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# Three dimensionless parameters influencing the optimal membrane orientation for forward osmosis

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## Abstract

In many forward osmosis applications, flux is maximised (and capital costs minimised) when the membrane is oriented such that the feed solution faces the support layer (PRO mode). Here, a framework is developed to understand the factors that determine the membrane orientation that maximises flux. In the absence of fouling, a dimensionless form of the water transport equations reveals the importance of three dimensionless groups: the ratio of draw to feed osmotic pressure; the ratio of draw to feed solute diffusivity; and the resistance to water transport of the support layer relative to the active layer. A parametric study of these parameters and an application of the dimensionless equations to three important FO processes, reveals that having the draw solution face the support layer (FO mode) can maximise flux in specific instances. Interestingly, this implies operation in FO mode can both maximise flux and minimise fouling for fertigation applications and the concentration of flowback waters from hydraulic fracturing.

## 1 Introduction

Forward osmosis involves water being drawn from a solution of lower osmotic pressure, through a semi-permeable membrane, into a solution of higher osmotic pressure<sup>1</sup>. The flux of water through the membrane is important, as it determines the amount of membrane area and number of membrane pressure vessels required

for a given process. Via modelling<sup>2,3</sup> and experimental validation<sup>4,5</sup>, three factors have been identified as retarding the rate of water transport: the resistance of the salt-rejecting active layer to water transport, the build up of a high (or low, depending on membrane orientation) concentration region within the support layer (internal concentration polarisation, ICP) and the build up of high and low concentration regions within the solutions on either side of the membrane (external concentration polarisation, ECP). Of the three factors, internal concentration polarisation is regarded as most detrimental to water flux<sup>5</sup>, since the lack of crossflow within the support layer results in a significant transverse concentration difference.

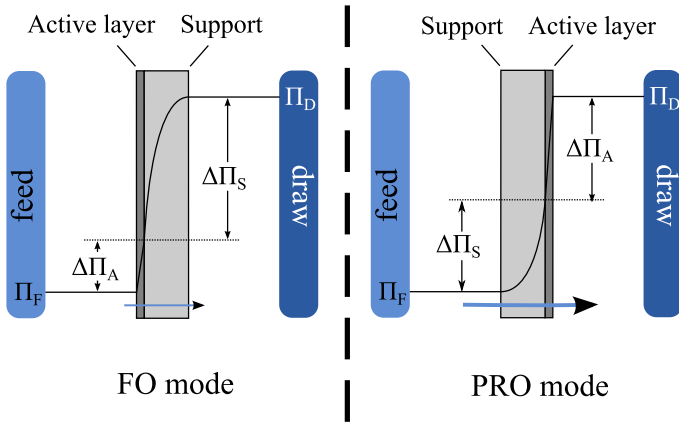
The existence of internal concentration polarisation has important implications when optimising the membrane orientation. Membranes are typically asymmetric and consist of a porous support layer and a salt-rejecting active layer. It is well known in literature that the degree of concentration polarisation depends on whether the support layer is facing the feed or the draw solution<sup>1</sup> (Fig. 1). When the feed is facing the active layer and the draw faces the support layer this is commonly known as the forward mode, forward osmosis mode or FO mode. When the feed is facing the support layer and draw faces the active layer this is commonly known as the reverse mode or PRO (Pressure Retarded Osmosis) mode. Given the same feed and draw solution chemistries, flux is often maximised with the support layer facing the feed<sup>6-82</sup>.

Beyond this observation, examinations of the optimal membrane orientation have largely focused upon

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<sup>1</sup>See Figs. 1 & 9 in<sup>1</sup> for the principle of operation and a typical spiral-wound membrane implementation.

<sup>2</sup>Fig. 5 in Mehta and Loeb<sup>6</sup>, Fig. 4a in Gray et al.<sup>7</sup> and Fig. 4a in Tang et al.<sup>8</sup>



**Figure 1** In FO mode, the orientation of the support layer towards the solution of higher concentration (the draw) results in stronger internal concentration polarisation, a lower osmotic driving force across the active layer and lower water flux. The effects of external concentration polarisation are not shown.

considerations of fouling in both FO and PRO mode, where the rate of fouling and the dependence post-cleaning flux recovery upon membrane orientation (often better in the support-to-draw orientation<sup>9,10</sup>) dictate the optimal membrane orientation for a given application. Specifically, experimental results indicate that flux decline is indifferent to membrane orientation for alginate fouling<sup>9,11</sup> but that flux decline is more significant with the feed facing the support layer for gypsum<sup>10</sup>, bovine serum albumin<sup>9,10</sup> and Aldrich humic acid<sup>9</sup>.

Finally, draw solution diffusivity has also been recognised as an important factor influencing water flux. Tests conducted to compare the water flux using different draw solutions at the same osmotic pressure, with the membrane support layer facing the draw solution, reveal that draw solutions with higher solute diffusivity bring about higher water flux<sup>7,10,12–14</sup>. As a result diffusivities will effect the optimal membrane orientation.

To summarise, operation in FO mode tends to favour reduced fouling, while PRO mode tends to favour enhanced flux. This suggests a fouling-flux dilemma where the choice of membrane orientation requires a compromise between low fouling resistance and higher flux (at least before fouling sets in). However, with draw solutes of higher diffusivity, it is worth asking whether operation in FO mode may, in some instances, maximise flux. Examination of the literature on the ef-

fects of draw solution diffusivity, feed and draw solution osmotic pressure and membrane orientation, shows that a framework has not yet been developed to understand the combined roles of these factors on water flux. Here, setting considerations of fouling aside, we develop such a framework and apply it to three commercial forward osmosis processes in order to identify scenarios where operation in FO mode maximises flux.

## 2 Dimensionless water transport equations

Since the effects of internal concentration polarisation typically dominate over external concentration polarisation, we adopt a model for membrane flux that incorporates the permeability of the active layer and concentration polarisation within the support layer. Considering a forward osmosis membrane with perfect salt rejection, we model water transport in the FO and the PRO orientations using equations from literature<sup>2,3</sup>:

$$J_w^{FO} = A_m [\pi_D \exp(-J_w K^{FO}) - \pi_F] \quad (1)$$

$$J_w^{PRO} = A_m [\pi_D - \pi_F \exp(J_w K^{PRO})] \quad (2)$$

Here,  $J_w$  is the water flux,  $A_m$  the permeability of the active layer, and  $\pi_D$  and  $\pi_F$  are the osmotic pressure of the draw and feed solutions respectively.  $K^{FO}$  and  $K^{PRO}$  are the solute resistivities of the support layer<sup>2,3</sup> when the draw and the feed, respectively, are facing the support.  $K$  may be formulated as:

$$K = t'/D_s \quad (3)$$

where  $t'^3$  represents the effective thickness of the support layer<sup>15</sup> and  $D_s$  represents the solute self diffusion coefficient within the porous support layer. Dividing across by the membrane permeability and the osmotic pressure of the feed solution gives the same equations in dimensionless form:

$$\bar{J}_w^{FO} = \Pi \exp(-\bar{J}_w^{FO} \bar{K}^{FO}) - 1 \quad (4)$$

$$\bar{J}_w^{PRO} = \Pi - \exp(\bar{J}_w^{PRO} \bar{K}^{PRO}) \quad (5)$$

In these equations,  $\bar{J}_w$  is the dimensionless water flux, defined as

$$\bar{J}_w \equiv \frac{J_w}{A_m \pi_F}, \quad (6)$$

<sup>3</sup>The effective thickness may be modelled as  $t\tau/\epsilon$  where  $t$  is the support layer thickness,  $\tau$  the support layer tortuosity and  $\epsilon$  the porosity<sup>2</sup>.

$\Pi$  is the draw-to-feed osmotic pressure ratio, defined as

$$\Pi \equiv \frac{\pi_D}{\pi_F}, \quad (7)$$

and  $\bar{K}$  is the dimensionless support layer mass transfer coefficient, defined as

$$\bar{K} \equiv KA_m\pi_F. \quad (8)$$

$\bar{K}$  represents the resistance of the support layer to water transport relative to the active layer ( $1/A_m\pi_F$  is the resistance of the active layer to water transport). To analyse the effect of membrane orientation we consider the ratio  $\bar{J}_w^{FO}/\bar{J}_w^{PRO}$  by comparing Eq. 4 to Eq. 5. In doing so, we examine the dependence of this ratio upon three dimensionless parameters:  $\Pi$ , the osmotic pressure ratio;  $\bar{K}^{PRO}$ , the relative resistance of the support layer to water transport when the support layer faces the feed; and  $\bar{K}^{PRO}/\bar{K}^{FO}$ , the ratio of solute resistivities in the two membrane orientations. Using a non-linear solver<sup>16</sup>, we study the dependence of the flux ratio upon these three parameters.

Figure 2 illustrates how the ratio of flux in the FO and PRO mode depends upon the osmotic pressure ratio, the relative resistance of the support layer to water transport and the ratio of solute resistivities in the two orientations. Left-to-right consideration of Fig. 2a to c, reveals an important trend:

1. When the relative resistance of the support layer,  $\bar{K}^{PRO}$ , is small, the osmotic pressure has a strong effect upon flux. Even at high resistivity ratios ( $\bar{K}^{PRO}/\bar{K}^{FO} \approx D^{F,S}/D^{D,S}$ ), the possibility of enhanced flux in FO mode is small and limited to very low osmotic pressure ratios<sup>4</sup>.
2. At high values of  $\bar{K}^{PRO}$ , the resistivity ratio has a strong effect on flux and allows for higher flux in the FO mode, provided  $\bar{K}^{PRO}/\bar{K}^{FO}$  is above unity and the osmotic pressure ratio is sufficiently small.

We conclude from Fig. 2 that for processes with  $\bar{K}^{PRO}$  values of approximately unity or less, PRO mode will maximise flux. Secondly, for  $\bar{K}^{PRO}/\bar{K}^{FO}$  values of unity or less, PRO mode will again maximise flux. Only for values of  $\bar{K}^{PRO}$  and  $\bar{K}^{PRO}/\bar{K}^{FO}$  above unity (and in certain cases sufficiently low values of the osmotic pressure ratio) can the FO mode of operation maximise flux.

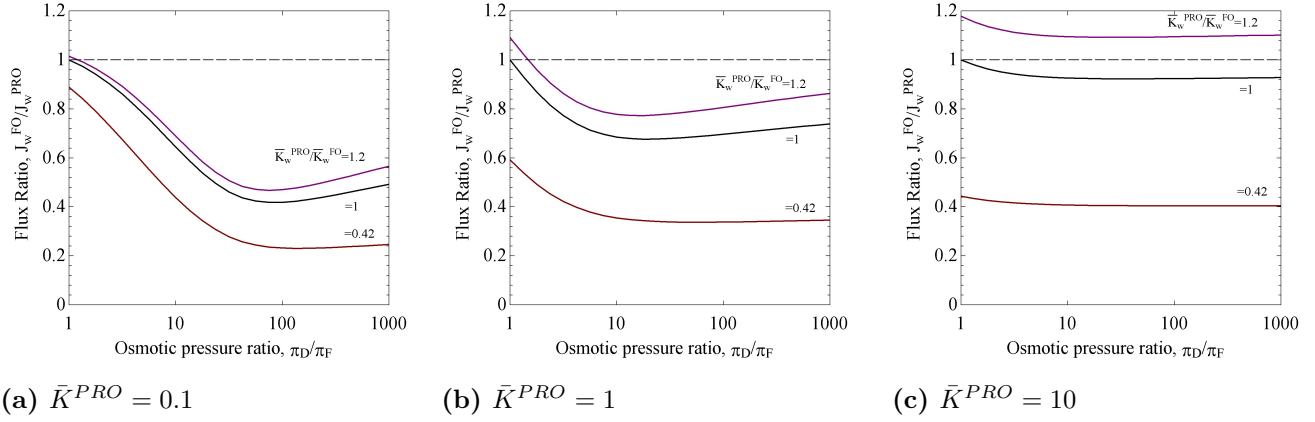
<sup>4</sup>This approximation is affected by the variation of the effective thickness  $t'$  with solution composition and concentration. These effects, which involve ion-support layer interactions are complex to model and represent the subject of ongoing work<sup>10</sup>.

### 3 Application to FO Processes

To demonstrate the implications of the above analysis we apply the theory to three FO processes: the concentration of flowback water from hydraulic fracturing<sup>17</sup>, the dilution of concentrated fertilisers for subsequent irrigation (fertigation)<sup>18,19</sup> and the filtration of impaired waters for personal hydration<sup>20</sup> (*e.g.* the production of a hydration drink.). These three processes exhibit a clear energetic advantage over competing filtration processes<sup>21</sup>, either because regeneration of the draw solution is unnecessary (fertigation or personal hydration) or because draw regeneration is competitive with an alternate direct desalination processes<sup>17</sup> (flowback water concentration, where the primary competing technologies are based on evaporation).

For flowback concentration, we consider a feed stream of 75,000 ppm total dissolved solids (7.5% by wt) and an ammonia-carbon-dioxide draw solution<sup>22</sup>. We consider fertigation with source water provided by the sea and using an ammonium nitrate fertiliser. Nitrogen fertilisers account for the largest portion of fertilisers used in the United States by mass<sup>23</sup>. Of fertilisers that satisfy the requirement of generating significant osmotic pressure at a close to neutral pH<sup>14</sup>, ammonium nitrate provides a high percentage of nitrogen (34%). For personal hydration, we consider source water of low total dissolved solids content and a dextrose (glucose) draw solution, in line with the Hydropack<sup>20</sup>, where dextrose is the most abundant ingredient by weight. Figure 3 illustrates the osmotic pressures and limiting diffusivities of the solutions considered while Table 4 provides numerical values of the three dimensionless parameters.

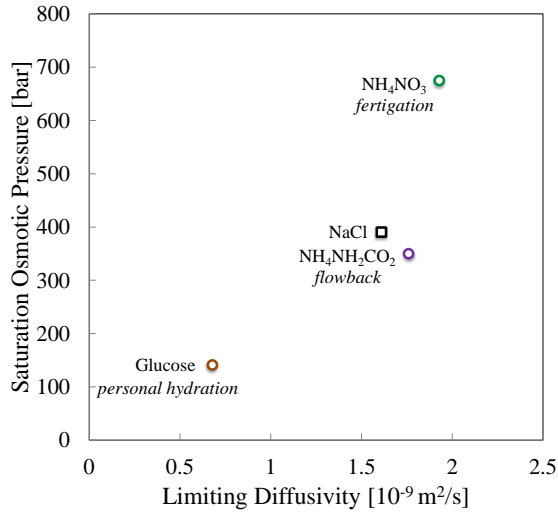
Figure 4 illustrates, for each of the three processes in question, the role of the osmotic pressure ratio upon the ratio of flux in FO mode to flux in PRO mode. From the figure, we may identify the orientation that maximises flux in the absence of fouling. For the flowback and fertigation processes flux is greatest when operating in FO mode, provided that the fertigation process is operated at a low osmotic pressure ratio. The relative resistivity  $\bar{K}^{PRO}$  is greater than unity in both cases, meaning the resistivity ratio has a more significant effect than the osmotic pressure ratio, although as in Fig. 2c, the flux ratio does fall with the osmotic pressure ratio. For the hydration process, flux is greatest operating in PRO mode because the resistivity ratio is less than unity: the draw solute is less diffusive than the feed solute. The solute resistivity  $\bar{K}^{PRO}$  is also



**Figure 2** Influence of the three dimensionless parameters upon the ratio of flux in FO mode to flux in PRO mode. A resistivity ratio of 1 implies that the feed and draw have similar solute diffusivities. The resistivity ratios of 1.2 and 0.42 are representative of processes with higher and lower diffusivity draw solutes, selected to be in line with the flowback concentration and hydration applications considered in Section 3.

Application	Aqueous Feed	Aqueous Draw	Osmotic Ratio $(\Pi_D/\Pi_F)_{max}$	Relative Resistivity $\bar{K}^{PRO}$	Resistivity Ratio $\bar{K}^{PRO}/\bar{K}^{FO}$
Flowback	NaCl (7.5% wt)	NH <sub>4</sub> -CO <sub>2</sub> 6 M, N:C=2:1	$5.4 \times 10^0$	$1.2 \times 10^1$	1.1
Fertigation	NaCl (3.5% wt)	NH <sub>4</sub> NO <sub>3</sub> (68% wt)	$2.4 \times 10^1$	$5.3 \times 10^0$	1.2
Hydration	NaCl (500 ppm)	Glucose (48% wt)	$3.4 \times 10^2$	$7.8 \times 10^{-2}$	0.42

**Table 1** Numerical values for the three dimensionless parameters influencing the role of membrane orientation upon flux in Fig. 4. Data are computed using osmotic coefficients<sup>24</sup>, limiting diffusivities<sup>24,25</sup>, and a representative membrane permeability and support layer structural parameter<sup>17</sup>. Further information is provided in A.



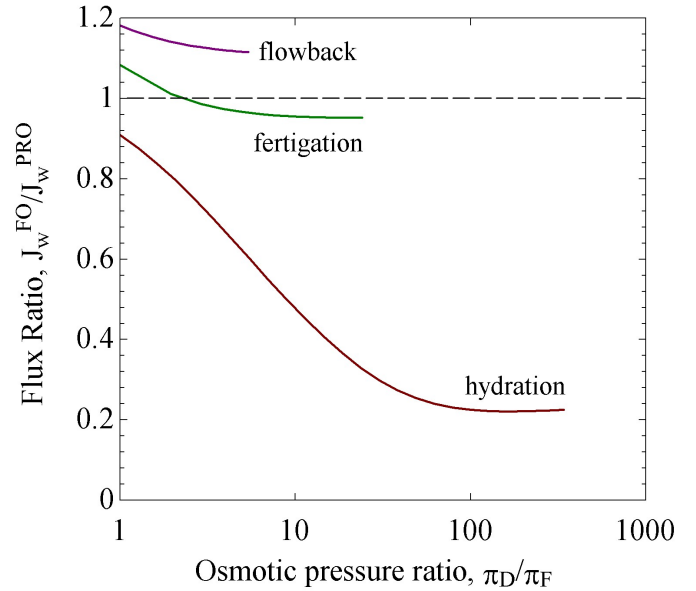
**Figure 3** Osmotic pressure at saturation versus the limiting salt diffusivity<sup>24,25</sup>. See A for numerical values and a detailed description.

much smaller than unity, meaning the osmotic pressure ratio has a strong influence upon flux.

## 4 Implications for the design of flowback, fertigation and hydration processes

Most often, flux is greatest when operating in PRO rather than in FO mode. As discussed in Section 1, this is somewhat unfortunate since fouling occurs more readily when the feed is facing the porous support layer rather than the active layer. However, when the draw solute is more diffusive than the feed solute<sup>5</sup> and when the relative resistance  $\bar{K}^{PRO}$  is large, the flux can be greatest in FO mode. Interestingly, the two examples of flowback brine concentration and fertigation fall into this category. These applications therefore lie in the fortunate position of simultaneously minimising fouling and maximising flux when operating in FO mode.

Unfortunately, in hydration applications the draw solute diffusivity (typically that of sucrose or glucose) is smaller than that of solutes typically found in feeds (*e.g.*, sodium chloride and other mineral salts). Hydration applications thus face the fouling-flux dilemma when optimising the membrane orientation. In this case, Fig. 4 emphasises just how significant the trade-off in flux can be if a process is forced to operate in



**Figure 4** Role of the osmotic pressure ratio (abscissa) on influencing the optimal membrane orientation (ordinate)

FO mode to avoid fouling. If membrane designs could minimise fouling in PRO mode, the time required for the generation of a hydrating drink could potentially be reduced by approximately half.

## 5 Conclusion

When seeking to maximise flux, a high draw-to-feed osmotic pressure ratio tends to favour the ‘PRO’ membrane orientation, while a high draw-to-feed diffusivity ratio tends to favour the FO mode. However, the relative resistance to water transport of the membrane support layer compared to the active layer ( $\bar{K}^{PRO}$ ) also plays an important role. When  $\bar{K}^{PRO}$  is small the optimal membrane orientation is primarily dictated by the osmotic pressure ratio, whereas when  $\bar{K}^{PRO}$  is large the diffusivity ratio is more important. The relative resistance of the support layer in PRO mode increases with the osmotic pressure of the feed. Thus, applications with low osmotic pressure feeds, such as the generation of personal hydration solutions, favour operation in the PRO mode. Applications with high osmotic pressure feeds and draw-to-feed diffusivity ratios above unity, such as the concentration of flowback waters or fertigation employing a seawater feed, favour operation in the FO mode. Thus, they constitute an interesting example of a case in which the FO mode of operation can maximise flux and minimise fouling.

<sup>5</sup>Strictly speaking we should say when  $\bar{K}^{PRO}/\bar{K}^{FO} > 1$

## 6 Acknowledgements

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# A Determination of osmotic pressures, diffusivities and membrane parameters

## A.1 Membrane parameters

Recent experimental measurements on Oasys Water forward osmosis membranes<sup>17</sup> were employed in selecting a membrane permeability of  $1.13 \times 10^{-6}$  m/s bar and a support layer structural parameter of  $2.65 \times 10^{-4}$  m.

## A.2 Diffusivities

Experimental data was employed to determine the limiting diffusivities of solutes in aqueous solution<sup>24</sup> with the exception of  $\text{NH}_4\text{NH}_2\text{CO}_2$ , whose limiting diffusivity was simulated<sup>25</sup>.

## A.3 Osmotic Pressures

Osmotic pressures were computed via experimentally determined osmotic coefficients<sup>24</sup>,  $\phi$ , and the following relation:

$$\pi = RT \frac{\phi \nu m M_w}{V_{m,w}} \quad (9)$$

where  $R$  is the universal gas constant,  $T$  is the temperature,  $\nu$  is the number of dissociated moles of ions per mole of solute,  $m$  is the molal concentration of the solution,  $M_w$  is the molecular weight of water, and  $V_{m,w}$  is the molar volume of water. The saturation concentration of solutions (which influences the maximum osmotic pressure) was also determined using experimental data<sup>24,26,27</sup>.

The exception to this procedure was the aqueous  $\text{NH}_4\text{NH}_2\text{CO}_2$  solution, where the osmotic pressure at concentration of 6 M and a N:C ratio of 2:1 was simulated<sup>25</sup>.

A summary of osmotic pressures and diffusivities employed in the generation of Table 1 is provided in Table 2.

# B Optimal membrane orientation for reverse osmosis pre-dilution and post dilution

Reverse osmosis desalination systems have been proposed whereby forward osmosis is employed to pre-

dilute the feed to a reverse osmosis process, to post-dilute reverse osmosis brine (Fig. 5), or to achieve a combination of the two<sup>28</sup>. The primary purpose of pre-dilution is to reduce the osmotic pressure of the reverse osmosis feed stream, thus saving energy, while the purpose of post-dilution is to reduce the salinity (and possibly temperature) of brine rejected to sea.

The main challenge faced by pre-dilution processes is competition with single or two-pass reverse osmosis systems that could directly provide a pure product from the impaired water stream. The direct reverse osmosis approach would benefit from treating a feed stream (the impaired stream) of lower osmotic pressure compared to diluted seawater emerging from an FO unit.

Where concentration of an impaired stream is the goal, the use of reverse osmosis brine as an osmotic agent for post-dilution offers an energetic advantage over concentration with reverse osmosis. However, post-dilution processes employed to reduce the salinity of reject brine face competition from direct blending with further seawater, which would circumvent the need for membranes.

Setting commercial considerations aside, by considering representative values for the feed and draw salinities (Table 3), the optimal membrane orientation may be examined (Fig. 6). Since the diffusivity of solutes in the feed and draw are approximated as equal, operation in FO mode, where the support layer faces the solution of higher concentration, necessarily reduces flux relative to PRO mode. Thus, the optimal membrane orientation is likely to depend upon the rates of fouling present in each orientation; a finding that is in line with previous studies<sup>9,10</sup>.

# C The role of individual ions in determining solute diffusivity

The self-diffusion coefficient of a quasi-electroneutral dilute binary electrolyte is described by Eq. (10).

$$\frac{1}{D_s^0} + \frac{1}{D_s^0} = \frac{1}{|z_+|} \frac{1}{D_+^0} + \frac{1}{|z_-|} \frac{1}{D_-^0} \quad (10)$$

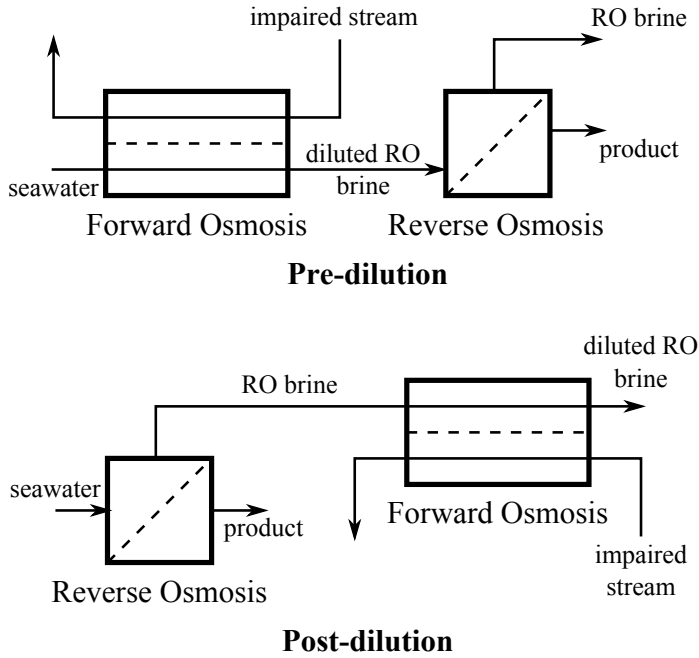
This self-diffusion coefficient is a “harmonic mean of the limiting ionic diffusivities, weighted by the inverse of the ionic charges. We ask the question as to whether there is an inherent benefit in choosing multivalent over monovalent ions. To do this, let us consider all monovalent ions to have the same ionic diffusivity,  $D_1^0$ , and

Application	Aqueous Feed	Aqueous Draw	Osmotic Pressure [bar]		Diffusivity [ $10^{-9}\text{m}^2/\text{s}$ ]	
			$\pi_D$	$\pi_F$	$D_D$	$D_F$
Flowback	NaCl (7.5% wt)	$\text{NH}_4\text{-CO}_2$ 6 M, N:C=2:1	350	65.2	1.76	1.61
Fertigation	NaCl (3.5% wt)	$\text{NH}_4\text{NO}_3$ (68% wt)	675	28.3	1.93	1.61
Hydration	NaCl (500 ppm)	Glucose (48% wt)	141	0.42	0.679	1.61

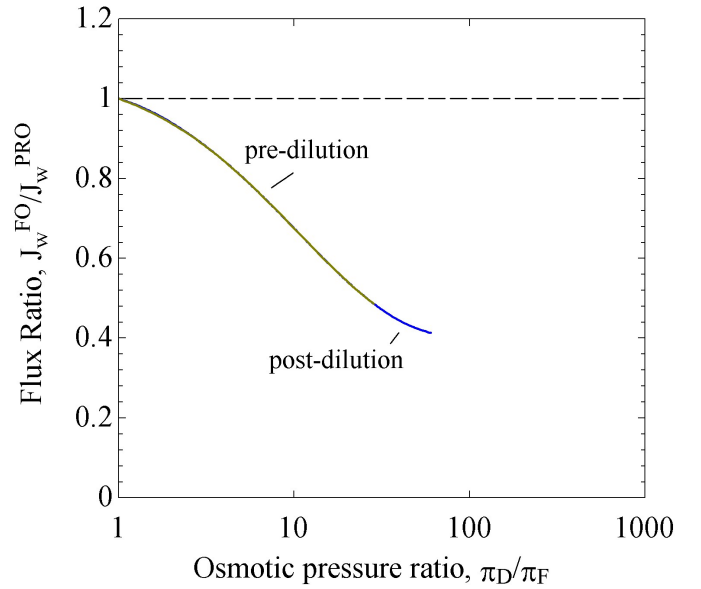
**Table 2** Osmotic pressures and limiting diffusivities employed in the generation of Fig. 3 and the determination of parameters in Table 1.

Application	Aqueous Feed	Aqueous Draw	Osmotic Ratio $(\Pi_D/\Pi_F)_{max}$	Relative Resistivity $\bar{K}^{PRO}$	Resistivity Ratio $\bar{K}^{PRO}/\bar{K}^{FO}$
Pre-dilution	NaCl (500 ppm)	NaCl (3.5% wt)	$6.7 \times 10^1$	$8 \times 10^{-2}$	1
Post-dilution	NaCl (500 ppm)	NaCl (7% wt)	$1.4 \times 10^2$	$8 \times 10^{-2}$	1

**Table 3** Numerical values for the three dimensionless parameters influencing the role of membrane orientation upon flux in Fig. 6. Data are computed using osmotic coefficients<sup>24</sup>, limiting diffusivities<sup>24,25</sup>, and a representative membrane permeability and support layer structural parameter<sup>17</sup>.



**Figure 5** Reverse osmosis pre- and post-dilution processes (reverse osmosis pressure recovery not shown)



**Figure 6** Role of the osmotic pressure ratio (abscissa) on influencing the optimal membrane orientation (ordinate) for reverse osmosis pre- and post-dilution

all divalent ions to have ionic diffusivity  $D_2^0$ . Considering Eq. (10), we find that binary monovalent (1:1) salts and binary divalent (2:2) salts would have the same solute diffusivity provided  $D_1^0 = D_2^0$ . We may also ask how an asymmetrically charged 2:1 or 1:2 electrolyte would compare to a 1:1 electrolyte. Equation 10 again reveals that, for equal solute diffusivity, we would require  $D_1^0 = D_2^0$ . Thus, ionic diffusivities being equal, no intrinsic benefit results from employing higher or lower valence ions. From a sensitivity standpoint, however, an increase in the diffusivity of one ion causes an increase in the overall solute diffusivity magnitudes that differ depending upon the ionic charge permutation. In the case of an asymmetrically charged solute, incremental changes in the diffusivity of the lower charged ion will have a greater effect on solute diffusivity than changes to the higher charged ion, as can be proven using Eq. (10).

Fig. 7 illustrates that the ions with the highest diffusivity are predominantly monovalent. Monovalent spherical ions demonstrate a clear trend in diffusivity with ion size, with a discernible maximum diffusivity present for monovalent cations and anions. For diffusion in dilute solutions, the chloride ion is close to the peak ionic diffusivity in Fig. 7a, leaving little room for improvement on anion diffusivity if our reference is an NaCl solution. The sodium ion, however, is below peak diffusivity in Fig. 7b, allowing for an improvement of approximately 40% in cation diffusivity by selecting K or  $\text{NH}_4^+$ . Returning to Eq. (10), this would allow for an improvement in solute diffusivity of approximately 25%. This brief analysis serves to show that at best we should expect  $\bar{K}^{PRO}/\bar{K}^{FO}$  values of approximately 1.25 by tailoring the draw solution, if we assume an NaCl feed. Furthermore, we ascertain that NaCl, as a draw solution, already provides excellent diffusivity. Thus, when selecting other draw solutions over NaCl, it is important consider the implications upon membrane flux, particularly if the relative resistivity  $\bar{K}^{FO}$  is greater than unity.

## Nomenclature

### Roman Symbols

$A_m$	Membrane permeability, m/s bar
$D$	Diffusivity, $\text{m}^2/\text{s}$
$J_w$	Water flux, m/s
$K$	Solute resistivity, s/m
$m$	molality, mol/kg solvent
$M_w$	Molar mass of water, kg/mol
$R$	Ideal gas constant, J/mol K
$t'$	Effective thickness, m
$T$	temperature, K
$V_{m,w}$	molar volume of water, $\text{m}^3/\text{mol}$
$z$	Charge number, -

### Greek Symbols

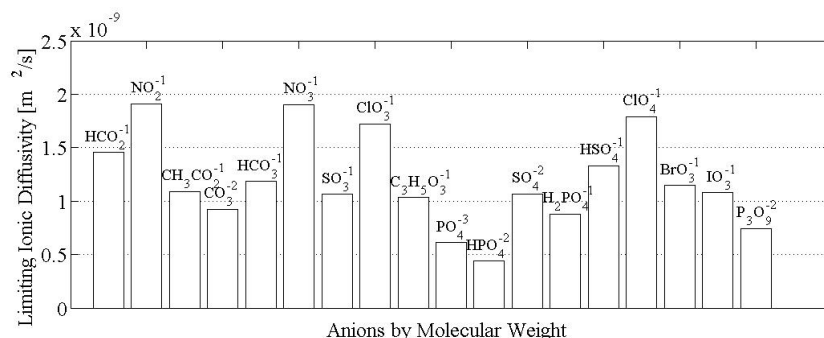
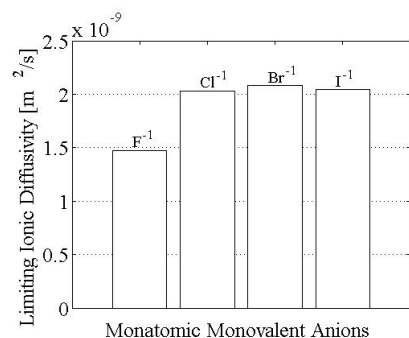
$\nu$	moles dissociated ions per mole of solute, -
$\pi$	Osmotic pressure, bar
$\Pi$	Osmotic pressure ratio, -
$\phi$	Osmotic coefficient, -

### Subscripts

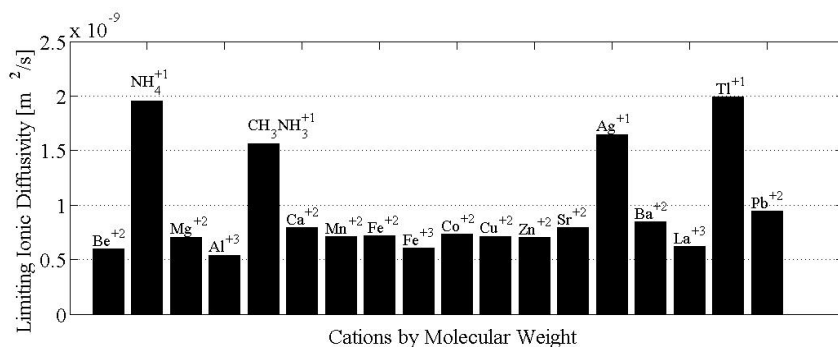
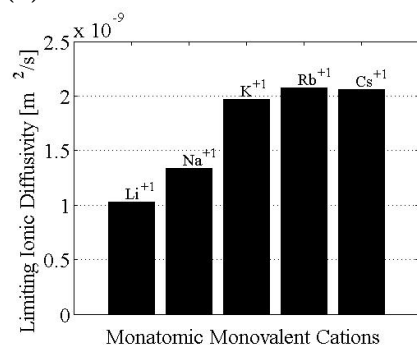
$A$	Active layer
$D$	Draw
$F$	Feed
$+$	Positive charge
$-$	Negative charge
$s$	Salt
$S$	Support layer

### Superscripts

$D$	Draw
$FO$	FO mode (draw-to-support)
$F$	Feed
$PRO$	PRO mode (feed-to-support)
$0$	dilute solution limit
$-$	Dimensionless



(a) Anions



(b) Cations

**Figure 7** Limiting ionic diffusivities at 25°C as calculated from the limiting ionic conductivity,<sup>24,29,30</sup>. The diffusivity maximum based on critical ionic size is seen very well in (a) and (b) where the ions are spherical. Other ionic radii, especially in molecules composed of multiple elements, follow a less predictable trend. Not included is the  $\text{H}^+$  ion with a value of  $9.3 \times 10^{-9} \frac{\text{m}^2}{\text{s}}$ <sup>24</sup>, due to its natural affinity as an ion in water.

R.K. McGovern, J. Mizerak, S.M. Zubair, and J.H. Lienhard V, "Three dimensionless parameters influencing the optimal membrane orientation for forward osmosis," J. Membrane Science, 458:104-110, 15 May 2014.