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On the asymptotic flux of ultrapermeable seawater reverse osmosis membranes due to concentration polarisation

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ABSTRACT

Just as thermodynamic considerations impose a finite limit on the energy requirements of reverse osmosis, concentration polarisation imposes a finite limit on flux, or equivalently, on system size. In the limit of infinite permeability, we show the limiting flux to be linearly dependent on the mass transfer coefficient and show this to be true for low recovery systems just as well as moderate and high recovery single stage and batch reverse osmosis system designs. At low recovery, the limiting flux depends on the logarithm of the ratio of hydraulic to bulk osmotic pressure and at moderate or higher recovery, the relationship with this pressure ratio is a little more complex but nonetheless can be expressed as an explicit analytical formula. For a single stage seawater reverse osmosis system operating at a hydraulic pressure, recovery ratio, and value of mass transfer coefficient that are typical today, the flux asymptote is roughly 60 L m^{-2} h^{-1} – roughly four times where average fluxes in seawater reverse osmosis systems currently stand.

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1. Asymptotic flux, as compared to asymptotic energy consumption

Even with infinitely permeable reverse osmosis membranes, there are finite limits on the flux that can be achieved in the future. We quantify the asymptotic limit on flux imposed by concentration polarisation – the phenomenon whereby solvent flux through the membrane results in the elevation of solute concentration, and hence osmotic pressure, at the membrane surface. We show that the limiting flux depends linearly on the mass transfer coefficient in the feed water channel and also in a logarithmic fashion on the ratio of the applied hydraulic pressure to the feed osmotic pressure.

In recent years, considerable discussion has been directed to the potential impact of highly permeable (ultrapermeable) membranes [1–7], which one might consider to be membranes with permeability above 10 L m^{-2} h^{-1} bar^{-1}. In particular, authors have examined how ultrapermeability might affect the energy consumption of seawater reverse osmosis and concluded that as membrane permeability improves, there are strongly diminishing returns in the form of energy savings [4,6,7]. Indeed, as illustrated in Fig. 1, at ultrapermeabilities, specific energy consumption (per unit volume of permeate), E_s, in a single stage seawater reverse osmosis system reaches an asymptote.

Also presented, but receiving less coverage, is the impact of higher membrane permeability on average membrane flux (or system size), in which form diminishing returns also occur as membrane permeability becomes very high [4,7,8], as represented in Fig. 2. In this work, we show and explain that there is a finite limit on flux that results from concentration polarisation and derive analytical expressions for that limit. Just as thermodynamic limitations impose a finite limit on energy consumption, transport based limitations impose a finite limit on flux. Interestingly, it might be said that the thermodynamic limitations on energy consumption are more strongly felt in seawater RO systems today than the transport based limitations on flux, *i.e.*, while there is little room for improvement in energy consumption, there is still substantial room for improvement in flux. To a significant extent, this is an artefact of the conventional single stage process design, in which the applied hydraulic pressure cannot be lower than the osmotic pressure of the exiting brine.

Figure 3 illustrates a comparison of the osmotic pressure profiles and net pressure profiles (hydraulic minus osmotic) for membranes of finite and infinite permeability. The centerline osmotic pressure is equal in both cases, but the osmotic pressure at the membrane surface is higher for the membrane of infinite permeability, as a result of higher concentration polarisation. The net pressure at the centerline is also the same regardless of permeability. However, the net pressure at the membrane's inner surface is finite and positive when permeability is finite, but zero

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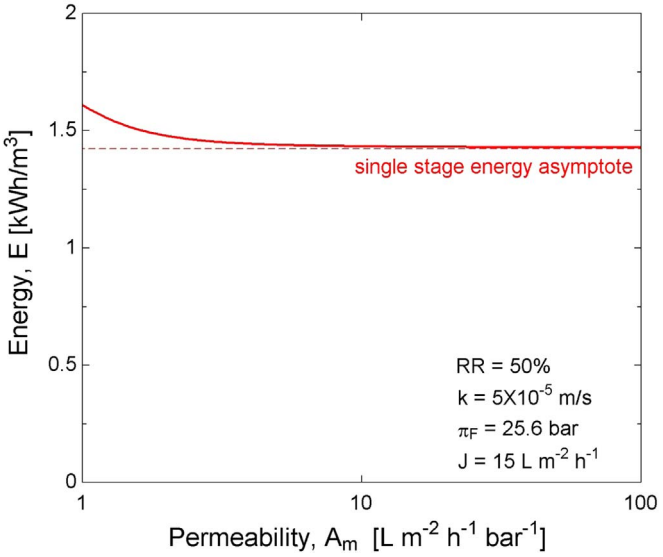

Fig. 1. Impact of permeability on specific energy consumption at constant average flux for single stage reverse osmosis (based on the model developed in Section 3).

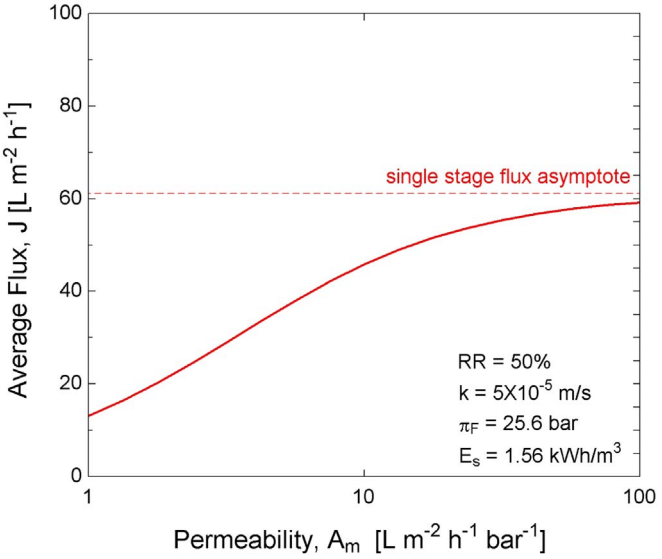

Fig. 2. Impact of permeability on average flux at constant specific energy consumption for single stage reverse osmosis (based on the model developed in Section 3).

when permeability is infinite. For infinite permeability, conditions on either side of the membrane are in thermodynamic equilibrium (in the sense that the chemical potential of water is the same).

2. Asymptotic limits on flux at infinitesimal (or low) recovery

We seek to understand why concentration polarisation imposes a finite limit on flux. One way to do so is to combine a solution-diffusion model [9] for membrane permeability and a stagnant film model[1] [11] for concentration polarisation, and to do this for infinitesimal recovery – whereby the quantity of product water removed from the feed is small enough to consider the feed osmotic pressure constant. For such a model of reverse osmosis (assuming 100% salt rejection), water flux is given by:

[1] Mathematical justification for the use of a stagnant film model is provided by Zydney [10].

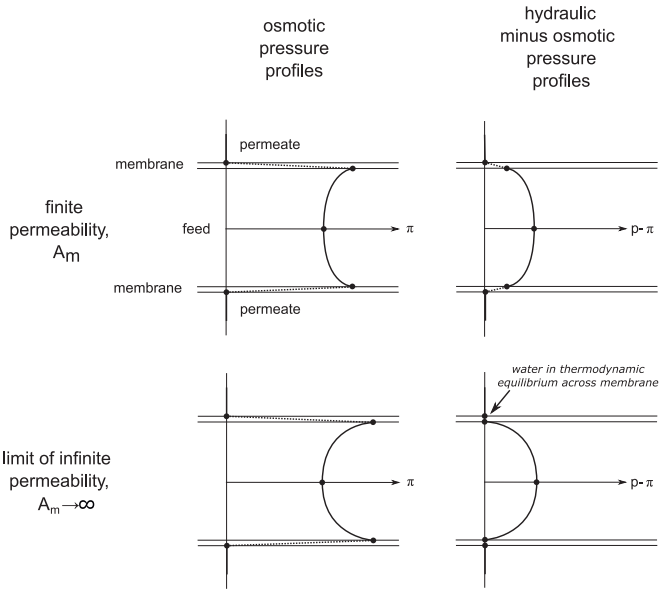

Fig. 3. Profiles of osmotic pressure and net pressure (hydraulic minus osmotic) for flux through membranes of finite and infinite permeability. The applied hydraulic pressure, the osmotic pressure of the feed and the mass transfer coefficient are equal in each case.

$$J = A_m\left[P - \pi_F e^{J/k}\right], \tag{1}$$

with P the hydraulic pressure, π_F the osmotic pressure of the feed and k the mass transfer coefficient. This may be rearranged to give[2]:

$$A_m = \frac{J}{\left[P - \pi_F e^{J/k}\right]}. \tag{2}$$

To understand what happens to flux at very high permeability, we can take the limit of flux as permeability, A_m, goes to infinity. Doing this, which is equivalent to finding the zero of the denominator in Eq. (2), leads to:

$$J_\infty = k\cdot\ln(P/\pi_F). \tag{3}$$

Fig. 4a is a log-linear plot of Eqs. (1) and (3) for a fixed ratio of hydraulic pressure to osmotic pressure of the feed. The implication for membrane development is that, for fixed hydraulic pressure, flux will not increase indefinitely if one increases permeability – the flux approaches an asymptotic value. The implication for system operation with high permeability membranes is that, for any value of permeability (even infinite), an increase in hydraulic pressure will always yield an increase in flux – but the increase in flux depends on the logarithm of the hydraulic to osmotic pressure ratio. In contrast, the limiting flux rises linearly with the mass transfer coefficient.

Dimensionless quantities may also be defined in the following manner:

$$J^* \equiv \frac{J}{k} \tag{4}$$

[2] More generally, the same result may be obtained without the need for the solution diffusion model. By assuming thermodynamic equilibrium of water across the membrane – true if the membrane is infinitely permeable to water – the net hydraulic pressure must exactly balance the osmotic pressure at the feed side surface of the membrane (*i.e.*, $P = \pi_F e^{J/k}$).

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