FORWARD OSMOSIS AS A PRE-TREATMENT TO REVERSE OSMOSIS

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Abstract

This paper presents some aspects of forward osmosis coupled with reverse osmosis using a recirculating draw solution, to produce desalinated water or for dewatering/concentrating a feed stream, with some data provided from a number of operational sites. Many of these aspects are applicable to other osmotic processes and provide an insight into where they may be appropriately considered.

A comparison is drawn between FO desalination and conventional reverse osmosis, from both real operational results and a theoretical comparison looking at the merits and demerits of the respective processes. This is of particular relevance when more complex pre and post treatments such as MF or UF and boron removal are applied to RO. Energy consumption figures with respect to the degree of fouling are presented, noting that both the practical and academic experience to date indicates that the FO process is much less prone to fouling than reverse osmosis.

It is concluded that there are a number of differences that when taken as a whole can make a significant difference, primarily associated with reduced rates of fouling and the ability to operate the reverse osmosis step at optimum conditions.

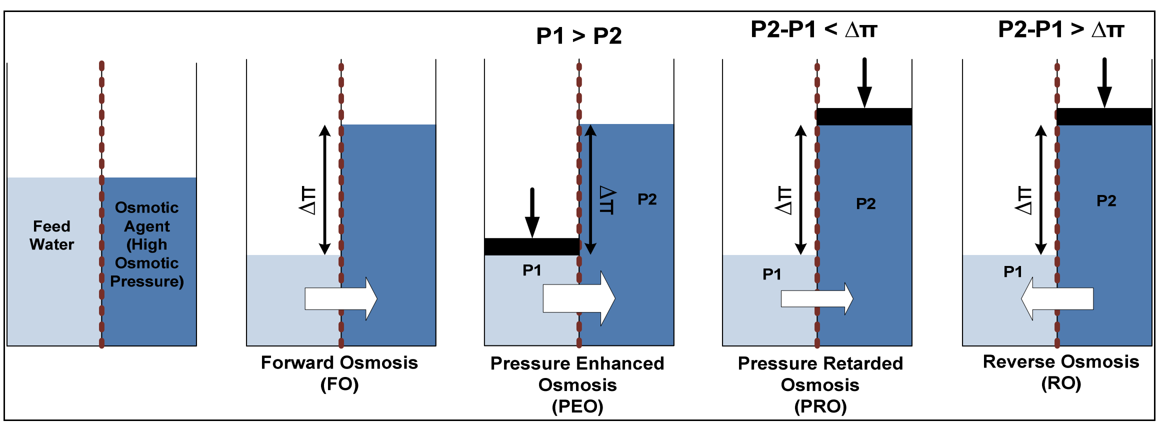
I. INTRODUCTION

Osmotically driven membrane processes (ODMPs) or forward osmosis (FO) processes may not currently be 'main stream', but it is apparent that they are increasingly becoming a topic of some interest. National Geographic [1] in an article in April 2010 cited it as one of the three most promising new desalination technologies and at the last IDA World Congress in Perth, Australia in September 2011, six papers were published on this subject. In the Journal of Membrane Science the number of papers published has seen a very significant increase over the last three years (24 in 2012), showing the increasing level of academic interest. We have also seen the emergence of a number of commercial organisations with significant funding to develop and exploit the technology, such as Modern Water plc, Oasys Water Inc, Hydration Technology Innovations Inc and Statkraft AS.

So why this interest in forward osmosis, or more simply just osmosis, given that it has been used in nature for rather a long time by, plants, trees, sharks and human cells to name just a few? It also takes place as drawback when a reverse osmosis plant shuts down and the permeate flows back across the membrane to dilute the feed solution, so this should give some clue as to its potential.

The process, just like reverse osmosis (RO), requires a selectively permeable membrane separating two fluids with different osmotic pressures and was first observed by Albert Nollet in 1748 [2]. If the solvent is water then effectively almost pure water flows from the fluid of lower osmotic pressure to dilute the fluid of higher osmotic pressure. The process in its pure form takes place at atmospheric pressure, with variations such as pressure enhanced osmosis and pressure retarded osmosis. These are simply illustrated in Figure 1.

Figure 1: Osmotic Processes



It is worth just reminding ourselves just what forward osmosis can do:

- It can dilute a solution of higher osmotic pressure with a solution of lower osmotic pressure.
- It can concentrate a solution of lower osmotic pressure with a solution of higher osmotic pressure.

So why might this be useful in a water treatment application? One key element is the dilution/concentration process takes place across a selectively permeable membrane, at low pressure and the ions are rejected in both the direction of forward flow and reverse flow. In a similar way to reverse osmosis we talk about salt passage in the direction of forward flow, but ion mass transfer also takes place in the reverse direction which is often termed as back diffusion.

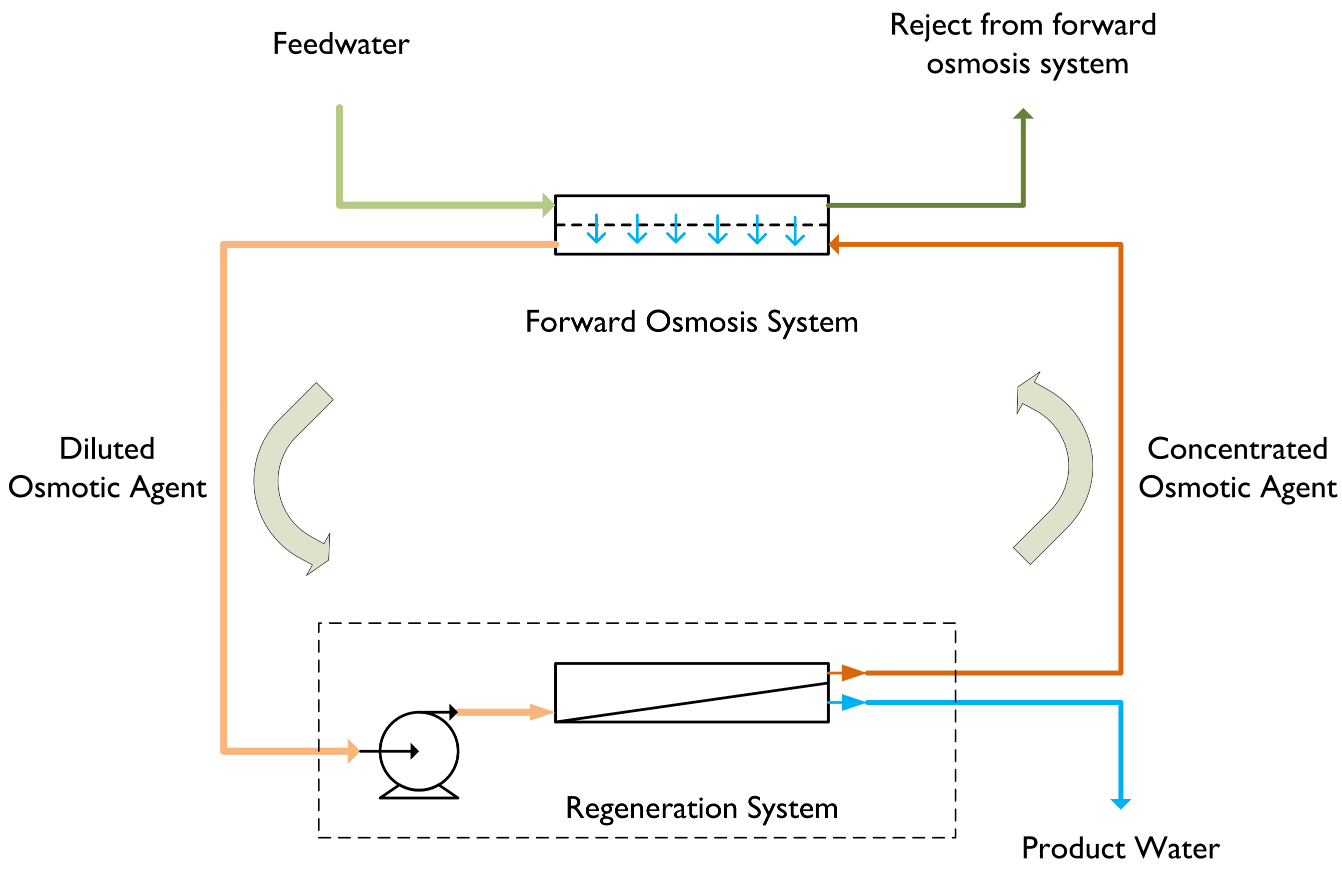
The process has considerable potential across a wide variety of applications; emergency drinks [3], power generation [4], enhanced oil recovery [5], produced water treatment [6], fluid concentration [7], thermal desalination feedwater softening [8], water substitution [9] and desalination [10]. However only a few of these applications have been currently commercialised; emergency drinks, produced water treatment, desalination and water substitution. A desalination process using combined FO and RO is the subject of this paper, which has been successfully deployed at a number of sites.

II. FORWARD OSMOSIS DESALINATION

The basic principles of this process, in all its variations, is an initial forward osmosis step followed by a regeneration step to re-concentrate the osmotic agent / draw solution for reuse and to separate the 'desalinated' water, prior to any post-treatment. This process of course can be used for 'de-watering' or indeed concentration of the feed solution. The regeneration step is generally either thermal or membrane based. Modern Water has successfully used a reverse osmosis regeneration step, with a simplified process illustrated in Figure 2. At first sight this might seem a trivial problem to have solved, however what also must be considered is:

- The selection of the osmotic agent / draw solution, which by necessity must be non toxic
- Maintaining a constant osmotic pressure for the concentrated osmotic agent
- Managing the contamination of the osmotic agent with salts from the feed solution
- Minimising back diffusion of the osmotic agent to the feed solution
- A robust forward osmosis membrane that can adequately deal with flow on both sides
- Operating on a continuous and economic basis

Figure 2: Simple FO/RO Process



So given the above challenges why then bother to have solved them? The answers again are not so straight forward and like all membrane processes can be site specific. For brevity the two main advantages over conventional reverse osmosis are lower fouling propensity and lower energy consumption, which are discussed in more detail later

The significantly lower fouling potential of the forward osmosis process compared to reverse osmosis membranes, operating under the same feed conditions, has been shown by a number of academic researchers. However more importantly under real world conditions on challenging feedwaters, Modern Water has demonstrated that on one particular site in Oman no chemical cleaning was required over several years operation, yet the conventional process required cleaning every few weeks with several membrane changes [10]. This of course also means a reduction in the use of membrane cleaning chemicals and improved availability.

The potential for a lower energy consumption, which is sometimes not so readily understood and requires careful explanation, comes about in a number of ways:

- If we consider that a 'state of the art' reverse osmosis system has a similar energy consumption to a 'state of the art' FO system in the clean state. Then given that FO fouls at a lower rate than RO then it is clear that to maintain the same output the RO based process will require more energy. The degree of energy saving depends on the degree of fouling.

- Now consider the regeneration step, which is where the bulk of the energy is consumed for this forward osmosis desalination process. The osmotic agent is free of all particulates and large molecular weight organics from the feedwater, as the solution is made from permeate and as such a parallel should be drawn with the normal design criteria for second pass RO systems. The result is that the degree of irreversible flux decline is reduced. Additionally the recovery rate (50% for minimum energy), the membrane selection and configuration can be fully optimised and with conventional energy recovery systems applied to the high pressure concentrated osmotic agent stream.

- The regeneration step, again because it is fed with a 'perfect' solution has improved salt rejection compared to conventional RO. This may eliminate the use of a second pass and as such, energy is saved.

- Boron in desalinated water produced by reverse osmosis has long presented a challenge to the membrane industry with very poor rejection and the necessity for special high pH second passes or the use of ion exchange columns, to meet the relevant in country standards. These of course add not just complexity, capital cost and operational cost but increased energy consumption. The advantage of having a re-circulating osmotic agent is that its properties can be controlled and as such, in combination with the forward osmosis membranes, has improved boron rejection characteristics.

- The regeneration system operates at an elevated temperature compared to the feedwater as a result of the recirculating osmotic agent and therefore again energy is saved.

The desalination process, as it has currently been implemented by Modern Water, may be considered as an advanced pre-treatment to RO and as such the process could be retrofitted to existing conventional reverse osmosis plants, in circumstances where the economics of the process make sense and in particular when micro-filtration or ultra-filtration are being considered.

Modern Water's first full scale seawater plant (18 m^3/day) was commissioned in Gibraltar in September 2008 at an AquaGib site (Figure 3), with water going into the public supply after extensive independent testing on the 1 May 2009. This was followed by a much larger plant (100 m^3/day) located at the Public Authority for Electricity and Water's site at Al Khaluf (Figure 4) in Oman in November 2009 [10]. In an open public tender for conventional reverse osmosis, Modern Water was awarded a turnkey contract to build a 200 m^3/day forward osmosis based desalination plant at Al Najdah (Figure 5) again in Oman. Each of these plants has built upon the experience and development of the previous one, together with FO membrane development and work undertaken within the laboratory.

Figure 3: Gibraltar Plant

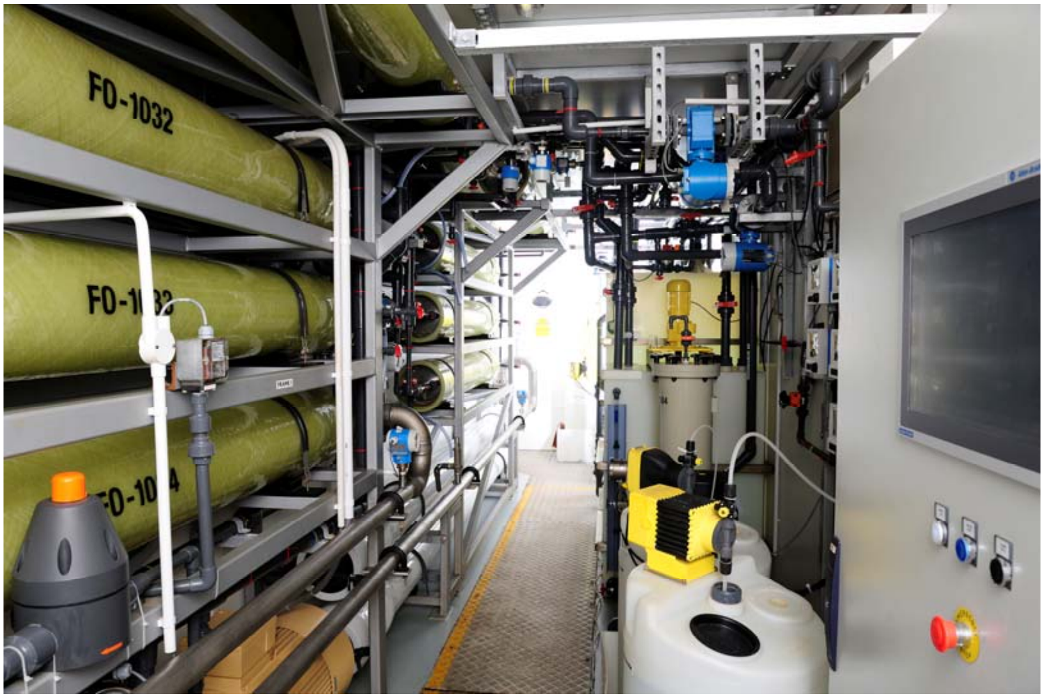


Figure 4: Inside the Process Container at Al Khaluf

Figure 5: Al Najdah 200 m^3/day FO Desalination Plant

We will now consider some of the differences in more detail between reverse osmosis and forward osmosis coupled with reverse osmosis (FO/RO).

2.1 Forward Osmosis Membranes

Membranes designed for forward osmosis, as has been reported in the literature [12] [13], need to have rather different characteristics compared to conventional reverse osmosis membranes. A thin rejection layer and a support layer with high porosity and low tortuosity. There are similarities in terms of geometry in that they can be of spiral wound, flat sheet, tubular or hollow fibre.

Modern Water has deployed a number of different membrane geometries and our current preferred geometry for the desalination application, as has currently been deployed, is the follow fibre type. This geometry is inherently more robust than the spiral wound type, given the susceptibility of the spiral wound type to glue line rupture and failure of the membrane.

There are advantages and disadvantages to each of the different geometries and it is the field of use that will dictate the most appropriate membrane design, not withstanding the lack of generally commercially available forward osmosis membranes. Although it is pleasing to note that this situation is beginning to change as more membrane suppliers enter the market, as the potential for forward osmosis based processes is beginning to be realised.

2.2 Comparison of product water quality

The recirculating osmotic agent (draw solution), allows this stream to be treated in a more economic manner as opposed to a once through system, where additives are discarded. In this way a number of interesting things can be done, for instance the pH may be increased or decreased relative to the feedwater. This has particular advantages when for instance it may be desirable to increase the overall boron rejection of the system between the feedwater and the final permeate.

2.2.1 Boron

There are varying guidelines / limits for boron for drinking water set by various governments and organisations. These vary from having no specific limit to having quite strict limits, the lowest being 0.5 mg/l. This is illustrated in Table 1.

Table 1: Boron standards

Country / Organisation	Boron (mg/l)	Reference
Australia	4	Australian Drinking Water Guidelines 6 2011 http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/eh52_aust_drinking_water_guidelines_update_120710_0.pdf
World Health Organisation	2.4	Guidelines for drinking-water quality, fourth edition http://whqlibdoc.who.int/publications/2011/9789241548151_eng.pdf
Environmental Protection Agency, USA	1.4	Health Effects Support Document for Boron http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1009WX4.PDF
Abu Dhabi, UAE	1.0	The Water Quality Regulations 2009 http://www.rsb.gov.ae/uploads/WaterQualityRegs2009.pdf
European Union	1.0	Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31998L0083:EN:NOT
India	1.0	Drinking Water Specification IS: 10500, 1992 (Reaffirmed 1993)
China	0.5	National Standard for the Peoples Republic of China, GB5749-2006, Standards for Drinking Water Quality
Oman	0.5	Omani Standard No. 8 / 2006
World Health Organisation	0.5	Guidelines for Drinking-water Quality, third edition http://www.who.int/water_sanitation_health/dwq/fulltext.pdf

Reverse osmosis membranes do not provide good rejection for boron, which is usually in the form of boric acid in the normal operating pH ranges. This rejection ranges from 43% - 93% [14], [15], [16] hence the many papers and studies published on the subject. This low rejection for reverse osmosis leads to both higher capital costs and operational costs in treating it to the required standard, as reported by the Bureau of Reclamation [16].

In seawater, boron primarily exists as boric acid, a week Lewis acid. The dissociation of boric acid occurs via a hydrolysis process, which is dependent on pH, ionic strength, pressure and temperature:

$$B(OH)_3 + 2H_2O \leftrightarrow B(OH)_4^- + H3O^+$$

Figure 6 [17] shows the significance of both pH and salinity on the dissociation constant (pKa) of boric acid, noting that in the dissociated form the rejection is significantly higher [14], [15].

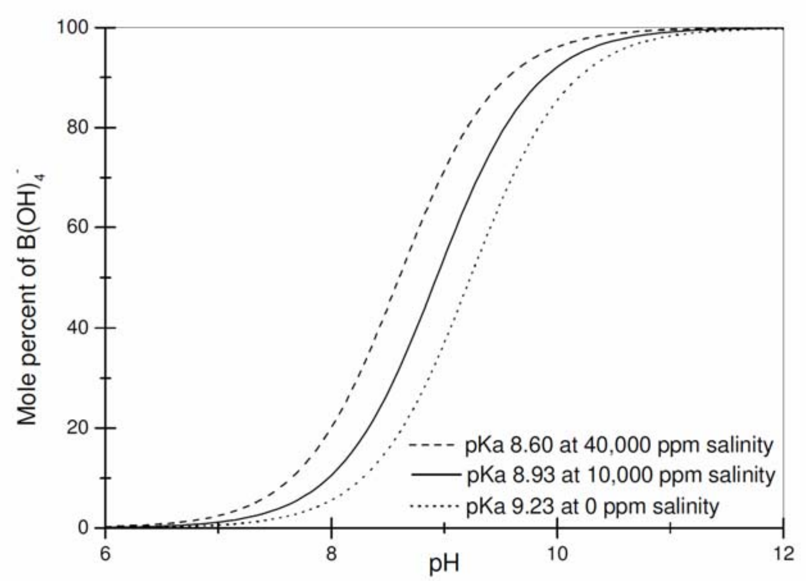


Figure 6: pH and salinity affects on the dissociation of boric acid

The osmotic agent is of course of high ionic strength (high osmotic pressure) and the pH can be varied depending on the membrane chemistry of the FO and RO membranes. Furthermore, because it is recirculated, chemical additives such as antiscalants can be economically added, with specific other treatments aimed at reducing particular contaminants (boron being one).

We have conducted limited work on this, including pH correction, antiscalant addition and treatment. It has previously been reported by Thompson [10] and as illustrated in Figure 7 that through a number of simple process changes that boron levels could be reduced from 1.2 mg/l to 0.7 mg/l. Further work has been done to improve this, but for commercial reasons is not reported here.

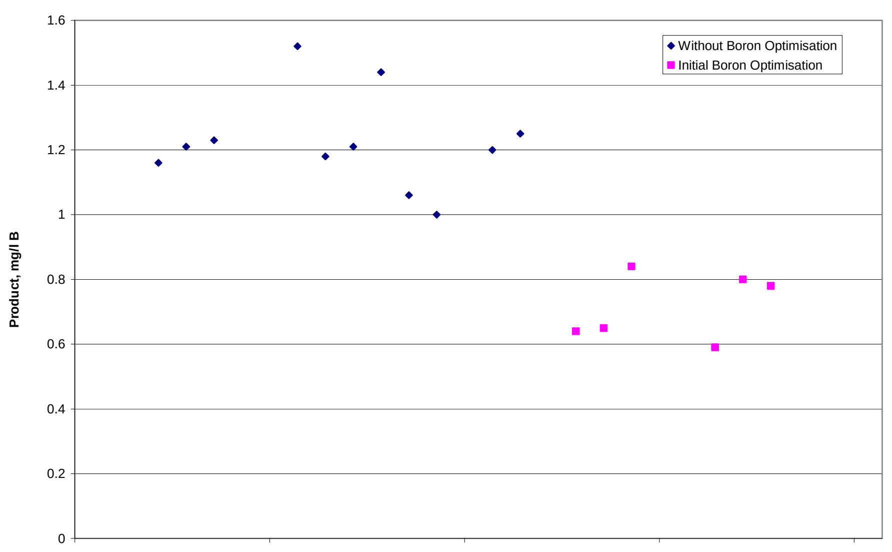


Figure 7: Simple boron optimisation following flow regime change. Taken from [10]

2.2.2 Salt passage

The forward osmosis desalination processes employs RO membranes for the second step; regenerating the osmotic agent and producing the desalinated water as RO permeate. RO membrane suppliers based on field experience have determined typical design values to be used depending on the feedwater to the plant. There is some variation between suppliers, but what is clear is that feedwater that is of RO permeate quality has significantly lower salt passage over time compared to other feedwaters. This is illustrated in Table 2 for three membrane vendors, for which information was readily available.

Table 2: Fouling factors and salt passage

	RO Permeate		MF/UF Pre-treatment		Open seawater intake	
	Fouling Factor (3 years)	Salt passage increase (3 years)	Fouling Factor (3 years)	Salt passage increase (3 years)	Fouling Factor (3 years)	Salt passage increase (3 years)
Hydranautics [18]	91%	15%	85%	21%	79%	30%
Toray [19]	94%	15%	88%	21%	85%	21%
Woongjin Chemical Co Ltd [20]	85%	21%	79%	30%	79%	30%

Figure 8 graphically illustrates the differences between an open seawater feed, ultra filtration treated feed and a RO permeate feed for a simple system with a feedwater TDS of 40,000 mg/l NaCl at 40% recovery and a membrane rejection of 99.8%.

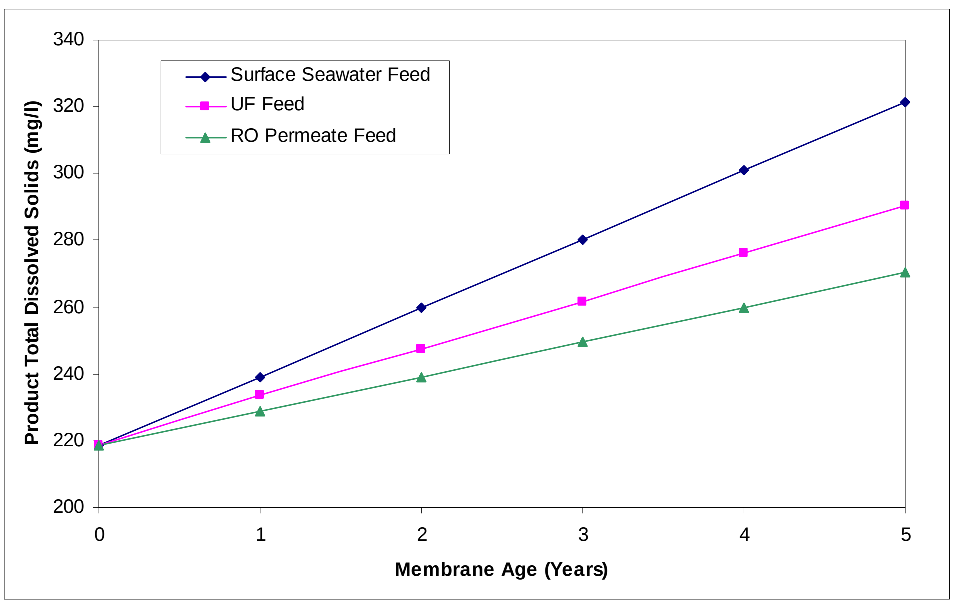


Figure 8: Permeate quality comparison

Long term data from the forward osmosis desalination plant located at Al Khaluf in Oman has shown a normalised salt passage for the regeneration system (RO) in the range 0.19% - 0.34% as illustrated in Figure 9. This is consistent with what was expected, although if anything the apparent salt rejection has increased with time.

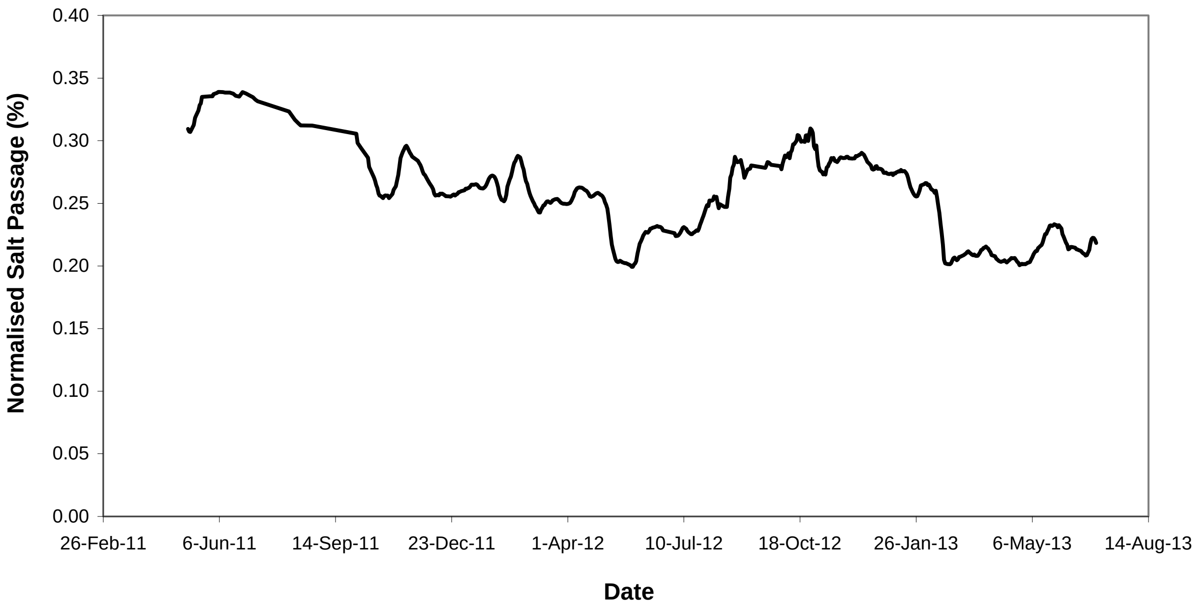


Figure 9: Normalised salt passage

There may be an imbalance between the FO membranes salt passage (in both the forward direction and reverse directions). In order to maintain stable operating conditions for both the FO and the regeneration (RO) systems the osmotic pressure of the draw solution must be kept constant. This can be done in a number of ways, depending on the operating conditions and the degree of imbalance in solute diffusion between the two systems. If there is reverse solute diffusion of the draw solution to the feed solution then osmotic agent will need to be added to the recalculating draw solution. In addition to this there will be an imbalance between the FO and the RO systems membranes with respect to the passage of contaminants from the feed solution, again this must be managed and controlled.

2.3 Membrane fouling

This is a key differentiator between osmotically driven processes and reverse osmosis, which has been investigated by a number of academic researchers and reported by Modern Water based on actual operating experience.

Lee et al. [21] reported in a comparison between forward osmosis and reverse osmosis organic fouling that organic fouling under FO conditions could be controlled entirely by increasing the cross flow velocity on a flat sheet membrane, while no noticeable change was observed for the RO system.

Holloway et al. [22] compared FO and RO membrane fouling when investigating the concentration of anaerobic digester centrate. They reported that the rate of flux decline was higher with RO than FO (Figure 10) and that the FO fouling was reversible, whereas the RO fouling was not. They further speculated that the reason for both the lower rate of fouling and its reversibility was due to the affects of hydraulic pressure on the foulants on the membrane surface, which occurs rapidly in RO.

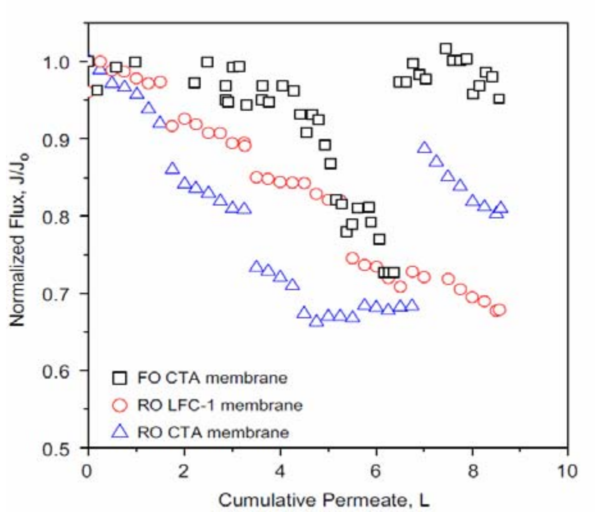
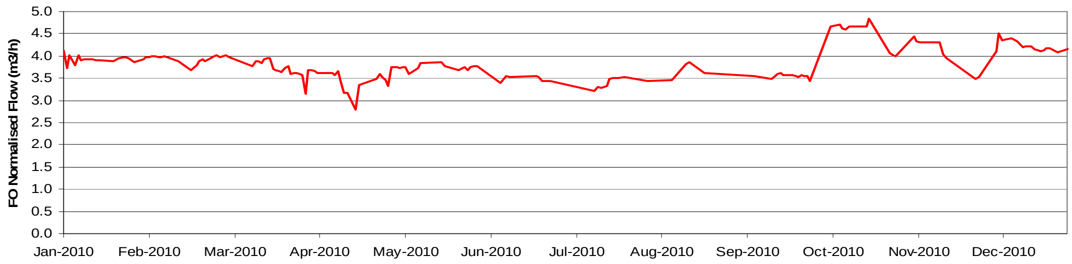


Figure 10: Relative water flux as a function of water produced for three experiments, including one chemical clean each. Taken from [22].

Nicoll [11], compared a seawater reverse osmosis plant operating in parallel with a FO/RO desalination plant, using a common pre-treatment in Oman and also reported on a FO/RO plant in Gibraltar, where there was no requirement to chemically clean the FO/RO plant but there was in the case of the reverse osmosis plant. What was not reported by Nicoll at the time was that the membrane active layer was on the seawater side of the membrane and the membrane was in a hollow fibre configuration. In a more extreme fouling situation, Cornelissen et al. [23] used an osmotic membrane bio reactor system to treat activated sludge, where they reported that neither reversible nor irreversible fouling was observed when the membrane active layer was facing the sludge.



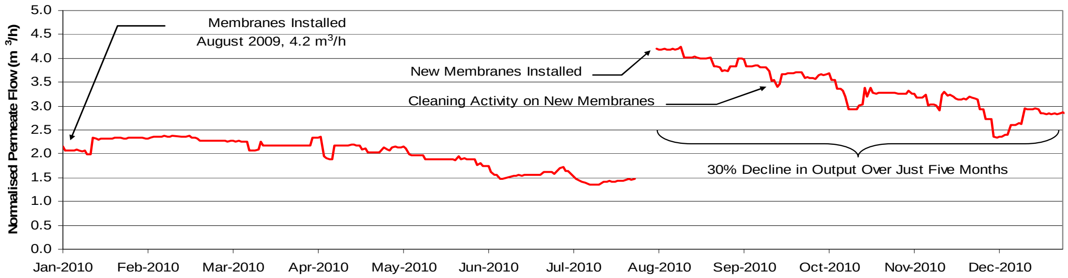


Figure 11: Comparison of a FO membrane system and a RO membrane system operating on a common feed water. Taken from [10].

The potential reasons for the lower fouling propensity were investigated by Lay et al. [24], where it was suggested that the low water fluxes, the use of hydrophilic and smooth membranes and the effect of internal concentration polarisation that is inherent to FO, were behind this phenomena.

There is much to understand, however it is clear that FO does have inherently lower fouling compared to reverse osmosis and this aspect is where there is much potential when operating on extremely challenging feedwaters.

2.4 Energy consumption and decrease in membrane permeability

Reverse osmosis membrane suppliers projection programmes do not normally account for reversible fouling, it is normally only irreversible fouling that is accounted for by the 'Fouling Factor'. In real operating conditions as the membranes foul the differential pressure across the feed / reject side of the membrane increases due to fouling. Typically the maximum allowable differential pressure across a single eight inch spiral wound membrane is 1 bar and for a six element pressure vessel the maximum is normally 4 bar. Normally a chemical clean is undertaken before these values are reached, which may be half the allowable limit. One consequence of this differential pressure is an increase in energy consumption, as either there is less energy to be recovered by an energy recovery device and/or a higher feed pressure is required. It is therefore important that this reversible fouling is also accounted for when comparing different pre-treatment systems, noting that it is frequently ignored.

If the differences in both the rate of fouling and the magnitude of the reversible fouling are accounted for, we can see for a simple system with different feed water qualities (Figure 12), again with feedwater TDS of 40,000 mg/l NaCl at 40% recovery.

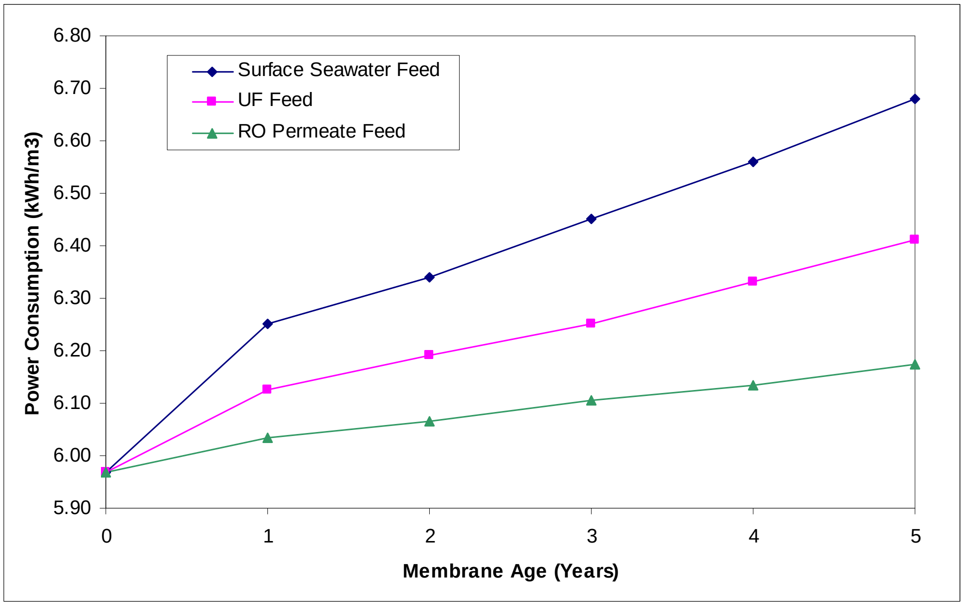


Figure 12: Power consumption with different feed waters

This difference in the rate of performance decline with different feed waters can be fully exploited by the osmotic agent regeneration system and as such its performance changes little with time.

2.5 Regeneration / RO membrane surface area and minimum brine flow rate

All membrane manufacturers set a minimum brine flow rate, which is again dependent on the type of feed water to the membranes. This is important in that it dictates, in practical terms, the amount of membrane surface area that can be practically deployed. Hence for systems fed with RO permeate type water it means that more surface area can be deployed compared to those fed by conventional systems including ultra filtration. Hence, the reject pressure can more closely approach the reject osmotic pressure, therefore for a given RO membrane the minimum possible energy consumption. As an example Hydranuatics [18] allow a minimum brine flow rate of 33% less in their design guidelines for a RO permeate feedwater compared to a surface seawater fed plant. This is illustrated in Figure 13 where effectively there is no increase in power consumption with time for the case of the RO quality feed water. This is directly applicable to the regeneration system of the osmotic agent, however when maximum surface areas are deployed to minimise energy consumption it is at the detriment of salt passage.

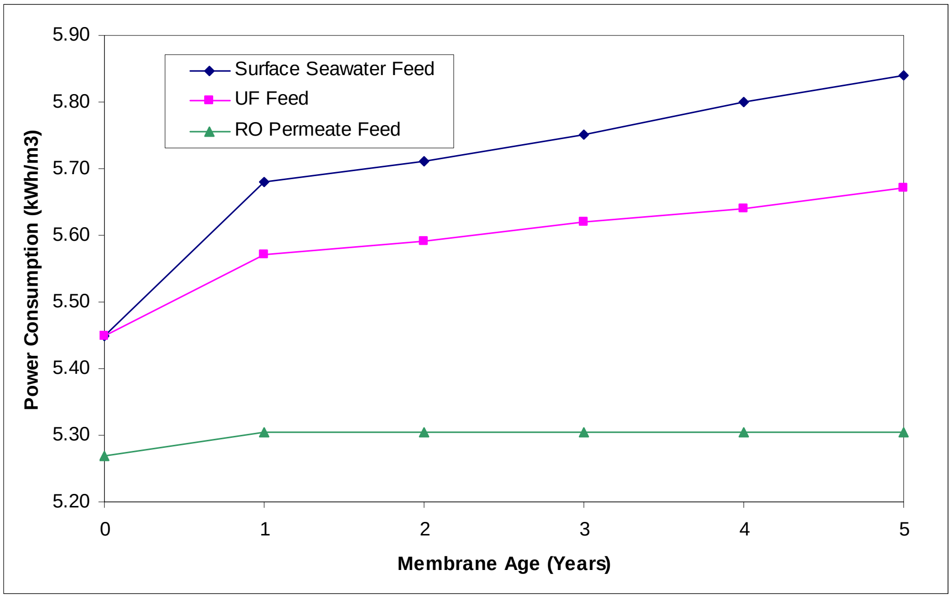


Figure 13: Power consumption with maximum membrane surface area

2.6 Temperature Effects

The membrane permeability both FO and RO (regeneration membranes) is increased with temperature due to a reduction of viscosity of the fluid. The increase in solvent flow is approximately 3% per degree Celsius, conversely the osmotic pressure increases reducing the effects of the rise in temperature. The net result may be modest depending on the nature and concentration of the osmotic agent. It is also worth noting that with increasing concentration of the draw solution there is an increase in viscosity. This is another factor to be accounted for in the selection of the draw solution in particular where minimising the energy consumption of the process is important.

The temperature affects also have an impact on the forward osmosis step, in particular when the feedwater solution is at a lower temperature than the osmotic agent, as has been reported by Xie et al. [25]. Here the affects of dilutive concentration polarisation are reduced with the decrease in viscosity and there is effectively an increase in the net driving osmotic pressure, which increases the flow of permeate from the FO membranes.

The recirculating draw solution is at an elevated temperature compared to the feedwater, the degree of elevation is dependent on the high pressure pump type used for the regeneration system and any measures taken to reduce or increase heat loss from the osmotic agent. For small scale plants a high efficiency positive displacement pump may be used, with efficiencies greater than 90%, but when it comes to larger plant then there is only multi-stage centrifugal pumps available which generally have a much lower efficiency. This difference is reflected in a higher temperature rise of the pumped fluid across the high pressure pump for large scale plants.

2.7 System Recoveries

The recovery or conversion factor of a reverse osmosis system is dictated by a number of factors, these include scaling from sparingly soluble salts and the maximum allowable feed water pressure for the particular membrane. Typically seawater based plants have recoveries in the range 30 – 45% [26].

The reverse osmosis based regeneration system does not have the same constraints as a RO system operating on feedwater and as such it can be fully optimised to operate at minimum energy at 50% recovery. Hence we can have a plant whereby the FO system operates at a lower recovery (similar to a conventional SWRO plant) but the regeneration system operates at higher recovery. The overall recovery of this system is simply the FO recovery, as the regeneration product flow is essentially equal to the FO permeate flow. This difference in the two systems can be exploited so that the FO based desalination system will use less energy than a conventional SWRO plant.

This can be simply illustrated by considering three different designs of desalination plant; the first based on conventional pre-treatment with a dual media filter (DMF), cartridge filtration and SWRO, the second based on a UF based pre-treatment with SWRO and the last on a conventional pre-treatment feeding a FO/RO plant. The assumptions are as follows:

1. For simplicity assume for each pump an overall efficiency of 71% (78% pump and 91% motor), with no energy recovery
2. Assume 5% additional flow for backwashing of media filters and 5% additional flow for the UF
3. Feedwater TDS equivalent to 40,0000 mg/l NaCl
4. Allow an average of 0.5 bar across the media filter
5. Allow an average of 1 bar trans membrane pressure for the UF system
6. Allow 0.5 bar across cartridge filters (only on DMF/RO and DMF/FO/RO system)
7. Assume 2 barg to meet NPSH requirements for HP pump
8. Assume 1 bar required for intake etc
9. The RO system (6 element x 12 vessels) associated with the FO plant has the same number of RO membranes and as such no advantage is taken of the allowable lower brine flow rates
10. The DMF/FO/RO system's HP pump duty is based on using a dilute osmotic agent with an osmotic pressure of 1.6 bar above the feed seawater (from Modern Water mathematical model)

Table 3: Summary calculations

Product flow (m^3/day)	1000		
Overall Recovery	40%		
FO recovery	40%		
Regeneration recovery	50%		
	DMF/RO	**DMF/UF/RO**	**DMF/FO/RO**
Seawater intake pump			
Flow (m^3/h)	109.65	115.42	109.65
Developed Pressure (bar)	4.00	4.50	3.00
Power (kW)	12.18	14.43	9.14
Osmotic agent booster pump			
Flow (m^3/h)			83.33
Developed Pressure (bar)			2.00
Power (kW)			6.52
HP pump			
Flow (m^3/h)	104.17	104.17	83.33
Developed Pressure (bar)	62.30	60.30	70.50
Power (kW)	253.90	245.75	229.85
Total kWh/m^3 of product	6.39	6.24	5.89

It is clear from the simple summary calculations summarised in that the DMF/FO/RO configuration has the lowest energy consumption. The energy savings decrease as the recovery of the regeneration system approaches that of the conventional systems, noting that the dilute osmotic agent coming out of the FO membranes must always have a higher osmotic pressure than the feedwater.

It is also interesting to note that as the recovery of the regeneration system decreases in order to maintain the same osmotic flow within the FO membranes it is necessary to increase the concentration of osmotic agent. This and other factors such as; membrane surface area (FO and RO), recoveries of the two systems, flow rates and temperature all directly affect the performance of the FO/RO system.

III. CONCLUSIONS

There are several distinguishing features of a FO/RO desalination process when compared to conventional reverse osmosis; lower fouling propensity of the forward osmosis step, a ‘perfect’ feed to the more energy intensive reverse osmosis step and the double membrane barrier between feed stream and product stream.

The ability to recycle additives to the osmotic agent such as antiscalants, while significantly reducing any contaminate species from the product stream, such as boron, that may be present in the feedwater that may be otherwise difficult or costly to remove using a conventional membrane process.

The elimination or significant reduction of any fouling of the more energy intensive reverse osmosis step, provides for a more sustainable solution over a long term period, where the real savings will be seen.

There is a lower energy consumption with the process, in particular where it is deployed on more challenging feedwaters, where a conventional RO plant would otherwise operate at lower recovery than the regeneration step.

It is this combination of a number of these individual smaller advantages, across a variety of areas that can add up to a significant advantage, depending on where and how the technology is deployed. This experience can be used in the development of other forward osmosis processes, ranging from power generation to water substitution

The progress made by Modern Water and others primarily over the last four years is enormous, yet this is only the beginning with much more yet to come in both process and FO membrane development from this common platform. Progress can be accelerated by further vision, recognition and support by public utilities and industry as a whole, which I believe we are beginning to see.

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