ForwardOsmosisTech's forward osmosis guide

FORWARDOSMOSISTECH

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Introduction

ForwardOsmosisTech believes forward osmosis membrane based systems for industrial water treatment have the potential to significantly reduce water treatment costs.

However, to this day the commercial success of forward osmosis systems has been limited.

The aim of this eBook is to speed-up the commercialization of water treatment systems utilizing forward membrane technologies through knowledge-based demystification.

To achieve our goal we have organized our favorite articles from the ForwardOsmosisTech portal into the following chapters:

- Chapter 1 – Brief Introduction to Forward Osmosis
- Chapter 2 – Forward Osmosis Membranes
- Chapter 3 – Forward Osmosis Membrane Modules
- Chapter 4 – Forward Osmosis Systems
- Chapter 5 – Forward Osmosis Applications and Commercialization
- Chapter 6 – Forward Osmosis Literature Review
- Chapter 7 – Forward Osmosis Guides

We sincerely hope you enjoy our book.

Please do not hesitate to contact us at forwardosmosistechportal@gmail.com for questions, feedback, comments, and suggestions.

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Chapter 1 - Brief introduction to forward osmosis

> Imagine a system where two compartments, holding aqueous solutions with different solute concentrations, are separated by a semi-permeable membrane, which only allows water to pass through. For the system in question, the difference in solute concentrations is spontaneously minimized by diffusion of water through the semi-permeable membrane. The direction of water diffusion is from the low concentration side to the high concentration side. This is the process of **forward osmosis (FO)** and the semi-permeable membrane is classified as a **forward osmosis membrane (FO membrane)**

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1.1 The principles of forward osmosis (FO)

Forward osmosis, the second law of thermodynamics, and entropy

The goal of this article is to give readers a detailed introduction and explanation to the principles of forward osmosis (FO). In addition, the FO process will be explained through relevant equations, data tables, and figures.

Now, imagine a system where two compartments, holding aqueous solutions with different solute concentrations, are separated by a semi-permeable membrane, which only allows water to pass through. For the system in question, the difference in solute concentrations is spontaneously minimized by diffusion of water through the semi-permeable membrane. The direction of water diffusion is from the low concentration side to the high concentration side. This is the process of **forward osmosis (FO)** and the semi-permeable membrane is classified as a **forward osmosis membrane (FO membrane)**.

The spontaneous process described above can be explained by the second law of thermodynamics, which states that the entropy (or amount of disorder) of an isolated system never decreases. This implies that isolated systems will always spontaneously evolve towards thermodynamic equilibrium – the state with maximum entropy.

Now, from a thermodynamic viewpoint the two-compartment system in question is imbalanced – one compartment contains a solution with higher solute concentration than the other – and, according to the second law of thermodynamics, it will spontaneously evolve towards a state of equilibrium where the difference in solute concentrations is minimized and the entropy is maximized.

Osmotic pressure and the forward osmosis process

The driving force for water diffusion in **forward osmosis processes** is quantified by the **osmotic pressure** ∏. In ideal solutions with low solute concentration the osmotic pressure can be approximated by the Morse equation:

$$\prod = iRTM$$

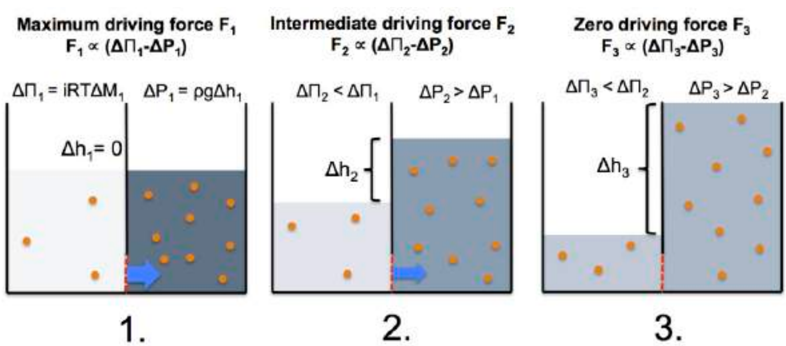
- i is The Van't Hoff factor, which reflects the dissociation multiple of the solute species in question. For a dilute solution of sodium chloride, the Van't Hoff factor is equal to 2 because 1 mole of NaCl dissociates into 2 moles of solutes in aqueous solution.
- R is the gas constant in $L*atm*K^{-1}*M^{-1}$
- T is the temperature of the solution in Kelvin [K]
- M is the molarity of the solution in Molar [M]

The table below summarizes osmotic pressures (in bar) of common solutions encountered in FO processes:

Solute	Concentration in aqueous solution	Osmotic pressure
Mixture of ions in average seawater	N.A.	≈28 bar
NaCl	35,2 g/l	28 bar
$CaCl_2$	43,8 g/l	28 bar
$MgSO_4$	141,3 g/l	28 bar
$MgCl_2$	34,2 g/l	28 bar

Data from Achilli et. al. 2010: "Selection of inorganic-based draw solutions for forward osmosis applications"

Now let's imagine a simple **FO process** in a system where two compartments with different solute concentration are separated by an ideal semi-permeable membrane, which only allows water molecules to pass through. The evolution of the system is illustrated below (figure and matching text):



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1. At the starting point the osmotic pressure difference between the two compartments is largest, and since the water levels are equal, there's no hydrostatic pressure working against the osmotic pressure. As a result, there's a large flow of water (blue arrow) through the semi-

permeable membrane (red dashed line) from the low concentration compartment to the high concentration compartment.

2. At the second stage of the process, the aqueous solution in the low concentration compartment has been concentrated and the aqueous solution in the high concentration compartment has been diluted due to exchange of water from the low concentration side to the high concentration side. The change in concentrations lowers the osmotic pressure difference. In addition, the water flow into the high concentration compartment has caused an increase of the water level resulting in an opposing hydrostatic pressure. Consequently, the overall driving force has been decreased, which lowers the water flow of water across the semi-permeable membrane.
3. At the third stage of the process, the osmotic pressure difference has decreased to a level where it is equal to the opposing hydrostatic pressure. As a result, the overall driving force has disappeared thus effectively stopping the water flow.

Q: Why is there a picture of a mangrove tree associated with this article?

image from http://www.mangrove.at/mangrove_forests.html

A: Forward osmosis is the predominant method of water transport across cells of all living organisms. And root cells of mangrove trees are a great example of a naturally occurring FO process. The cells utilize a highly concentrated internal solution of sugars to extract fresh water from the surrounding seawater.

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Chapter 2 - Forward Osmosis Membranes

> In the context of the water treatment industry, a membrane is a thin, porous structure that can be used as a selective barrier between two aqueous solutions – allowing some molecules to pass through but not others

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2.1 Forward osmosis (FO) membranes and membrane processes

Q: What is a membrane?

In the context of the water treatment industry, a membrane is a thin, porous structure that can be used as a selective barrier between two aqueous solutions – allowing some molecules to pass through but not others. In most cases, the goal of water treatment membranes is to clean aqueous streams by removing pollutants in the form of suspended particles or dissolved solutes. Here, membrane selectivity is quantified by the membrane's rejection to pollutants as solution travels through the membrane. Rejection values are largely determined by the average pore-size of the membrane's selective layer (a membrane with a 1μm average pore-size rejection layer will allow molecules with sizes below 1μm to pass through and reject molecules with sizes above 1μm). The classical membrane filtration spectrum is summarized below:

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Filtration type	Typical rejection range (in size of pollutant)	Types of particles/molecules rejected
Microfiltration (MF)	40nm to 3μm	Bacteria, paint pigments
Ultrafiltration (UF)	3nm to 100nm	Proteins
Nanofiltration (NF)	1nm to 6nm	Sugars, pesticides, and divalent ions
Reverse Osmosis (RO)	1nm and below	Monovalent ions

Data adopted from the Filtration Spectrum by GE Osmonics

Q. What is a forward osmosis membrane?

Key Takeaways

- A forward osmosis membrane is a water treatment membrane capable of facilitating forward osmosis processes

FO membranes are a relatively new addition to the classical membrane filtration spectrum outlined above. The typical rejection ranges of FO membranes are comparable to tight nanofiltration (NF) membranes as well as reverse osmosis (RO) membranes.
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Forward osmosis membrane performance

The performance of FO membranes is routinely quantified by the following parameters:

- Flow of water (measured in L/m^{2}h – also written as LMH) from the low concentration side (the FEED side) to the high concentration side (the DRAW side)
- Reverse diffusion (measured in g/m^{2}h – also written as GMH) of DRAW solutes from the DRAW side to the FEED side
- The rejection (measured in %) properties of the membrane towards molecules on the FEED side entering the DRAW side

Flow of water (J_W), reverse diffusion of draw solutes (J_S), and rejection (R) are illustrated in the figure below. The FO membrane is indicated by a dashed rectangle and consists of thin rejection layer / active layer (dark grey) incorporated into an underlying porous support (light grey).

The active layer of an FO membrane must be sufficient at rejecting both molecules in the feed (green stars) and solutes in the draw (orange dots). The support layer must provide the FO membrane with mechanical stability and at the same time allow water and solutes to pass through with as little resistance as possible.
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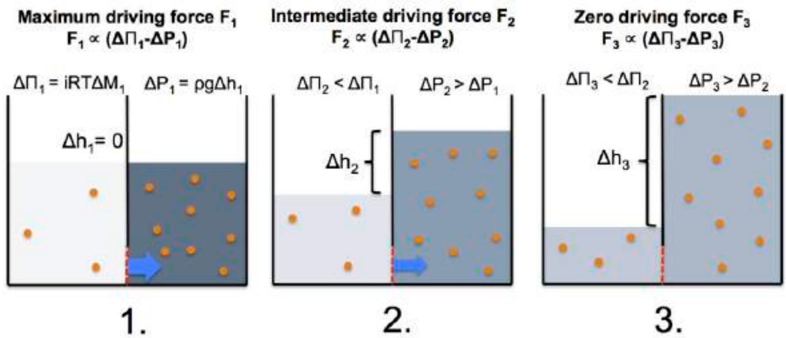

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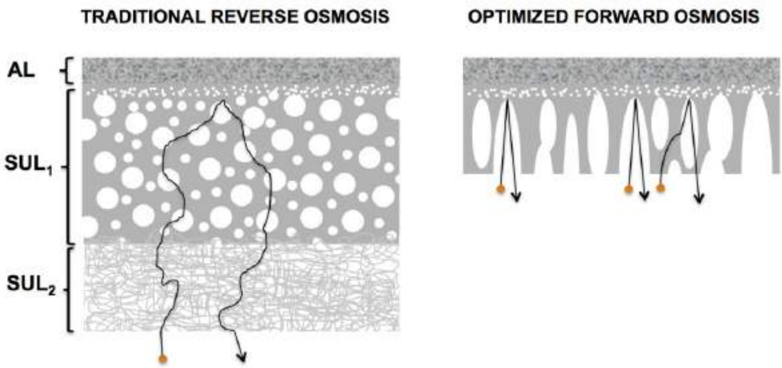
NB: When reporting the performance of FO membranes it is important to include information such as the chemical composition of feed and draw solutions, the cross flow velocity (V) of feed and draw solutions across either side of the membrane, the orientation of the membrane's active layer (towards feed or draw), and if any hydrostatic pressure difference exists between the feed and draw solutions.

Forward osmosis membrane design

FO membrane processes are powered by an osmotic pressure difference between the low concentration feed solution on one side of the membrane's active layer and the higher concentration draw solution on the reverse side of the active layer. The higher the osmotic pressure difference and the shorter the distance over which the gradient is maintained, the higher the water flux across the membrane. Hence, FO membrane performance is critically dependent on efficient diffusion of draw solutes into the support layer and support layer design is therefore one of the most important elements of the overall design of FO membranes.

The effect of support membrane design on diffusion of draw solutes is illustrated in the figure below showing schematic membrane cross sections of traditional RO and optimized FO membranes. The figure demonstrates why traditional RO membranes make poor FO membranes. Since RO membranes facilitate water treatment through application of hydrostatic pressures, the membranes must have mechanical strength. The mechanical strength is typically achieved by sandwiching together a sponge-like upper support layer (SUL1 with a loose mesh (SUL2). Note that the upper support layer becomes denser towards the active layer (AL), which secures a smooth surface for active layer formation. It is easy to picture the difficulties draw solutes face when diffusing through the support layers of a traditional RO membrane.

FO membranes, on the other hand, do not have the same requirements for mechanical strength and can therefore make do with a single support layer. In addition, the FO membrane support layer can be thinner and have a more open pore structure compared to its counterparts in RO membranes. The reduced thickness combined with the change in pore structure enhances draw solute diffusion into the support layer thus greatly improving the FO performance.



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For a great scientific resource on the relationship between support membrane structure and FO performance, check out:

- *Tiraferri et. al. , 2011 "Relating performance of thin-film composite forward osmosis membranes to support layer formation and structure"*

2.2 The difference between a PRO process and the PRO membrane orientation mode

PRO process vs. PRO membrane orientation mode – a question from one of our readers

A reader approached ForwardOsmosisTech with the following questions:

Hi

I'm really confused, and have one question about What is the difference of PRO process and PRO as one mode of membrane orientation in FO process?

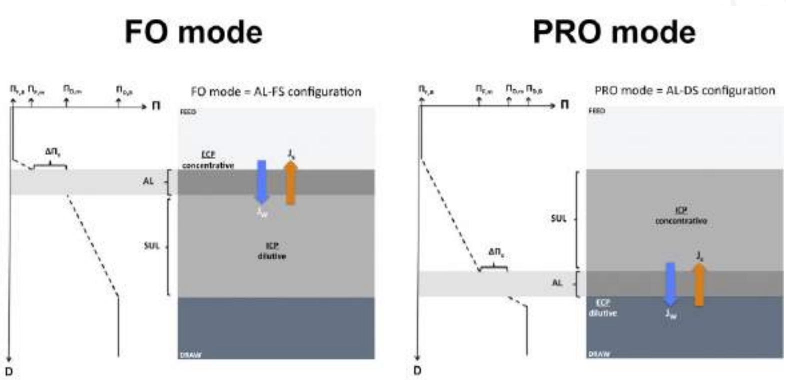
What is similar and difference between this two processes as in result they have the same name?

What are they have the same name in forward osmosis technology?

Thanks for your response

One of the goals of ForwardOsmosisTech is to eliminate any confusion regarding the forward osmosis technology, so we are always more than happy to answer any questions from our readers:

PRO is an abbreviation for pressure retarded osmosis and has two meanings in the field of forward osmosis. PRO either refers to the forward osmosis driven process of generating energy from an osmotic pressure difference or to the forward osmosis membrane orientation mode where the active layer faces the draw solution (AL-DS). In the PRO process of generating energy, forward osmosis membranes are orientated with the active layer facing the draw solution, which is why the process and the membrane orientation are referred to with the same abbreviation. The difference between the FO (AL-FS) membrane orientation mode and the PRO (AL-DS) orientation mode is illustrated below.



2.3 Forward osmosis (FO) membrane designs and materials

Asymmetric cellulose acetate and cellulose triacetate based forward osmosis membranes formed by phase inversion (both support membrane and active layer)

Before proceeding with the main content sections of this article, we would like to note that the information presented below is based – in part – on the excellent forward osmosis review article by Zhao et. al. (2012)

- *"Recent developments in forward osmosis: opportunities and challenges", Zhao et. al. 2012*

Asymmetric cellulose acetate and cellulose triacetate (CTA) membranes were some of the first polymeric membranes used by researchers in forward osmosis applications. And from a commercial point of view, a CTA based membrane was for a long time the only commercially available forward osmosis membrane product and is still produced and sold by Hydration Technology Innovations today.

One of the advantages of cellulosic membranes is that the support and active rejection layer are formed in the same process – phase inversion of a precursor dope solution followed by hot water annealing. In addition, cellulosic membranes are quite hydrophilic (i.e. good water flux performance and low propensity to fouling), have good mechanical strength, and membrane components are readily available commodities.

On the negative side, cellulosic membranes must be kept within a narrow operational window (pH 4-6 and temperature below 30° Celcius) in order to maintain operational integrity. This excludes cellulosic membranes from being used for treatment of harsh industrial waste waters.

When it comes to determining the performance characteristics of cellulose acetate or cellulose triacetate membranes forward osmosis membranes, research groups have directed their focus towards the CTA based membrane from HTI. Below is a short summary of some representative work. It is evident that the CTA membrane has some performance variation from batch to batch, or alternatively, that research groups have different ways of determining A, B, and S values.

Research work	A (LMH/ bar)	B (NaCl) (LMH)	S (μm)
Reverse draw solute permeation in forward osmosis: modelling and experiments, Philip et. al., 2010	0,44	0,265	481
Influence of concentrative and dilutive internal concentration polarization on flux behaviour in forward osmosis, McCutcheon et. al., 2006	N.A.	N.A.	360
Nano gives the answer: breaking the bottleneck of internal concentration polarization with a nanofiber composite forward osmosis membrane for a high water production rate, Song et. al., 2011	0,39	0,57	620

Thin film composite polyamide-based forward osmosis membranes formed by phase-inversion (support membrane) and interfacial polymerization (active layer)

Recently, polyamide-based thin film composite (TFC) membranes have been prepared for forward osmosis applications. TFC membrane formation is a two-step process. First a support membrane, typically composed mainly of polyethersulfone, is formed by phase inversion of precursor dope solution. Next, a thin (around 200nm) polymeric rejection layer is formed on top of the support membrane by interfacial polymerization of m-phenylenediamine (MPD) and trimesoyl chloride (TMC). A similar process has been used since the 1990ies to produce RO membranes. The difference between TFC FO and TFC RO membranes lies mainly is the support substrate, which for FO membranes is considerably more porous, more hydrophilic, and thinner.

Thin film composite forward osmosis membranes have several advantages over cellulosic FO membranes:

- Support higher working temperatures (in excess of 60° Celcius)
- Increased tolerance towards pH (pH range of 2-11 is tolerated)
- Higher A-values

The advantages of TFC membranes make them the preferred design for commercial forward osmosis membranes. However, due to the two-step process and the inherent difficulties in controlling the interfacial polymerization, TFC membranes are more expensive to produce than their cellulosic counterparts.

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Below is a short summary of TFC forward osmosis membrane performances reported in literature.

Research work	A (LMH/ bar)	B (NaCl) (LMH)	S (µm)
Relating performance of thin-film composite forward osmosis membranes to support layer formation and structure, Tirraferri et. al., 2011	1,90	0,33	312
Nano gives the answer: breaking the bottleneck of internal concentration polarization with a nanofiber composite forward osmosis membrane for a high water production rate, Song et. al., 2011	1,25	0,49	450

Thin film composite polyamide-based forward osmosis membranes based on electrospun nanofiber webs (support membrane) and interfacial polymerization (active layer)

Researchers have investigated different strategies for creating support membranes with smaller structural parameter values to reduce the negative effects of concentration polarization on forward osmosis performance. One promising strategy is to replace the traditional phase inverted polyethersulfone-based support membrane with a support membrane consisting of a thin polyethersulfone nanofiber web coupled to a poly (ethylene terephthalate) (PET) nonwowen substrate. Here, the nanofiber web provides a suitable interphase for interfacial polymerization and the PET substrate provides mechanical strength. With this approach, researchers have achieved structural parameters as low as 80µm.

Research work	A (LMH/ bar)	B (NaCl) (LMH)	S (µm)
Nano gives the answer: breaking the bottleneck of internal concentration polarization with a nanofiber composite forward osmosis membrane for a high water production rate, Song et. al., 2011	1,70	1,17	80

Thin film composite polyelectrolyte-based forward osmosis membranes formed by phase-inversion (support membrane) and layer-by-layer deposition (active layer)

In some applications, forward osmosis membranes with low rejection to NaCl outperform traditional high rejection membranes. In a sense, the trade-offs between low and high NaCl rejection FO membranes can be compared to the trade-offs between pressure-driven NF and RO membranes. Here, the larger pore diameter in the active layer of NF membranes yields higher water flux performance at the expense of lower rejection towards small solutes such as NaCl.

Low NaCl rejection forward osmosis membranes can be used in applications where the NaCl content of feed and draw streams is negligible or alternatively where it is advantageous to have NaCl pass across the membrane.

Within the last couple of years, researchers have utilized layer-by-layer deposition of oppositely charged polyelectrolytes to form selective layers with larger pore diameters. As shown in the brief summary below, A-values of polyelectrolyte-based forward osmosis membranes can exceed high NaCl rejection membranes by a factor 3-4.

Research work	A (LMH/bar)	B ($MgCl_2$) (LMH)	S (µm)
Synthesis of high flux forward osmosis membranes by chemically cross linked layer-by-layer polyelectrolytes, Qiu et. al., 2011	6,9	0,92	N.A.

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2.4 How forward osmosis (FO) performance is limited by concentration polarization

What is concentration polarization and why does it limit forward osmosis membrane performance?

Key Takeaways

- Concentration polarization is the build-up of concentration gradients both inside and around forward osmosis membranes during operation. Said gradients reduce the effective osmotic pressure difference across the membrane active layer and thus limit the attainable water flux.

In membrane processes there are – generally speaking – 4 types of c**oncentration polarization** falling into two main categories, namely **external concentration polarization (ECP)** and **internal concentration polarization (ICP)**, and two sub-categories; dilutive and concentrative:

For dense, symmetric membranes that reject feed and draw solutes, external concentration polarization takes places at the membrane surfaces:

1. On the feed side, solutes are concentrated at the surface, as water permeates through the membrane, giving rise to **concentrative ECP**
2. On the draw side, solutes are diluted at the surface, as water enters from the feed side, giving rise to **dilutive ECP**

For asymmetric membranes – containing both a dense rejection layer and an underlying porous support – internal concentration polarization takes place in the porous support layer and external concentration polarization on the inter-phase between the rejection layer and surrounding solutions:

1. When the dense rejection layer faces the feed solution (known as AL-FS or “FO-mode” configurations), the water permeating through the porous support layer dilutes the draw solutes inside the support, giving rise to **dilutive ICP**. In addition, **concentrative ECP** takes place on the dense rejection layer
2. When the dense rejection layer faces the draw solution (known as AL-DS or “PRO-mode” configurations), solutes inside the support are concentrated as water permeates through the membrane, giving rise to **concentrative ICP**. In addition, **dilutive ECP** takes place on the dense rejection layer

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Having introduced the basic concepts, the next part of this article will present a detailed overview of concentration polarization effects in FO membranes from a more scientific point of view. Equations, data and figures are based – among others – on the excellent research article by McCutcheon et. al.:

- *"Influence of concentrative and dilutive internal concentration polarization on flux behaviour in forward osmosis", McCutcheon et. al. 2006*

Forward osmosis membrane performance parameters and equations

In forward osmosis processes, the water flux J_W across the membrane and the reverse salt flux J_S from draw to feed are important membrane performance parameters. J_W and J_S are determined by the following equations:

$$J_W = A\Delta\prod_e$$

- A is the "pure water permeability coefficient" – an intrinsic membrane property
- $\Delta\prod_e$ is the effective osmotic pressure difference across the membrane's active layer (the dense rejection layer)
- J_W is predominantly reported in L/m^{2}h or LMH in short

$$J_S = B\Delta C$$

- B is the "salt permeability coefficient" – an intrinsic membrane property depending on the solutes used in the draw solution
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- ΔC is the difference in solute concentration across the active layer
- J_S is predominantly reported in g/m^{2}h or GMH in short

Thus, the build-up of concentration gradients in concentration polarization phenomena reduce both J_W and J_S through a decrease in both the effective osmotic pressure difference and the difference in solute concentration across the active layer, respectively. In order to quantify concentration polarization effects, the following assumption is traditionally made (McCutcheon et. al., 2006):

- J_S does not affect bulk solute concentrations and is therefore not considered

With this assumptions in place, the effective osmotic pressure across a FO membrane experiencing concentration polarization becomes (McCutcheon et. al., 2006):

<u>AL-FS configuration: dilutive ICP & concentrative ECP</u>

$$\Delta\prod_e = \prod_{D,m} - \prod_{F,m} = \prod_{D,B}*\exp(-J_W K) - \prod_{F,B}*\exp(J_W/k)$$

- $\prod_{D,m}$ is the osmotic pressure of the draw solution on the draw side of the active layer
- $\prod_{F,m}$ is the osmotic pressure of the feed solution on the feed side of the active layer
- $\prod_{F,B}$ is the bulk osmotic pressure of the feed solution
- $\prod_{D,B}$ is the bulk osmotic pressure of the draw solution
- J_W is the water flux
- K is the solute resistivity for diffusion (see below)
- k is the mass transfer coefficient

- $\exp(-J_W K)$ is the reduction factor of draw solution osmotic pressure due to dilutive ICP
- $\exp(J_W/k)$ is the amplification factor of feed solution osmotic pressure due to concentrative ECP

In the case of feed solutions with low bulk osmotic pressures, the effect of concentrative ECP is limited meaning that $\Pi_{F,m} \approx \Pi_{F,B}$ (i.e. $\exp(J_W/k) = 1$). Hence, in forward osmosis processes under the AL-FS configuration, the main contribution to concentration polarization comes from dilutive ICP when the feed water has low osmotic pressure.

AL-DS configuration: concentrative ICP & dilutive ECP

$$\Delta\Pi_e = \Pi_{D,m} - \Pi_{F,m} = \Pi_{D,B} * \exp(-J_W/k) - \Pi_{F,B} * \exp(J_W K)$$

- $\exp(-J_W/k)$ is the reduction factor of draw solution osmotic pressure due to dilutive ECP
- $\exp(J_W K)$ is the amplification factor of feed solution osmotic pressure due to concentrative ICP
- See above for remaining parameter descriptions

In the case of feed solutions with low bulk osmotic pressures, the effect of concentrative ICP is limited meaning that $\Pi_{F,m} \approx \Pi_{F,B}$ (i.e. $\exp(J_W K) = 1$). Hence, in forward osmosis processes under the AL-DS configuration, the main contribution to concentration polarization comes from dilutive ECP when the feed water has low osmotic pressure.

The mass transfer coefficient k depends on the flow configuration across membrane surfaces, which again is determined by characteristic dimensions of the flow chamber surrounding the FO membrane. Mass transfer coefficients are thus not determined by intrinsic FO membrane parameters and will not be treated in detail here. The solute resistivity for diffusion (K) turns out to be a key determinant of FO membrane performance determined – in part – by intrinsic membrane parameters . Within the scientific field of FO membrane performance optimization, the majority of developments are focused on reducing K values. And from the equations above it is easy to see why.

Key Takeaways

- The smaller the K value, the easier it is for solutes to diffuse inside the porous support layer, and the smaller the negative effect of internal concentration polarization on membrane performance becomes.

The K value therefore deserves further elaboration:

$$K = (t*\tau)/(D*\varepsilon) = S/D \text{ , where } S = (t*\tau)/(\varepsilon)$$

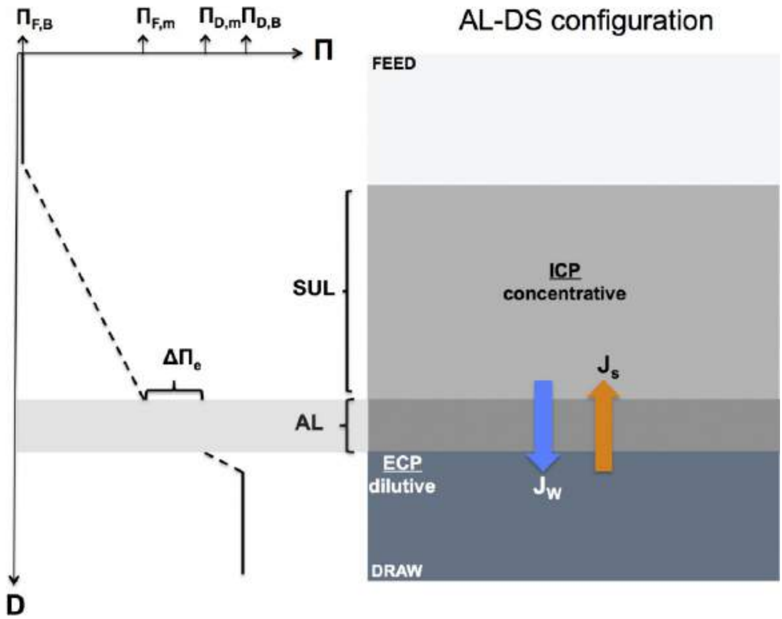
- t is the support layer thickness
- τ is the support layer tortuosity (a measure of the degree of “twisting” of the pores in the support layer)
- ε is the support layer porosity (a measure of the amount of “empty” space in the support layer)
- D is the diffusion coefficient of the draw solute
- S is known as the structural parameter and it is an intrinsic property of the support layer. Typical S values for good forward osmosis membranes are around 300μm (Tiraferri et. al., 2011)

For a great article relating performance of FO membranes to the structural parameters of their support layers, please refer to:

- *"Relating performance of thin-film composite forward osmosis membranes to support layer formation and structure", Tiraferri et. al. 2011*

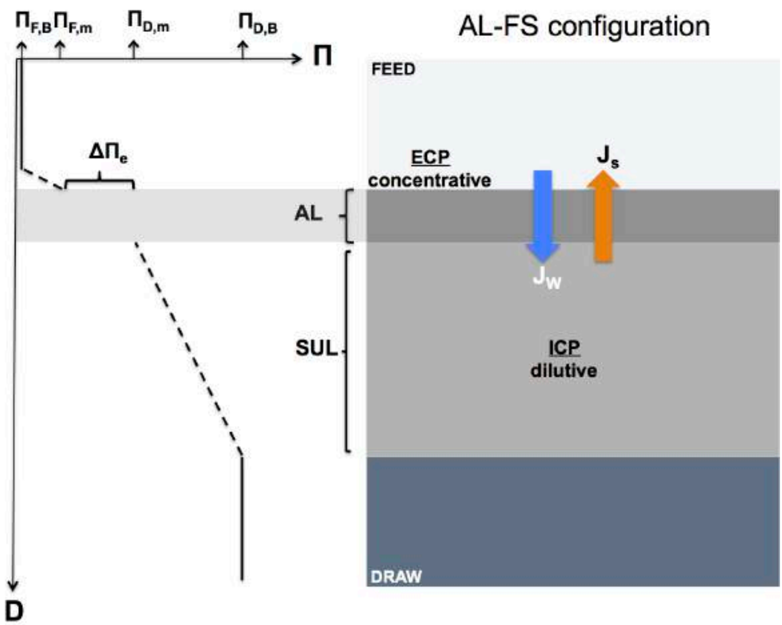
Forward osmosis concentration polarization when the active layer faces the draw solution (AL-DS or "PRO mode" configuration)

The figure below illustrates how concentration polarization reduces the effective osmotic driving force in the AL-DS configuration. Notice that both external and internal concentration polarization have been included in the figure for illustrative purposes.



Forward osmosis concentration polarization when the active layer faces the feed solution (AL-FS or “FO mode” configuration)

The figure below illustrates how concentration polarization reduces the effective osmotic driving force in the AL-FS configuration. Notice that both external and internal concentration polarization have been included in the figure for illustrative purposes.



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Some calculated examples of flux reduction as a result of internal concentration polarization

The numbers in the tables below are based on the following data for a good performing forward osmosis membrane with sodium chloride (NaCl) as draw solution:

- S = 300µm (Tiaferri et. al., 2011)
- D_{NaCl} = 1,61*10^{-9} m^2/s (Philip et. al., 2010)
- A = 2 LMH/bar (Tiaferri et. al., 2011)

→ Let's first examine the case where there's no internal concentration polarization:

$\Pi_{D,B}$ (bar)	$\Pi_{F,B}$ (bar)	$\Delta\Pi$ (bar)	J_w (LMH)
20	4	16	32
30	4	26	52
40	4	36	72
50	4	46	92

→ And the case with concentrative ICP in the AL-DS configuration:

$\Pi_{D,B}$ (bar)	$\Pi_{F,B}$ (bar)	Fixed J_w (LMH)	Fixed J_w (m/h)	J_w*K	$\Pi_{F,m}$ (bar)	$\Delta\Pi_e$ (bar)	J_w potential (LMH)
20	4	10	0,01	0,52	7	13	26
30	4	20	0,02	1,0	11	19	38
40	4	30	0,03	1,6	19	21	42
50	4	40	0,04	2,1	32	18	36

In the calculations above, a fixed system water flux has been adopted and based on this value, the reduced osmotic pressure difference ($\Delta\Pi_e$) due to concentrative ICP has been calculated along with the water flux potential associated with the reduced osmotic pressure difference. Now, fixing the system water flux is a bit artificial – but a necessary step to performing the calculations. It is interesting to note, that $\Delta\Pi_e$ for the $\Pi_{D,B}$ = 50 example is actually lower than for $\Pi_{D,B}$ = 40, indicating that progressively higher draw solution osmotic pressures are needed to overcome concentration polarization effects in high-flux FO processes. This fact is illustrated in the following table where it has been calculated what the bulk draw solution bulk osmotic pressures should actually be for the fixed J_W's to equal the potential J_W's.

$\Pi_{D,B,\ actual}$ (bar)	$\Pi_{F,B}$ (bar)	Fixed J_w (LMH)	Fixed J_w (m/h)	J_w*K	$\Pi_{F,m}$ (bar)	$\Delta\Pi_e$ (bar)	J_w potential (LMH)
12	4	10	0,01	0,52	7	5	10
21	4	20	0,02	1,0	11	10	20
34	4	30	0,03	1,6	19	15	30
52	4	40	0,04	2,1	32	20	40

→And finally, the same two tables for dilutive ICP in the AL-FS configuration:

$\Pi_{D,B}$ (bar)	$\Pi_{F,B}$ (bar)	Fixed J_w (LMH)	Fixed J_w (m/h)	J_w*K	$\Pi_{D,m}$ (bar)	$\Delta\Pi_e$ (bar)	J_w potential (LMH)
20	4	10	0,01	0,52	12	8	16
30	4	20	0,02	1,0	11	7	14
40	4	30	0,03	1,6	8	4	8
50	4	40	0,04	2,1	6	2	4

$\Pi_{D,B,\ actual}$ (bar)	$\Pi_{F,B}$ (bar)	Fixed J_w (LMH)	Fixed J_w (m/h)	J_w*K	$\Pi_{D,m}$ (bar)	$\Delta\Pi_e$ (bar)	J_w potential (LMH)
15	4	10	0,01	0,52	9	5	10
39	4	20	0,02	1,0	14	10	20
90	4	30	0,03	1,6	19	15	30
190	4	40	0,04	2,1	24	20	40

Notice how the draw solution osmotic concentration must be increased to 190 bar to achieve a J_w of 40 LMH in the AL-FS configuration whereas only 52 bar was necessary to achieve the same flux in the AL-DS configuration. This example clearly demonstrates how dilutive internal concentration polarization on the draw side has a severer negative effect on water flux than concentrative internal concentration polarization on the feed side. For the same reason, researchers, publishing articles on forward osmosis membrane developments, almost always choose the AL-DS configuration when determining membrane water flux performance:

Key Takeaways

- Membrane researchers prefer the AL-DS when reporting the performance of their membranes, because forward osmosis membranes have the best water flux performance in this configuration

Notes: We do our best to check the validity of our calculations, however, no responsibility is taken for calculation errors.

2.5 S-value calculator for forward osmosis membranes

ForwardOsmosisTech has just made it easier for you to estimate structural parameters (S-values) of FO membranes

From our article covering concentration polarization effects in forward osmosis membranes, it is clear that FO membrane performance – to a large extent – is determined by S-values.

Below we present an easy-to-use calculator for estimating structural parameters of forward osmosis membranes. The calculator is based on equations developed by McCutcheon et. al.

Here's what you need to estimate FO membrane S-values

In order to estimate S-values using ForwardOsmosisTech's calculator you will need to determine the following FO membrane performance parameters and intrinsic membrane properties:

- The pure water membrane permeability coefficient (A)
- The salt permeability coefficient (B)

- The water flux J_W – IN FO MODE – at a given osmotic driving force

For more details, please refer to our guide on how to determine FO membrane performance.

A few notes and suggested guidelines

- The calculator is based on the following S-value equation for an FO membrane operating in FO mode:
  - $S = (D/J_W)*\ln((B+A*\prod_{D,B})/(B+J_W+A*\prod_{F,m}))$.
  - D is the diffusion coefficient for the draw solute used for J_W (our equation assumes NaCl is used as standard)
  - $\prod_{D,B}$ is the osmotic pressure of the bulk draw solution
  - $\prod_{F,m}$ is the osmotic pressure of the feed solution close to the membrane surface
  - Providing membrane water flux performance is determined according to our suggested standardized methods, $\prod_{F,m}$ is assumed to be negligible (i.e. $\prod_{F,m} = 0$)
- Due to our assumption of $\prod_{F,m} = 0$ along with other assumptions made by McCutcheon et. al., ForwardOsmosisTech's S-value calculator should be used for estimations only
- For an improved estimation, we suggest researchers to measure J_W – and calculate the corresponding S-value – at 4 different initial draw solution concentrations, namely 0.25M NaCl, 0.5M NaCl, 1M NaCl, and 2M NaCl. The final S-value estimation is to be reported as the average of the 4 independent measurements

- For cutting-edge FO membrane performance, researchers should aim for S-values below 300μm

And with no further ado, here's the online version of the calculator:

ForwardOsmosisTech's S-value calculator

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2.6 Membrane fouling in forward osmosis (FO) processes is reversible

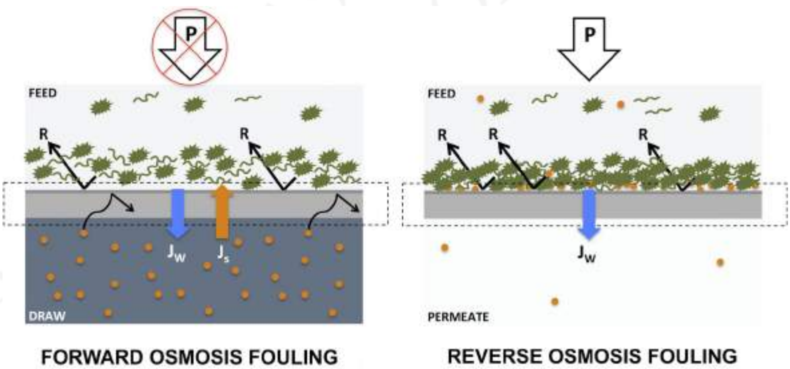
Membrane fouling in reverse osmosis and forward osmosis processes

The difference in membrane fouling between reverse osmosis and forward osmosis processes can be attributed to the underlying driving force for water transport.

In reverse osmosis, a hydraulic pressure is applied to overcome the osmotic pressure of the feed solution, thus – in effect – pushing water molecules through the rejection layer of the RO membrane.

In forward osmosis, an osmotic gradient is used to drive water molecule diffusion through the rejection layer of the FO membrane.

In both reverse osmosis and forward osmosis processes, pollutants are retained on the feed side of the rejection layers, causing a build-up of fouling layers over time (see the illustration below). However, due to the lack of hydraulic pressure in the FO process, fouling layers on FO membranes are less compact and therefore easier to remove in subsequent cleaning cycles. This phenomenon has been described in several scientific publications including Mi et. al. 2009 (“Organic fouling of forward osmosis membranes: Fouling reversibility and cleaning without chemical reagents”) and Kim et. al. 2013 (“Combined organic and colloidal fouling in forward osmosis: Fouling reversibility and the role of applied pressure”).



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Organic fouling comparison: forward osmosis and reverse osmosis membranes

In their 2009 work, Mi and co-workers used a CTA forward osmosis membrane and feed solutions containing alginate – a model organic foulant – to demonstrate higher cleaning efficiency of the CTA membrane when it was run in forward osmosis mode as compared to reverse osmosis mode. Using a 15 min in situ cleaning process based on running 50mM NaCl through the test chamber at a crossflow velocity of 21 cm/s (i.e. simple physical cleaning based on scouring), CTA membrane performance returned to 99% of baseline performance for forward osmosis mode and only 70% for reverse osmosis mode.

Mi et. al. attributed this reversibility of forward osmosis membrane fouling to the loose structure of the fouling layer and conclude that:

Key Takeaways

- Operating in FO mode may offer an advantage of significantly reducing or even eliminating the need for chemical cleaning (from Mi et. al., 2009)

Fouling reversibility comparison: forward osmosis and reverse osmosis processes

In related work from 2013, Kim and co-workers investigated the fouling reversibility of combined organic (alginate) and colloidal (silica particles) fouling on a CTA forward osmosis membrane run in forward osmosis and reverse osmosis modes respectively. After fouling runs, membranes were subjected to a 1 h physical cleaning process based on running the original feed and draw solutions from the start of the experiment at an elevated crossflow velocity of 34,44 cm/s (up from 8,61 cm/s during the fouling run). Care was taken to ensure that the water flux across membranes were identical in individual fouling runs when comparing fouling in forward osmosis and reverse osmosis mode respectively.

The researchers found that fouling in forward osmosis mode was fully reversible – with the given physical cleaning process – when either organic or colloidal foulants were used individually. However, for the combination of organic **AND** colloidal foulants, flux reversibility was reduced to between 80% and 95% depending on the pH of the feed solution. Importantly, when hydrostatic pressure was introduced in reverse osmosis fouling runs, the fouling layers caused more severe flux reduction and **COULD NOT** be removed with the given physical cleaning process described above.

In line with the findings of Mi et. al., Kim et. al. conclude:

Key Takeaways

- Operation under an osmotic pressure driving force (i.e. FO) results in less fouling and exhibits higher fouling reversibility compared to operation at hydraulic pressure driving force (i.e. RO). The impact of hydraulic pressure is attributed to the formation of more compact and dense fouling later of the deformable organic foulants and organic-colloidal aggregates (from Kim et. al., 2013)

Chapter 3 - Forward Osmosis Membrane Modules

FO membrane modules come in 4 generic design variants, namely the plate & frame module, the spiral wound module, the tubular module, and the hollow fibre module.

In this chapter each FO membrane module design is introduced and characterized according to achievable packing density and industrial application areas.

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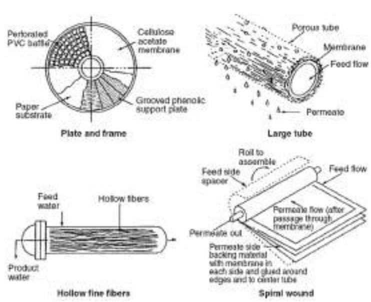
3.1 The 4 different designs of forward osmosis (FO) membrane modules

An overview of the 4 different types of forward osmosis (FO) membrane modules



From SINCERO & SINCERO (2003)

FO membrane modules come in 4 generic design variants, namely the plate & frame module, the spiral wound module, the tubular module, and the hollow fibre module. Arguably, the tubular module and the hollow fibre module are quite similar in as much as the only difference between them is the inner dimensions of their tubular/hollow fibre membrane components. Nevertheless, here, the designs are treated separately because they potentially cater to different application areas.

In the following article series, each FO membrane module design is introduced and characterized according to the following criteria:

1. Achievable packing density (i.e. active membrane area per inner unit volume of the module)
2. Industrial application areas

The packing density has been chosen as a characterization criteria because it significantly contributes to the overall footprint of an FO system (smaller packing density = larger FO system footprint and vice versa).

3.2 Plate and frame forward osmosis membrane modules

Plate & frame modules made from flat sheet forward osmosis membranes

Plate & frame (stacked) FO module summary

Packing density	typically below 100 m^2/m^3
Advantage	ease of operation when waste streams contain high amounts of fouling agents and/or solutions entering the module have high viscosities
Disadvantage	large footprint increases space requirements – not suitable for high volume applications

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Detailed description

Image courtesy of Google

Plate & frame membrane modules – also known as stacked membrane modules – are used in many water treatment applications where the waste streams to be treated contain high amounts of fouling agents and/or have high viscosities. In fact, many commercial membrane bioreactor (MBR) modules belong to the plate & frame configuration. Plate & frame modules typically consist of flat sheet membranes sealed to frames, which provide the overall mechanical integrity and flow distribution needed to stack individual frames together in a modular way. Thus, individual frames function as membrane cassettes where the waste stream to be treated typically flows outside the cassette with the clean water permeating to the inner volume of the cassette for subsequent collection.

Forward osmosis plate & frame modules are – in principle – constructed in a similar manner with the added complexity that the frame/cassette/module designs must accommodate cross flow distribution of feed and draw streams across each individual membrane layer while avoiding direct mixing of said feed and draw streams.

From an engineering point of view, it is difficult to achieve such cross flow distributions, and at the same time avoid unstirred regions/flow maldistribution, when the distance between
~~~

individual membrane layers is reduced. As a result, plate and frame forward osmosis membrane modules typically have the lowest packing density / largest footprint of the 4 module design variants considered here (see the table below).

The large footprint of plate & frame forward osmosis membrane modules excludes these modules from being used in high volume applications such as municipal waste water treatment and desalination of seawater. However, in many lower volume applications, where the waste streams to be treated contain high amounts of fouling agents and/or have high viscosities, the low packing density of plate & frame modules represents an operational advantage. The reason being, that a larger distance between membrane sheets results in a lower pressure drop across the module (i.e. lower energy requirement for pumping solutions through the module) as well as a lower propensity towards clogging of flow channels due to accumulation of fouling agents.

Parameter	Value
Area of individual sheets (including sealing)	0,25m^2
Active membrane area per sheet (excluding sealing)	0,23m^2
Thickness of individual membranes	200µm
Distance between membrane sheets	8mm
Number of sheets per module	43
Internal volume of module	0,09m^3
Active area per module	9,9m^2
Packing density	110

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3.3 Tubular forward osmosis membrane modules

Tubular modules made from tubular forward osmosis membranes

Tubular module summary

Packing density	Up to 500 m^2/m^3
Advantage	ease of modularization and ease operation when wastestreams contain high amounts of fouling agents and/or solutions entering the module have high viscosities
Disadvantage	tube wall thickness might limit the water flux performance of tubular FO membrane modules to a level where the modules are not economically viable

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Detailed description

Image from trihigh.com

Membrane modules based on tubular membranes are well-know in the water treatment industry for ultra-filtration applications with high fouling / high viscosity waste water streams. Briefly, porous tubes with inner diameters ranging from 5mm to 15mm are coated with micro-porous layers of PVDF or PES on either the inside or outside walls. Depending on the orientation of the micro-porous layer, tubular modules – consisting of individual tubular membranes fitted into a cylindrical housing – are either operated in outside-in (waste water stream flowing outside individual tubes) or inside-out (waste water stream flowing inside individual tubes) configurations.

From a forward osmosis module point of view, tubular modules should be seen as an alternative to plate and frame modules in applications with high fouling / high viscosity waste water streams. Compared to plate and frame modules, tubular modules offer two main advantages compared to plate and frame modules:

1. Up to 4-5 times higher packing densities (refer to the table below) significantly reduce the overall footprint of tubular forward osmosis modules
~~~

2. Tubular modules are inherently easier to produce since they only require sealing at either end of the module

However, there are also drawbacks to using tubular forward osmosis membranes. First of all such membranes are currently not commercially available and most R&D efforts are directed towards flat sheet and hollow fibre FO membranes. Secondly, the overall thickness of the porous tube wall – including the PVDF or PES micro-porous layer – might render the tubular configuration unfit for forward osmosis processes due to severe build-up of internal concentration polarization.

Parameter	Value
Tube length	1m
Tube wall thickness	0,4mm
Tube inner diameter	10mm
Tube inner area	0,031m^2
Inner diameter of module	220mm
Number of tubes in module	319**
Internal volume of module	0,038m^2
Active area per module	10m^2
Packing density	260

** See engineeringtoolbox.com for an online calculation tool of how many small circles fit into a large circle

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3.4 Spiral wound forward osmosis membrane modules

Spiral wound modules made from flat sheet forward osmosis membranes

Spiral wound module summary

Packing density	up to 600 m^2/m^3
Advantage	suitable for large-volume applications due to high packing density and resulting small membrane footprint
Disadvantage	membrane fouling is a big problem if waste water streams are not pre-treated to remove the majority of fouling agents,

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Detailed description

Image from microdyn-nadir.com

Spiral wound modules represent the most common membrane configuration in today's water treatment industry. The reason mainly being a combination of high achievable packing density and the fact that spiral wound modules are based on flat sheet membranes – the most common membrane form factor in today's membrane production industry. Spiral wound modules for reverse-osmosis mediated desalination of seawater can reach packing densities as high as 1200 m^2/m^3 (8 inch modules from Toray). To achieve this kind of packing density, the distance between membrane layers becomes less than 1mm, and as a result spiral wound modules tend to foul very easily if waste water streams are not pretreated before entering the modules.

When it comes to spiral wound forward osmosis modules, packing densities cannot reach the same values as is the case for spiral wound reverse osmosis modules (refer to the table below for a calculation example). The reason being, that in forward osmosis processes there must be a cross flow of solutions on either side of each individual membrane layer. This requirement increases the total thickness of spacers between
~~~

membrane layers and subsequently decreases the packing efficiency. Having said that, spiral wound forward osmosis membrane modules from Hydration Technology Innovations have packing densities close to 600 m^2/m^3. Since flat sheet membranes are currently the predominant membrane configuration in the FO membrane production industry, it is expected that spiral wound modules will constitute the bulk of upcoming FO module products for large-volume water treatment applications. For reasons similar to what was mentioned for hollow fiber FO membrane modules, usage of spiral wound FO modules for industrial water treatment is limited to applications where waste water streams contain low concentrations of fouling agents. Such applications include:

1. Desalination
2. Downstream waste water processing steps

Parameter	Value
Membrane width	0,5m
Membrane length	20m
Thickness of individual membranes	200µm
Spacer thickness	3mm
Inner diameter of collection tube	10mm
Outer diameter of membrane roll	278mm*
Internal volume of module	0,03m^3
Active area per module	9,5m^2
Packing density	320

* See giandrandi.ch for an online calculation tool of membrane roll diameter

3.5 Hollow fiber forward osmosis membrane modules

Hollow fibre modules made from hollow fibre forward osmosis membranes

Hollow fibre module summary

Packing density	up to 1600 m^2/m^3
Advantage	ideally suitable for high volume applications due to high packing density and resulting small module footprint
Disadvantage	prone to fouling / membrane clogging at low concentrations of fouling agents

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Detailed description

Image from pentair.com

Hollow fibre modules are basically tubular modules with very high packing densities (see the table below), and are used extensively for large-volume water treatment applications, such as desalination of seawater via reverse osmosis processes, where a small module footprint is essential for the economical viability of the given membrane installation. Hollow fibre membranes are prone to fouling and clogging due to their small internal diameters. This is also the case for forward osmosis hollow fibre membranes and therefore usage for industrial water treatment is limited to applications where waste water streams contain low concentrations of fouling agents. Such applications include:

1. Desalination
2. Downstream waste water processing steps

Parameter	Value
Hollow fibre length	1m
Hollow fibre wall thickness	0,2mm
Hollow fibre inner diameter	1mm
Hollow fibre inner area	0,0031m^2
Inner diameter of module	90mm
Number of hollow fibres in module	3227***
~~~

Internal volume of module	0,0064m^3
Active area per module	10m^2
Packing density	1600

*** See engineeringtoolbox.com for an online calculation tool of how many small circles fit into a large circle

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3.6 Inquiry: draw and feed circulation paths in FO modules

How do draw and feed streams circulate in an FO module?

Most of us who are interested in forward osmosis technologies and their applications are familiar with the general concept of how forward osmosis works. There's a draw solution, a feed solution, a forward osmosis membrane, and some circulation of feed and draw solutions of either sides of the membrane. However, picturing the exact circulation paths inside FO modules with varying geometries and form factors can sometimes be challenging.

Jose approached ForwardOsmosisTech on exactly this topic with the following questions:

> *Please help!*
>
> *I can not understand the disposition on each design of plate*

and frame, spiral and tubular geometries. How does the raw water and draw solution flow inside these modules?

Could you describe the circulation path of each design for the FO membrane? I understand the circulation in the flow chart but I can´t understand it on the real module.

I think each module is like a RO module, but where is the path for the draw solution?

Is the membrane the same in RO than in FO?

Thanks in advance for your helping

Best regards

Jose

Here are ForwardOsmosisTech's answers to Jose's questions

Is the membrane the same in RO than in FO?

No. Since the driving force in reverse osmosis processes is hydraulic pressure compared to osmotic pressure in forward osmosis processes, reverse osmosis membranes and forward osmosis membranes are inherently different. A good RO membrane is a poor FO membrane and vice versa. We have previously published a guide on forward osmosis membranes and membrane processes, which gives an introduction to the difference between RO and FO membranes.

What are the circulation paths for feed (raw water) and draw solutions inside ***spiral wound FO modules, plate and frame FO modules****,* ***and tubular FO modules****?*

In general, forward osmosis processes require flow (typically cross flow) of draw and feed solutions on either side on the forward osmosis membrane. This requirement is the same in modules with varying geometric form factors.

Sterlitech have made a useful animation showing the counter current flow of feed and draw solutions in a forward osmosis test cell.

As for the flow path in different types of modules, I'm afraid we do not have any specific FO animations to help. Having said that, Hydranautics have made a useful animation on the flow paths in an RO spiral wound module. When viewing the animation try to imagine the permeate side being replaced by a flowing stream of draw solution; that's pretty much how the flow path will be in a spiral wound forward osmosis module.

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Chapter 4 - Forward Osmosis Systems

"FO system" is common term for all the components needed to enable FO membranes to be applied for real-life applications. These components typically include: The FO membrane housing (also know as an FO module), pumps, pipes, valves, feed stream pre-treatment systems, various instruments & meters for continuous performance evaluation, draw solution reservoir, feed solution reservoir, performance enhancing design elements, and – in the case of hybrid FO systems – a draw solution regeneration system.

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4.1 Forward osmosis system design

An introduction to forward osmosis system design

Image from htiwater.com

In any given real life application, forward osmosis membrane performance will be quantified by the water flux Jw, the reverse salt flux Js, and the rejection R towards feed stream contaminants. Improved Jw and Js values are obtained by increasing membrane A-values and decreasing membrane B-values and S-values. Real-life applications of FO membranes mounted in FO systems will have different requirements on Jw, Js, and R-values. And without a good understanding of these requirements, forward osmosis membrane developers run the risk of designing membranes that under-perform in the given application.

When considering FO system design, a definition of "FO system" is required. Here, "FO system" is common term for all the components needed to enable FO membranes to be applied for real-life applications. These components typically include: The FO membrane housing (also know as an FO module), pumps, pipes, valves, feed stream pretreatment systems, various instruments & meters for continuous performance evaluation, draw solution reservoir, feed solution reservoir, performance enhancing design elements, and – in the case of hybrid FO systems – a draw solution regeneration system.

FO system developers typically have 2 main objectives: reducing external concentration polarization effects and reducing membrane fouling. External concentration polarization (ECP) takes place on the surface of the active layer as water is extracted from the feed stream into the draw stream, and can be either concentrative (active layer facing feed stream) or dilutive (active layer facing draw stream). The end result of ECP is identical to that of internal concentration polarization: reduced effective osmotic driving force resulting in reduced water flux performance. Membrane fouling is common term for the build-up of deposited solutes or particles onto the membrane's surface or into the membrane's pores in a way that degrades overall membrane performance.

It is important to note, that current FO system design efforts work towards maintaining membrane A, B, and S values when the membrane is in operation but cannot improve A, B, and S values compared to what the membrane was "born" with.

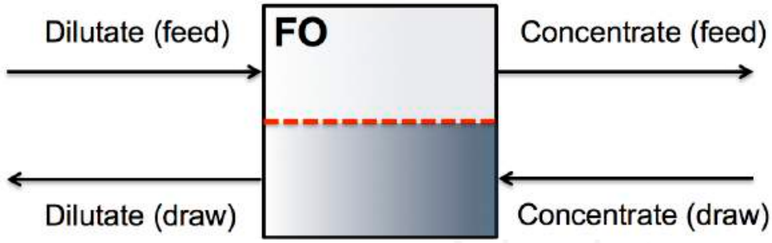
Key Takeaways

- In today's world, you cannot equip an FO system with an under-performing FO membrane and expect superior system design to boost membrane performance to acceptable levels

4.2 Stand-alone forward osmosis systems for low energy water extraction and osmotic power production

General classification of forward osmosis systems and their applications

FO systems can be divided into two broad categories, namely stand-alone FO systems and hybrid FO systems. Here, stand-alone FO systems are described in more details.



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In a stand-alone FO system, as illustrated schematically above, the outputs are a concentrated feed solution and a diluted draw solution. As such, the stand-alone FO system can be viewed as an energy-efficient water extractor; extracting water from the low concentration feed side to the high concentration draw side.

Water extractor for industrial process optimization

A typical example of a stand-alone FO system application is where the feed and draw solutions represent waste water streams, which become cheaper to dispose of once they are concentrated and diluted respectively.

Specifically, researchers have proposed to use the brine waste from the process of desalinating seawater as the draw solution to concentrate industrial or municipal waste water. Brine waste, with its higher density compared to seawater, drops to the ocean floor in large plumes upon discharge. If these plumes reach the ocean floor without being sufficiently diluted, the marine life on the seabed is damaged. Consequently, brine waste must be discharged through long pipelines to a distance from the shore where the ocean depth facilitates sufficient dilution of the brine plumes. Construction of said pipelines combined with the OPEX costs of pumping the brine constitute a significant part of the total costs of desalination.

Hence, the economical benefits of using a stand-alone FO system to dilute brine waste and at the same time concentrate industrial or municipal waste water, include:

- The diluted brine can be safely discharged closer to the shore, saving costs of pipeline construction & operation
- The industrial or municipal waste water has been reduced in volume, saving costs of transporting the waste water to subsequent treatment facilities

Osmotic power generators

In another application of a stand-alone FO system application, the feed stream is a low TDS (total dissolved solids) fresh water source (e.g. river water, reject from a water reclamation plant, surface water etc.) and the draw stream is a high TDS water source (e.g. seawater, brine reject from desalination etc.). During operation, the water extracted from the low concentration feed to the high concentration draw is used to build up hydraulic pressure on the draw side. The pressure generated in this process can subsequently be harnessed for energy production. The process of generating energy from osmotic pressure differences is referred to as pressure retarded osmosis (or PRO in short).

The economical benefits of PRO, in the case where the draw stream is brine reject from desalination, include:

- Energy production
- The diluted brine can be safely discharged closer to the shore, saving costs of pipeline construction & operation in desalination plants

The global energy potential of PRO is estimated to 2000 TWH/year compared to a global energy production of all renewable sources of 10000 TWH/year (Achilli et. al., 2009). At an estimated average global energy price of 0,2 USD/kWh (Wikipedia and www.energy.eu), the energy potential from PRO is worth a whopping 400 billion USD/year.

Statkraft, a Norwegian state owned Electricity Company with Europe’s largest production of renewable energy, and SINTEF, Scandinavia’s largest independent research organization, were until recently[1] at the forefront of PRO development. Scientists at Statkraft and SINTEF have estimated that PRO membranes are commercially profitable if they can deliver a power density of at least 5 W/m^2 or more (Achilli et. al, 2009). With a power density of 5 W/m^2 and energy prices of 0,2 USD/kWh, a PRO system will generate yearly revenue of 8,8 USD/m^2. According to Loeb et. al. (Loeb et. al., 1976), the yearly cost of energy production[2] – excluding membrane costs – in PRO systems amounts to 2,8 USD/m^2. Thus the net yearly revenue is 6 USD/ m^2, and with an expected membrane lifetime of 5 years, the lifetime gross profit generated per m^2 of membrane adds up to 30 USD/m^2. This leaves plenty of room for a potential PRO module sales price up to 20 USD/m^2 (leaving a net lifetime profit of 10 USD/m^2), which is double the current sales price of standard RO modules for desalination. The potential PRO module sales price is expected to increase in time as energy prices rise (potentially through subsidizing) and membrane performance increases.

With a power density of 5 W/m^2, a total installed membrane area of 46 Gm^2 (46000km^2 or roughly the size of Denmark) is needed to capture the full PRO energy potential of 2000 TWH/year. At a 20 USD/m^2 sales price, the total global market potential for PRO membranes – excluding overall osmotic generator system costs – then comes in at 920 billion USD.

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[1] December 20th 2013, Statkraft announced that they were puling the plug on their PRO work. Most likely this decision was a direct result of a lack of commercially available low-cost high-performance PRO membranes

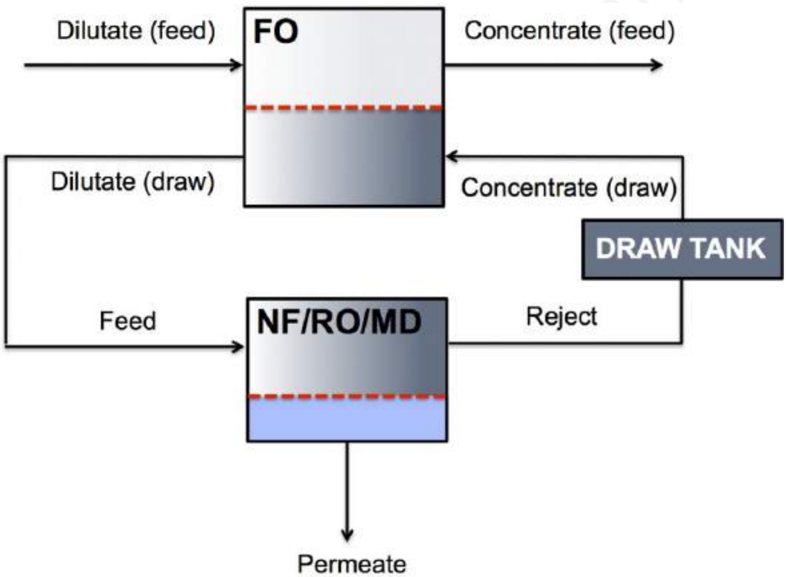
[2] Production costs include fixed costs of production, costs

of pre-treatment facilities, hydro turbine and generator costs, labor costs, and diversion dam costs.

4.3 Hybrid forward osmosis systems for desalination of seawater and wastewater treatment

General classification of forward osmosis systems and their applications

FO systems can be divided into two broad categories, namely stand-alone FO systems and hybrid FO systems. Here, hybrid FO systems are described in more details.



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In a hybrid FO system, as illustrated schematically above, the outputs are a concentrated feed solution and permeate consisting of reusable water (potable or non-potable depending on the design of the system). In a hybrid FO system, the FO part still functions as an energy-efficient water extractor; extracting water from a feed stream, which is difficult (=expensive) to treat with traditional membrane technologies, to a draw stream that is considerably easier (=less expensive) to treat when it is diluted by the FO process.

Seawater desalination systems for production of potable water

In one large-scale example of a hybrid FO system application, the feed stream is a high volume source of waste water such as municipal waste water or urban run-off water and the draw stream is seawater. During operation, the FO sub-system extracts fresh water from the waste water stream, thus reducing its volume, and at the same time the seawater draw is diluted to a point where it can be desalinated by a low pressure brackish water RO (BWRO) system to produce potable fresh water permeate.

Hence, the economical benefits of using a hybrid FO/BWRO system to dilute seawater and at the same time concentrate a high volume source of waste water, include:

- The diluted seawater requires less energy to be desalinated
- The waste water has been reduced in volume, saving costs of transporting the waste water to subsequent treatment facilities

Waste water treatment systems for waste water reduction and parallel production of reusable process water

In another, more specialized, example of a hybrid FO system application, the feed stream is waste water with high amounts of total suspended solids (TSS) and other difficult-to-treat pollutants and the draw stream is tailored for the given application. Waste water with high TSS is difficult to treat with traditional pressure-driven membrane technologies due to continuous membrane clogging (fouling) and ensuing membrane performance decrease. In order to treat high TSS waste waters with pressure-driven membranes, pre-treatment processes are necessary, which further increase CAPEX and OPEX costs. However, forward osmosis membranes are far less prone to fouling, which makes them ideally suited to treat high TSS waste water. During operation, the FO sub-system extracts fresh water from the high TSS waste water stream, thus reducing its volume, and at the same time the tailored draw is diluted and fed through a second membrane sub-system to produce potable fresh water permeate and a re-concentrated draw solution.

Hence, the economical benefits of using a hybrid FO/(RO, NF, or MD) system to reduce volumes of difficult waste water, include:

- Implementing low-fouling FO membranes as the first barrier towards the waste water reduces both the need for pre-treatment and the O&M (operation and maintenance) costs of running the pressure-driven membrane sub-systems since they now operate on lower fouling streams
- The waste water has been reduced in volume, saving costs of transporting the waste water to subsequent treatment facilities
- The permeate can be re-used for industrial processes

Finally, by tailoring the rejection properties of the FO membrane sub-system as well as the other sub-systems of the hybrid, it is also possible to recover low molecular weight solutes such as NaCl from the feed stream. This is especially of value in the textile industry where large amounts of salts are otherwise lost in waste water streams.

Chapter 5 - Forward osmosis applications and commercialization

> In comparison to traditional pressure-driven technologies, forward osmosis, being driven by osmotic gradients instead of energy intensive hydraulic pressure, represents a radical innovation from the viewpoint of minimizing energy expenditure in water treatment processes. As such, commercially available, high-performance FO-based systems have the potential to significantly outperform traditional technologies when it comes to increasing productivity.

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5.1 Commercialization drivers in today's water treatment market

Increased productivity is the main commercialization driver in today's water treatment market

Image courtesy of Google

We – humanity – find ourselves in a situation where, in order to solve the water challenges we have created for ourselves, we need energy to power water treatment systems. Couple this with the facts that accessible forms of energy are becoming increasingly scarcer – and thus more expensive – as well as an increasing amount of water related challenges originating from energy production, and it easy to see that we find ourselves in a classical example of a vicious circle.

When considering the commercialization of new water treatment technologies, the above explains why **increased**

productivity is the major drivers for developing and implementing new energy-efficient water treatment technologies. Another driver is **quality**. In order for increased productivity to be of value to the end user, the quality of the end product has to be up to par. Hence, new technologies delivering increased productivity – with adequate application specific quality of the end product – are sought after in the water treatment market. Of course, in an unsubsidised market, new technologies are only of commercial interest if the payback times of solutions implementing such new technologies are shorter as compared to existing solutions in the market.

In today's water treatment market, new solutions with higher productivity are mainly based on incremental innovation of existing pressure-driven membrane technologies. Here, a hydraulic pressure is used to force the water through microscopic pores in the membrane material. The smaller the pores, the higher the rejection of the membrane towards solutes in the water being treated and the higher the pressure (= the higher the energy) needed to drive the water through the membrane. The high-pressure operation of such systems causes severe fouling[1] problems when the aqueous solutions being treated contain high TDS (total dissolved solids).

In comparison to traditional pressure-driven technologies, forward osmosis, being driven by osmotic gradients instead of energy intensive hydraulic pressure, represents a radical innovation from the viewpoint of minimizing energy expenditure in water treatment processes. As such, commercially available, high-performance FO-based systems have the potential to significantly outperform traditional technologies when it comes to increasing productivity.

[1] Fouling is the process whereby solutes clog the pores of the membrane during operation, which severely decreases membrane performance

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5.2 Forward osmosis systems and their commercialization opportunities

Review of commercialization opportunities for forward osmosis systems

image from htiwater.com

Today, FO based systems are primarily used in niche applications where traditional pressure driven filtration membranes cannot be used. The US based company Hydration Technology Innovations (HTI) is currently commercially exploring such niche applications within survival systems, food concentration, landfill leachate, and oil and gas wastewater treatment. In addition, the UK based company, Modern Water, has designed and implemented forward osmosis systems in Oman for desalination of seawater and is also looking into forward osmosis systems for evaporative cooling towers. Very little information is publicly available on the FO-related revenue realized by HTI and Modern Water. Our best guesstimate puts the combined yearly revenue in a ballpark region of 10-20 million USD/year.

When estimating the future business potential of FO systems, it is helpful to first consider the range of FO system types and their main application areas. Previously we have described stand-alone FO systems and hybrid FO systems and their 4 main application areas:

Stand-alone FO systems

1. Water extractors for industrial process optimization
2. Osmotic power generators for energy production

Hybrid FO systems

1. Seawater desalination systems for production of potable water
2. Wastewater treatment systems for wastewater reduction and parallel production of reusable process water

Each of the 4 FO system application areas underlined above posses inherent promoting and inhibiting factors when it comes to commercialization. These factors are summarized below:

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Application area	Commercialization promoters	Commercialization inhibitors
Water extractors for industrial process optimization*(Stand-alone FO systems)* • Typical size of FO installation (installed membrane area): ◦ 100 – 10000m^2	Unique low-energy value proposition for FO systemsThe economical value generated for end-users is greater than the value of recycled water, which is beneficial from a system pricing point of view The small/medium membrane footprint means that systems can be commercialized based on a supply chain of small/medium scale FO membrane producers	Retrofitting FO systems to existing operations is challenging both from a technical and operational point of view Implementing FO systems in new facilities requires potentially costly co-localization of relevant wastewater streams Identifying suitable industrial application areas is challenging and requires in-depth process knowledge in a wide range of industries
Osmotic power generators for energy production *(Stand-alone FO systems)* • Typical size of FO installation (installed membrane area): ◦ >100000m^2	Unique value proposition for FO systems (only FO systems can be used for membrane based osmotic power generators) Energy prices are increasing as the availability of fossil fuels decreases	Large volume, low-cost, and high performance PRO membranes most likely wont be commercially available for another 5 years
~~~

Seawater desalination systems for production of potable water *(Hybrid FO/RO/NF/MD system)* • Typical size of FO installation (installed membrane area): ◦ >50000m^2	Decreasing global fresh water supplies, increasing energy prices, and environmental demands are creating a pull in the market for more productive water production systems. Hybrid FO/RO//NF/MD systems can reduce energy operational consumption in water production while in parallel reducing the cost of wastewater treatment	Large volume, low-cost, and high performance FO membranes most likely wont be commercially available for another 3 years Implementing FO systems in new facilities requires potentially costly co-localization of relevant wastewater streams Convincing price sensitive end users in the water production industry of the economical benefits of hybrid FO/RO/BWRO/NF systems requires extensive pilot plant field test data
Wastewater treatment systems for wastewater reduction and parallel production of reusable process water *(Hybrid FO/RO/NF/MD system)* • Typical size of FO installation (installed membrane area): ◦ 100 – 10000m^2	The economical value generated for end-users is greater than the value of recycled water, which is beneficial from a system pricing point of view Many industrial processes generate wastewater, which is very difficult to treat with conventional membrane technologies. Prime examples can be found in the oil & gas and textile dyeing industries The small/medium membrane footprint means that systems can be commercialized based on a supply chain of small/medium scale FO membrane producers	Convincing end users in the water treatment industry of the economical benefits of hybrid FO/RO/NF/MD systems requires proof-of-principle / pilot plant data

Based on the summary above of commercialization inhibitors and promoters, it is the opinion of ForwardOsmosisTech that short-term (1-3 year time horizon) FO system commercialization efforts should be focused on hybrid wastewater treatment systems for wastewater reduction and parallel production of reusable process water. From a long-term (> 3 years) perspective, FO system commercialization efforts should focus on hybrid seawater desalination systems. If the PRO membrane technology experiences a sudden burst of improvement resulting in commercially available large volume, low-cost, high performance membrane products, osmotic power generators are also of commercial interest.

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5.3 How forward osmosis can help cut energy usage in industrial water treatment processes

The main challenge with today's water treatment technologies

Today's water treatment technologies are effective but not always efficient. As a result, considerably more energy will be needed to replenish ever dwindling fresh water resources in the near future, however, less energy will be available to do so. One potential solution to this challenge is forward osmosis based water treatment systems.

Why water and energy are two sides of the same coin

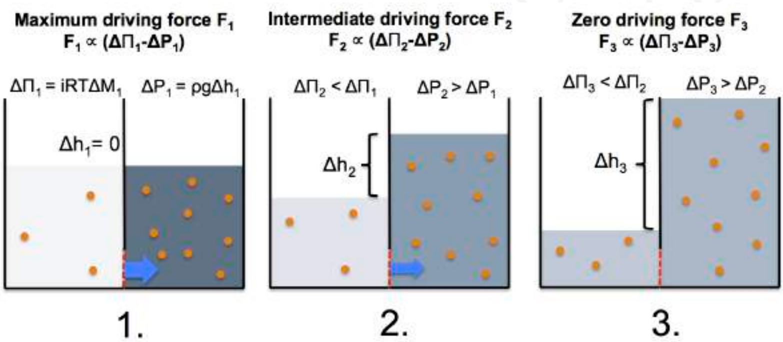
In today's world where energy prices are increasing, due to over-utilization of fossil fuels, and fresh water resources are declining, energy efficient water treatment technologies are becoming increasingly important for sustained global development. This is especially true because of the linkage of water and energy in what has been coined the water-energy nexus, where – on one hand – water is required in all forms of energy production (either in the energy production process itself or to generate raw materials), and – on the other hand – energy is required for all forms of water treatment.

Energy efficiency in water treatment processes

The water-energy nexus drives development of ever more efficient water treatment technologies. However, traditional pressure driven membrane technologies, such as reverse osmosis, nanofiltration, ultrafiltration, and microfiltration, are reaching their efficiency limits. As an example, McGovern et. al. recently treated the topic of energy consumption in seawater desalination processes (McGovern et. al., JMS, 2014). Here, the theoretical energy requirement for direct desalination of seawater (35000ppm, 50% recovery) is reported at 1,05 kWh/m^3. Throughout the last 30 years of research into improving the efficiency of reverse osmosis technologies, current RO systems are able to desalinate seawater at 47% thermodynamic efficiency corresponding to an energy usage of 2,34 kWh/m^3. Researchers agree that this number will be very hard to improve significantly in the future, and similar arguments apply for nanofiltration, ultrafiltration, and microfiltration technologies.

New technologies: forward osmosis

Hence, in order to radically improve the efficiency of water treatment systems, new technologies are needed. One such technology, which has been gaining increasing interest the last 10 years, is forward osmosis. According to ForwardOsmosisTech, forward osmosis is "the process of spontaneous water diffusion across a semi-permeable forward osmosis membrane in response to a difference in solute concentrations (i.e. osmotic pressures) on either side of the semi-permeable membrane". The figure below shows a schematic diagram of a forward osmosis process in action.



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Since forward osmosis processes are driven by osmotic pressure and not energy-consuming hydraulic pressures, the process of water diffusion across a forward osmosis membrane comes at zero energy costs. In fact, all that is needed – in form of energy usage – to operate a forward osmosis system is pumps for circulating feed and draw solutions across either side of the membrane. Researchers (McGovern et. al., JMOS, 2014 and McGinnis et. al, Desalination, 2007) have estimated the energy usage in forward osmosis systems to be in the region 0,16 kWh/m^2 to 0,25 kWh/m^3. This is one tenth of the energy usage of RO systems for desalination of seawater.

The sweet spot for forward osmosis-based water treatment systems

In order for forward osmosis-based water treatment systems to maximize energy savings, industrial applications must be found where the forward osmosis system can operate alone without the need for auxiliary pressure driven sub-systems. In essence, such stand-alone forward osmosis systems, perform low-energy water exchange from a low concentration stream to a high concentration stream, thus, resulting in two value generators for the end user:

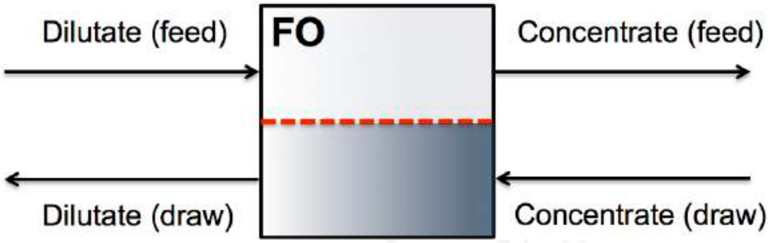
1. Concentration of a low concentration stream
2. Dilution of a high concentration stream

These value generators are extremely useful for industrial process optimization in factories / plants where concentration of low concentration streams and dilution of high concentration streams are handled separately. Examples of such factories / plants can readily be found in the oil & gas industry, the textile industry, and the white biotech industry.

To further clarify the energy saving potential of forward osmosis-based water treatment systems, imagine a factory with a process stream that must be diluted with fresh water before down stream processing can take place (the concentrate (draw) arrow in the figure below). The same factory has a difficult wastewater stream that is dewatered in an energy-intensive system containing both reverse osmosis membranes and evaporators (the dilutate (feed) arrow) in the figure below).

By combining said process streams in a forward osmosis-based water treatment system, the factory gains savings on two levels:

1. Reduction of fresh water usage for dilution
2. Reduction of energy usage for concentration



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What does the future hold for forward osmosis-based water treatment systems?

There are already a hand-full companies working hard to commercialize forward osmosis technologies in various industrial applications. However, so far, broad market adoption has been limited. Mainly because of a lack of available system capacity as well as real-life case studies where the forward osmosis value proposition has been proven. I expect this picture to change in the near future as more test-bedding is completed and forward osmosis membrane manufacturers are successful in up-scaling their production capacity.

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5.4 Why is it challenging to commercialize forward osmosis technologies?

Challenges when commercializing forward osmosis technologies

Image from htiwater.com

Water treatment systems based on forward osmosis membrane technologies are situated very early in the introduction stage of the product life cycle, and have been so ever since market introduction in 1990ies. Hence growth in product sales is slow and the market is hesitant to adopt the technology.

The barrier to adoption stems in part from a limited track record in real-life industrial applications and the fact that FO membrane systems, in general, cannot be easily retrofitted into traditional pressure-based water treatment systems. The limited track record has resulted in forward osmosis being widely viewed, among industrial end users, as an immature technology and as a result the visibility of the technology is low outside of academia. Furthermore, since changing an existing water treatment system to accommodate a new technology is CAPEX intensive, current operators prefer traditional – and compatible – technologies with proven track records although this means accepting a higher OPEX.

Another contributing factor to the adoption barrier is the lack of high-performing, commercially available FO membrane products. To this date, only a single – and relatively inefficient – FO membrane product is commercially available, which has limited the adoption of forward osmosis products to mainly personal and military survival systems.

5.5 Example: The use of fertilizer drawn forward osmosis for fertigation

The use of fertilizer drawn forward osmosis for fertigation – a real FO application or a pipe dream?

Fertigation is an agricultural irrigation process where water soluble fertilizers or soil improvement products are added to the irrigation water. Benefits of using fertigation compared to traditional fertilization methods include:

- Controlled dosage of nutrients leading to increased nutrient absorption of plants, which again leads to improved root systems
- Reduction in water consumption due to improved root systems
- Reduction in amount of nutrients needed due to controlled dosage
- Reduced leaching of nutrients to water supplies

The cost of installing, operating, and maintaining fertigation systems means that the process is currently primarily used

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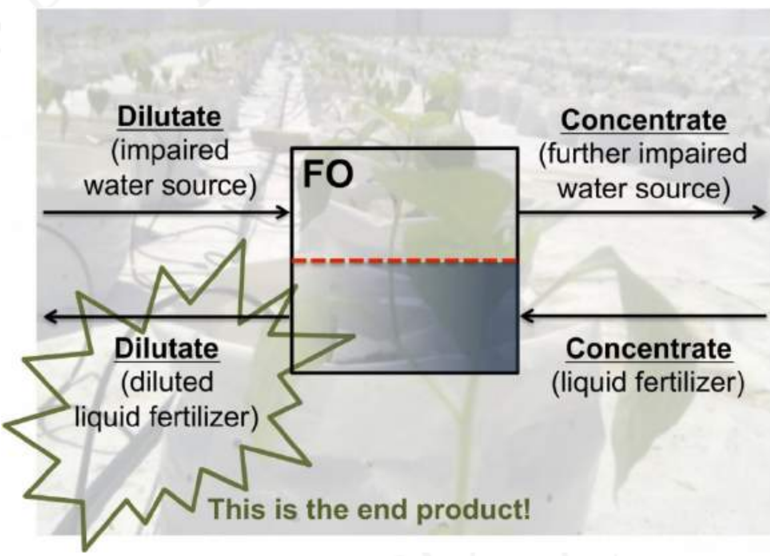
for high value crops such as vegetables, turf, fruit trees, and ornamentals.

The concept of fertilizer drawn forward osmosis (FDFO) for fertigation has been suggested as a means of decreasing fresh water usage in fertigation processes. Fertilizer drawn forward osmosis is based on a stand-alone forward osmosis system as illustrated below. Here, a liquid fertilizer concentrate is used to extract water from impaired water sources – the goal being to use impaired water sources instead of fresh water sourced to dilute the liquid fertilizer solution a prior to usage. As such, FDFO contributes to conserving fresh water supplies by reducing the amount of fresh water otherwise needed to dilute liquid fertilizer concentrates in fertigation.



What are the challenges facing fertilizer drawn forward osmosis for fertigation?

For many advocates of FDFO based fertigation, the ultimate dream is to provide an alternative source of fresh water to farmers in regions where fresh water sources are scarce. Although the prospect of using liquid fertilizer solutions to extract fresh water from impaired sources such as seawater, brackish water, or polluted ground water is tantalizing, there are major challenges to be overcome (similar to those described in our article on desert restoration) before a real-life application is achieved:

1. Logistics of transporting liquid fertilizer into close proximity to crops
2. Logistics of pumping impaired water to the farmland in question
3. Developing low-energy means of providing additional dilution, when FO processes cannot extract all the water needed to generate ready-to-use liquid fertilizer solutions (in cases where the impaired water is seawater, concentration polarization severely limits the water extraction potential of liquid fertilizer solutions to a point where less than 10% of the necessary dilution water can be supplied by the FDFO process)
4. Management of impaired water once it has been concentrated (and further impaired) during FO processes
5. Developing high-performance FO systems with reduced propensity towards fouling and concentration polarization
6. Developing a suitable business model for commercialization of the FDFO solution

Based on the list of challenges above, it is the opinion of ForwardOsmosisTech that widespread use of fertilizer drawn forward osmosis for fertigation of farmland is indeed a pipe dream. In other words:

Key Takeaways

- It is highly unlikely that FDFO will ever be a commercial success for large-scale fertigation of farmland.

Does this mean fertilizer drawn forward osmosis is a waste of time?

Definitely not! It just means that right application needs to be identified where FDFO makes sense from a technical and commercial point of view. One way of thinking is to view liquid fertilizer solutions as a potential draw solutions for industrial waste water treatment. Here, stand-alone forward osmosis systems could be utilized to reduce waste water problems and at the same time provide a source of fresh water for dilution of the liquid fertilizer solutions. With this mindset it should be possible to identify industrial segment of commercial interest to fertilizer drawn forward osmosis processes.

5.6 Example: Integrating forward osmosis in thermal desalination processes

Forward osmosis can reduce scaling and increase top brine temperature in thermal desalination (Multi-stage flash distillation, MSF) processes

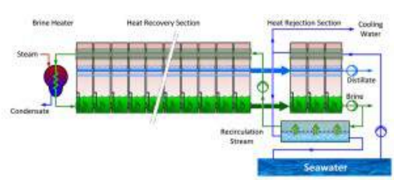


Image from: Darwish, Mohammed, et al. "Viability of integrating forward osmosis (FO) as pretreatment for existing MSF desalting unit." Desalination and Water Treatment (2015): 1-11.

In their article "Viability of integrating forward osmosis (FO) as pretreatment for existing MSF desalting unit" Darwish et. al. investigate the viability of using forward osmosis to reduce feed water scale constituents in MSF plants thus allowing for an increase in top brine temperature (TBT) resulting in increased efficiency of the MSF plant.

Briefly, the study concludes that a retro-fitted Forward Osmosis system is technically viable, however, economical viability depends heavily on FO membrane cost.

In this regard, it is interesting to note that Modern Water recently (January 2016) signed a joint product development and commercialization agreement with Bilfinger Deutsche Babcock Middle East aiming to integrate forward osmosis based pre-treatment and MSF desalination plants (both existing and under development) to improve plant efficiency.

Key Takeaways

- The MSF/FO integration described above is a great example of using a stand-alone forward osmosis system for industrial process optimization applications

So how does an MSF plant operate?

The Multi-stage flash distillation process in a widely used means of seawater desalination based on evaporation. Fundamentally, an MSF desalination plant works by heating saline water to produce vapor, which is then condensed to produce fresh water.

One of the biggest challenges in thermal desalination processes is scaling (precipitation of salts such as calcium sulfate as well as other sulfates and carbonates). Calcium sulfate, for example, precipitates above 115°C, which limits the top brine temperature and thus the efficiency of the distillation process. As a consequence, a substantial fraction of the OPEX costs in large-scale MSF plants is taken up by anti-scaling chemicals.

As illustrated below, the MSF process consists of a series of "stages" ranging in temperature (from hot to cold) and pressure (from low to lower). Circulating seawater provides the condenser coolant in individual stages and is heated as it passes through the system. At the heating section, additional heat is transferred to the seawater stream (typically raising the temperature up to 110°C) and it then enters into successive stages with lower temperature and pressure. Due to the gradually reduced (lower than atmospheric) pressure in each stage, the seawater immediately evaporates (flashes) upon entering stages.

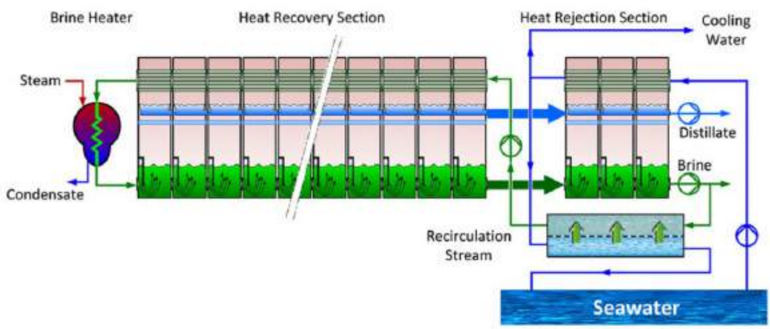


Image from: Darwish, Mohammed, et al. "Viability of integrating forward osmosis (FO) as pretreatment for existing MSF desalting unit." Desalination and Water Treatment (2015): 1-11.

Large MSF plants are divided into heat recovery and heat rejection sections for increased operational stability under conditions where the feed water temperature fluctuates. The division also has the added benefit of only having to treat (degassing and removal of scalants) the make-up seawater fraction entering the system.

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Where does forward osmosis fit in?

As described in the work by Darwish et. al., a forward osmosis system is used to pretreat the make-up seawater entering the MSF process loop. Briefly, the feed seawater enters the forward osmosis system as the feed water while the recirculating brine acts as the draw solution. During the process, the recirculating brine is diluted with fresh water that does not contain scaling precursors. Darwish et. al. have demonstrated that the FO-mediated removal of scaling precursors in the make-up water allows for the top brine temperature to be increased from 110° C to 135° C thus significantly improving the efficiency of the MSF process.
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Chapter 6 - Forward Osmosis Literature Review

> The forward osmosis research field has become increasingly active through the last 5 years as the technology matures towards commercialization and more membrane performance enhancers, forward osmosis system applications and operational aspects are being investigated. In this chapter we've summarized a brief selection of great academic work relating to forward osmosis.

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6.1 An all-encompassing review of forward osmosis technologies anno 2012 by Zhao et. al.

Why Zhao et. al. 2012 is one of the best recent review articles on forward osmosis technologies


Journal of Membrane Science

Review

Recent developments in forward osmosis: Opportunities and challenges

Shuaifei Zhao[a], Linda Zou[a,*], Chuyang Y. Tang[b], Dennis Mulcahy[a]

From Zhao et. al. 2012

In their article "Recent developments in forward osmosis: Opportunities and challenges" from 2012, Zhao and co-workers present an extensive review of forward osmosis technology applications, membrane theory, performance challenges, and forward osmosis membrane developments up until 2012.

Since publishing in 2012, the article has already been cited 397 times according to Google Scholar (April 2016) – an impressive feat confirming the quality of the review work carried out.

On the forward osmosis application side, the authors summarize the state-of-the-art within the following FO application areas:

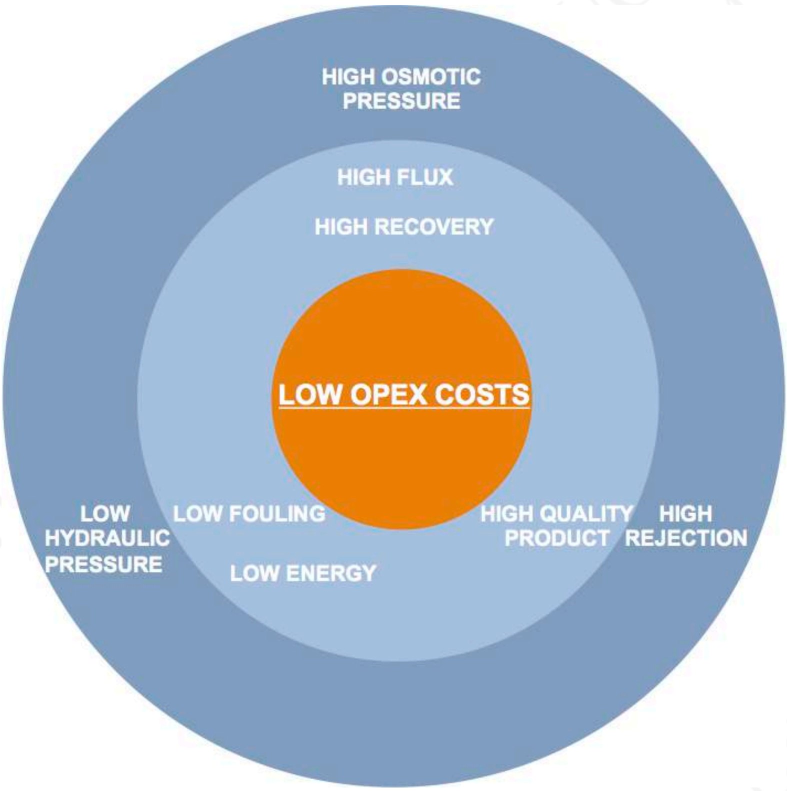
- Power generation
- Desalination
- Waste water treatment and the osmotic bioreactor (OMBR)
- Liquid food concentration
- Pharmaceutical applications
- Dialysis fluid regeneration, fertigation, and production of biomass energy

Furthermore, the history of FO membrane development is summarized for each of the following membrane designs:

- Cellulosic membranes prepared by phase inversion
- Thin film composite membranes
- Chemically modified membranes

Finally, the sections on membrane theory and FO performance challenges are well written and to-the-point, and we really appreciate the overview figures illustrating the potential OPEX cost savings from usage of FO systems and the challenges current faced by the FO technology. Inspired by the clarity of said figures, we have created our own versions and included them below:

Sources of potential OPEX savings in FO



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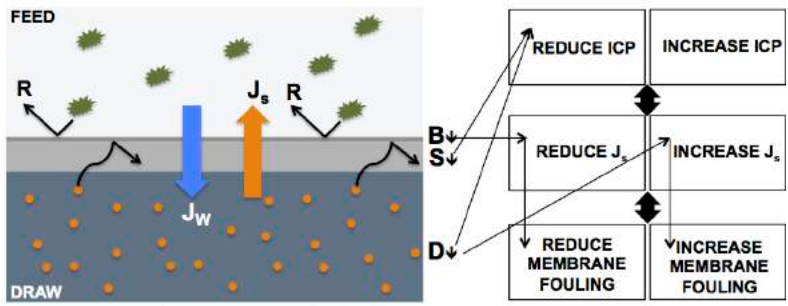
The 5 challenges currently faced by the FO technology



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Please refer to our article on concentration polarization in forward osmosis membranes for a detailed description of B, S, and D values.

6.2 Selection of inorganic draw solutes for forward osmosis applications by Achilli et. al. 2010

Why Achilli et. al. 2010 is a must read within the field of forward osmosis R&D


Contents lists available at ScienceDirect

Journal of Membrane Science

Selection of inorganic-based draw solutions for forward osmosis applications

Andrea Achilli[a,*], Tzahi Y. Cath[b], Amy E. Childress[a]

From Achilli et. al. 2010

In their article "Selection of inorganic-based draw solutions for forward osmosis applications" from 2010, Achilli and co workers screen more than 500 different inorganic compounds for their potential as draw solutes for forward osmosis applications.

An initial desktop screening removed all but 14 candidates through the following criteria:

1. Must be water soluble
2. Must be a solid at room temperature

3. Must be non-hazardous
4. Must have an osmotic pressure of more than 100 bar at saturation concentration
5. Must cost less than 10 USD/L based on chemical unit prices from Fisher Scientific

The fact that Achilli et. al. base one of their selection criteria on unit prices from Fisher Scientific – and not bulk chemical prices from bulk supplier web portals such as Alibaba.com – is our only criticism of their work. It would be very interesting to see how the final draw solute selections change when bulk chemical prices are considered instead of costly R&D products.

Nevertheless, with their short list of 14 draw solute candidates in place, the researchers then proceed to rate each candidate by the following parameters:

- Forward osmosis water flux (based on a CTA forward osmosis membrane from Hydration Technology Innovations) – should be as high as possible
- The loss of draw solute from reverse salt flux during forward osmosis operation – should be as low as possible to minimize FO OPEX
- The loss of draw solute when re concentrating the draw solution after it has extracted feed water – should be as low as possible to minimize FO OPEX
- The propensity of the cation/anion component of the draw solute to cause mineral salt scaling inside the membrane and on the membrane surface – thus irreversibly reducing membrane performance – when diffusing into real-life feed streams containing mineral salt scaling counterparts – mineral salt scaling should be avoided in as wide a range of feed streams as possible

The final conclusion in the article is that there is no preferred draw solute that is universally applicable to all water treatment applications. However, for water and waste water applications (where many mineral salt scaling counterparts are present), $MgCl_2$ is the best choice due to its low scaling propensity and good FO performance potential. And for applications with pure feed streams (e.g. food processing), $KHCO_3$ and $NaHCO_3$ are good choices because of their ability to deliver high water fluxes in combination with low reverse salt fluxes.

We regard the work of Achili and co-workers as a must read for anyone wanting solid background material on which to base their choice of draw solute. Additionally, Achilli et. al. 2010 has been cited 255 times since publishing – according to Google Scholar, April 2016 – which confirms the article's place among the most influential recently published forward osmosis literature.

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6.3 Overview of concentration polarization effects in forward osmosis membranes by McCutcheon et. al. 2006

Why McCutcheon et. al. 2006 is a must read within the field of forward osmosis R&D


ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Journal of Membrane Science 284 (2006) 237–247
Journal of MEMBRANE SCIENCE

Influence of concentrative and dilutive internal concentration polarization on flux behavior in forward osmosis

Jeffrey R. McCutcheon, Menachem Elimelech *

From McCutcheon et. al. 2006

In their article "Influence of concentrative and dilutive internal concentration polarization on flux behaviour in forward osmosis" from 2006, McCutcheon and Elimelech present a clear and comprehensive theoretical overview of how external and internal concentration polarization phenomena reduce the water flux performance in forward osmosis processes. The theory is confirmed and exemplified through extensive forward osmosis testing of a commercially available cellulose triacetate membrane from Hydration Technology Innovations.

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Since publishing, McCutcheon et. al. 2006 has been cited 509 times (according to Google Scholar, April 2016) making it one of the most frequently cited articles in the field of forward osmosis membrane R&D.

We regard McCutcheon et. al. 2006 as a must read for anyone wanting to understand forward osmosis membrane performance reductions under different feed and draw conditions. If you fall into this category – and don't have access to the article – we recommend reading our article on forward osmosis concentration polarization, which summarizes the most important take home messages from McCutcheon and Elimelech's work.

6.4 The relationship between forward osmosis membrane structure and performance by Tiraferri et. al. 2011

Why Tiraferri et. al. 2011 is a must read within the field of forward osmosis membrane development.


Journal of Membrane Science

Relating performance of thin-film composite forward osmosis membranes to support layer formation and structure

Alberto Tiraferri, Ngai Yin Yip, William A. Phillip, Jessica D. Schiffman, Menachem Elimelech*

From Tiraferri et. al. 2011

In their article "Relating performance of thin-film composite forward osmosis membranes to support layer formation and structure" from 2011, Tiraferri and co-workers perform a systematic study on how the structure of forward osmosis support membranes affect overall forward osmosis performance. Since publishing in 2011, the article has been cited 237 times according to Google Scholar (April 2016), which confirms its role as one of the most influential articles within the field of FO substrate development.

The study is based on polysulfone support membranes prepared by phase inversion and subsequent interfacial polymerization for the active layer formation. The researchers vary the following support membrane casting conditions to achieve support membranes with different structural parameters (S values):

- Solvent used to prepare the polysulfone membrane precursor solution (also known as the dope solution)
- Concentration of polysulfone in the dope solution
- Wetting of the polyester (PET) backing material
- Thickness of the polysulfone solution film prior to phase inversion

Based on their work, Tiraferri et. al. conclude that support membranes with low structural parameters reduce internal concentration polarization (ICP) effects during FO operation and hence increase overall FO membrane performance. Scanning electron microscope (SEM) images of different support membranes reveal that the lowest structural parameters are achieved when the support membrane structure is characterized by “fingerlike” macrovoid morphologies stretching the entire thickness of the support membrane.

Interestingly, the researchers observe that forward osmosis membranes based on support membranes with “spongelike” morphologies (i.e. larger structural parameters) often outperform their “fingerlike” counterparts despite internal concentration polarization effects being more pronounced in the former. Tiraferri et. al. conclude that the active layer separation properties are superior (i.e. larger A and smaller B values) when the active layer is formed on an underlying “spongelike” structure.

Hence, when designing the optimal forward osmosis membrane support, the following end-goals should be prioritized:

1. Maintaining a "fingerlike" membrane morphology in the bulk part of the FO membrane substrate to achieve low values of the structural parameter leading to reduced ICP effects during FO membrane operation.
2. Achieving a "spongelike" morphology in the top layer of the support membrane, which forms the interphase towards the active layer, to ensure superior separation properties of the active layer once it is formed by interfacial polymerization.

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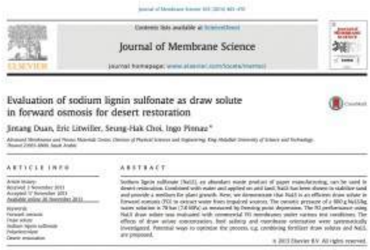
6.5 *Desert restoration through forward osmosis processes by Duan et. al. 2014*

Harnessing forward osmosis processes for desert restoration and desertification reversal


Journal of Membrane Science

Evaluation of sodium lignin sulfonate as draw solute in forward osmosis for desert restoration

Jintang Duan, Eric Litwiller, Seung-Hak Choi, Ingo Pinnau*

ARTICLE INFO

ABSTRACT

From Duan et. al. 2014

In their article "Evaluation of sodium lignin sulfonate as draw solute in forward osmosis for desert restoration" Duan et. al. describe the problem of dry land degradation to deserts through increasing loss of water, vegetation, and wildlife. This is a problem affecting up to 250 million people worldwide. To mitigate and reverse desertification the first step is to fixate sand to "immobilize sand dunes and provide an environment for seed germination".

One way of fixating sand is to spray aqueous solutions of chemical binders onto the sand. Water drains of the surface and leaves behind a firm crust of 0,5-1cm thickness, which prevents sand migration.

Water soluble sodium lignin sulfonate (NaLS) is an effective non-toxic chemical binder that improves the organic content of sand, helps retain moisture, and provides nutrients for plants. NaLS is a waste product of the paper industry and some 50 million tons of NaLS is generated annually around the World. This makes NaLS a cost-effective chemical binder at around 400 USD/ton.

A major challenge facing desertification reversal projects is the lack of fresh water resources to produce NaLS solutions. In arid regions, brackish water, seawater, and other impaired water sources are often available but until now, energy-intensive desalination techniques have been needed to generate fresh water.

Duan et. al. suggest to utilize forward osmosis technologies to solve the water scarcity challenge in an energy-efficient manner. In the author's proposed forward osmosis solution, NaLS is used as a draw solute for low-energy water extraction from impaired feed water sources. When the osmotic pressure of impaired feed waters is below 1,5 bar (corresponding to a 2000 ppm NaCl solution) saturated NaLS draw solutions are able to extract enough fresh water to reach a dilution of 1-2% NaLS, which corresponds to the working concentration for sand fixation. For impaired water sources with osmotic pressures above 1,5 bar (e.g. seawater, some forms of brackish water etc.) additional dilution systems are needed besides FO based water extraction systems to generate NaLS working solutions.

Here at ForwardOsmosisTech we think desert restoration using stand-alone FO systems are a great idea on paper. However, before being realized in real life, the following main challenges need to be solved:

1. Logistics of transporting NaLS to desert restoration sites
2. Logistics of pumping impaired water to desert restoration sites
3. Developing low-energy means of providing additional dilution, when FO processes cannot extract all the water needed to generate ready-to-use chemical binder solutions
4. Management of impaired water once it has been concentrated during FO processes
5. Developing high-performance FO systems with reduced propensity towards fouling and concentration polarization

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6.6 Efficiency of forward osmosis desalination by McGovern et. al. 2014

Article suggesting that forward osmosis is not energy efficient compared to reverse osmosis gains social media attention


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Perspective

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

Ronan K. McGovern *, John H. Lienhard V

From McGovern et. al. 2014

On June 21st 2014, McGovern, a post-doc at MIT's Department of Mechanical engineering, and co-workers published the article "On the potential of forward osmosis to energetically outperform reverse osmosis desalination" in the Journal of Membrane Science. The main take-home message of the article should come as no surprise for scholars and experts in the field of membrane based water treatment, namely that:

Key Takeaways

- A hybrid forward osmosis (FO)/ reverse osmosis (RO) seawater desalination system using a sodium chloride (NaCl) based draw solution will always use more energy than a direct desalination system based on RO alone.

What came as a surprise to us, however, was the amount of social media attention the article received in the months following its publication. Numerous tweets and Google+ posts started appearing during July 2014 – all singing to the same tune of "Forward osmosis is not energy efficient".

McGovern and co-workers actually did forward osmosis desalination (and forward osmosis commercialization in general) a huge favour – here's why

At a first glance, McGovern et. al.'s article could be viewed as a show-stopper for forward osmosis desalination activities and perhaps even limiting for forward osmosis commercialization in general, given the article's overall take-home message:

Key Takeaways

- It appears best for forward osmosis research to focus fully on high salinity applications and applications that do not require draw regeneration, where reverse osmosis cannot compete. McGovern et. al. 2014.

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We at ForwardOsmosisTech, however, are of a different opinion. For too long, forward osmosis desalination proponents have been claiming energy savings of 30-80% without presenting operational data to back their claims. This has, without a doubt, resulted in a natural skepticism towards the economical viability of forward osmosis desalination (and as a consequence also forward osmosis in general) among industrial end users and water treatment experts. McGovern et. al's article has become a scientific vessel for skeptics to latch onto, which explains the degree of attention it has received so far.

Moving forward, forward osmosis desalination proponents will have to beef up their efforts in producing real operational data to be held up against McGovern et. al's. scientific benchmark.

Key Takeaways

- It is ForwardOsmosTech's opinion that this is a very healthy – and much needed – development in the forward osmosis field, which will undoubtedly benefit the industry in the long run. Because, at the end of the day, any real market traction in the water treatment industry is critically dependent on real life operational data showing economical viability.

ForwardOsmosisTech's take on McGovern's article and forward osmosis based desalination in general

As mentioned earlier in this piece, the main take-home message in McGovern and co-workers research is that a hybrid
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forward osmosis (FO)/ reverse osmosis (RO) seawater desalination system using a sodium chloride (NaCl) based draw solution will always use more energy than a direct desalination system based on RO alone. If you think about it, this is really just common sense. In order to extract water from seawater through a forward osmosis membrane, the draw solution must have a higher osmotic pressure than seawater and hence the subsequent RO system for draw solution regeneration and fresh water production must operate at a higher hydraulic pressure. No operational advantages from coupling a forward osmosis with a reverse osmosis system will be substantial enough to compensate for the energy penalty of operating at higher pressure. Dr. Nathan Hancock from Oasys Water recently touched upon this subject in an excellent IDA webinar on forward osmosis.

So how can forward osmosis based desalination ever become more energy efficient that reverse osmosis desalination, you may ask? The solution is to use alternative – and lower energy – draw solution regeneration systems, which in the opinion of ForwardOsmosisTech – and contrary to the comments made by McGovern et. al. – are still very much in play:

- Exchanging NaCl with larger ionic species as draw solute enables the draw solution regeneration step to be performed with nanofiltration membranes, which are capable of sufficiently high rejection to the draw solute while at the same time lowering the overall energy requirements of the draw solution regeneration step. Although real life transparent operational data is still lacking on forward osmosis / nanofiltration hybrid system, the potential for energy savings compared to RO systems is still very much present. Modern Water have seemingly had some success already in this area.

- Exchanging ionic draw solutes with cloud-point polymers, which can be separated from bulk water by applying waste heat. Using waste heat has the potential to significantly reduce the energy costs of draw solution regeneration, but according to McGovern et. al. these energy cost reductions are offset by the large capital investments needed for heat exchangers. Indeed, heat exchangers are needed to transfer waste heat to the draw solution in order to separate out the polymeric draw solutes, but referring to the same study cited by McGovern et. al., the cost of heat exchangers can be as low as 200USD/kW, which should be sufficiently low to render temperature based draw solution regeneration economically viable at heat source temperatures of 60°C. Again, real life operational data are needed to prove the viability.

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Chapter 7 - General Guides to Forward Osmosis

> Since we started the ForwardOsmosisTech Portal in late 2013 we've written several general guides on forward osmosis ranging from forward osmosis membranes to forward osmosis systems & applications and even our take on how to measure forward osmosis membrane performance in a standardized way. This chapter summarizes the all the guides we have written so far.

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7.1 Guide to forward osmosis membranes

A general introduction to forward osmosis membranes

It can sometimes be difficult to find exactly what you're looking for in an extensive knowledge database such as ForwardOsmosisTech. For this reason, we have decided to summarize all our forward osmosis membrane related knowledge on a single page to give you – our readers – a more accessible entry point to the ForwardOsmosisTech portal. We hope you enjoy our efforts below. And don't forget: if you have questions, comments, and suggestions for improvements please feel free to drop us an email at forwardosmosistechportal@gmail.com.

What is forward osmosis?

Forward osmosis is the process of spontaneous water diffusion across a semi-permeable forward osmosis membrane in response to a difference in solute concentrations (i.e. osmotic pressures) on either side of the semi-permeable membrane. In essence, the diffusion of water can be explained by the second law of thermodynamics, which implies that systems always spontaneously evolve towards a state of thermodynamic

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equilibrium where the system's entropy (or amount of disorder) is maximized. And from an entropy point of view, maximum disorder – in a system consisting of two aqueous solutions with different solute concentrations separated by a semi-permeable membrane – is achieved when enough water has diffused from the low concentration side to the high concentration side to eliminate the difference in solute concentration.

Image courtesy of Google

Forward osmosis is a natural process, which takes place all around us on an everyday basis. Forward osmosis enables plants to transport water from their root systems to their leaves and it provides the primary means of transporting water in and out of cells across most organisms in Nature.

Key Takeaways

- For more detailed information on forward osmosis processes, please refer to our article: "The principles of forward osmosis (FO)

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How does a forward osmosis membrane work?

Generally speaking, membranes for water treatment applications are thin, porous, and permeable materials, which can be used as selective barriers between aqueous solutions. In most applications, water treatment membranes are used to remove unwanted substances (e.g. suspended solids, bacteria, solutes, etc.) from aqueous solutions. In simpler terms, contaminated water enters on one side of the membrane and – depending on the membrane's selectivity properties – less contaminated water exits on the other side of the membrane. Selectivity properties are commonly achieved by adjusting the pore size of the membrane material to prevent contaminants of interest to pass through the membrane.

Forward osmosis membranes are typically designed to be more or less exclusively selective towards water molecules, which enables them to separate water from all other contaminants. In forward osmosis membrane processes, the driving force for water separation is quantified by the osmotic pressure difference between solutions on either side of the forward osmosis membrane: higher osmotic pressure difference → higher rate of water diffusion. In ideal solutions with low solute concentration the osmotic pressure difference ($\Delta\Pi$) can be approximated by the Morse equation:

$$\Delta\Pi = iRT\Delta M$$

- i is The Van't Hoff factor, which reflects the dissociation multiple of the solute species in question. For a dilute solution of sodium chloride, the Van't Hoff factor is equal to 2
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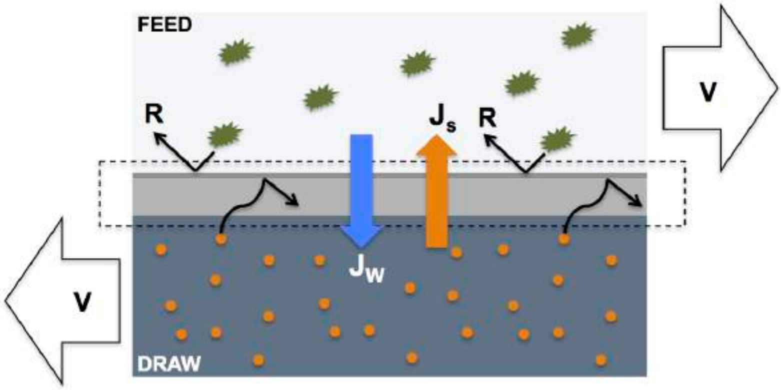
because 1 mole of NaCl dissociates into 2 moles of solutes in aqueous solution.

- R is the gas constant in L*atm*K^{-1}*M^{-1}
- T is the temperature of the solution in Kelvin [K]
- M is the molarity of the solution in Molar [M]

It is important to note, that osmotic pressure is a colligative property of solutions, meaning that it depends exclusively on the number ratio of solute particles to solvent molecules in a solution, and **NOT** on the type of chemical species present. Hence a 1M NaCl solution with a Van't Hoff factor of 2 will exert the same osmotic pressure as a 2M sugar solution with a Van't Hoff factor of 2.

Key Takeaways

- In our article "Forward osmosis (FO) membranes and membrane processes" you can find more detailed information about the forward osmosis membrane performance parameters illustrated in the figure below. You might also be interested in our article "Forward osmosis (FO) membrane designs and materials" where we summarize the main membrane designs and materials in the field of forward osmosis.



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How do forward osmosis membranes differ from reverse osmosis membranes?

Both forward osmosis membranes and reverse osmosis membranes are designed to be almost exclusively selective to water molecules – the difference lies in the means by which water molecules are driven through the membrane. To better understand how the mode of water transport across a membrane influences its physical design and resulting mechanical properties we start with the equation relating water flux (across a membrane to the driving force at work:

$J_W = A(\Delta P - \Delta \Pi)$

- A is the "pure water permeability coefficient" – an intrinsic membrane property
- ΔP is the difference in hydraulic pressure across the membrane

- ΔΠ is the difference in osmotic pressure across the membrane

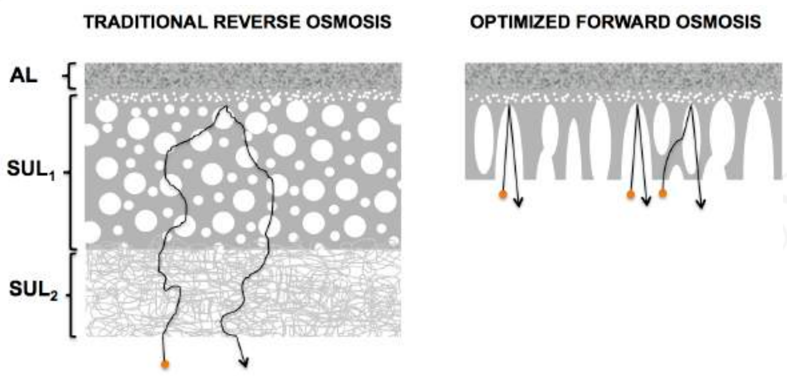
As mentioned earlier, forward osmosis process are driven by osmotic pressure differences and the direction of water diffusion is from low concentration (the feed side) to high concentration (the draw side). In most cases, there is no hydraulic pressure difference at work in forward osmosis processes (ΔP = 0). Reverse osmosis processes, on the other hand, are driven by hydraulic pressure differences and the direction of water diffusion is from high concentration to low concentration (i.e. against the osmotic pressure). In other words, in reverse osmosis applications, the hydraulic pressure applied must be larger than the osmotic pressure of the solution to be treated in order for water to diffuse through the reverse osmosis membrane.

So the main difference between forward osmosis membranes and reverse osmosis membranes is that reverse osmosis membrane require energy-intensive hydraulic pressures to operate whereas forward osmosis membranes require only osmotic pressures. Well – you may ask – if forward osmosis membranes do not require energy-intensive hydraulic pressures, why aren't all water membrane processes based on forward osmosis processes? The short answer to this question is that forward osmosis systems do not directly produce decontaminated water as is the case for reverse osmosis systems. In forward osmosis processes, the decontaminated water ends up in the high concentration draw solution and – if needed as an end product – must be subsequently separated from the draw solutes.

Key Takeaways

- Want an overview of applications where forward osmosis systems are ideally suitable? Check out our forward osmosis applications page!

The difference in driving force between reverse osmosis and forward osmosis processes is reflected in the physical design and mechanical properties of reverse osmosis and forward osmosis membranes as illustrated below. Reverse osmosis membranes must be mechanically stable to cope with prolonged exposure to hydraulic pressure while forward osmosis membranes must be as thin as possible to allow for rapid diffusion of water and solutes in the bulk membrane material:



Key Takeaways

- In our article “Forward osmosis (FO) membranes and membrane processes” you will find an in-depth description of the differences in membrane structure between reverse osmosis and forward osmosis membranes.

What determines forward osmosis membrane performance?

Before going into details about forward osmosis membrane performance, it is useful to note that most forward osmosis membranes are of the asymmetric composite type – meaning that they consist of a nanometer thin rejection layer (typically 100-200nm in thickness) fused with a micrometer sized underlying support layer (typically 100-200μm in thickness), which provides mechanical support and overall strength to the membrane material.

It turns out that forward osmosis membrane performance is governed by the physical properties of both the rejection layer and the underlying support layer:

The A-value of a forward osmosis membrane – the higher the better

The membrane A-value value (also known as the pure water permeability coefficient) is a property of the membrane’s active layer and it determines the water flux performance at a given osmotic pressure difference across the active layer of the membrane. FO membrane developers seek to increase the membrane A-value to improve the water flux across the membrane during FO operation.

The B-value of a forward osmosis membrane – the lower the better

The membrane B-value (also known as the salt permeability coefficient) is a property of the membrane's active layer and it determines the reverse diffusion of a given draw solute at a given concentration difference of the solute across the active layer of the membrane. FO membrane developers seek to reduce the membrane B-value to limit the amount of draw solute being lost into the feed stream during FO operation.

The S-value of a forward osmosis membrane – the lower the better

The membrane S-value (also known as the structural parameter) is a measure of the resistance of the membrane's support layer towards solute diffusion . FO membrane developers seek to reduce the membrane S-value because the smaller the S value, the easier it is for solutes to diffuse inside the porous support layer, and the higher the water flux performance.

Key Takeaways

- If you're interested in a more in-depth explanation of how A, B, and S values dictate forward osmosis membrane performance check out our article: "How forward osmosis (FO) performance is limited by concentration polarization".

Which geometrical form-factors are available for forward osmosis membranes?

Forward osmosis membranes fall into three general geometrical categories, namely:

1. flat-sheet forward osmosis membranes, which are assembled into plate & frame (stacked) or spiral wound modules
2. hollow fibre forward osmosis membranes, which are assembled into hollow fibre modules
3. tubular forward osmosis membranes, which are assembled into tubular modules

We have written 5 articles covering all aspects regarding geometrical form factors of forward osmosis membranes:

- The 4 different designs of forward osmosis (FO) membrane modules
- Plate and frame forward osmosis membrane modules
- Spiral wound forward osmosis membrane modules
- Hollow fiber forward osmosis membrane modules
- Tubular forward osmosis membrane modules

7.2 Guide to measuring forward osmosis membrane performance

There's a need for standardized methods of measuring FO membrane performance

Forward osmosis membrane performance results from a non-trivial combination of external test parameters such as (but not excluded to):

- Osmotic strength of feed and draw solutions
- Membrane orientation
- Cross flow velocity
- Flow conditions in the test chamber/module
- Temperature
- Molecular nature of osmolytes (e.g. NaCl, MgCl, etc)
- Design of the FO membrane test system
- Experimental design (e.g. run-in times, equilibration times, measuring times, etc.)

Given the parameters above and their non-linear interdependence it is virtually impossible (without doing the actual physical experiment) to project how a given FO membrane will perform under test conditions differing from the ones the membrane is being physically tested under. Hence, comparing performance of FO membranes from different suppliers requires said membranes to be tested under identical standard test conditions. Conversely, without widely accepted standard test conditions, FO membrane performance cannot be compared between different suppliers. We – at ForwardOsmosisTech believe – that transparent comparison of FO membrane performance contributes positively to breaking down commercialization barriers within the FO field.

So it all boils down to defining (and adopting) standard test conditions for determining FO membrane performance

Several good suggestions of standard forward osmosis membrane test conditions have already been proposed by leading experts in the field (see for example "Standard Methodology for Evaluating Membrane Performance in Osmotically Driven Membrane Processes" by Cath et. al.) but – to our knowledge – not yet widely adopted.

Here we present ForwardOsmosisTech's take on the subject, which is inspired in part by scientific literature and in part by our many years of practical experience assessing forward osmosis membrane performance.

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Membrane form factors and suggested sample sizes for performance evaluation

Form factor	Suggested sample size (surface area)	Notes
Flat sheet	50-100 cm^2	Traditionally, flat sheet coupons are cut to fit Sterlitech's CF042 chamber (5.5 x 11cm = 60.5 cm^2). Coupons of this size will transport roughly 60 g of water per hour given a typical FO membrane performance of 10 L/m^2h (abbreviated LMH)
Hollow Fiber	50-100 cm^2	Hollow fibers are a new FO membrane form factor and – as of yet – there's no consensus on fiber diameter, fiber length, and number of fibers in the hollow fiber test module. ForwardOsmosisTech suggests a total fiber inner surface area of 50-100 cm^2 as this results in a water transport of roughly 50-100g per hour, which fits well with the system component specifications summarized below
Tubular	50-100 cm^2	Same as above for the hollow fiber form factor
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Membrane conditioning and storage

Stage	Hydration level	Conditioning	Storage	Notes
Upon delivery	Wet	No conditioning needed	4°C in ultra pure water	Exchange water on a weekly basis to avoid bacterial growth. Use within 1 month of delivery unless otherwise specified by the supplier
Upon delivery	Dry	No conditioning needed	Room temperature in a dry environment	Use within 6 months of delivery unless otherwise specified by the supplier
Before testing	Wet	Rinse thoroughly in ultra pure water	N.A.	Take care not to damage the rejection layer / active layer during the washing process
Before testing	Dry	Hydrate by rinsing thoroughly in ultra pure water followed by 15 minutes of low-pressure driven permeation of ultra pure water through the membrane Alternatively, hydration can be done by soaking for 5 minutes in a 50% mixture of ultra pure water and ethanol or isopropyl alcohol (IPA)	N.A.	Care must be taken in the hydration step to ensure complete wetting of the FO membrane's support structure as well as to remove any protective coatings (such as glycerol) added by the supplier Take care not to damage the rejection layer / active layer during the washing process
After testing	Wet	Rinse thoroughly with ultra pure water to remove any buildup of salt	4°C in ultra pure water	ForwardOsmosisTech recommends no more than 3 independent performance measurements on individual membrane samples
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Overview of system components needed for determining FO membrane performance

The table below summarizes the main system components needed in a bench-top system for determining FO membrane performances of membrane samples ranging in membrane area from 50cm^2 to 100cm^2.

Component	Main functions	Specifications	Importance
1 laptop	Record data from conductivity meters and the electronic scale	Any Windows based laptop will suffice	Need to have
2 gear pumps (one for the feed loop and one for the draw loop)	Maintain cross velocity flow speeds of 20cm/s on the membrane feed and draw sides	1000-3000ml/min pumping capacity depending on the inlet cross sectional area of the membrane test cell	Need to have
1 laboratory chiller and associated cooling coils	Maintain stable feed and draw solution temperature of 20-22°C	Any bench-top chiller with the following specifications will do: • Working Temperature: -20° to +40°C • Temperature Stability: ±0.1°C • Cooling Capacity: Up to 1290 watts @ 20°C	Nice to have if the ambient lab temperature is stable around 20-22°C Need to have if the ambient lab temperature fluctuates excessively
2 conductivity meters	Continuously measure the feed loop increase in conductivity due to reverse salt flux from the draw solution and the draw loop decrease in conductivity due to continuous dilution as water is transported across the membrane	• Automatic data logging • Sensitivity range for feed loop conductivity probe: 0-400μS • Sensitivity range for draw loop conductivity probe: 50-100mS • Probe placement: the feed and draw probes should be placed after the bulk feed and draw loop reservoirs and before the FO test chamber feed and draw solution entrances, respectively	Need to have: feed loop probe Nice to have: draw loop probe

1 electronic scale	Continuously measure the decreasing feed reservoir weight to determine the FO membrane mediated water flux from feed to draw	• Automatic data logging • 3-5kg max weight • 0.1 g accuracy	Need to have
1 magnetic stirrer	Continuously stir the draw reservoir solution to ensure uniform bulk osmolyte concentration	Any standard lab-scale magnetic stirrer capable of providing 200-1000 RPM will do the trick	Need to have
1 FO test chamber (for flat sheet membrane coupons)	Provide an enclosed & sealed environment with stable (non-turbulent), uniform, and identical flow conditions on both the draw side and the feed side of membrane coupons	Many FO researchers opt for the CF042 test chamber from Sterlitech. Alternatively, for those researchers with access to engineering/workshop facilities, "homemade" acrylic/PMMA test chambers are equally suitable providing they secure an enclosed & sealed environment (i.e. leak free) with stable (non-turbulent), uniform, and identical flow conditions	Need to have
Tubing, feed&draw reservoir containers, and various fittings	Tubing and containers make up the feed and draw loops while the various fittings ensure that individual system components can easily be removed for cleaning and maintenance	Silicone-based or other flexible (and transparent) tubing is preferable. The tubing must be chemically resistant to intended feed and draw solution components	Need to have

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Overview of system components needed for determining intrinsic FO membrane properties

The table below summarizes the main system components needed in a bench-top system for determining intrinsic FO membrane performance properties of membrane samples ranging in membrane area from 50cm^2 to 100cm^2.

Component	Main functions	Specifications	Importance
1 gear pump (identical to the ones used for measuring FO membrane performance) can be used for simultaneous measurements in two individual test chambers	Maintain cross flow velocity speeds of 20cm/s on the membrane feed side as well as generate hydraulic pressure of up to 5 bar on the membrane feed side	1000-3000ml/min pumping capacity depending on the inlet cross sectional area of the membrane test cell	Need to have
1 laboratory chiller and associated cooling coil	Maintain stable feed solution temperature of 20°C	Any bench-top chiller with the following specifications will do: • Working Temperature: -20° to +40°C • Temperature Stability: ±0.1°C • Cooling Capacity: Up to 1290 watts @ 20°C	Need to have
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1 handheld conductivity meter	Measure the conductivity of feed and permeate to determine membrane rejection properties towards various salts	A handheld/ portable, battery powered conductivity meter is preferable. The meter must be able to measure conductivity reliably in the range 1μS – 200mS	Need to have
2 dead-end membrane filtration cells	Provide an enclosed & sealed environment at a pressure up to 5 bar with stable (non-turbulent) and uniform feed flow. The cell should have a porous support on the permeate side to reduce the likelihood of membrane breakage. Finally the cell should allow for easy sampling/ collection of permeate	The CF042 dead-end RO filtration cell from Sterlitech works well	Need to have
1 digital pressure gauge	Provide real-time readings of the pressure in the feed loop	Any digital pressure gauge designed for in-line pressure recordings in the interval 1-10 bar will suffice	Need to have
Pressure resistant tubing, feed reservoir container, needle valves, and various fittings	Together, the tubing, container, and various fittings make up the feed loop. The needle valve restricts flow through the feed loop to build up pressure	All tubing and fittings must be pressure resistant up to 10 bars. However, it is not recommended to operate the system at more than 5 bars	Need to have

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Standard conditions, equations, and protocols for determining FO membrane performance

Below we summarize experimental standard conditions to be used when determining FO membrane performance.

Experimental condition	Value	Units	Notes
Feed and draw solution cross-flow velocity across the membrane surface	20	cm/s	Use the cross-sectional area of the chamber's feed and draw inlets to evaluate respective cross-flow velocities from the equation Q(flow rate) = A (cross-sectional area) * V (cross-flow velocity)
Draw solution concentration	1	M	NaCl
Feed solution concentration	0	M	De-ionized (MilliQ) water as standard. Pollutants/ contaminants may be added to the feed solution to assess application-specific forward rejection properties
Hydraulic pressure	≈ 0	bar	Care should be taken to minimize the hydraulic pressure difference across the membrane's active layer (the dense rejection layer). Aim for less than 0.2 bar hydraulic pressure difference
Feed and draw solution temperature	20-22	°C	No need for temperature control if the ambient lab temperature is stable within the required interval
Feed and draw solution pH	≈ 7	N.A	Use feed and draw solutions as close to neutral pH as possible. However, there's no need for pH adjustment
Membrane orientation	FO mode and PRO mode	N.A	FO membrane performance (water flux (J_W) and reverse salt flux (J_S)) should be determined in both FO and PRO mode. Forward rejection to specific feed solution contaminants (R_{xxx}) should be determined in FO mode only.
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Below we summarize our take on standard protocols for determining FO membrane performance.

Performance parameter	Equation	Measurement protocol	Notes
Water flux (J_W)	$J_W = A\Delta\Pi_e$	• Start the experiment by pumping feed and draw solutions around the fully assembled system and make sure to remove air-bubbles in the test chamber • Set the electronic scale to record readings in 5 minute intervals. Start recording (t=0) immediately after all air-bubbles have been removed • Run the experiment for 45 minutes in total: 15 minutes initial run-in (not included in the data analysis) followed by 30 minutes membrane operation (included in the data analysis) • Calculate the average water flux for the 30 minute operation interval from the total feed reservoir weight reduction during said 30 minute interval. For a more detailed water flux analysis, the average water flux can be calculated and plotted for each 5 minute interval • J_W for any given FO membrane type is reported as the average of at least 3 measurements (in both PRO and FO mode) – as described above – of individual randomly selected membrane coupons	• A is the "pure water permeability coefficient" – an intrinsic membrane property • $\Delta\Pi_e$ is the effective osmotic pressure difference (assuming the absence of any hydraulic pressure difference) across the membrane's active layer (the dense rejection layer) • J_W is predominantly reported in L/m^{2}h or LMH in short
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Reverse salt flux (J_S)	$J_S = B\Delta C$	• Prepare a calibration curve relating conductivity to NaCl concentration in the feed probe's sensitivity range (0-400µS) • Calibrate the feed probe according to the manual • Set the conductivity meter and the electronic scale to record readings in 5 minute intervals. Start recording (t=0) immediately after all air-bubbles have been removed • Run the experiment for 45 minutes in total: 15 minutes initial run-in (not included in the data analysis) followed by 30 minutes membrane operation (included in the data analysis) • Calculate the average reverse salt flux for the 30 minute operation interval from the increase in feed loop conductivity during said 30 minute interval. For a more detailed reverse salt flux analysis, the average reverse salt flux can be calculated and plotted for each 5 minute interval • J_S for any given FO membrane type is reported as the average of at least 3 measurements (in both PRO and FO mode) – as described above – of individual randomly selected membrane coupons	• B is the "salt permeability coefficient" – an intrinsic membrane property depending on the solutes used in the draw solution • ΔC is the difference in solute concentration across the active layer • J_S is predominantly reported in g/m^2h or GMH in short

Forward rejection to specific feed solution contaminants (R_{xxx})	R_{xxx} = $(1-C_P/C_F)*100\%$	• A separate set of protocols must be developed to quantify trace amounts of feed solution contaminants of interest within a 1M NaCl solution (the draw). Alternatively, samples may be sent for external chemical analysis by external vendors • Start recording (t=0) immediately after all air-bubbles have been removed • Run the experiment for 45 minutes in total: 15 minutes initial run-in (not included in the data analysis) followed by 30 minutes membrane operation (included in the data analysis) • Calculate the average forward rejection for the 30 minute operation interval from the increase in contaminant concentration in the draw loop during said 30 minute interval. For a more detailed forward rejection analysis, the average forward rejection can be calculated and plotted for each 5 minute interval • R_{xxx} for any given FO membrane type is reported as the average of at least 3 measurements (in FO mode only) – as described above – of individual randomly selected membrane coupons	• C_P is the average concentration of contaminant in the permeate over the sampling time interval where forward rejection is assessed • C_F is the average concentration of the contaminant in the feed over the sampling time interval where forward rejection is assessed In forward osmosis experiments it is impractical/difficult to directly measure C_P. Instead, one can measure the concentration of contaminant in the draw solution at the end of the sampling time interval (C_D) and calculate C_P as follows: $C_P=C_D*V_D/V_P$ • V_D is the draw volume at the end of the sampling time interval • V_P is the volume of permeate passing across the membrane during the sampling time interval

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Standard conditions, equations, and protocols for determining intrinsic FO membrane properties

Below we summarize experimental standard conditions to be used when determining intrinsic FO membrane properties.

Experimental condition	Value	Units	Notes
Feed solution cross-flow velocity across the membrane surface	20	cm/s	Use the cross-sectional area of the chamber's feed and draw inlets to evaluate respective cross-flow velocities from the equation Q(flow rate) = A (cross-sectional area) * V (cross-flow velocity)
Feed solution concentration when determining the pure water permeability coefficient (A)	0	M	MilliQ water as standard
Feed solution concentration when determining the salt permeability coefficient (B)	200ppm	NaCl	MilliQ water with 200mg/L reagent grade NaCl corresponding to an osmotic pressure of 0.15 bar
Hydraulic pressure (for both A and B value determination)	2	bar	In order to avoid compaction of potential delicate FO membrane substrate materials, the applied hydraulic pressure should not exceed 2 bar
Feed solution temperature	20	°C	Maintain the feed solution temperature by use of the laboratory chiller
Feed solution pH	≈ 7	N.A	Use feed solutions as close to neutral pH as possible. However, there's no need for pH adjustment
Membrane orientation	N.A	N.A	Membrane active layer (the dense rejection layer) against the permeate
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Below we summarize our take on standard protocols for determining intrinsic FO membrane properties.

Performance parameter	Equation	Measurement protocol	Notes
Pure water permeability coefficient (A)	$J_W = A\Delta\Pi_e$	• Use MilliQ water as the feed solution (zero osmotic pressure) • Equilibrate the system until the hydraulic pressure and permeate flow are stabilized • Once equilibrated set the starting time (t=0) and start collecting permeate (at least 5 g) • The A value for any given FO membrane type is reported as the average of at least 3 measurements – as described above – of individual randomly selected membrane coupons	• $\Delta\Pi_e$ is the hydraulic pressure difference across the membrane's active layer (the dense rejection layer) • J_W is reported in L/m^2h or LMH in short
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Salt permeability coefficient (B)	$J_S=B\Delta C$ $B = \exp(-J_W/k)*J_W*(1-R_{NaCl})/R_{NaCl}$	• FO membrane B values are calculated from J_W and R_{NaCl} : • $B = J_W*(1-R_{NaCl})/R_{NaCl}$ • The B value for any given FO membrane type is reported as the average of at least 3 J_W/R_{NaCl} measurements of individual randomly selected membrane coupons	• ΔC is the difference in solute concentration across the active layer • J_S is predominantly reported in g/m^2h or GMH in short • k is the mass transfer coefficient • In the case of high feed flow rate and low feed salt concentration, external concentration polarization can be neglected, meaning $\exp(-J_W/k) \approx 1$

Rejection to NaCl (R_{NaCl})	R_{NaCl} = $(1-C_P/C_F)*100\%$	• Immediately after determining the A value, carefully empty the test chamber, tubing, permeate collection tube, and exchange the feed solution to 200ppm NaCl • Equilibrate the system until the hydraulic pressure and permeate flow are stabilized • Collect a sufficient amount of permeate (usually 5 ml) to allow for the measurement of permeate conductivity • Measure the bulk feed conductivity immediately after permeate collection • The R_{NaCl} value for any given FO membrane type is reported as the average of at least 3 measurements – as described above – of individual randomly selected membrane coupons	• C_P (permeate concentration) and C_F (feed concentration) are assumed to be proportional to the conductivities of said solutions, hence: • R_{NaCl} $=(1-S_P/S_F)*100\%$ where S_P and S_F are the permeate and feed conductivities, respectively

7.3 Guide to forward osmosis systems

A general introduction to forward osmosis systems

If forward osmosis membranes are the engine of forward osmosis based water treatment processes, then forward osmosis systems are all the other components that enable the car to move from A to B, or in this case carry out actual water treatment tasks. We have written several articles relating to forward osmosis systems, and the goal of this page is to give you – our reader – an overview of the work we've done. If you have suggestions on how to improve this page or simply want to let us know that we did a good job (thanks in advance!), please feel free to drop us an email on forwardosmosistechportal@gmail.com.

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What does a forward osmosis system consist of?

Key Takeaways

- ForwardOsmosisTech's definition of a forward osmosis system: "All the components needed to enable forward osmosis membranes to be used in water treatment applications"

With this definition in mind, forward osmosis systems typically include the following components:

- The forward osmosis membrane housing (also know as a forward osmosis module)
- Low energy pumps to move the draw and feed stream in a cross-flow configuration across either side of the FO membrane
- Pipes and valves
- Feed stream pretreatment systems to remove large contaminants
- Various instruments & meters for continuous performance evaluation
- Draw solution reservoir tank
- Feed solution reservoir tank
- Performance enhancing design elements
- A draw solution regeneration system (i.e. a system able to separate draw solutes from the water continuously extracted
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from the feed stream) if one of the end products of the system in question is reusable water

Key Takeaways

- For more detailed information on forward osmosis systems and systems designs, please refer to our article: "Forward osmosis system design".

Forward osmosis system classification: stand-alone & hybrid

There are many ways of classifying forward osmosis systems. Here at ForwardOsmosisTech we have chosen the simplest approach, namely classifying forward osmosis systems into two broad categories:

1. Stand-alone forward osmosis systems where the system outputs are a concentrated feed solution and a diluted draw solution
2. Hybrid forward osmosis systems where forward osmosis elements are combined with other membrane technologies and where the outputs are a concentrated feed solution and permeate consisting of reusable water (potable or non-potable depending on the design of the system)

How can the performance of forward osmosis systems be improved?

The main purpose of forward osmosis systems is to create operating conditions that maximize the performance of the system's engine – the forward osmosis membranes – while at the same time minimizing the energy needed to maintain said conditions. With this in mind, forward osmosis system performance can be improved through the following general strategies:

1. Minimizing the energy needed to pump and recirculate feed and draw streams through the system
2. Improving the forward osmosis module design to increase fluid turbulence and thus reduce external concentration polarization
3. Improving forward osmosis membrane performance

7.4 Guide to forward osmosis applications

A general introduction to forward osmosis applications

We realize that navigating any portal can be challenging at times. To make life easier for you – our readers – we have therefore decided to summarize all our forward osmosis application related knowledge on a single page with the aim of creating a more accessible entry point to the ForwardOsmosisTech portal. We hope we have succeeded in doing so below. As always, send us a mail at forwardosmosistechportal@gmail.com if you have suggestions for improvements or simply have something on your mind you want to share with us.

Concentration, dilution, water production, and energy production

As the title suggests there are essentially 4 ways for forward osmosis systems to provide value in end user applications:

1. **Concentration**, where water is extracted by forward osmosis processes from specific feed streams. Continuous extraction of clean water from said feed solutions will

result in volume reduction, which in effect concentrates solutes and any other components. This process is also known as dewatering.

2. **Dilution (indirect water production)**, where water is extracted from feed streams by forward osmosis processes into a given draw solution. Continuous extraction of clean water into the draw solution will result in volume increase, which in effect dilutes solutes and any other components. Dilution can be seen as an indirect way of producing water.
3. **Direct water production**, where the clean water extracted from feed streams into draw solutions is separated from the draw solutes by means of complementary separation processes (e.g. reverse osmosis, nanofiltration, ultrafiltration, membrane distillation, thermal separation etc.).
4. **Energy production**, where the clean water extracted from feed streams into draw solutions is used to generate hydraulic pressure on the draw side, which in turn can be used to generate electrical energy via turbines. This process is known as pressure retarded osmosis.

The table below summarizes a few examples of real-life applications, where the 4 value generators described above are put to use. Notice that some applications utilize more than one value generator and thus provide value to end users on several levels.

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Application	Utilized value generator
Industrial wastewater treatment – example 1 Some industrial waste-waters are inherently difficult to treat with conventional pressure-driven water treatment technologies due to a high content of fouling agents (TDS & TSS) and/or a high salt content. Examples include – but are in no means limited to – wastewater from the oil and gas industry, wastewater from wet scrubbers used to remove contaminants from sources of air pollution, and wastewater from the textile dying industry. In all the aforementioned applications, forward osmosis systems are a good low-energy alternative to installing expensive pre-treatment systems or using evaporators. Since disposal costs for industrial wastewater are mostly volume-based, the primary role of the forward osmosis system is to dewater the industrial wastewater to a point where disposal costs have been reduced to an acceptable level. In a continuous water treatment system, the water extracted through forward osmosis must be separated from the draw solutes in order to regenerate the osmotic strength of the draw solution. This process of water separation can be carried out by traditional pressure-driven membrane technologies, which are now operating directly on a diluted forward osmosis draw solution with greatly reduced fouling propensity. An important driver for designing forward osmosis based wastewater treatment systems with continuous draw solution generation is the simultaneous production of reusable water.	• Concentration • Direct water production
Industrial wastewater treatment – example 2 In some industrial applications, the value of the wastewater treatment system lies in its ability to produce a dilutate without consumption of precious fresh water resources. One good example of such applications is fertigation, an agricultural process where a forward osmosis system is used to extract clean water from impaired water sources into a concentrated liquid fertilizer solution. In the process, the liquid fertilizer solution becomes diluted to a point where substantially less fresh water resources are needed to produce the final fertilizer-containing irrigation water.	• Dilution (indirect water production)
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Industrial wastewater treatment – example 3 One of the best application areas for forward osmosis systems can be found within the field of industrial process optimization. Imagine a factory/plant with two separate aqueous streams: one needs to be concentrated an another needs to be diluted. Traditionally these streams are treated separately but a forward osmosis system is able to utilize the osmotic pressure in the concentrated stream to extract water in a low energy fashion from the diluted stream. Thus, forward osmosis systems offer the possibility to replace two costly treatment processes with a single-step, low energy process. In our article about stand-alone forward osmosis systems we give an example of how forward osmosis technologies can be used for industrial process optimization in traditional RO-based desalination plants.	• Concentration • Dilution (indirect water production)
Osmotic power generation – example 1 Osmotic power generation plants generate electricity from the osmotic pressure difference of two aqueous streams via the principle of pressure retarded osmosis (PRO). Briefly, PRO is a forward osmosis process where the water extracted into the draw solution is used to generate hydraulic pressure, which in turn can run a turbine. Traditionally, osmotic power generation plants have been envisioned to utilize the osmotic pressure difference between river water and seawater.	• Energy production
Osmotic power generation – example 2 Forward osmosis systems capable of running in PRO mode could potentially also be used for combined osmotic power generation and industrial process optimization. The idea is to co-localize desalination plants and wastewater treatment plants and utilize the brine waste from the desalination plant to both dewater wastewater streams and at the same time generate electricity through pressure retarded osmosis. In the process, the brine waste becomes diluted to seawater salinity levels, thus, greatly reducing the cost of brine discharge.	• Energy production • Dilution (indirect water production) • Concentration