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Perspective

On the potential of forward osmosis to energetically outperform reverse osmosis desalination

Ronan K. McGovern*, John H. Lienhard V

Center for Clean Water and Clean Energy, Massachusetts Institute of Technology, Cambridge, MA 02139, United States

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ABSTRACT

We provide a comparison of the theoretical and actual energy requirements of forward osmosis and reverse osmosis seawater desalination. We argue that reverse osmosis is significantly more energy efficient and that forward osmosis research efforts would best be fully oriented towards alternate applications. The underlying reason for the inefficiency of forward osmosis is the draw-dilution step, which increases the theoretical and actual energy requirements for draw regeneration. As a consequence, for a forward osmosis technology to compete with reverse osmosis, the regeneration process must be significantly more efficient than reverse osmosis. However, even considering the optimisation of the draw solution and the benefits of reduced fouling during regeneration, the efficiency of an optimal draw regeneration process and of reverse osmosis are unlikely to differ significantly, meaning the energy efficiency of direct desalination with reverse osmosis is likely to be superior.

1. Introduction

Energy consumption accounts for approximately 20–35% of the total cost of water in reverse osmosis desalination of seawater [1], and a greater fraction when the price of electricity is high. In this context, forward osmosis, a technology with the benefit of operating at low pressures [2–9], has been promoted as an alternative to reverse osmosis. Indeed, seawater desalination is very frequently cited as a motivating application for the study of forward osmosis; 17 of the 20 most cited articles that include the words ‘forward’ and ‘osmosis’ within their titles on the Thomson Reuters Web of Science Database address seawater desalination [2,4,5,8,10–25]. This level of interest in forward osmosis for seawater desalination is surprising given that FO processes have higher theoretical and actual energy requirements than reverse osmosis, though this is seldom acknowledged [26] or analysed.

In this context, we perform an energetic comparison of reverse osmosis, the most energy efficient commercial desalination technology [1], and forward osmosis, an indirect means of desalination, consisting of two steps; the dilution of a concentrated draw solution, and, its subsequent regeneration (Fig. 1). We outline how the draw-dilution step of Fig. 1 influences the theoretical and actual energy consumption of draw-regeneration, we assess how efficient draw-regeneration need be for forward osmosis to compete with reverse osmosis, and we outline what efficiency might be achievable by the most efficient draw-regeneration systems.

2. Thermodynamic limits upon draw regeneration

The minimum theoretical energy[1] required for the direct desalination of a feed stream depends upon the feed composition and the recovery ratio. For a seawater feed of 35,000 ppm total dissolved solids and a recovery of 50%, the theoretical energy requirement [27] of 1.05 kWh/m^3 places single-stage seawater reverse osmosis, with an energy consumption of about 2.5 kWh/m^3 [1], at a thermodynamic efficiency of about 42% (if pre-treatment, raw and treated water conveyance are excluded).

Since forward osmosis involves the initial transfer of water from the feed to a draw solution of higher osmotic pressure, the theoretical energy required for regeneration is different. Specifically, the theoretical energy required to remove an infinitesimal volume of pure water dV_p from a solution at an osmotic pressure of π is πdV_P. On a volumetric basis, say in J/m^3 (equivalent to pascals), the minimum energy required is given by the osmotic pressure π. Thus, by first drawing water from a feed solution at π_F into a draw solution at π_D, the theoretical energy required to produce pure water increases by a factor of π_D/π_F.

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* Corresponding author.
E-mail addresses: mcgov@alum.mit.edu (R.K. McGovern), lienhard@mit.edu (J.H. Lienhard V).

[1] The ‘minimum theoretical energy requirement’, which may also be termed the ‘minimum thermodynamic energy requirement’ or the ‘reversible work requirement’ will from here on, for brevity, be referred to as the ‘theoretical energy’.

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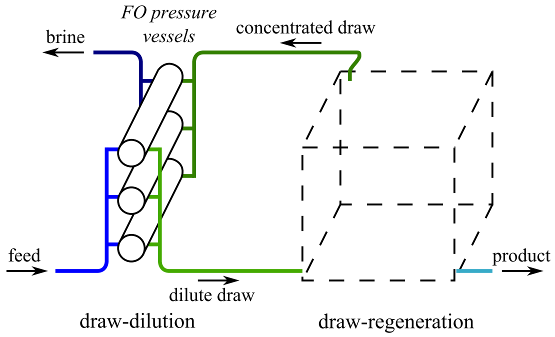

Fig. 1. A two step desalination process involving draw dilution by forward osmosis and a draw regeneration process.

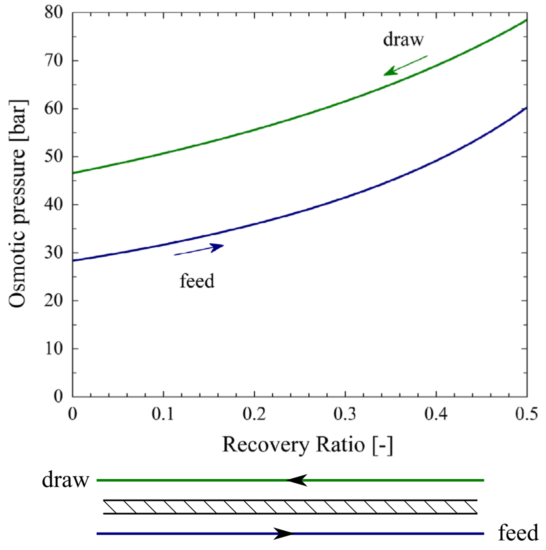

Fig. 2. A counterflow feed concentration and draw solution dilution forward osmosis process. Feed stream of 35,000 ppm NaCl at 25 °C. Draw solution of aqueous NaCl at an inlet osmotic pressure of 78.5 bar. Osmotic coefficients taken from Robinson and Stokes [28].

The same arguments hold for a desalination process where a finite recovery (*i.e.*, greater than infinitesimal) of the feed stream is desired. Fig. 2 illustrates a counter-flow draw dilution process where the relative mass flow ratio of the feed and draw is controlled to facilitate a driving osmotic pressure difference that is close to uniform. The feed salinity is a 35,000 ppm NaCl solution and the inlet draw osmotic pressure is 78.5 bar. The draw solution in this case is modelled as NaCl, though this is in-consequent as an almost identical osmotic pressure profile may be obtained with almost any draw solution[2] by tailoring the mass flow rate ratio. To calculate the theoretical energy for water production, the product of osmotic pressure and permeate production are integrated over the process:

$$E_T = \frac{1}{\dot{V}_P^{tot}} \int_0^{\dot{V}_P^{tot}} \pi(\dot{V}_P)\, \mathrm{d}\dot{V}_P \tag{1}$$

$$= \frac{1}{RR^{tot}} \int_0^{RR^{tot}} \pi(RR)\, \mathrm{d}RR \tag{2}$$

Fig. 3 illustrates the effect of the mean osmotic pressure ratio (π_D/π_F—averaged over water permeation through the membrane) in Fig. 2 upon the theoretical energy required for draw solution regeneration. The theoretical energy penalty is the difference between the theoretical energy required for direct desalination and the theoretical energy for draw regeneration. Both the magnitude of this energy penalty, and the total theoretical energy required for draw solution regeneration depend only on the osmotic pressure of the draw solution and not on its chemical composition.

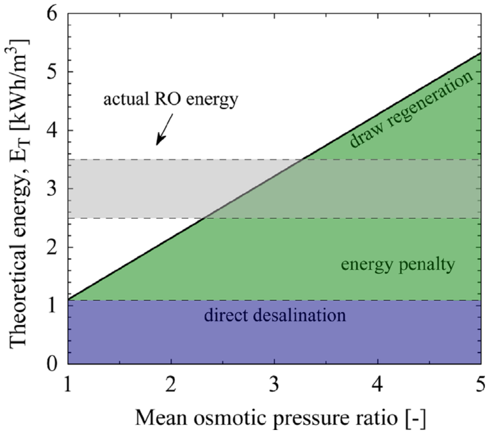

Fig. 3. Effect of the mean osmotic pressure ratio upon the energy penalty imposed by draw solution dilution. Feed stream as in Fig. 2. Draw solution of aqueous NaCl with the inlet osmotic pressure and mass flow rate varied to achieve the desired mean osmotic pressure ratio.

The magnitude of the energy penalty increases rapidly with an increasing mean osmotic pressure ratio. At a mean pressure ratio of 2.3 (mean osmotic pressure differential of 50 bar), the theoretical energy requirements for a forward osmosis process reach 2.5 kWh/m^3 — the *actual* energy requirement of energy efficient reverse osmosis plants. Therefore, if forward osmosis systems are to achieve energy efficiency that is comparable to RO, low osmotic pressure ratios during draw-dilution are a necessity.

3. An energetic comparison of FO and RO

While reverse osmosis is typically electrically driven, the regeneration process in forward osmosis may also be thermally or chemically driven. Rather than delve into the amortised equipment (*e.g.* solar collectors or waste-heat exchangers) and fuel costs for various different direct desalination and draw regeneration processes, we compare FO and RO systems on the basis of their thermodynamic efficiencies. For the reverse osmosis process, the thermodynamic efficiency, η_R, is the ratio of the theoretical energy required to recover a defined portion of the feed water as a pure water product, E_T, to the actual energy (or more strictly exergy [29]), E, required:

$$\eta_R^{RO} = \frac{E_T^{RO}}{E^{RO}} = \frac{\frac{1}{RR^{tot,RO}} \int_0^{RR^{tot,RO}} \pi_{sw}(RR)\, \mathrm{d}RR}{E}. \tag{3}$$

For a draw regeneration process η_R^{regen} differs only in that osmotic pressure of the draw solution, rather than of seawater, is integrated over the recovery ratio of the draw regeneration process:

$$\eta_R^{regen} = \frac{E_T^{regen}}{E^{regen}} = \frac{\frac{1}{RR^{tot,regen}} \int_0^{RR^{tot,regen}} \pi_{draw}(RR)\, \mathrm{d}RR}{E^{regen}}. \tag{4}$$

E^{regen} is the exergy required to drive the actual regeneration process, which for an electrically driven process equals the electrical energy required and for a thermally driven process is related, by the dead state temperature, T^0, and the temperature,

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[2] The saturation osmotic pressure of the draw must be above the maximum desired osmotic pressure of the draw.