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Technology developments in forward osmosis to address water purification

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ABSTRACT

Forward osmosis (FO) is a natural process, occurring in the cells of all living things when liquids of differing solute concentrations are separated by a semipermeable membrane at ambient temperatures. FO differs from reverse osmosis (RO) in that natural osmotic pressure, resulting from the difference in solute concentration in the two liquids, is the sole driving force for the transport of water across a membrane. The purpose of this paper is to illustrate the energy/cost of water trade-offs when comparing RO and FO technology for water purification. Trials of the FO system were conducted by a third party consulting firm, Carollo Engineers and the US Navy to monitor energy consumption, with results demonstrating the feasibility of operating an FO plant at one-sixth the electrical energy of current RO systems, i.e. 0.8 kilowatt hours per cubic meter of water. The FO process uses "waste" or low-grade thermal heat to drive the systems energy requirements of <70 mega joules per cubic meter of water. The availability of a low-cost heat source largely dictates the selection of the proposed technology. FO has two claimed advantages over RO, (1) lower energy consumption and (2) lower fouling. In this paper, we will discuss the findings of both in a year-long sea water desalination trial.

Keywords: Desalination; Forward osmosis; Energy efficient desalination; Reverse osmosis

1. Energy savings

Trevi Systems Inc. has developed a forward osmosis (FO) process that relies on a source of low-grade heat at a temperature between 70 and 90˚C to supply 99% of the system's energy requirements. Waste heat, rather than electricity, is used to increase the concentration of the brine stream, so that the electrical energy of the system does not increase significantly with increasing brine concentrations. The FO process is at least six times more energy efficient than reverse osmosis (RO) at standard sea water total dissolved solids (TDS) levels and can readily desalinate at levels exceeding 100,000 mg/L. Fig. 1 shows the rapid increase in energy consumption for RO systems with increasing brine concentrations: in 70% of the world's desalination sites, the specific energy consumption (SEC) is >4.5 kilowatt hours per cubic meter of water (kWh/m^3).

In other areas such as produced water for oil and gas, Trevi has tested waters with TDS in excess of 100,000 mg/L with acceptable membrane flux of greater than 4 LMH. With this high concentration, recoveries greater than 70% can be achieved in seawater applications, and novel antiscaling techniques are

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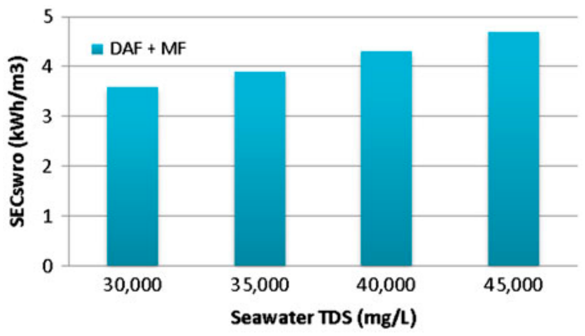

Fig. 1. Max SEC values of SWRO plant with flotation and membrane pretreatment system [1].

being developed without the use of chemical additives.

The uniqueness of Trevi System's FO desalting process rests on its use of a custom formulated osmotic agent made from food-safe polymers. The osmotic agent is retrograde in its solubility, meaning that it separates from water when heated as shown in Fig. 2. Trevi's FO system concentrates brine to levels 2–3 times greater than that of RO due to the osmotic agents "equivalent" pressure of >300 bar, thus increasing water yield, reducing brine volume (pumping energy) and evaporation storage pond capacity. In an FO system, the "feed" solution or contaminated water is pumped to one side of the semipermeable membrane at low pressure, ideally <1 bar. The "draw" solution, which has a high concentration of the specially designed osmotic agent and a low concentration of water relative to the feed solution, is pumped to the other side of the membrane where normal osmosis is allowed to happen. Controlling pump velocities, membrane surface areas and geometries as well as thermal coupling allows for an energy efficient implementation.

When RO technology was in development in the early 1970s, the cost of electricity in the USA was less than 4 c/kWh, making water produced by reverse osmosis very competitive against other thermal technologies. Energy cost has more than tripled in the last 30 years and is expected to do so again in the next 30 years. FO technology fills a natural market segment where electricity costs are high and waste heat is available.

2. Fouling

Although much has been published on the reduced fouling properties of FO (particularly in Singapore and at KAUST), organic fouling is still of significant concern in the year-long trial conducted by Trevi. Pretreatment in the seawater FO trial used a similar pretreatment system to existing RO plants to limit the number of variables when comparing energy

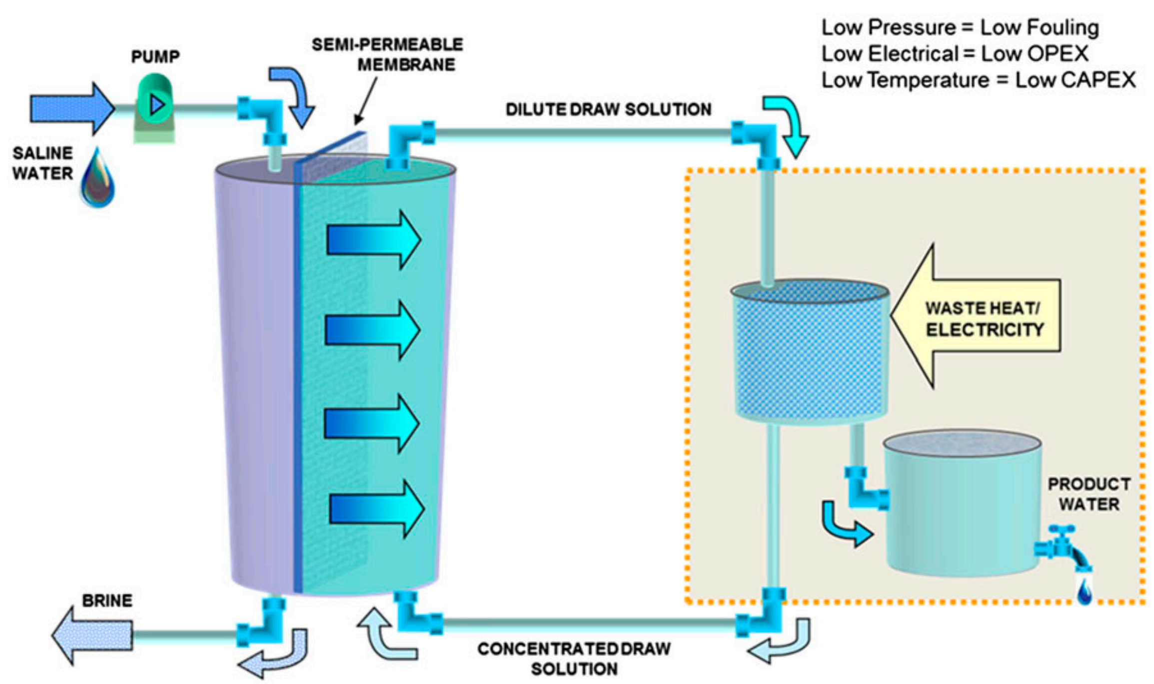

Fig. 2. Simplified FO process diagram as used by Trevi.

Table 1
SEC_{prf} of pretreatment processes and configurations [1]

Number	Pretreatment process	Number of filtration stages	Abbreviation	SEC_{prf} kWh/m^3
1	Floc filtration gravity + static mixer	1	FF + SM (1F)	0.02
		2	FF + SM (2F)	0.03
2	Floc filtration gravity + floc basins	1	FF + FB (1F)	0.10
		2	FF + FB (2F)	0.12
3	Floc filtration pressure + static mixer	1	FFP + SM (1F)	0.10
4	Sedimentation + filtration	1	S + F (1F)	0.14
		2	S + F (2F)	0.15
5	Flotation + filtration	1	DAF + F (1F)	0.15
		2	DAF + F (2F)	0.16
6	Membrane filtration	–	MF	0.1–0.2
7	Flotation + membrane filtration	–	DAF + MF	0.24

consumption. The use of cellulose acetate membranes allowed for continuous chlorination to control microbial growth.

Table 1 gives the SEC_{prf} of various types of pretreatment; this study was commissioned by the IDA and is considered a good representation of the current "state of power consumption" for pretreatment. Most new RO plants use the DAF + MF approach, which uses approx. 0.24 kWh/m^3 for pretreatment energy consumption.

A practical limitation to increasing permeate flow in the RO process is scaling. Scaling occurs on RO membranes when the concentration of scale-forming species exceeds saturation; producing additional solids within the RO feed water. Scalants include such chemical species as calcium carbonate, calcium sulfate, barium sulfate, strontium sulfate, and reactive silica. Since these species have very low solubilities, they are difficult to remove from RO membranes. Scaling decreases the effectiveness of the membranes in reducing the solids and causes more frequent cleanings. Scale on a membrane provides nucleation sites that increase the rate of formation of additional scale and promote biological growth.

In order to minimize scaling, pretreatment methods involving chemical or ion-exchange techniques are used. Ion-exchange methods remove scale-forming species from the RO feed water, while chemical techniques change the characteristics of the RO feed water so that crystal formation is not favored. Another pretreatment technique to prevent scaling is acidification, which specifically reduces the crystallization of calcium carbonate. Sulfuric acid is most commonly used in this process, but can often increase the formation of sulfate scales. Therefore, where sulfuric acid cannot be used, hydrochloric acid is substituted. Often used with acidification, or by itself, are antiscalants. Antiscalants are chemicals added to wastewater to minimize scale carbonate or sulfate based scale. They consist of acrylates and phosphates which inhibit the precipitation of carbonate or sulfates. The large volumes of water to be treated make the use of acidification or ion exchange impractical since chemical addition would significantly increase the cost of treating water.

An advantage of the FO process is that the FO membrane is more resistant to scaling, due to 2 factors (1) the generally lower fluxes in FO membranes and (2) the absence of hydraulic "pancaking." With RO, the hydraulic pressure results in scalants being mechanically imbedded in the membrane. In the FO process, osmotic pressure drives the water through the membrane and scalants are loosely agglomerated on the face of the FO membrane. The scalants can be dislodged by vibration, air bubbles, or reverse osmotic flux, where fresh water is used as the feed and salt water is used as the draw. The osmotic backflush method has been used with great success by Trevi in its trial to control scaling, eliminating the need for antiscalants or acids.

3. Technology developments

A longtime impediment to the successful development of a working FO system has been the draw solution; the first patents filed in the 1960s used ammonium bicarbonate as a draw solution [2]. Much has been written about ammonium bicarbonate as a draw agent; it exhibits decomposition into a gas phase and liquid phase at moderately high temperatures, but in order to remove the ammonium from the water to meet drinking water standards, a final RO polish stage is needed. The large distillation columns, reverse ammonium flux through the FO membrane, and low final product water yield make it best suited to high TDS/energy intensive applications such as those found in the oil and gas sector.

Trevi's research and development efforts have produced a draw solution that can be easily separated from the product water at temperatures below 75°C and meets potable drinking water standards without the RO polish stage. The polymer is engineered to have a high molecular weight so that separation occurs under gravity in a fairly short time period (2–3 min). The polymer is operated in a continuous (nonbatch) mode of operation, with lifetime expectations greater than 2 years when properly conditioned. The cost of the polymer is less than the typical cost of antiscalants in RO systems.

Another popular draw solution is magnesium chloride, which exhibits high solubility, allowing it to be used as a draw solution against seawater feed TDS levels. The magnesium chloride when used as a draw solution is safe and environmentally benign; however, to separate it from the product water requires a high pressure RO system. The approach should best be viewed as a low fouling pretreatment (using FO technology) rather than as a complete FO system, as one of the most significant advantages, energy savings, is actually in deficit due to the higher osmotic power required for separation. High TDS levels become unmanageable with this pretreatment approach.

Membrane research in FO remains active, with perhaps two dozen different groups, both private and public producing membranes for FO. Given the active area of research, Trevi Systems has chosen to partner with the membrane community, rather than attempt to design a FO membrane itself. Flux levels are targeted to be between two and three times lower than RO membranes, with a target of 5–7 LMH, the lack of pressure vessels, high pressure piping, mechanical membrane support, and size constraints due to the pressures required, more than offset the cost increase of the extra surface area that FO has. Since high-pressure backing material is not required, on a price per kg of material, the lower flux is not seen as a financial penalty, but rather as a significant fouling advantage.

4. Test results

There have been few documented trials of true sea water desalination FO systems, due in part, because FO systems have not regenerated their draw solution. The US Navy Pilot System was installed in October 2012 and ran, virtually continuously until November 2013, when it was shutdown and relocated to the Romberg Environmental facility in Tiburon, CA. The system is currently operating on severely fouled San Francisco Bay water and continues to generate data on a variety of different membranes and pretreatment options necessary in the industrial and oil and gas sector. A 100 m^3/d system is under construction for the Orange County Waste Water treatment plant in Los Angeles, CA, to investigate some of the scale up challenges prior to commencing commercial scale systems.

Carollo Engineers provided third party verification testing of the 1 m^3/d pilot system at the US Navy [3]; the results indicate that approximately 1 m^3/d of product water was consistently produced during the pilot testing period. Overall system recoveries ranged from 24 to 31% due to limitations imposed by the FO membrane manufacturer (subsequently corrected). System salt rejection ranged between 99.5 and 99.7%, as calculated from measured feed and product conductivities.

Raw seawater water quality parameters such as chlorophyll, turbidity, dissolved oxygen, and temperature were measured using instruments permanent to the Naval Test Facility's seawater pump station, and manually recorded once per day. Samples of raw seawater, FO system feed (downstream of UF pretreatment system), and FO system product water were also collected on a daily basis for laboratory analysis of water quality parameters including total dissolved solids (TDS), ions such as sodium, chloride, boron, calcium, magnesium, as well as alkalinity, silica, conductivity, and pH. Fig. 3 shows a picture of the

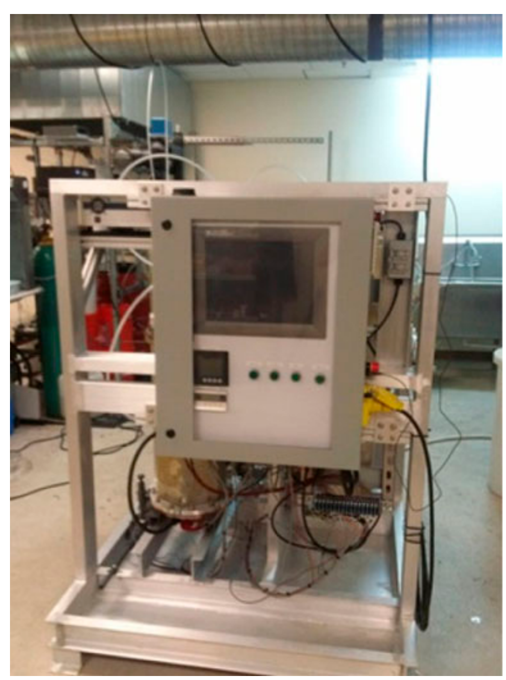

Fig. 3. Navy test skid showing instrumentation cluster.

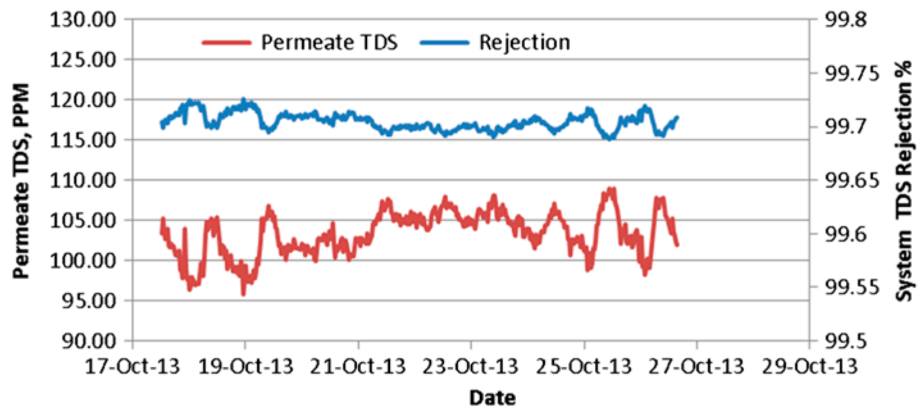

Fig. 4. Product water TDS and system rejection.

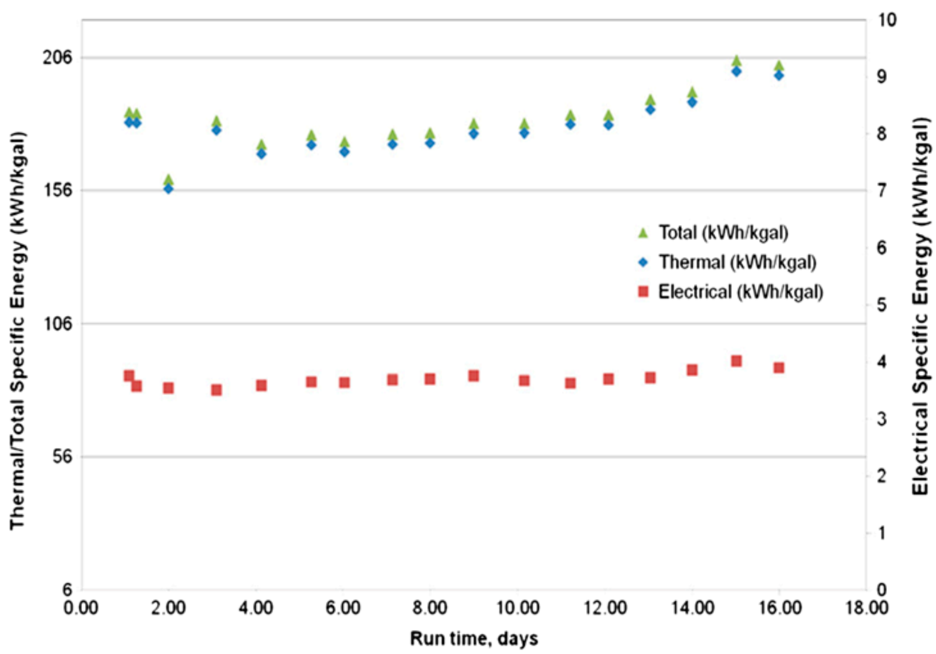

Fig. 5. System thermal energy and electrical energy consumption.

Navy 1 m^3/d skid with the instrument cluster drawing more power than the pumps. Heat was supplied using an inline electrical heater with temperature adjustment, so that precise kWh ratings could be determined using electrical power meters.

Trevi believes its FO design to be one of the first to be verified as successfully desalinating seawater for drinking quality standards, while using a fraction of the electrical energy required by current RO systems. Fig. 4 presents plots of product water TDS and overall system rejection over the testing period.

The system's first pilot trial period demonstrated an electrical energy consumption below 1.0 kWh/m^3 and thermal costs of 160 mega joules per cubic meter of water (MJ/m^3) in a 1 m^3/d system (Fig. 5). Trevi is now conducting a second round of field trials at the Romberg Center for Environmental Studies in Tiburon, California, to further validate energy savings, monitor the long-term water quality, and verify that thermal operating parameters of the FO system remain within acceptable ranges. Pumps used in the navy trial were small DC "fish tank" pumps with

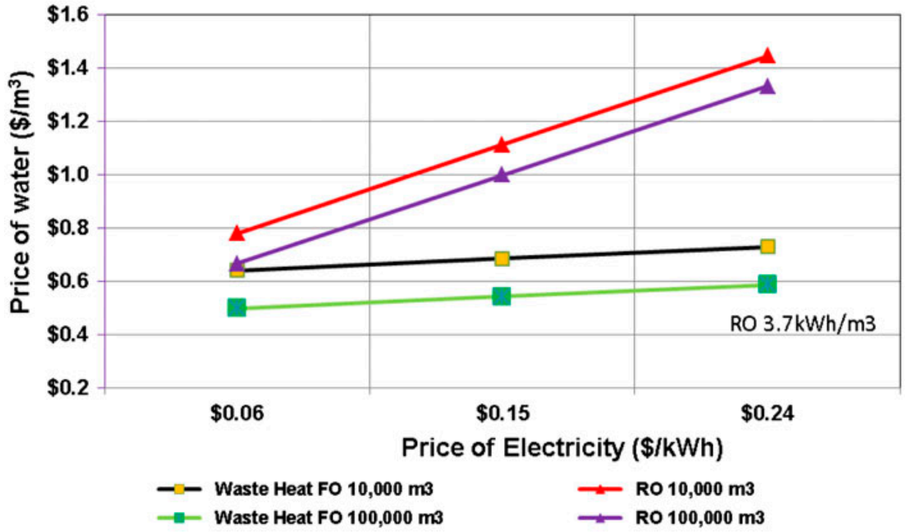

Fig. 6. Cost of water produced vs. cost of energy.

efficiencies of 25%. Simulations indicate that at sizes of 500 m^3/d and above, pump efficiencies climb to 70% and power consumption drops below 0.5 kWh/m^3. So, too, heat exchanger designs are better optimized for effectiveness at moderate flow rates, indicating, using Aspen simulator models, that thermal energy can readily drop below 70 MJ/m^3.

5. Discussion

The cost of water per m^3 model has been developed in order to show that using the most expensive source of thermal heat, solar thermal flat plate collectors, results in a cost equal to the current island electricity rates of 42 c/kWh. The cost savings of the Trevi FO system as compared with RO systems depends on the cost of thermal energy and electricity in a particular location. For instance, when using natural gas at $2.75 per million BTU (mmbtu) and electricity at 15 c/kWh, the FO system produces a 25% annual savings over a RO system. When a co-gen heat source is used at $0.12/mmbtu and the same 15 c/kWh electricity cost, the FO system produces a 45% savings in the cost of water over a RO system, as shown in Fig. 6. These savings are very significant considering the large scale of desalination systems as well as the growing worldwide demand for such systems.

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