water is transferred from the saline stream into the draw (or pure) stream, reducing the velocity in the flow direction
2. As water diffuses toward and through the membranes, salts are convected to the membrane surface, but must accumulate near the surface (leading to back diffusion) and producing a high salt concentration near the membrane than in the feed. This so-called concentration polarization is entirely analogous to the incondensable gas effect in a heat exchanger, and it impedes water flux through the membrane.

As is the case for heat exchangers, there is interest in having higher flux through the membranes, in order to obtain a more compact system; and so significant attention is devoted to increasing the membrane permeability A . However, just as one would not simply insert a high U heat exchanger into to a thermal system with examining the overall design and staging, the benefits of high A taken by itself are limited.

4. REVERSE OSMOSIS AND ULTRAPERMEABILITY

The invention of graphene desalination membranes [18] and other high permeability materials was greeted with great excitement based on initial expectations of drastically reduced energy requirements. Subsequent analysis [19] showed that potential energy savings were more modest: around 15% for seawater systems and around 45% for brackish water systems in a standard cross-flow RO configuration (Fig. 2a). These gains are achieved by lowering the applied hydraulic pressure toward final osmotic pressure of the outlet brine, holding system size and water production fixed. However, for this configuration, the benefits are strictly limited by the overall osmotic pressure change. An imperfect analogy would be using a higher U in a single-stream heat exchanger to operate at a given heat duty with slightly reduced temperature differences so as to lower \dot{S}_{gen} . Large gains are not possible by changing U alone: the process configuration must also change.

System size reductions for the standard cross-flow configuration as a result of higher permeability (Fig. 2b) are more promising, but are ultimately limited by concentration polarization. Thus, the full benefits of high permeability will require enhanced mass transfer coefficients in the standard RO configuration (which may not be easily achievable at the levels required [13]). McGovern and Lienhard [20] have recently explored these limits, showing that, as with energy efficiency, batch RO configurations can better capture the benefits of higher permeability membranes where system size is concerned.

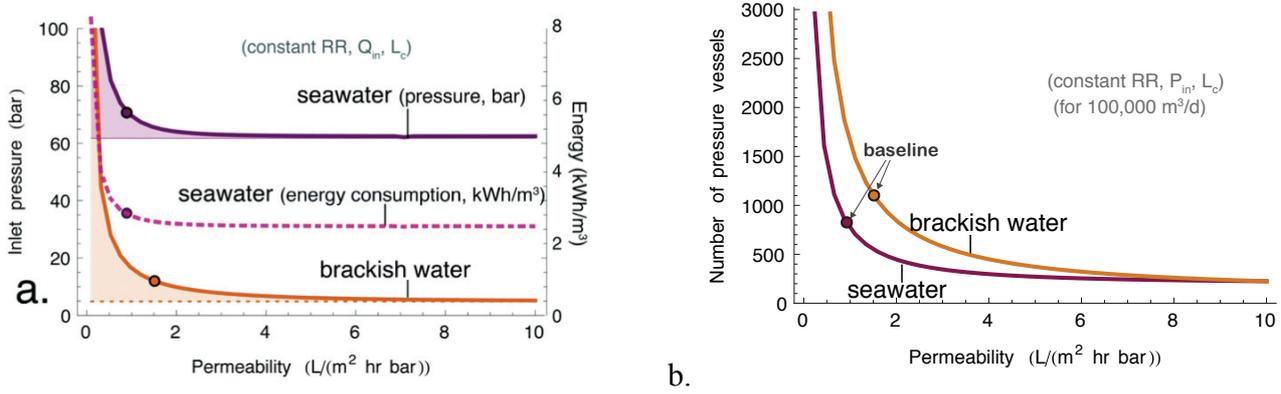


Fig. 2 Energy (a) and system size (b) of single-stage reverse osmosis versus membrane permeability [19].

5. VARIABLE MASS FLOW RATES IN MEMBRANE CHANNELS: SUPERPOSITION

In thermal engineering, accurate prediction of stream-to-stream heat flux is required for sizing and rating heat exchangers. Likewise, predicting water flux through the membrane is required for the design of osmotic mass exchangers. Concentration polarization (CP) results from water flux, and it in turn drives salt back-diffusion, reduces osmotic driving potential [see Eq. (2)], and retards water flux. Traditionally, CP is modeled as diffusion through a stagnant film [21] and ignores the growth of the mass transfer boundary layer. As RO systems push towards higher permeabilities and higher salinity feeds, the impact of CP on water flux increases, meaning better mass transfer modeling is required for ultrapermeable RO systems.

The buildup of diffusive resistance by CP can be accounted for using an analogy to convective heat transfer and superposition [22]. Using a pseudo-concentration, $\partial\omega/\partial w = 1/w$, the governing salt conservation equation can be reduced to a form that is analogous to the energy equation in convective heat transfer, as illustrated in Fig. 3. Combined with a no-salt-flux boundary condition, this transformation yields a relationship between water flux v and salt mass transfer that mimics convective heat transfer:

$$v = -D \left. \frac{\partial\omega}{\partial y} \right|_w = h_m (\omega_w - \omega_b) \leftrightarrow q = -k \left. \frac{\partial T}{\partial y} \right|_w = h (T_w - T_b) \quad (6)$$

where the mass transfer coefficient h_m is defined based on the pseudo-concentration difference ($\omega_w - \omega_b$), rather than actual concentration difference Δw . Consequently, solutions for local convective heat transfer coefficient can be used for the local mass transfer coefficient in RO, if the boundary conditions match.

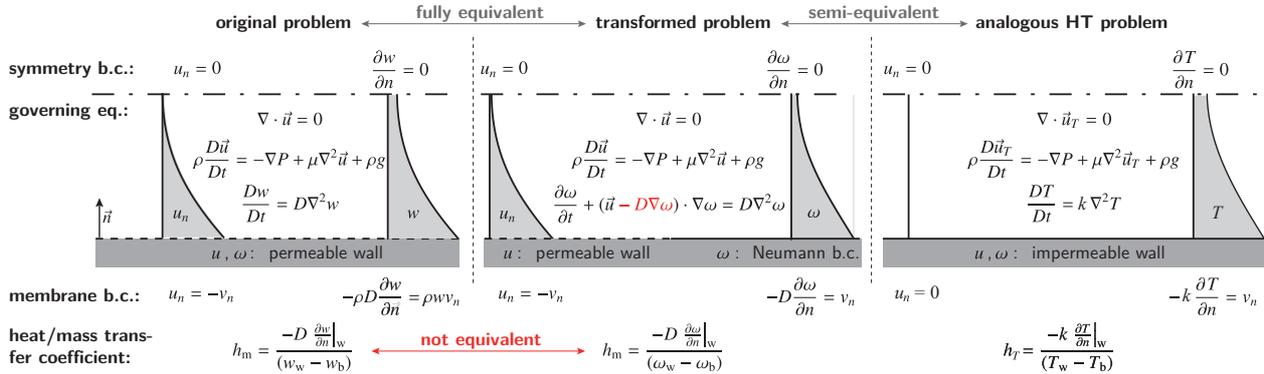


Fig. 3 Governing equations and boundary conditions for the original problem in concentration w , the transformed problem in pseudo-concentration ω , and the analogous heat transfer problem in T . Equivalence of the original and transformed problem is complete. The analogy to convective heat transfer holds under conditions where the velocity field is not significantly impacted by the permeate flux and axial diffusion.

However, in RO, the boundary conditions do not mimic the usual uniform wall heat flux or wall temperature cases found in convective heat transfer literature. Thus, the principle of superposition [23] is used to fit uniform wall flux solutions to the varying water flux b.c. in RO, such that the local Sherwood number is

$$\widetilde{\text{Sh}} = \frac{v_0 + \int_0^x \frac{\partial v}{\partial \xi} d\xi}{\frac{v_0}{\text{Sh}(x)} + \int_0^x \frac{\partial v}{\partial \xi} \frac{1}{\text{Sh}(x-\xi)} d\xi} \quad (7)$$

where $\text{Sh}(x)$ is the Sherwood number for a uniform wall flux b.c. Applying solution–diffusion theory and several bulk conservation relations in conjunction with the superposition theorem, this results in the effectiveness–MTU relationship shown in Fig. 4.

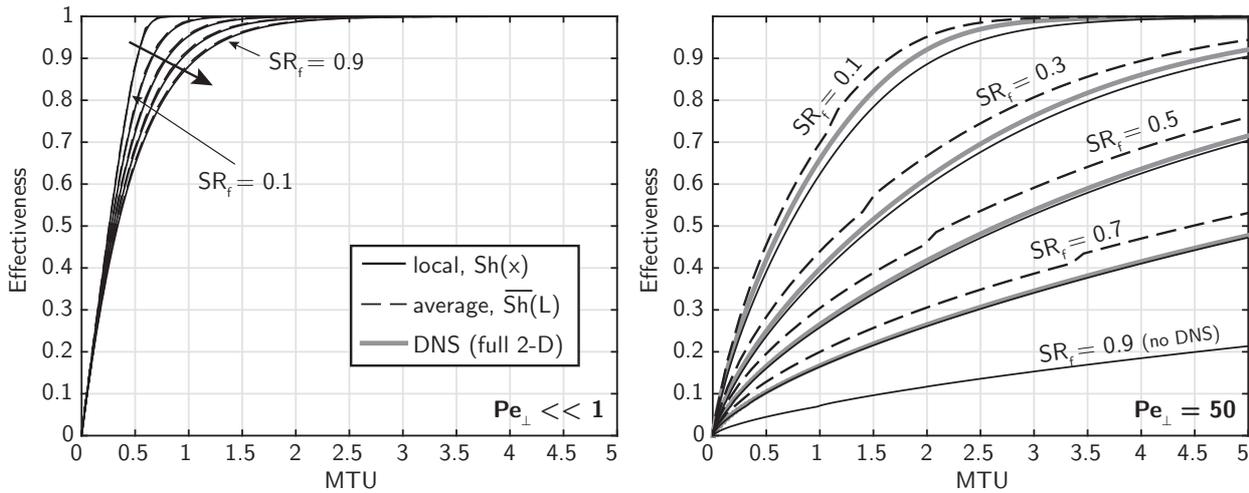


Fig. 4 Effectiveness–MTU curves for increasing values of the transverse Peclet number: as the effects of CP become more significant, correctly accounting for variations in the local mass transfer coefficient becomes more important, as seen by comparison to DNS and traditional, average Sh modeling approaches. The DNS fully accounts for the 2-D mass transfer process in the channel, treating the concentration as a passive scalar, with the permeable wall boundary condition and constant fluid properties [24]. The present model agrees well with the full 2-D model over the entire parameter space (MTU, SR, Pe_\perp), but the average Sh approach breaks down for high Pe_\perp .

The transverse Peclet number, Pe_\perp (Fig. 4), arises as an additional dimensionless parameter that compares water flux to salt back-diffusion, scaling the effect of concentration polarization:

$$\text{Pe} = \frac{D_h A (\Delta P - \pi_f)}{D} \quad (8)$$

As Pe_\perp increases with higher permeabilities, the effects of concentration polarization increase. In those cases, results with the varying mass transfer coefficient agree better with direct numerical simulation (DNS) than traditional, constant mass transfer coefficient modeling approaches [22].

As membrane permeability continues to rise, RO hydrodynamic design must evolve with it. Models that account for variations in mass transfer coefficient are thus critical to the next generation of RO system design. Fortunately, convective heat transfer theory provides a large body of solutions that are applicable.

6. CONCLUSIONS

Concepts from the design and use of heat exchangers in thermal power systems are entirely applicable to the design of desalination systems, in which the useful power is the work of desalination and in which irreversibilities raise the energy requirements further. While many of these techniques are immediately evident for thermal desalination systems (minimizing temperature differences, balancing capacity rates, energy recovery, staged design, and lowering thermal resistance to minimize system size), they have direct analogies in considering osmotic mass exchangers and reverse osmosis desalination. The concept of MTU may be used for sizing and rating and high permeabilities can be used to reduce system size; but mass transfer coefficients must be managed so as to offset concentration polarization and variable mass flow rates.

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