FORWARD OSMOSIS DESALINATION: A COMMERCIAL REALITY

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Abstract

Modern Water is one of the few companies that have developed and deployed a forward osmosis desalination process on a commercial scale. This paper presents some of the background development work undertaken at Modern Water over the last three years to take the process from the lab to a commercial reality.

Data and discussion are offered covering laboratory work in the UK, a trial facility installed in Europe on the Mediterranean Sea and a commercial plant operating in Oman on the Arabian Sea.

Operational results taken from a commercial scale manipulated osmosis plant operating alongside a seawater reverse osmosis plant, located in Oman, utilising a common pre-treatment system are outlined. The forward osmosis plant demonstrated significant advantages in performance, both in energy consumption and in particular very low fouling. The plant has operated over a nineteen month period without any chemical cleans, whereas the conventional plant had numerous chemical cleans, a change of membranes and showed a marked decline in productivity over the same period. The manipulated osmosis plant also demonstrated the inherent capability for higher boron rejection than conventional membrane plant.

I. INTRODUCTION

Forward Osmosis (FO) is a process that may be used to extract high quality water from a low quality feedwater source using a semi-permeable membrane and a high osmotic pressure solution.

There are strong drivers to develop this process and apply it commercially in a number of fields, not least because this method of extracting high quality permeate occurs with very low energy consumption; it occurs naturally at low pressures and ambient temperatures.

Since 2007, Modern Water has developed this process in a number of different applications. As the core of Modern Water's Manipulated Osmosis Desalination (MOD) process it has been deployed in a number of facilities ranging from the university lab to a full-scale commercial facility providing drinking water to the residents of a remote fishing village in the Al Wusta region of the Sultanate of Oman.

This paper describes the key steps in the development process, as well as some of the key operational results and experiences.

II. FORWARD OSMOSIS

In order to explain the process, first let us consider the principles of forward osmosis. In the industry most people are familiar with reverse osmosis (RO), where high quality permeate is separated from a feed solution such as seawater or brackish water by a selectively permeable membrane. When the hydraulic pressure of the feed is greater than its osmotic pressure (a property of the solution) it causes essentially pure water to flow through the membrane. This water can then be collected and used for various purposes, the most common application being the production of fresh water suitable for human consumption or irrigation. This is a high-pressure, high-energy process.

"Forward osmosis", or just "osmosis", are the terms used to describe the natural phenomenon whereby a solvent flows from a region of lower osmotic pressure across a selectively permeable membrane to an area of higher osmotic pressure. A good example of this in nature is the mechanism whereby plants take up moisture in their root systems and become turgid.

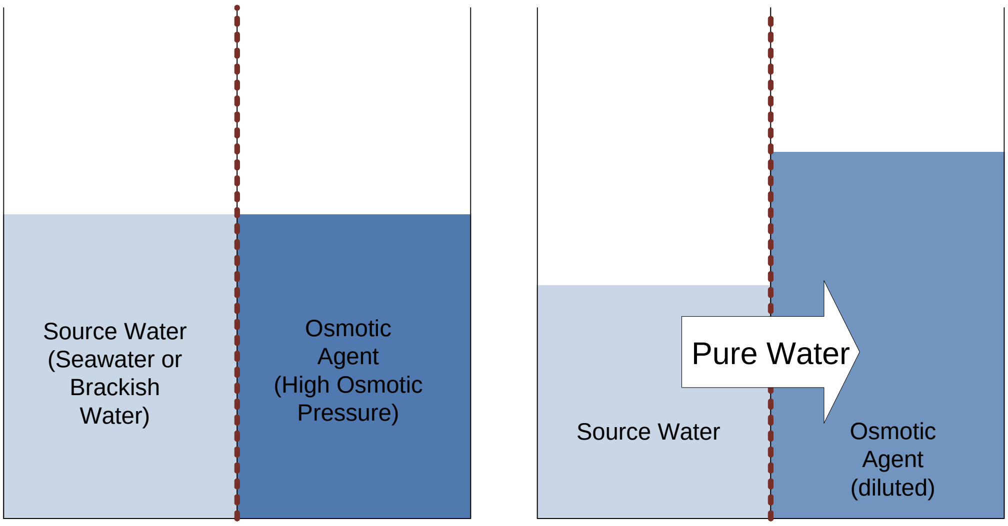

Figure 1 – Forward Osmosis

We can manipulate two fluids with differing osmotic pressures to exploit this natural phenomenon so that, for instance, we can make essentially pure water flow out of seawater across a selectively permeable membrane to dilute a solution with a higher osmotic pressure. It is important to note that this process takes place at ambient temperatures and without any significant applied pressure. The only external energy input needed is to overcome the frictional resistance on either side of the membrane (typically 2 – 3 barg). This is markedly different to the case for reverse osmosis where very high pressures may be applied, generally up to 82 barg. High osmotic pressure solutions may be made safely and easily, without any impurities or foulants, by dissolving in water a suitable salt or combination of salts, of which there are many.

Successful "real-world" applications of this phenomenon are emerging. One example of these applications has been developed by Hydration Technology Innovations (HTI) in the USA. HTI's emergency sugar drink [1] can be produced from contaminated water simply by placing a pouch fabricated from a selectively permeable membrane in the available water. The sugar solution inside the pouch has a high osmotic pressure and, over time, clean water flows from the contaminated side to the sugar side to produce an energy drink. Two examples on an industrial scale are Modern Water's multi-patented manipulated osmosis desalination process (the subject of this paper) which produces drinking water, and Modern Water's evaporative cooling make-up water system [2].

When compared to a RO system, there are many advantages of a FO system. Among the most obvious advantages are that whilst RO systems involve high pressures, and therefore high energy inputs and exotic materials, the FO process takes place at low pressures and therefore does not require the same energy input or high strength materials.

FO systems do have additional complications, however, when compared to RO systems. In particular, the FO process does not provide high quality water for use in a single step; after the forward osmosis step, the high quality water is mixed with the osmotic agent.

III. MANIPULATED OSMOSIS DESALINATION (MOD)

To make the high quality water available, Modern Water's MOD process integrates the FO system in a single cycle with a regeneration system.

This cycle is shown schematically in Figure 2.

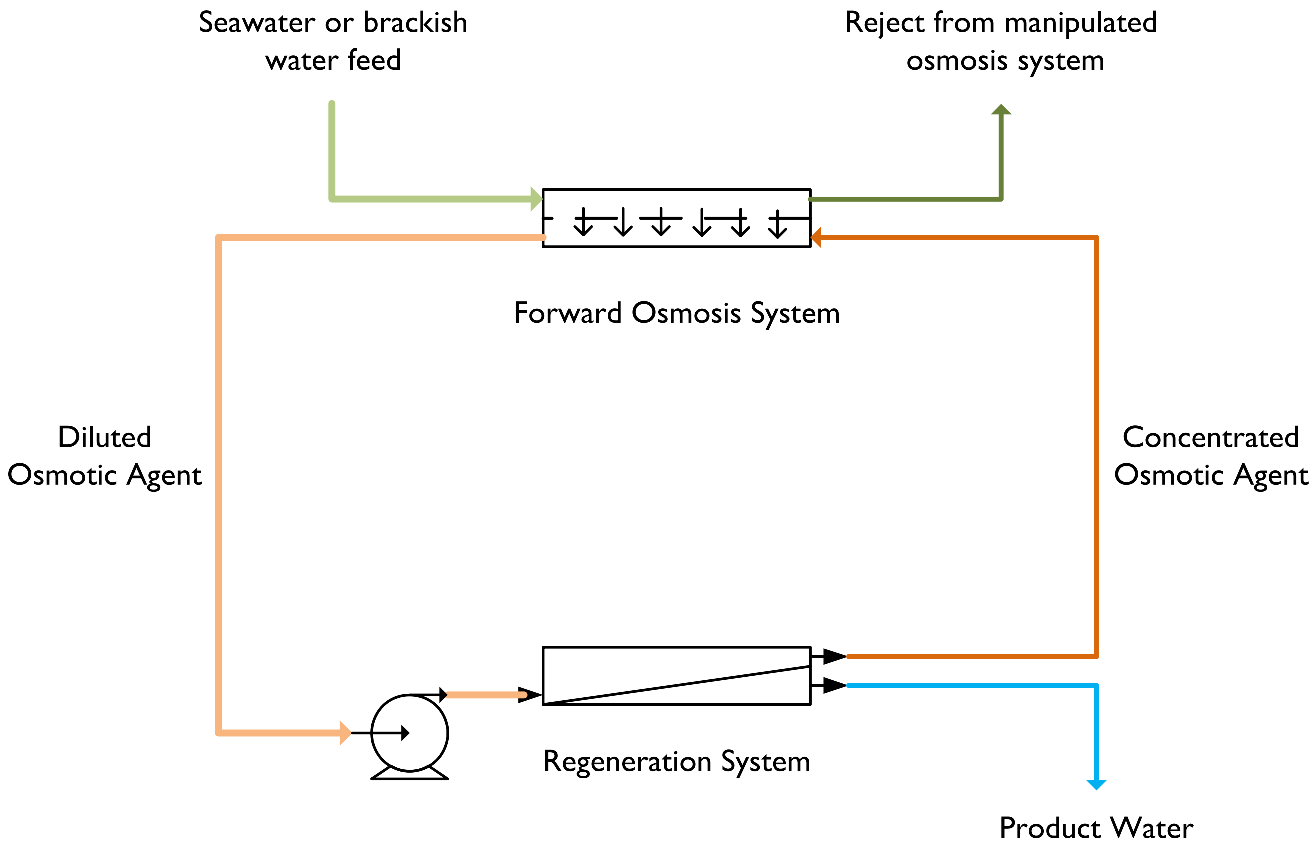

Figure 2 - Simplified MOD Process Diagram

The two systems are integrated by a recirculating osmotic agent (OA). One key property of the OA, also often referred to as a draw solution, is that it has a higher osmotic pressure than the feedwater.

In summary, concentrated osmotic agent is used to draw fresh water from the feedwater in the FO system. In doing so, the osmotic agent becomes diluted. The dilute osmotic agent is then "regenerated" by the removal of this fresh water in the regeneration system. The matching of the operation of these two systems is a key design and operating factor that is necessary for easy and reliable operation of the MOD process.

Key benefits of the MOD process, which have been demonstrated at our various facilities and which are expanded on later in this paper, include:

- Lower fouling propensity and consequently lower operating cost;
- Energy consumption lower than conventional RO, particularly with difficult feedwaters;
- Reduced membrane whole life costs, as a result of fewer replacements;
- Provision of a double membrane barrier between feedwater and desalinated water;
- Reduction in capex and opex due to the process's inherent ability to significantly reduce problematic seawater contaminants, such as boron;
- Lower cost and easier fabrication due to extensive use of low pressure (plastic) pipework and fittings;
- Further membrane development will provide significant benefits in terms of reduced chemical consumptions, plant footprint and energy.

Key variables in the system include:

1. Number and performance of forward osmosis membranes;
2. Composition, concentration and recirculation rate of osmotic agent;
3. Performance of regeneration system;
4. Temperature, composition and flowrate of feedwater.

Successful operation of the facility depends on a suitable consideration and combination of all the above factors during design and operation.

3.1 Forward Osmosis Membranes

Modern Water's membranes are contract manufactured specifically for Modern Water and to our specific design requirements. It is worthy of note that there have been a number of design and specification improvements over the last three years, with significant improvements in the bulk permeability. The membrane chemistry means that the membranes are, unlike most conventional reverse osmosis membranes, chlorine resistant. The details are commercially sensitive and so are not presented here.

The arrangement of the forward osmosis membranes is selected according to the feedwater conditions and the required plant performance (for instance seawater recovery). Although the osmotic agent is typically fed in parallel to every membrane, on the feedwater side, banks of membranes may be arranged in parallel or in a tapered array.

3.2 Regeneration System

In the MOD process, at present, the regeneration system is also membrane based. The membranes are commercially available semi-permeable membranes and, although this step does consume energy, by careful selection of the osmotic agent and the system operating conditions, this energy consumption is minimised.

3.3 Osmotic Agent

Modern Water is often asked about the chemistry of the osmotic agent used in our forward osmosis systems and in the MOD system in particular. In every case, the osmotic agent is based upon a low cost, non-toxic, commodity chemical. For the MOD process in particular, the components of the osmotic agent are suitable for use in drinking water facilities. The details of Modern Water's proprietary osmotic agent are commercially sensitive and so are not presented here.

3.4 Feedwater Conditions

As for conventional RO facilities, the performance of a particular plant is dependent on the feedwater conditions. For example, in conditions of high TDS or lower temperature feedwater, additional FO membrane area or higher strength osmotic agent may be required. The ability to vary membrane performance, membrane area and osmotic agent strength permits a great degree of flexibility in design.

IV. MOD FACILITIES

The MOD development process from the laboratory to a commercial facility is illustrated by looking at three of Modern Water's key facilities.

4.1 Laboratory Test Rig (Surrey University, UK)

Modern Water's development programme began at the test facility it owns at the Centre for Osmotic Research and Applications (CORA) at the University of Surrey.

Figure 3 – Laboratory Test Rig

The CORA team used this facility to investigate the performance of various membrane units and techniques to develop the concept of Manipulated Osmosis Desalination. Key membrane performance parameters, physical configurations and analytical techniques were identified to pave the way for implementing the system outside of the laboratory environment.

4.2 Trial Facility (Gibraltar, Mediterranean Sea)

In September 2008, Modern Water commissioned and successfully operated the first implementation of the MOD system outside of the laboratory environment. The plant was located at a site in Europe, on the northern Mediterranean Sea coast at Gibraltar. Following a number of planned upgrades, this plant has been successfully delivering water to the local drinking water system since 1 May 2009.

Figure 4 – Gibraltar Trial Facility Prior to Containerisation

The plant is housed in a 20’ ISO shipping container, and has the following key features:

1. Provision for a number of forward osmosis membrane elements;
2. Provision for a number of regeneration membrane units. The test facility in Gibraltar currently uses a reverse osmosis process to regenerate the OA, however there is also provision for a nano filtration based system;
3. Extensive automated measurements throughout the cycle of flowrates, pressures, temperatures, pH and conductivity;
4. A Programmable Logic Controller (PLC) coupled with an industrial PC running SCADA software for recording measured data;
5. Pumps, tanks and pipework with significant margin in performance to permit testing of future membranes;
6. Interconnections to external services, including a pressurised seawater supply, a pressurised brine discharge system, permeate from the adjacent plant (for initial fill etc), product export line and power supply;

The feedwater on site at Gibraltar is common to an adjacent SWRO facility, with a shared pre-treatment facility delivering water with SDI_{15} figures of between 3 and 4. The product water is independently tested, and typically has a TDS of less than 200 mg/l and boron levels of less than 0.6 mg/l.

Figure 5 - Gibraltar Trial Facility on Site

The key objectives for the plant were:

1. To commission and demonstrate continuous stable operation of the MOD cycle;
2. To confirm the accuracy of Modern Water's internal mathematical models for cycle performance;
3. To establish the presence and magnitude of any performance deterioration over time;
4. To provide a stable platform on which the MOD process can be optimised and on which forward osmosis membranes can be tested (both for MOD and other applications);
5. To gather long-term operational data on the process;
6. To identify and address real-world issues that may not be apparent in the laboratory environment.

The plant in Gibraltar, together with a series of laboratory scale tests, has formed a vital element of Modern Water's membrane development process, as it allows full scale operation of the membranes in a real-world environment.

The plant in Gibraltar is currently successfully operating with Modern Water's third generation of full-scale forward osmosis membrane. This latest membrane development has improved productivity by over 30% and with further developments in the pipeline this will be improved further. These developments will lead to reduced CAPEX and smaller plant footprint.

Regeneration of the osmotic agent takes place in the Gibraltar facility using a reverse osmosis process. This process was chosen for expediency (it is a well understood process), so that efforts could be focussed on the novel FO step, and the integration of the FO step into a continuously operating cycle.

It is notable that in this cycle, the performance of the reverse osmosis membranes can be more fully exploited than in a conventional SWRO plant – i.e. significantly higher flux rates can be achieved, because the composition of the membrane feed (osmotic agent) can be fully controlled. For instance, to achieve a 40% recovery in a conventional SWRO plant, we may expect to need six or seven membrane elements in a pressure vessel, whereas in the regeneration stage of the MOD cycle in Gibraltar a 50% conversion can be achieved with only three elements in one pressure vessel.

One key benefit of the system is the ability to modify the properties of the osmotic agent and thereby modify the product quality, by making relatively small operational or chemical changes, for example pH adjustment.

By way of illustration, the concentration of boron in the product water over the course of one month is summarised in Figure 6, below. Boron is of particular international interest at present, and is notoriously difficult and costly to effectively remove. A reduction on average of over 40% was achieved by a very straightforward modification to the operating flow conditions.

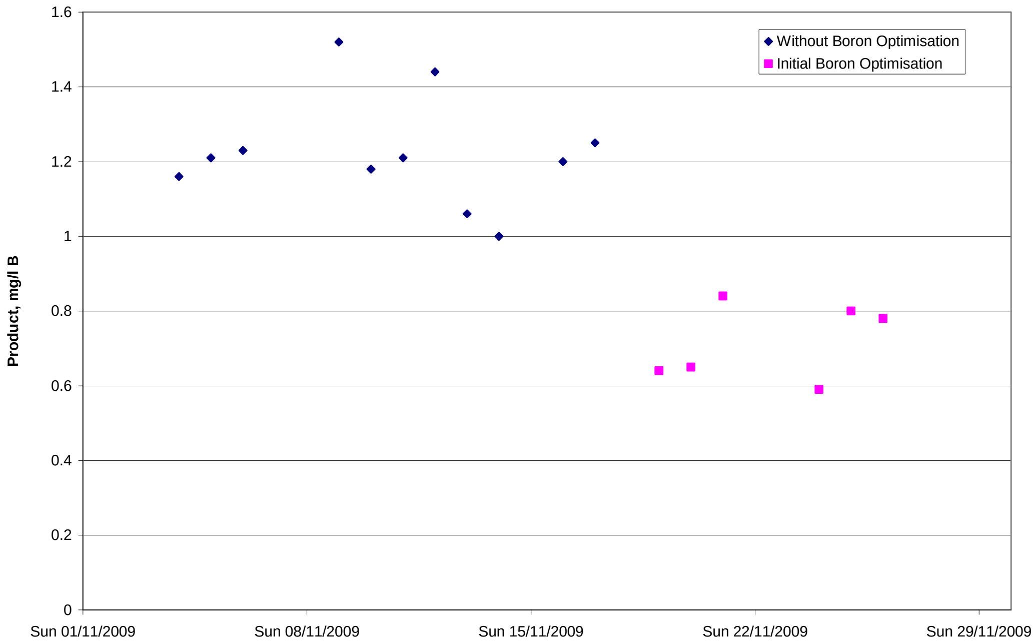

Figure 6 - Example Optimisation of Product Water Boron

4.3 Production Facility (Al Khaluf, Sultanate of Oman)

Based on successful results from the trial site, Modern Water's laboratory testing programme, and discussions with suppliers, an enhanced plant (with a design capacity of 100 m^3/d) was designed and deployed to a site in the Sultanate of Oman in July 2009.

The site is located some 450 km south of Muscat near the fishing village of Al Khaluf in Wilayat Mahoot, in the Al Wusta region of Oman.

Figure 7 - Location of Al Khaluf in the Sultanate of Oman

The site is owned by the Public Authority for Electricity and Water (PAEW) and, prior to Modern Water's arrival, contained a reverse osmosis water plant with a nominal capacity of 100 m^3/day. This existing plant comprises the following main components:

- Two borewells (one not operational)
- Temporary seawater intake
- Feedwater chlorination
- Media filter
- Feedwater storage
- Main process hall containing two RO vessels (8" spiral wound type), dosing pumps etc.
- Permeate storage
- Boron removal equipment
- Chlorine dosing (product water)
- Product water storage
- Tanker filling station

Figure 8 - The PAEW Water Site at Al Khaluf (including MW's Containerised MOD Plant)

Having agreed with the PAEW to share both the pre- and post-treatment equipment on the site with the existing facility, this site provides an excellent opportunity to demonstrate the benefits of Modern Water's technology side by side with a conventional seawater reverse osmosis plant, while helping to meet the local water demand.

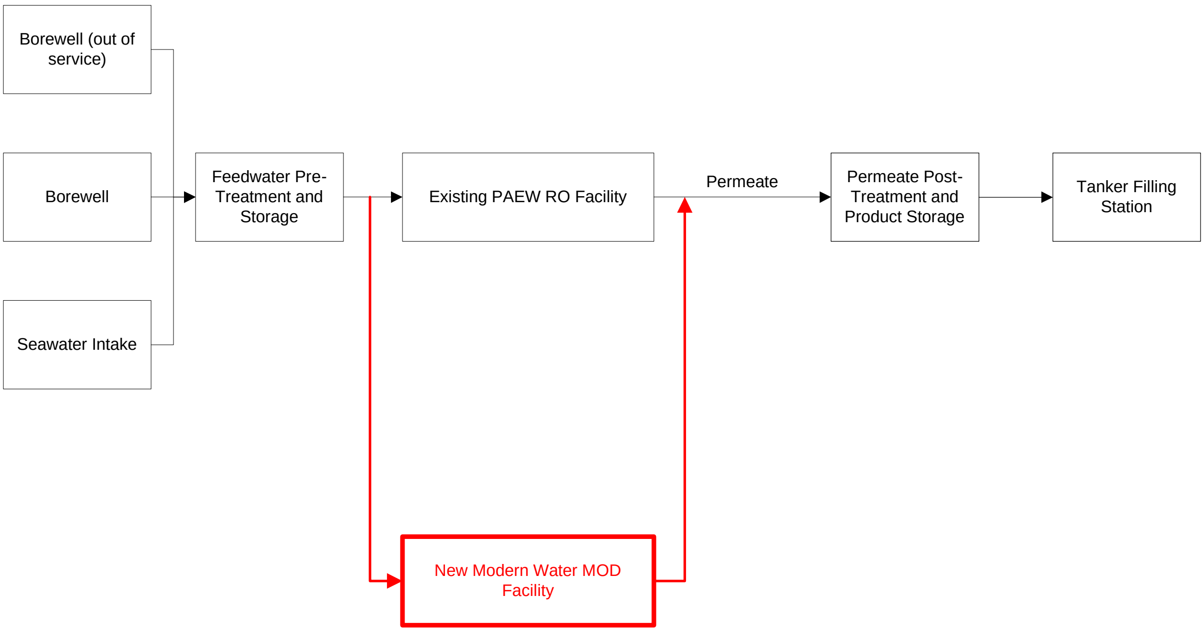

Figure 9 - Site Integration Overview

Modern Water's containerised water plant was designed to tie in with the existing pre- and post-treatment equipment. All equipment, and a small laboratory, are housed in a single 40' high-cube ISO shipping container.

Key features of the facility are:

1. Provision for a flexible number of forward osmosis membrane elements;
2. A membrane based regeneration system.
3. Extensive automated measurements throughout the plant of flowrates, pressures, temperatures, pH and conductivity;
4. A Programmable Logic Controller (PLC) coupled with an industrial PC running SCADA software for plant control and data recording;
5. Membrane clean-in-place equipment;
6. Interconnections to external services, including:
   a. filtered feedwater supply;
   b. brine discharge line;
   c. export line to permeate storage tanks;
   d. supply from the permeate storage tank (for initial fill etc);
   e. 415VAC 3-phase power supply.

Figure 10 - The Modern Water Plant at Al Khaluf

The key objectives for the plant were:

1. To undertake a direct comparison between a conventional reverse osmosis process and the manipulated/forward osmosis process, utilising identical feedwater and pre-treatment;
2. To demonstrate the advantages of the process;
3. To reliably provide high quality drinking water for distribution to consumers in and around Al Khaluf;
4. To increase Modern Water’s experience of operating their facility in more challenging feedwater conditions.
5. To gather operational data on the process to enhance the design and operation of future facilities;
6. Provide a facility on which operators can receive training.

The facility has been fully operational since November 2009, when water was introduced into the public supply.

Modern Water's experience on the site has been challenging. The site is remote, with relatively arduous ambient conditions (temperatures up to 50°C, high winds, wind blown sands). The benefits of a fully containerised plant meant that construction and much testing could take place in more amenable surroundings, and the fully sealed, air conditioned enclosure afforded by the ISO container minimised disruptions due to the ambient conditions.

The plant has been subjected to disruptions associated with the external services; both the electrical and feedwater supplies have been subject to difficulties.

Planned and unplanned power outages are common and, although the robustness of the process has meant that there has been no significant impact on the plant, it has provided the motivation for Modern Water to implement additional plant protection and operating procedures to ensure continued reliable operation under such conditions.

The external feedwater supply to Modern Water's facility has also been problematic; the quality of the feedwater is typically of very low quality. Although there are borewells available on the site, the bulk of the feedwater is supplied from a shallow open seawater intake. The existing pre-treatment facilities on the site include one dual media filter that operates with a velocity of between 16 and 25 m/h. The SDI_5 of the feedwater supplied by the existing pre-treatment facility is normally not measurable. Modern Water's facility includes simple cartridge filtration (10 micron nominal) that improves the SDI_5 of the feedwater to approximately 5, the facility also includes a feedwater antiscalant dosing system and a system for periodic low dose chlorination.

Despite these challenges, the FO system has been operating successfully with a seawater recovery of 35%.

With post-treatment, the product water fully meets the requirements of the Omani Standard No. 8/2006. The untreated product typically has a TDS content of less than 200 mg/l and a boron content of between 0.6 and 0.8 mg/l.

The real difficulties associated with the site, and the benefits of the FO system, may best be illustrated by comparison of the MOD with the performance of the existing SWRO facility on the site. This is operated for the government by a contractor with extensive operational experience in the region.

Figure 11 shows the normalised output from the adjacent SWRO facility over the course of 2010. Despite repeated cleaning of the membranes, there is a 30% decline in the output from new membranes in just five months.

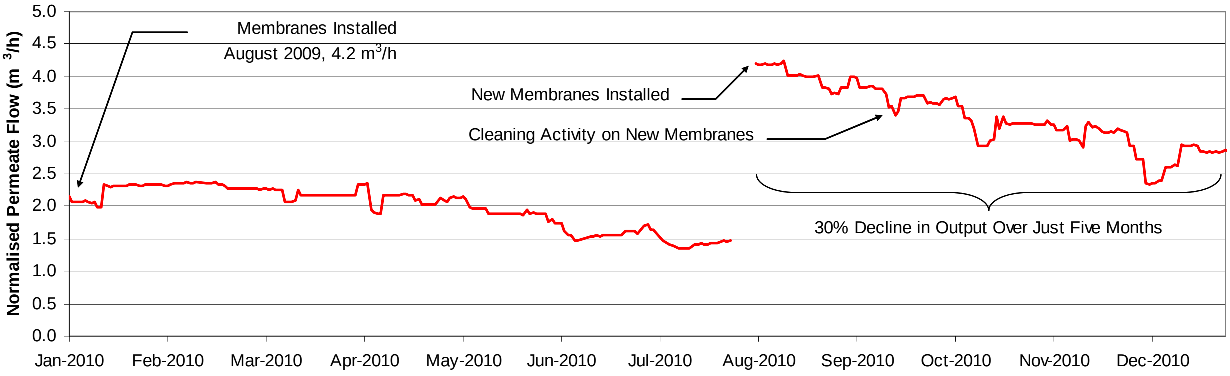

Figure 11 - Normalised Output from Adjacent SWRO Facility 2010

In contrast, the normalised output from the FO system over the same period has remained relatively unchanged. This is despite the fact that no chemical cleaning has been performed, and operation has been at a higher seawater recovery.

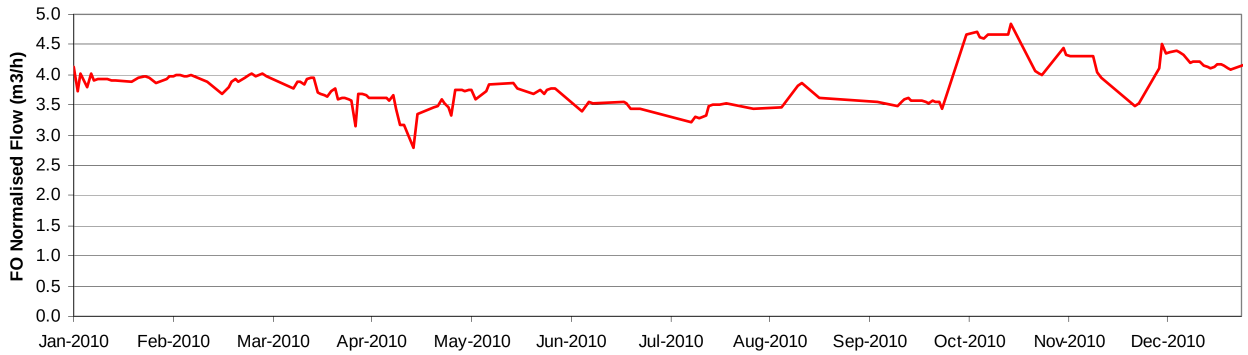

Figure 12 - Normalised Output from FO System 2010

This demonstrates one of the key benefits of the MOD process, namely reliable performance in particularly challenging feedwaters.

The other key performance parameter of the MOD process that attracts interest is the energy consumption. Low energy consumption is a real potential benefit associated with FO systems in general, and one that has been achieved with the MOD process in particular. By way of illustration, the performance of the MOD facility may be simply compared with the conventional SWRO facility.

Technology		SWRO	MOD
Permeate Extraction from Feedwater			
Feedwater Recovery	%	25	35
Product Water Flow	m^3/d	71.4	100
	m^3/h	3.0	4.2
Feedwater Supply	m^3/h	11.9	11.9
	bar	65	4
Feedwater Pump	eff%	85	85
	kW absorbed	25.3	1.6
Osmotic Agent Regeneration			
Osmotic Agent Recovery	%		47
Dilute Osmotic Agent Feed	m^3/h		8.9
	bar		65
OA Regeneration Pump	eff%		85
	kW absorbed		18.8
Overall Plant			
Specific Energy Consumption (per unit product)	kWh/m^3	8.5	4.9

In this particular case, using representative figures from the field, the MOD process is seen to be operating at about 60% of the energy consumption of the competing SWRO facility. Note that the summary above excludes the impact of the energy recovery device that is actually installed in the MOD facility, but which if included would give an unfair comparison to the adjacent SWRO which does not. Despite this, we note that this particular MOD facility was not designed with optimum energy consumption in mind, so there is further scope for improvement.

V. CONCLUSIONS

Over the course of a four year period, Modern Water has successfully taken the Manipulated Osmosis Desalination process from the laboratory to a full-scale commercial facility. In doing so, Modern Water has obtained several years' operating experience of the forward osmosis process in very challenging environments. Key advantages of the system have been proven, including demonstrating in both of Modern Water's operational Manipulated Osmosis Desalination plants that the process is far less prone to fouling than reverse osmosis. There is a high degree of confidence in the robustness and reliability of the core aspect of the process.

Modern Water is actively tendering for commercial desalination facilities in the Middle East, including facilities on a build-own-operate basis, where guarantees and penalties associated with the performance of the process will be applied.

Nevertheless, there are still areas for improvement, both related to the membrane technology and the optimisation of the process. Modern Water has an ongoing programme with a number of membrane suppliers and research organisations to improve the performance of our forward osmosis membranes, in parallel with a programme for further development of the proprietary osmotic agent and regeneration system.

The experience that Modern Water has gained in the forward osmosis stage of the Manipulated Osmosis Desalination process is already being applied to differing applications, including a new and ground breaking technology for the preparation of make-up water for evaporative cooling processes.

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