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Going big with forward osmosis

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ABSTRACT

The frontier of water treatment technologies is being defined by hybrid processes and thoughtful design integration within treatment trains. The use of increasingly sophisticated process trains is driven by the need to treat dramatically impaired water supplies while maintaining low cost, high utilization, and high operational flexibility. Integrating forward osmosis (FO) technology is one notable, emerging opportunity to realize substantial advantages in cost and performance compared to the use of either conventional membrane processes or thermal technologies. Reverse osmosis technology remains ideally suited to desalinate low fouling streams to moderate levels of recovery. Spr ay dryers or crystallizers employing mechanical or thermal vapor compression cycles are still best used to convert saturated or organic rich liquors to solid products. But what of the multitude of waters, especially industrial streams, that are too saline or high in foulants to be well treated by reverse osmosis and are not of high enough value to warrant direct crystallization? The traditional answer defaults to a 90 + year old technology in the thermal brine concentrator. Today, Oasys Water is offering an alternative solution by using thermolytic draw solutions to enable FO processes that challenge traditional treatment paradigms in diverse commercial applications.

Keywords: Forward osmosis; Brine concentration; Membrane processes; Industrial wastewater treatment; Flue gas desulfurization

1. Introduction

Forward osmosis (FO) or engineered osmosis requires the combination of two primary components: an FO membrane system and a draw recovery system (Fig. 1). FO is driven by an osmotic pressure gradient created across a semi-permeable membrane to achieve spontaneous and preferential diffusion of water molecules from a saline feed into a draw solution [1,2]. As it passes through the FO membrane system, the draw solution extracts clean water from the feed stream and becomes diluted. A separation step, or draw recovery process, must be performed to reconcentrate the draw solution and to separate the product water stream.

Oasys is the world's leading supplier of FO technology, having developed proprietary FO membranes, draw solutions, and draw solution recovery technology. Equally important as the proprietary technology

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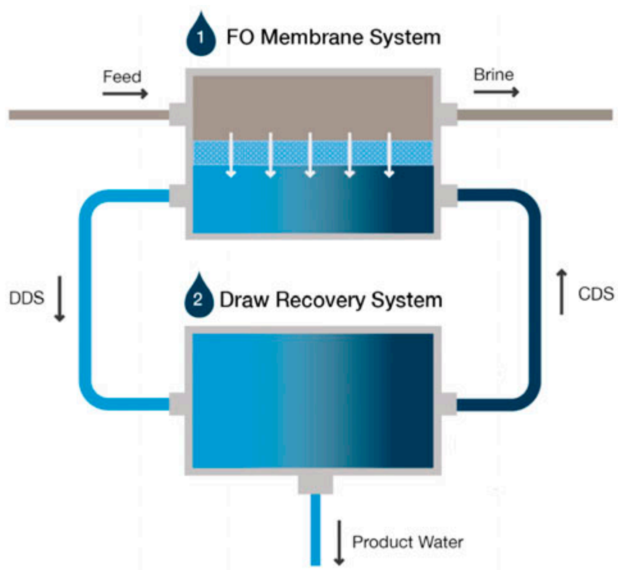

Fig. 1. High level view of a forward osmosis process, which relies on two primary systems: (1) the FO membrane system and (2) the draw recovery system.
Notes: CDS: concentrated draw solution and DDS: diluted draw solution.

is the expertise in integrating these process-critical components into a complete engineered system. The Membrane Brine Concentrator (MBC™) System employs state-of-the-art FO technology to provide the capabilities of a thermal evaporator with the simplicity and modularity of a membrane system (Fig. 2). The Oasys draw solution consists of a complex mixture of ammonia and carbon dioxide thermolytic salts, existing primarily as an ammonia carbamate solution. The high solubility of this draw solution provides an extremely high osmotic potential and produces a strong driving force (i.e. gradient) across the membrane that facilitates permeation even when the salinity of the stream being treated reaches >250,000 mg/L total dissolved solids (TDS) as NaCl. This represents a vastly differentiated membrane treatment paradigm compared to conventional membrane processes.

The MBC FO membrane system is designed in a counter-current, staged configuration in order to balance driving force and flux. This means that the most concentrated draw solution is opposite the most concentrated brine and the most diluted draw solution is against the least concentrated feed. The FO separation occurs at ambient pressure and temperature providing a greater resistance to irreversible fouling and scaling than both high pressure RO and thermal evaporators [3,4]. In addition, any scaling that does occur is more easily handled with simple cleaning procedures since it does not experience the compaction of high-pressure membrane processes. This provides the ability to treat impaired water streams with less energy, more flexibility, and often times less chemical consumption, compared to thermal desalination technologies.

Since the majority of the energy demand for the MBC System is dedicated to the draw solution recovery process, significant work has been done to provide optionality and high efficiency. Diluted draw solution exits the FO membrane system and is pumped into

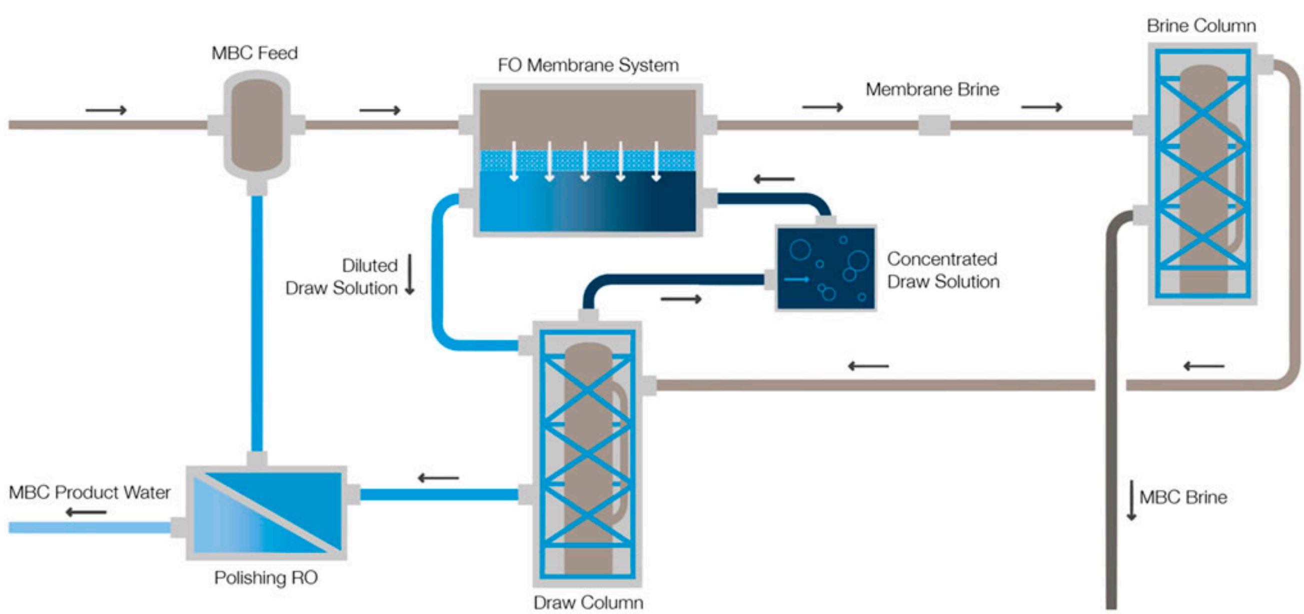

Fig. 2. Overall process flow schematic of the fully integrated MBC System.

the draw recovery column where the draw solutes are stripped from the solution along with some water vapor. The concentrated brine exiting the FO membrane array is pumped into the brine column where any draw solutes that reverse-permeated into the brine are also recovered and then routed to the draw recovery column to allow for energy recapture [5]. The mixed gas stream flows out the top of the draw recovery column, where it is fully condensed and cooled. Cooling water is typically used as the heat sink in the concentrated draw solution condenser. Concentrated draw solution is then returned to the FO array for continuous operation in a closed loop.

Intermediate product water is collected at the bottom of the draw column and passed through the polishing RO system. While the FO membrane system has >99% rejection of dissolved solids, when treating extremely high concentration waters this often results in a higher concentration product stream than typical permeate standards. The polish RO reduces the product water TDS to <100 mg/L and ensures recovery of any non-volatized draw solutes (e.g. alkalinity). The concentrate from the RO system is routed to the front of the MBC System. The high quality, low TDS permeate from the RO system can be reused in the customer operations or safely discharged. The MBC draw solution recovery system integrates the draw column, the brine column, and the polishing RO in order to maintain virtually 100% of the draw solutes within the system while maximizing energy efficiency.

In a steam-driven MBC, steam is applied directly to the reboilers of the columns and the latent heat of condensation is used to drive the separation (Fig. 3). In an electric-driven MBC, the mixed gas stream flows out the top of the draw column, where it is compressed, partially condensed in the column reboilers, and then fully condensed and cooled in a final heat exchanger. A second compressor is used to maintain a slight vacuum on the brine column to maintain a low enough column bottom temperature and allow for heat extraction from the partially condensed draw solution stream. The electric design allows for less energy input and less cooling water demand; however, in application, selection of thermal configuration often comes down to customer and site preferences. For power industry projects—where the MBC steam and cooling water demands are marginal relative to the overall plant process volumes—steam-driven configuration is often favored for lower cost and simplicity. In moveable systems and remote locations, the electric-driven MBC is often favored. Typical utility requirements for the two types of MBC thermal draw recovery systems are shown in Table 1. There are wide ranges on the requirements, depending on both the feed TDS and target recovery.

2. Commercialization timeline

Oasys Water is devoted to commercializing FO technology in fully integrated water treatment designs (Fig. 4). Oasys (i.e. Osmotic Applications and Systems) was founded in 2008 and funded through venture investment in early 2009 [6,7]. Much of the early work was focused on tailoring a membrane element to perform well in FO processes. The Oasys thin film composite membrane—based on a polyamide RO backbone and tailored in chemistry and structure for the Oasys FO process—was launched in 2010 [8]. Since then, further incremental improvements have led to the high-performance product Oasys manufactures today. Significant work was also done to understand the draw solution and recovery process in order to design fully integrated systems and provide a high value product to the commercial space.

In 2011 and 2012, pilot demonstrations were performed on oil and gas produced waters from the Marcellus Shale and Permian Basin [9,10]. These demonstrated the ability of the fully integrated Oasys MBC to treat high salinity waters, achieve high water recovery, and produce high quality product water. This success also led to a strategic partnership with National Oilwell Varco focused on the global oil and gas market in 2013 [11]. A strategic partnership was also formed with Beijing Woteer focused on the industrial wastewater market in China [12]. In 2014, Oasys was named the Water Technology Company of the Year by the Global Water Intelligence [13]. Also in 2014, Oasys opened its first international office in Australia to focus on that country's coal seam gas market [14,15]. This same branch focuses on the emerging industrial wastewater market in India as well as the oil and gas markets in the Middle East. 2014 also marked the first sale of an MBC in China, in partnership with Beijing Woteer [16,17]. This MBC System was commissioned at the Changxing Power Plant in 2015 [18]. Future opportunities and projects in the United States, China, and other regions are enabling Oasys' continued growth and the implementation of Oasys FO technology world-wide.

3. Case study: Changxing power plant

3.1. Project Background

Increasing regulations are changing the way industrial power producers think about plant design. Air pollution legislation in the People's Republic of China apply strict limits to NOx, SOx, particulate matter, and Hg discharges and effectively mandate electrostatic precipitation and flue gas desulfurization (FGD)

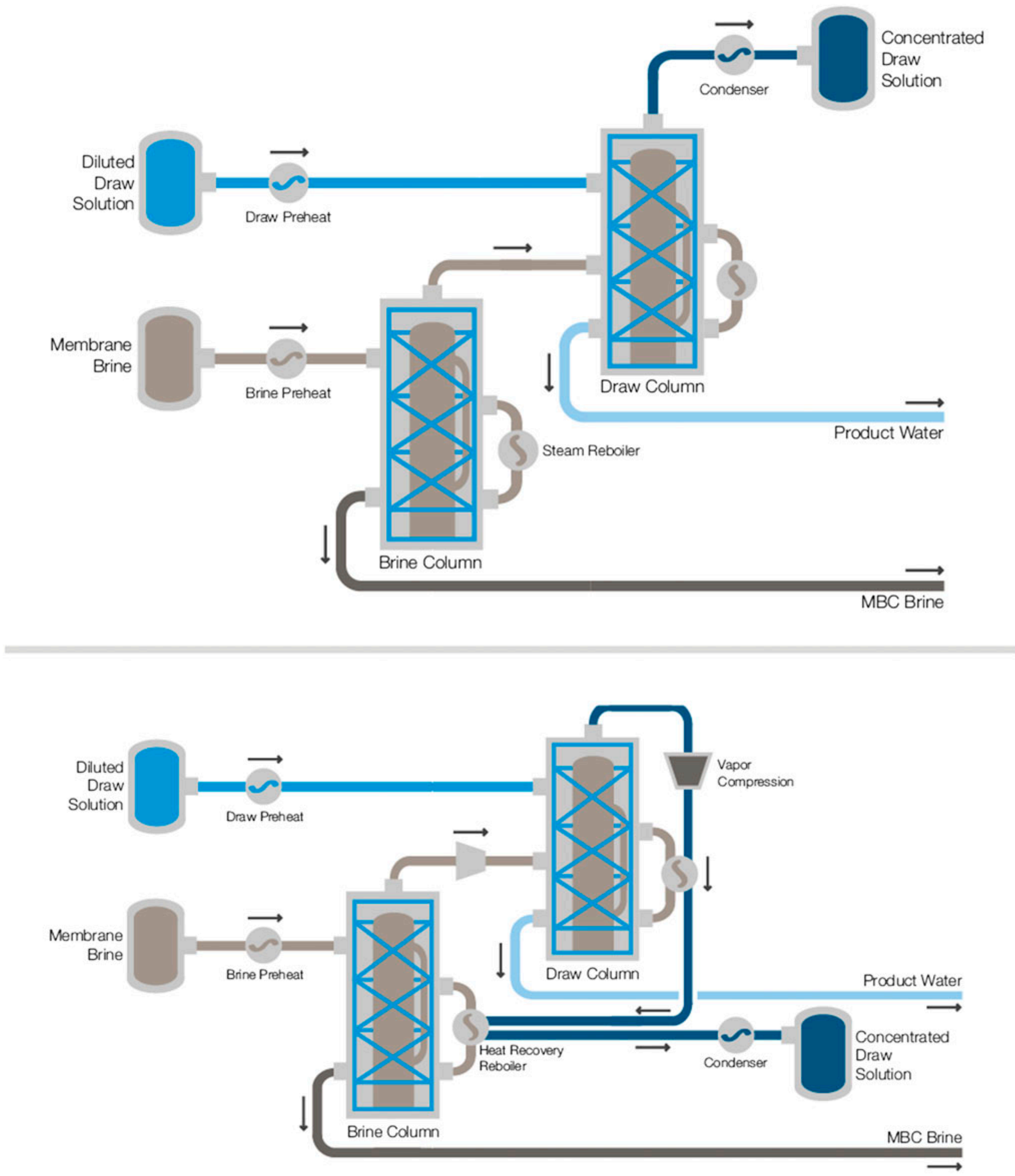

Fig. 3. Process configurations for the thermal draw recovery system in the Oasys MBC System. In the steam-driven MBC energy is extracted from the latent heat of condensation of plant steam (top). In the electric-driven MBC electrical energy powers process gas compressors and the latent heat of condensation of the draw solution vapor stream is extracted (bottom). Pre-heating of the column feed streams is done either with the column bottoms or other process streams, depending on the project and customer requirements.

Table 1
Comparison of typical utility requirements for the steam- and electric-driven MBC fully integrated systems. Specific value within the range depends on the feed TDS, composition, and the overall recovery being achieved. Values are given on a per volume treated basis

Utility consumption	Steam-driven MBC	Electric-driven MBC
Electric power (kWh_e/m^3)	3–4	7–30
Thermal demand[a] (kWh_t/m^3)	20–200	–
Cooling demand[b] (kWh_t/m^3)	20–200	3–20

[a]Steam consumption depends on the quality of the steam available.

[b]Cooling water consumption depends on the cooling water temperature and the allowable temperature rise.

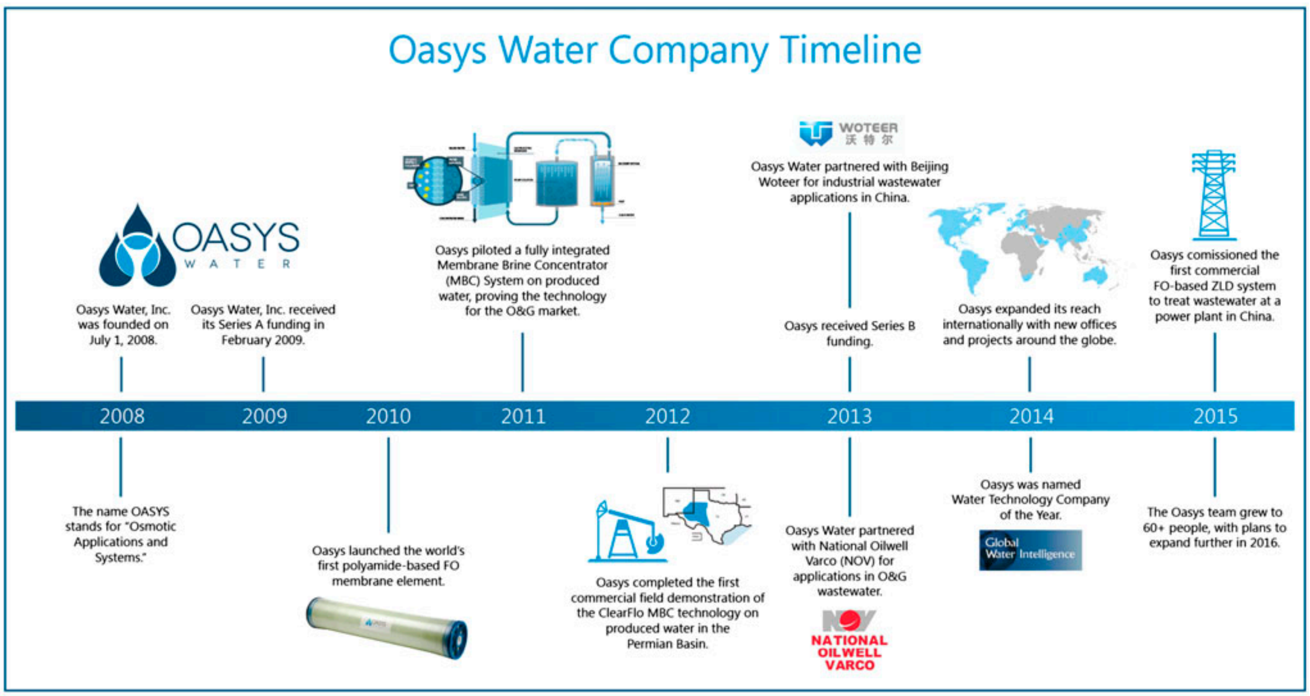

Fig. 4. Timeline of Oasys Water and the path to commercialization of FO technology.

technology be utilized at coal fired power plants. In addition, recent regulations (detailed in the State Council document No. [2012]3) represent the strictest limits to date for water intake and discharge [19].

The Huaneng Group, China's largest power producer, is one such company impacted by these new regulations. In 2014, they completed design of an ultra-supercritical coal fired power plant at the Changxing Power Plant in Zhejiang Province, approximately three hours southwest of Shanghai. The 2×660 MW steam generator plant included wet limestone slurry FGD units for pollution control [20]. A wastewater treatment plant was required to treat a combined waste stream, including the FGD blowdown wastewater and cooling tower blowdown. To meet water intake and discharge limits a full zero liquid discharge (ZLD) system was designed with recycle of the recovered fresh water to the boiler feed. Oasys Water's FO technology was selected as the brine concentration technology for the ZLD train, making Changxing the first power plant to incorporate FO on an industrial scale.

3.2. Water treatment design

The full water treatment plant design as it is incorporated into the Changxing Power Plant is shown in Fig. 5. Raw FGD blowdown wastewater from the power plant is directed into the pretreatment system in the water treatment plant. The pretreatment

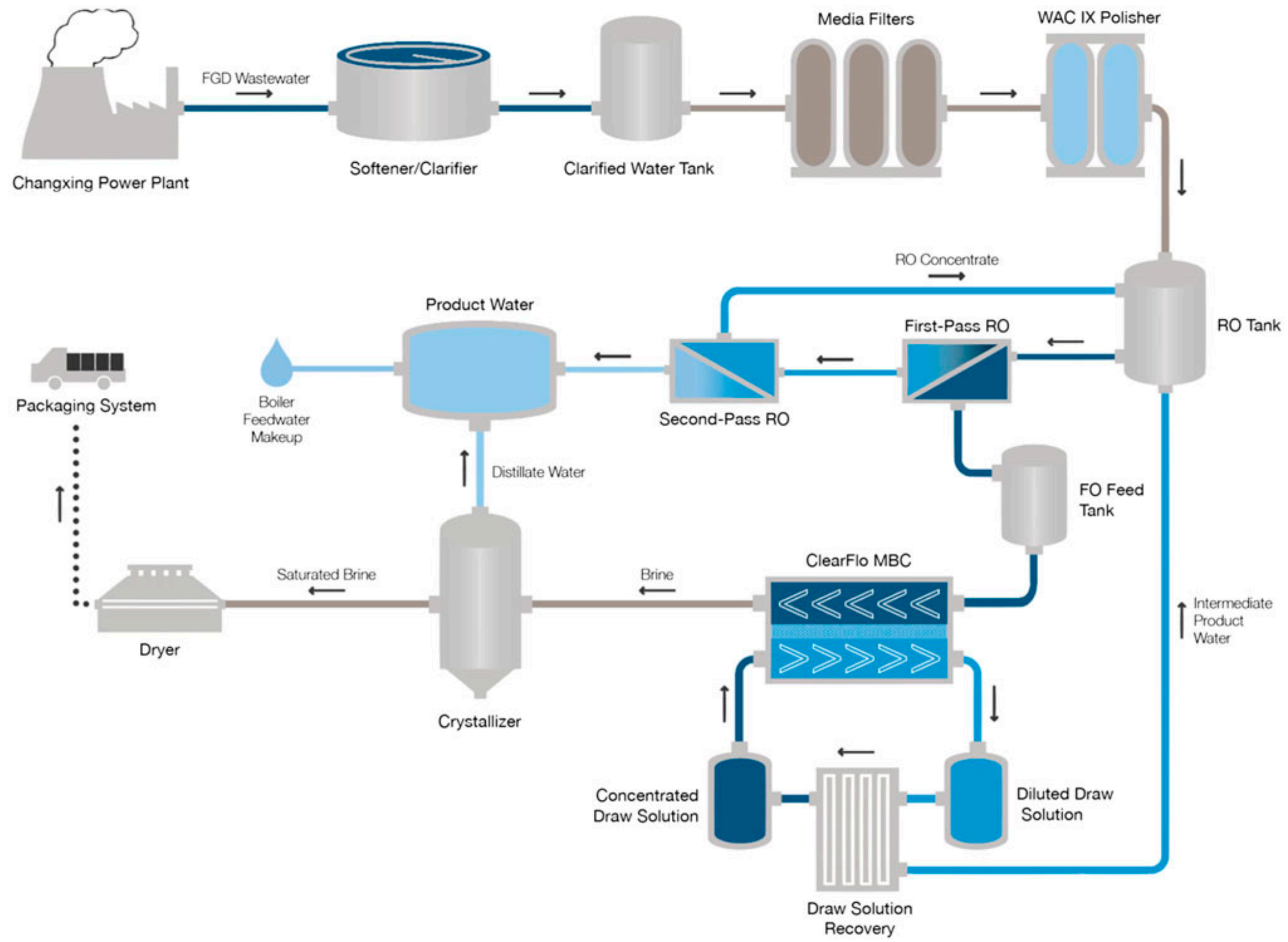

Fig. 5. Process flow schematic of the Changxing Power Plant water treatment, including pretreatment, MBC (i.e. RO, FO, and thermal recovery systems), crystallization, and drying.

includes chemical precipitation softening, multimedia filtration, and a weak acid cation exchange polishing step. The strict requirements on pretreatment effluent and robust design were required due to the high concentration factor of the overall ZLD system, the wide raw water variability anticipated, and the requirements of the downstream crystallizer. The MBC design was based on projections of pretreated effluent flows between 15.0 and 26.4 m^3/h with TDS ranging from 25,000 to 45,000 mg/L.

Effluent from the pretreatment process is fed to the MBC System, which includes a dual-purpose preconcentrating and polishing RO membrane system, the FO membrane system, and the thermal draw recovery system. Brine from the MBC is fed to the crystallizer and dryer. Final ZLD solids are bagged and trucked off-site for disposal. Final recovered product water is directed to the boiler feedwater makeup in the power plant.

The MBC System is designed with a two pass, single-train RO membrane system (Fig. 6). Pretreated water is combined with the intermediate product water and concentrated up to a TDS of ~60,000 mg/L ahead of the FO array. This preconcentration step reduces the size of the brine concentration process and allows the system to take advantage of the low energy demand of RO in the lower TDS range. The first pass RO concentrate is directed to the FO membrane array where it is processed in a counter-current configuration with the Oasys thermolytic draw solution. In this design, an ammonia carbamate draw solution is used with a composition of 4.0–6.0 M on a carbon basis.

Based on the design specifications and accounting for the ranges in raw water flow and TDS, the FO membrane system needed to handle a minimum capability of 60% turn down on a feed flow basis (Table 2). This flexibility was delivered by providing three

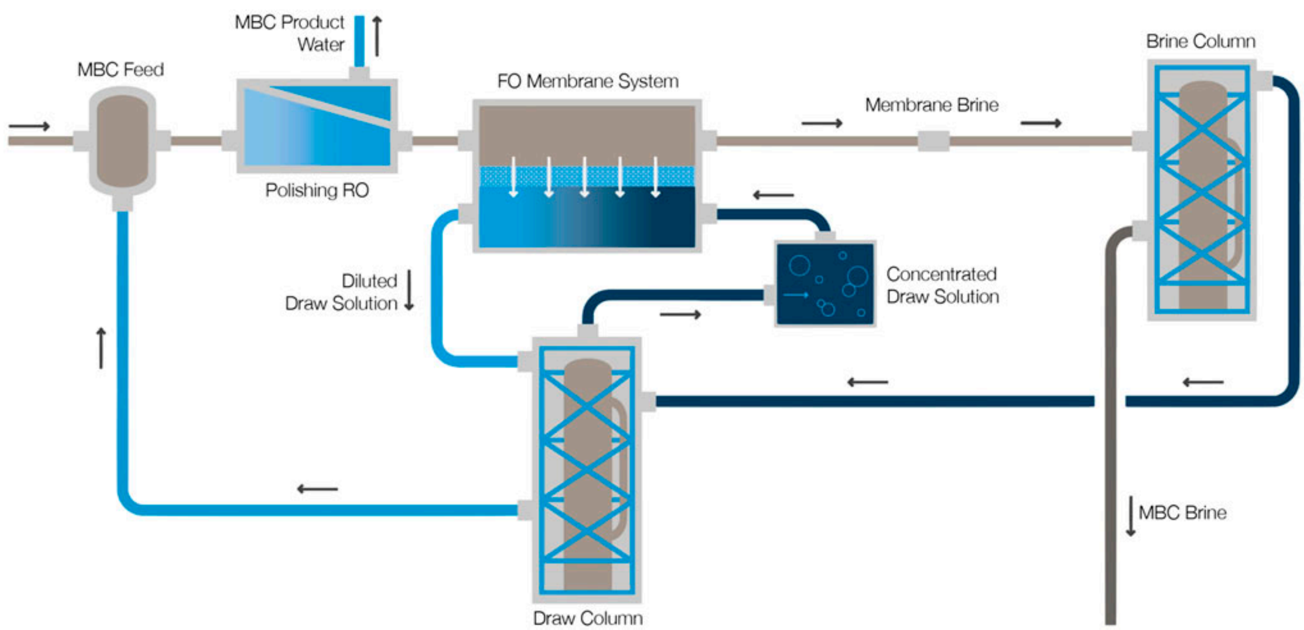

Fig. 6. Process flow schematic for the Changxing Power Plant MBC, including the preconcentration/polish RO membrane system, FO membrane system, and thermal draw recovery system. The primary difference between this process and the standard MBC is the preconcentration RO step used to treat the low TDS feedwater and improve overall process economics.

Table 2
Map of the full MBC design space that the system was designed to cover. As the feed flow and TDS float, the water recovery of the RO system and the overall MBC System were allowed to float, in order to deliver a consistent brine quality to the thermal crystallizer

Design case	Pretreated effluent (MBC feed)	RO concentrate (FO feed)	MBC product brine	MBC product water	Overall water recovery (%)
High flow High TDS	26.4 m^3/h 45,000 mg/L	22.2 m^3/h 60,000 mg/L	5.2 m^3/h >220,000 mg/L	21.1 m^3/h <100 mg/L	79.9
High flow Low TDS	26.4 m^3/h 25,000 mg/L	14.3 m^3/h 60,000 mg/L	3.3 m^3/h >220,000 mg/L	23.1 m^3/h <100 mg/L	87.5
Low flow High TDS	15.0 m^3/h 45,000 mg/L	13.9 m^3/h 60,000 mg/L	3.2 m^3/h >220,000 mg/L	11.8 m^3/h <100 mg/L	78.7
Low flow Low TDS	15.0 m^3/h 25,000 mg/L	9.1 m^3/h 60,000 mg/L	1.9 m^3/h >220,000 mg/L	13.1 m^3/h <100 mg/L	87.3

parallel FO arrays. The FO membrane arrays for this project are staged in a $3 \times 2 \times 1$ configuration in order to balance feed cross flow velocities throughout the array. The guiding philosophy for the water treatment design train was to design the MBC System such that the membrane processes absorb swings and variation in the feedwater and protect the crystallizer downstream, allowing for reliable ZLD success.

After recovery of water from the feed stream, the diluted draw solution is sent to the draw recovery column where draw solutes are volatilized as CO_2 and NH_3 gas. The concentrated brine is sent a brine stripper column where any reverse diffused draw solutes are recaptured. The concentrated stream of draw solution vapor is sent to a condenser where it is cooled and then directed to the concentrated draw solution

Table 3
Comparison of the MBC design basis and the actual operation to date

Parameter	Units	Design basis	Actual
Pretreated feed flow to oasys MBC	m^3/h	15.0–26.4	27.0–30.0
Pretreated feed TDS to oasys MBC	mg/L	25,000–45,000	8,600–9,500[a]
FO feed flow	m^3/h	9.1–22.2	4.1–4.8
FO feed Tds	mg/L	60,000	39,000–52,000[b]
MBC final brine TDS	mg/L	>220,000	>220,000[b]
MBC product water TDS	mg/L	<100	35–50[b]
MBC water recovery	%	80–88	93–97

[a]Estimated with in-field measurements of conductivity and density.
[b]Based on measurement of dry weight TDS.

tank for continuous use in the FO membrane system. The intermediate product water from the draw recovery column is directed to the RO system for final polishing to the product water specification of <100 mg/L. The final MBC brine, at a TDS <220,000 mg/L, is directed to the crystallizer and drying system for final processing.

The thermal draw recovery system for the Changxing Power Plant utilizes plant steam (5 bar, saturated) as the energy source. Based on the design conditions, utility requirements for the MBC portion of the water treatment process include a thermal demand of <90 kWh_t/m^3 feed (approximately 160 kg/m^3 of steam) to heat the brine and draw recovery columns, an electric demand of 4.0 kWh_e/m^3 for the RO system and pumping requirements, and 6,000 kg/m^3 cooling water (with a 10 degree allowable temperature rise). In this case, a slightly higher steam demand for the MBC was accepted by not extracting sensible heat in cooling the brine stream. Instead, the MBC brine was fed directly to the crystallizer warm to save energy in that step and to avoid any operational issues with cooling a highly concentrated waste stream. Further heat integration and process optimization of the MBC System since the time of the Changxing design have further reduced both the steam and the cooling water demands for future projects, including ZLD opportunities.

3.3. Operation to date

FGD wastewaters are known for their wide variability and the Changxing wastewater is no exception [21]. In 2015, the Changxing Power Plant started up and the water treatment process was commissioned. Throughout initial operation the TDS of the wastewater was substantially lower than the design basis (Table 3). The MBC feed water was consistently at a lower TDS than the design basis (8,600–9,500 mg/L). The result was that the MBC System was operated at a much higher overall recovery and, therefore, higher concentration factor than designed (24× vs. the 5–10× design basis). Thanks to the flexibility and robustness of the MBC design, the overall targets of brine TDS feeding the crystallizer, product water specification, and overall water recovery are met despite the discrepancies in feed stock.

With the low feed TDS to the MBC, the RO is operated at higher recovery than design; however, the RO concentrate (i.e. FO feed) is still lower than design at 39,000–52,000 mg/L. The FO system was able to deliver higher recovery than the design basis in order to make up for this. Also with the high recovery operation of the RO, the flow to the FO system has been much lower than anticipated—approximately half of the lowest design condition (4.1–4.8 m^3/h). Thanks to the multiple train design of the FO system, the MBC has been able to accommodate the low capacity. While the design included operation of two or three parallel FO trains depending on the location in the design matrix and flow rate to the FO, current operation requires only one FO train, with the other two essentially serving as redundant units. In time, the TDS of the wastewater may increase with changes in the plant operation or coal source, requiring use of more FO trains. The flexibility that the MBC has demonstrated to date ensures that future fluctuations will be managed with ease.

4. Conclusions

As interest in Oasys FO technology and commercialization of the MBC System continues to increase, it is clear that FO is here to stay. Future projects are expected to focus in the power, mining, and oil and gas markets, with additional niche markets emerging in time. With intelligent process design and optimization, it has been shown that Oasys FO is a complementary process to conventional RO, enabling far more recovery to be done in membrane processes than ever before. In certain applications, it has also been seen that the Oasys MBC is a lower cost alternative to a traditional thermal evaporation-based brine concentrator. With the flexibility in energy sources, the MBC can be designed to reduce capital and operational costs for customers in a holistic and tailored approach. The commercial award and deployment of the Changxing MBC System indicate that there will be a growing demand for FO technology in near-ZLD and total ZLD applications, especially as regulations guide customers towards these requirements.

Meanwhile, as Oasys grows into a fully commercial entity and proves out FO technology as a cost-effective and viable option, it remains a relatively young technology provider. This means that there are still substantial improvements to be made as the technical boundaries are explored. Future gains are anticipated in reducing pretreatment requirements, draw and membrane replacement costs, and energy demands both through learning in the field and improvements to the core technology components.

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References

[1] R.L. McGinnis, M. Elimelech, Global challenges in energy and water supply: The promise of engineered osmosis, Environ. Sci. Technol. 42 (2008) 8625–8629.
[2] T.Y. Cath, A.E. Childress, M. Elimelech, Forward osmosis: Principles, applications, and recent developments, J. Membr. Sci. 281 (2006) 70–87.
[3] S. Lee, C. Boo, M. Elimelech, S. Hong, Comparison of fouling behavior in forward osmosis (FO) and reverse osmosis (RO), J. Membr. Sci. 365 (2010) 34–39.
[4] Y. Kim, M. Elimelech, H.K. Shon, S. Hong, Combined organic and colloidal fouling in forward osmosis: Fouling reversibility and the role of applied pressure, J. Membr. Sci. 460 (2014) 206–212.
[5] N.T. Hancock, T.Y. Cath, Solute coupled diffusion in osmotically driven membrane processes, Environ. Sci. Technol. 43 (2009) 6769–6775.
[6] R. McBride, Oasys Water Aims to Make Desalination Cheap Enough to Crack Mainstream Market, Relieve Shortages, Xconomy, 2009. Available from: <http://www.xconomy.com/boston/2009/03/02/oasys-water-aims-to-make-desalination-cheap-enough-to-crack-mainstream-market-relieve-shortages>.
[7] J. Glasner, Clean Water Drives Oasys Funding, Reuters, 2009. Available from: <http://www.reuters.com/article/us-oasys-vcj-smbiz-idUSTRE51M5VC20090224>.
[8] Oasys water Commercializing Forward Osmosis Membrane, Reuters 2010. Available from: <http://www.reuters.com/article/idUS132321+10-May-2010+BW20100510>.
[9] R.L. McGinnis, N.T. Hancock, M.S. Nowosielski-Slepowron, G.D. McGurgan, Pilot demonstration of the NH_3/CO_2 forward osmosis desalination process on high salinity brines, Desalination 312 (2013) 67–74.
[10] J.M. Donnelly, Firm's Water Treatment Technology Catches Wave, Boston Business Journal, 2012. Available from: <http://www.bizjournals.com/boston/print-edition/2012/11/30/firms-water-treatment-technology.html>.
[11] National Oilwell Varco, Opportunities with Cleaner Fracking and FPSO, Seeking Alpha, 2013). Available from: <http://seekingalpha.com/article/1970021-national-oilwell-varco-opportunities-with-cleaner-fracking-and-fpso>.
[12] Oasys Water Culminates Year with New Partnerships and Sale of World's Largest, Most Capable Forward Osmosis System, Oasys Water Newsroom, 2013. Available from: <http://oasyswater.com/news-post/oasys-water-culminates-year-with-new-partnerships-and-sale-of-worlds-largest-most-capable-forward-osmosis-system>.
[13] Oasys Water Named 2014 Water Technology Company of the Year by Global Water Intelligence, Reuters, 2014. Available from: <http://uk.reuters.com/article/ma-oasys-water-idUKnBw085966a+100+BSW20140408>.
[14] J. Doom, BNEF Pioneer Oasys Water may Target Australia After China Bids, Bloomberg Business, 2014. Available from: <http://www.bloomberg.com/news/articles/2014-04-07/bnef-pioneer-oasys-water-may-target-australia-after-china-bids>.
[15] Oasys Water's Global mOmentum Continues with Asia-Pacific Expansion, Oasys Water Newsroom, 2015. Available from: <http://oasyswater.com/news-post/oasys-water-global-momentum-continues>.
[16] Oasys Water Continues Growth and Commercialization Momentum in Global Markets, Flagship Ventures, 2014. Available from: <http://www.flagshipventures.com/about/news/oasys-water-continues-growth-and-commercialization-momentum-global-markets>.
[17] Oasys Water to Treat Waste From Coal-Fired Plant in China, Bloomberg Business, 2014. Available from: <http://www.bloomberg.com/news/articles/2014-09-02/oasys-water-to-treat-waste-from-coal-fired-plant-in-china>.
[18] J. Tracy, M.M. Pendergast, M. Nowosielski, D. Wang, X. Cheng, Forward osmosis based membrane brine concentration of wastewater streams in coal-fired power generation, International Water Conference Proceedings, 76th Annual Meeting, IWC, 2005, pp. 15–43.

[19] State Council, Guowuyuan Guanyu Shixing Zuiyange Shuiziyuan Guanli Zhidu de Yijian [State Council Opinion Regarding the Most Strict Water Resource Management System], State Council Document No. 3, 2012. Available from: <http://www.gov.cn/zwgk/2012-02/16/content_2067664.htm>.
[20] Babcock & Wilcox Signs 10 year Wet FGD License Agreement with Wuhan Kaidi Electric Power Co. Ltd in China, Power Engineering, 2003. Available from: <http://www.power-eng.com/articles/2003/03/babcock-wilcox-signs-10-year-wet-fgd-license-agreement-with-wuhan-kaidi-electric-power-co-ltd-in-china.html>.
[21] W.M. Kennedy, J.G. Potts, Sources of variability in flue gas desulfurization wastewaters, International Water Conference Proceedings, 76th Annual Meeting, IWC, 2015, pp. 15–41.