MEMBRANE DISTILLATION TEST FOR CONCENTRATION OF RO BRINE AT WESSCO, JEDDAH

Authors:

K. Syed Amir Basha, Moya Bushnak
Henrik Dolfe, XzeroAB
Miriam Åslin, Xzero AB
Lamyaa El-Gabry, The American University in Cairo

Presenter: *K. Syed Amir Basha, Senior Vice President, Moya Bushnak, Saudi Arabia*

Abstract

An industrial size demonstration MD-unit was supplied by Xzero AB of Stockholm, Sweden to Moya Bushnak's WESSCO Desalination Plant in Jeddah, Saudi-Arabia, in order to test RO brine concentrate.

The demonstration plant supplied by Xzero had a capacity of 1 m^3/day. The membrane area was 2,8 m^2. The membranes were hydrophobic microfiltration membranes.

The feed water concentration was increased from 39,5 g/L to 136,8 g/L gradually during the test period. The degree of separation achieved was 99.99 %.

Testing was discontinued in February 2010, when heater broke down. At that point it was considered that the data was sufficient to motivate further development of equipment for concentration of RO brine.

Treating and concentrating the brine increases recovery ratio and may also, if complemented with crystallization or evaporation, be used as a base for zero liquid discharge.

I. INTRODUCTION

Membrane Distillation (MD) is a new technology that can become an energy saving alternative to presently existing separation technologies. Among the advantages of MD are that; it works at ambient pressure and can be run on low grade waste heat, it exhibits a high level of rejection, produces high quality permeate and the quality of permeate remains constant regardless of increases in feed water concentrations.

MD technology has been used in a number of applications. Martinetti et al. used vacuum-enhanced direct contact membrane distillation to treat reverse osmosis brine stream and showed 81% water recovery from the brine [1]. When periodic cleaning of the membrane was used, the recovery increased to 96%. Manna et al. used a solar-driven direct contact membrane distillation module to remove arsenic from contaminated groundwater [2]. The MEDESOL project is also investigating the use of solar energy to drive a multi-stage MD system with target yields of 0.5 m^3/d to 50 m^3/d [3]. In the MEDINA project, MD is considered as part of a strategy to approach the concept of Zero Liquid Discharge where water is recovered by 95% using Membrane Distillation [4]. The technology has also been used in high purity crystallization [4-8].

One of the challenges associated with MD is the scaling that occurs within the module which can reduce the output by more than 50% after 50-100 hours or operation [9]. The effect of various parameters on fouling such as feed temperature and flow rate have been studied [10-12]. Another way to reduce fouling (besides changing the operating conditions) is through chemical additives such as HCl [11,13-14] or installation of pre-filtration upstream of the module [15].

A second challenge to the commercial implementation of MD is the low water fluxes and the high heat requirements. To increase the water flux, studies have been carried out to investigate the influence of operating parameters such as feed temperature, velocity, and flow rate but also evaluating different membrane materials [16-18]. Zhang et al. [16] tested four different membranes of different materials and pore sizes and determined the performance under different hot feed flow rates and feed inlet temperatures. Al-Obaidani et al. [17] performed a sensitivity study of feed to operating and material parameters and additionally carried out an economic analysis for direct contact membrane distillation. In addition to the experimental research, computational fluid dynamics models have also been developed to evaluate the various parameters and understand and improve performance [19].

An industrial size demonstration MD-unit was supplied by Xzero AB of Stockholm, Sweden to the Moya Bushnak's WESSCO Desalination Plant in Jeddah, Saudi-Arabia in order to test concentrate of RO brine. The production of permeate in a standard RO unit is about 40-50% of the seawater feed. MD can be operated close to saturation, also enabling crystallization of NaCl from aqueous solutions [5]. MD can therefore be a good complement to RO. Treating and concentrating the brine will increase recovery ratio and may also, if complemented with crystallization or evaporation, be used as a base for zero liquid discharge. The MD unit has been thoroughly investigated in laboratory experiments. Also industrial grade equipment of a capacity of 5 000-10 000 l/day has been tested [20]. The Royal Institute of Technology, Stockholm, Sweden and Xzero AB conducted the test at a power plant and the feed was flue gas condensate. The tests at WESSCO were set up in order to verify these results in industrial size equipment. The tests show that MD can be used to concentrate RO brine.

II. OVER VIEW OF MD TECHNOLOGY

Since neither high pressure nor high heat is used, MD technology is intrinsically robust and safe. It has operational advantages in that it is self-regulating and therefore neither calibration nor complicated controls are necessary. In contrast to RO and other membrane separation technologies, no water is pressed through the membrane, which reduces the need for pre-filtration and backwashing.

The driving force in MD is the partial vapor pressure difference between a hot side and a cold side across a hydrophobic membrane. Pressure on the cold side can also be reduced by sweeping gas or vacuum. A variety of methods can thus be employed to create the vapor pressure difference.

2.1. Direct Contact Membrane Distillation

The cool condensing solution directly contacts the back side of the membrane. This is the simplest configuration. It is best suited for applications such as desalination and concentration of aqueous solutions (e.g., juice concentrates).

2.2. Air-Gap Membrane Distillation

An air gap is followed by a cool surface in this process. The air gap configuration is the most general and can be used for any application.

2.3. Sweeping-Gas Membrane Distillation

A sweeping gas pulls the water vapour and/or volatiles out of the system. This is useful when volatiles are to be removed from an aqueous solution.

2.4. Vacuum Membrane Distillation

A vacuum is used to pull the water vapour out of the system. This is useful for higher through put.

2.5. General advantages of membrane distillation:

General advantages of membrane distillation process are:

- It produces high-quality distillate.
- Water can be distilled at relatively low temperatures, under 100 °C.
- Low-grade heat (solar, industrial waste heat or desalination waste heat) may be used.
- The raw feed water does not require extensive pre-treatment.

III. XZERO'S PILOT TEST EQUIPMENT

The tested equipment was of the air-gap type as shown in figure 1

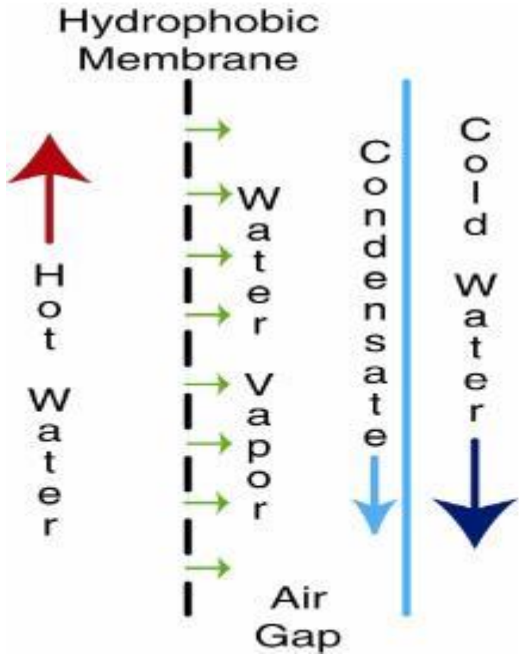

Figure-1, Air Gap type MD membranes

In the Pilot test skid, the RO brine is heated and passed on one side of the membrane. Water vapour diffuses across the membrane and the air gap and condenses on a surface that is cooled by water. The overall process is driven by a gradient in water vapour pressure, rather than a difference in total pressure. Thermal energy is required to elevate the vapour pressure of water in the hot stream.

The demo skid supplied by Xzero had a capacity of producing 0.2-1 m^3/day high quality permeate from RO concentrate. The membranes are hydrophobic with pore sizes usually in the range of 0.05 to 0.2 µm—the same range as microfiltration. Each module has a membrane area of 2.8 m^2. Auxiliary equipment consist of a tank (boiler) for hot water, variable flow gear pumps to drive the hot and cold water, with adjacent visual rotameters, digital pressure transducers to measure pressure drop, digital thermo probes to measure temperatures and a PC for data logging and controlling the system.

IV. EXPERIMENTAL SET-UP

A process flow diagram of the demo is shown below, describing the basic set-up of the hot and cold water flow circulation. Permeate is measured and collected in the conductivity vessel.

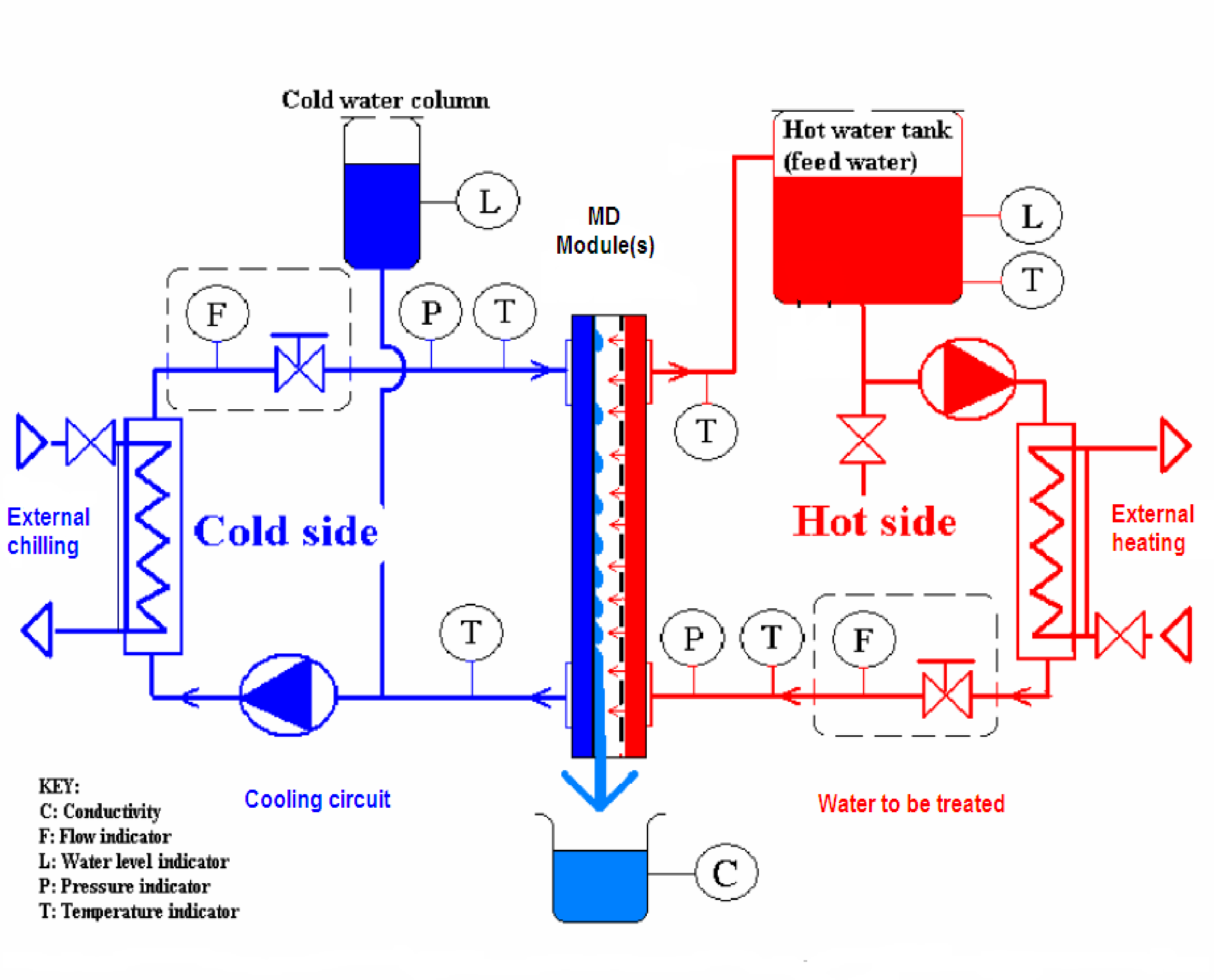

Figure- 2. Process flow diagram of the MD unit

The major purpose of the test was to: (a) Increase feed water concentration to measure permeate stability. (b) Determine performance over a range of operational parameters and (c) attempt to deduce controlling factors based upon experimental results. A secondary goal was to evaluate membrane stress, e.g. fouling during desalination, as well as durability of the module.

No other pre-treatment was provided for the water than basic media pre-filters. Flows and temperatures were recorded directly by a computer. Distillate production was measured by hand into a volumetric flask.

V. EXPERIMENTAL SCENARIO

The test started July 12, 2009 and ran until February 2010. It was stopped at evenings to be started every morning. It was also stopped for maintenance a couple of days and three weeks in September and during holidays. The total running time for the demo was 170 days.

Initially, the system was fed with salt water and SWRO permeate (TDS around 350 ppm) in intervals in order to measure variation in the flux of permeate over time. Feed water salinity and temperature vs. flux and conductivity of permeate was measured. Later, higher concentrations of saline feed water was tested to evaluate how the demo performed with respect to stress from temperature and saline feed water, and how these parameters impacted the yield.

The demo provided was known to be sensitive to start-up pressure if filled too rapidly and one leak developed early in the testing. However, since further measurements showed that the leak was constant we could continue testing.

After initial testing, RO brine was slowly introduced. Concentrate was recycled back into the hot source water tank to achieve sequentially more concentrated feed. During January and February (see sep. concentration test fig. 7) extra salt was added also manually to increase the concentration more rapidly.

Measurements of flux and distillate quality, increasing input water salinity, hot side temperature, and temperature drops were made. Data was collected from July 2009 to February 2010 and presented as an excel sheet report from Moya Bushnak to Xzero.

Testing was discontinued in February 2010, when heater broke down. At that point it was considered that data was sufficient to motivate further development of equipment for concentration of RO brine.

VI. RESULTS

The total running time for the demo was 170 days.

For the first two weeks the flux of the permeate was measured to between 4,6 and 6,0 litres per hour (module) (1,7-2,1 l/m²), at 62º C hot side (39.55 gram per litre salinity in feed water). The degree of separation of salinity by comparing the conductivities of feed water vs. permeate, was 99.99 % (e.g. 41 000 µS/cm vs. 2.51 µS/cm (2009-07-15), 34 200 µS/cm vs. 2.1 µS/cm (2009-07-22) and 56 500 µS/cm vs. 4.62 µS/cm (2009-07-23).

Early in the test a leak was detected (July 27). We had the leak for observation and found it to be constant. We therefore decided to continue the tests. Below the results are presented in a diagram showing feed conductivity versus permeate conductivity over time. When conductivity of feed water goes up the permeate increases but lies relatively steady. February 28 we decided to end the test due to heater failure

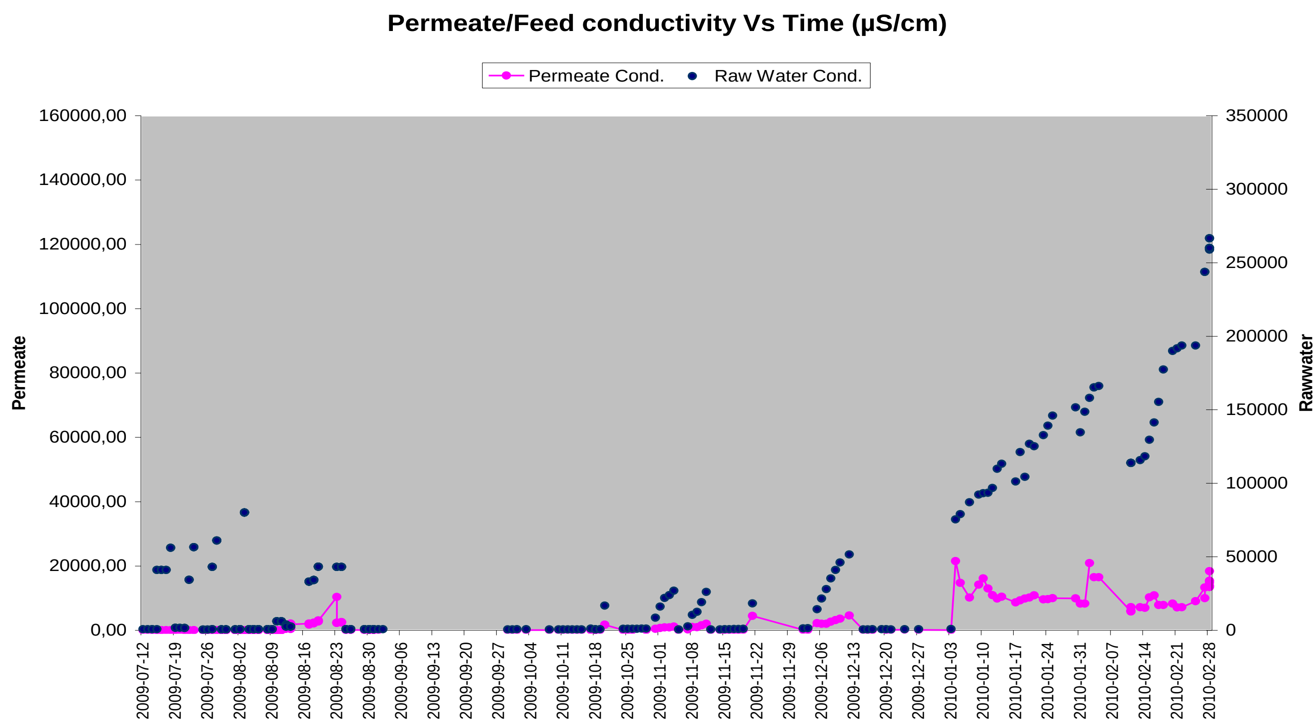

Figure -3 Permeate & Feed Conductivity Vs Time

The diagram below illustrates the permeate flux over time (without taking temperature in account). The fluctuation is due to temperature.

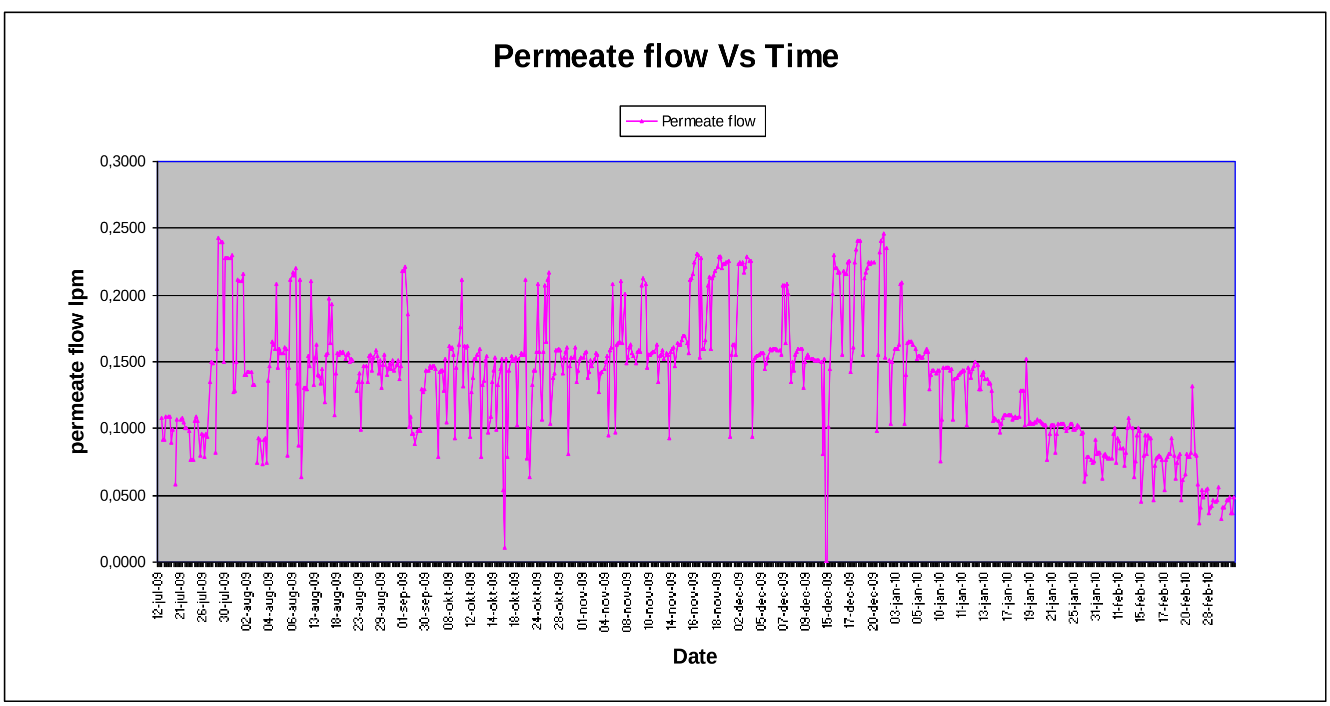

Figure 4 Permeate flux over time

The diagram below illustrates the permeate flux with respect to time with varying salinity and temperature. The diagram illustrates flux ± 33%. This is due to temperature difference. The demo was started daily at approximately 45-50 ºC to later reach approximately 75ºC. As illustrated the permeate flux decreases when the temperature goes down and increases as the temperature goes up. Higher concentrations also result in lower flux.

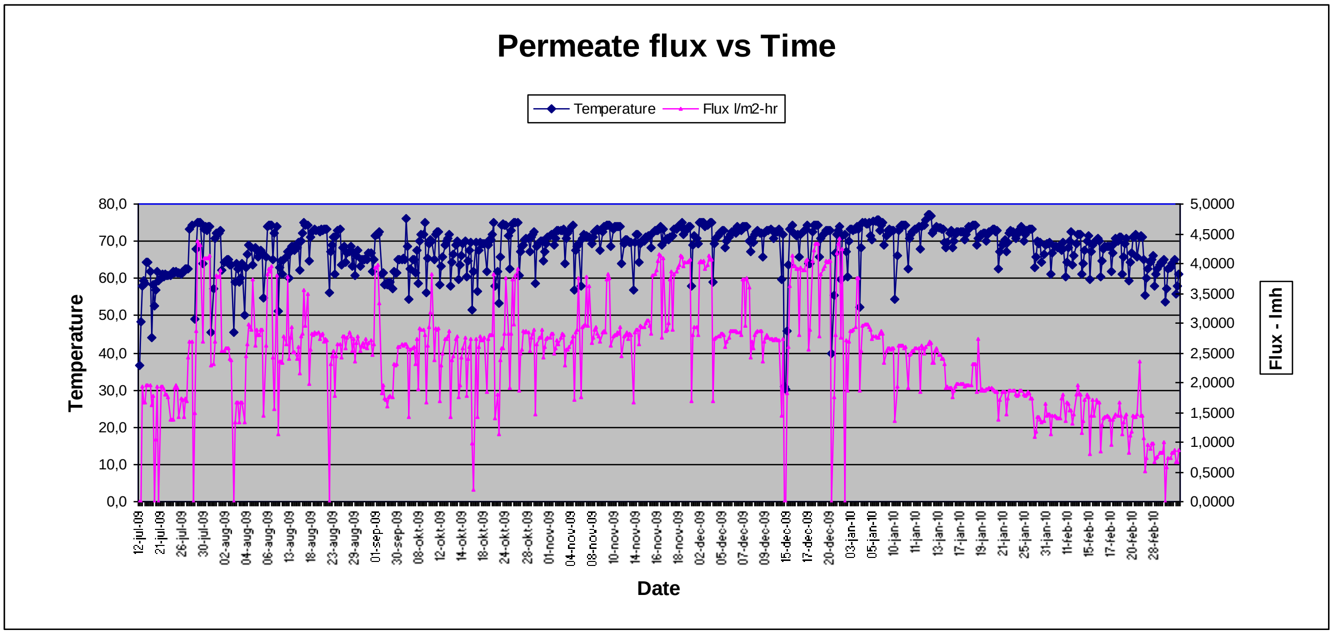

Figure. 5 Permeate flux compared with temperature over time

Below is the effect on permeate conductivity with varying feed temperatures and cooling water temperatures shown. The variation in feed water temperature did not have any effect on permeate conductivity.

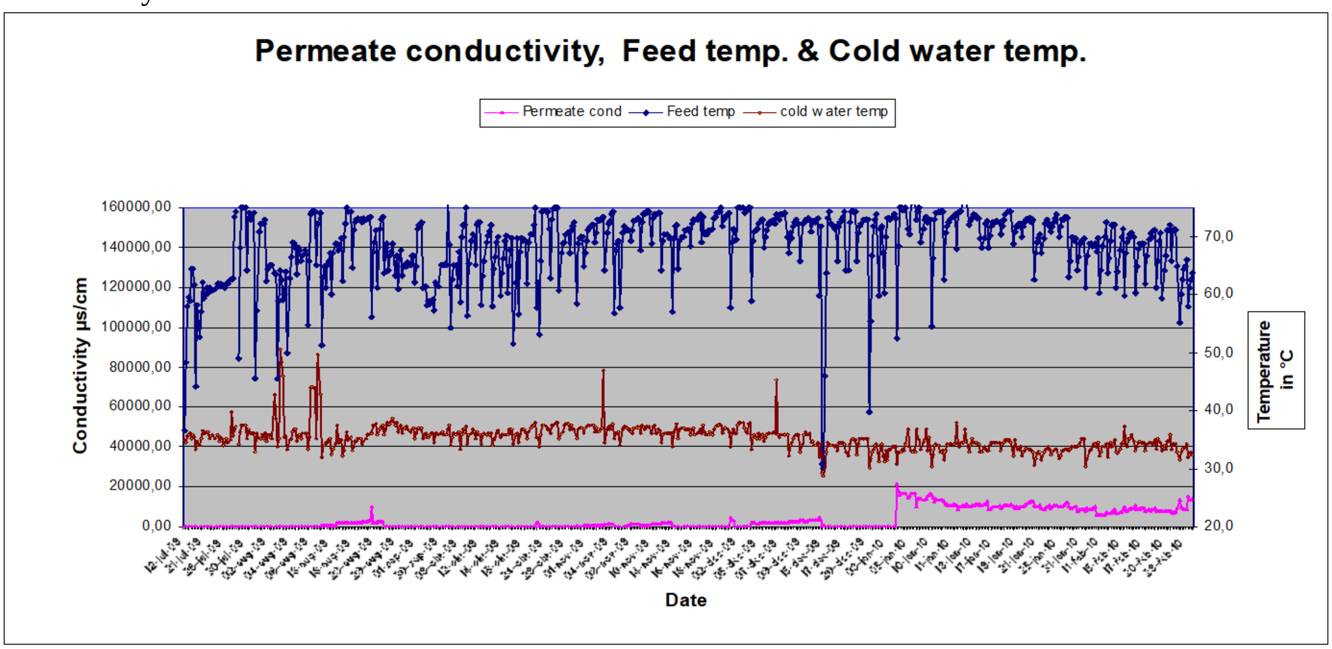

Figure 6 Permeate conductivity compared with temperature of feed and cooling water.

The results of a final concentration test made during Jan-Feb 2010 are shown in Fig 7. As shown, the conductivity of the permeate is high (due to a leak) but relatively constant even at the end when conductivity for the feed water goes up. The feed water concentration increases steadily from 39,5 g/L to 136,8 g/L. The permeate concentration level is constant at approximately 5,2 g/L. In this test salt was added manually to achieve a more rapid increase in the concentration for the feed water. This to put more and see how the rapid concentration increase in feed water affected the permeate.

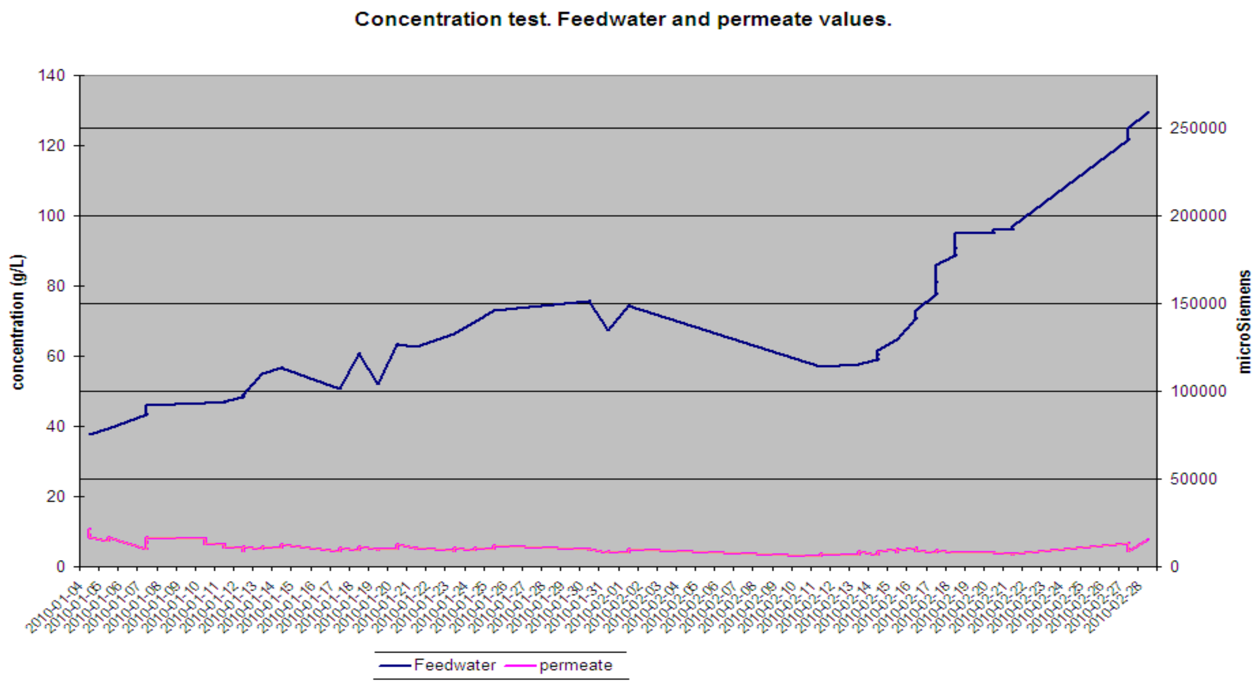

Figure. 7 Concentration test show conductivity (µS) during the test period January to end of Feb 2010.

VII. ENERGY CONSUMPTION

A measurement of energy used was made on data from November 24, 2009.

In this test the energy consumption was 642 kW/m^3 calculated at a water flow of 13.2 l/min (13.2/60 = 0.22 l/sec) over the module.

The specific heat capacity for water (Cp) is 4, 18 kWs per kg and ºC. (With the approximation one litre water eq. one kilogram). At a steady state, dT was 6, 8 ºC for the hot feed circulation water over the module. This gives 6, 25 kW(h) (6, 8 * 4, 18* 0, 22 = 6, 25) energy consumption for the hot side.

The permeate production was 0, 1632 l/min (9, 79 l/h).

To produce 1m^3 required 102 h (1000/9, 79 = 102) and this gives the energy consumption of 642kWh/m^3 (6.25 *102 = 642).

G.O.R without heat recovery is 1 (639 * 0, 00979/6, 25).

In comparison, lab results with heat recovery (if heat in cold circulation channel is used somewhere else) have given a net heat energy consumption of 13, 74 kWh/m³ which gives a G.O.R. of 23 (639 * 0, 024/0, 665). (Heat on hot side 634,35 - recovery on cold side 620,61 = 13,74)

Nominal performance ratio for one module is 0, 97 (9,79kg/h (Flow rate) * 2257 kJ/kg (latent heat of evaporation) / 22678 kJ (heat input rate)).

VIII. DISCUSSION

The demo was built to stand a test of approximately three months in high salinity conditions. Since the test period was extended to more than six months some of the components broke down because of corrosion and had to be replaced. Ultimately the testing was discontinued after a heater failure because sufficient data had been collected to show that the equipment was able to treat RO brine.

For the first two weeks the flux of permeate was measured to between 4.62 to 6 litres per hour (module) (1,65-2,14 l/m²), at 62° C hot side (39.55 gram per litre salinity in feed water). The degree of separation of salinity by comparing the conductivities of feed water vs. permeate was 99.99 %. This was the expected result and we continued with RO brine concentration.

The welds in the membranes were sensitive to internal pressure differences and spikes. Special caution was needed during start-up and while changing water in system. At one point early in the testing a leak developed. Xzero has since then developed a new welding method and installed equipment for it to make the membrane less sensitive to pressure spikes. However the leak was constant and we decided to continue with the already installed equipment.

We had a leak early during the test and therefore kept a relatively low flow of 13.2 l/min in the test in order to avoid more stress on the module. The temperature was max 70°C during testing. This resulted in a relatively low flux. The flux was also observed to decrease during the duration of the test which indicates the necessity of a better control of interfacial phenomena.

The feed water conductivity during the later concentration test, is going from 75 000 µS to 260 000 µS but permeate lies quite constant at 10 000 µS and is not dependent of feed water concentration. Expected permeate conductivity without leak is around 1-2 µS.

As indicated results shows that MD is an interesting technology that can be used as a complement to RO.

IX. CONCLUSIONS

The feed water conductivity during the final concentration test rose from 75 000 µS to 260 000 µS while permeate was relatively constant at 10 000 µS and was thus not feed water dependent. (Fig 7.) This shows that MD can be used to concentrate RO brine.

The equipment used for the test included one industrial size module with a capacity of 0, 2-1 m³/day (output depends on operating conditions, particularly on hot side water temperature). The next step in development is a demonstration plant with a capacity of 5 000-10 000 l/day, possibly 50 000 – 100 000 l/day.

A decrease in flux over time was observed. More testing is needed to determine how concentration of feed influences flux.

Future testing should be made with pumps, heaters and other ancillary equipment made of materials that withstand high salt concentration.

A set-up with a crystallizer should also be tested to evaluate zero liquid discharge.

REFERENCES:

[1] Martinetti, R., Chlidress, A., Cath, T., 2009, "High recovery of concentrated RO brines using forward osmosis and membrane distillation," *Journal of Membrane Science*, **331**, pp. 31-39.
[2] Manna A.K., Sen M., Martin A.R., Pal P., 2009, "Removal of arsenic from contaminated groundwater by solar-driven membrane distillation," *Environmental Pollution*, **158**, pp. 805-811.
[3] Galves, J., Garcia-Rodriguez, L., Martin-Mateos, I., 2009, "Seawater desalination by an innovative solar-powered membrane distillation system: The MEDESOL project," *Desalination*, **246**, pp. 567-576.
[4] Drioli E, 2010, *Membrane Based Desalination an Integrated Approach*, IWA Publishing: London, UK.
[5] Curcio,E., Criscuoli, A., Drioli, E., 2001, "Membrane Crystallizers," Industrial & Engineering Chemistry Research, **40**, pp. 2679–2684.
[6] Lakerveld R., Kuhn J., Kramer, H., Jansens, P., Grievink, J., 2010, "Membrane assisted Crystallization using Reverse Osmosis: Influence of solubility Characteristics on experimental Application and energy saving Potential," Chemical Engineering Science, **65**, pp. 2689-2699.
[7] Tun C.M., Fane A.G., Matheickal J.T., Sheikholeslami R., 2005, "Membrane distillation crystallization of concentrated salts – flux and crystal formation," *Journal of Membrane Science*, **257**, pp. 144-155.
[8] Mariah, L., Buckley, C., Brouckaert, C., Curcio, E., Drioli, E. ,Jaganyi, D., Ramjugernath, D., 2006, "Membrane distillation of concentrated brines – Role of water activities in the evaluation of driving force," *Journal of Membrane Science*, **280**, pp. 937-947.
[9] Gryta, M., 2008, "Fouling in direct contact membrane distillation process," *Journal of Membrane Science*, **325**, pp. 383 – 394
[10] El-Bourawi, M.S., Ding, Z., Ma, R., & Khayet, M., 2006, "A framework for better understanding membrane distillation separation process," *Journal of Membrane Science*, **285**, pp. 4 – 29.
[11] Gryta, M., 2008, "Alkaline scaling in the membrane distillation process, *Desalination*, **228**, pp. 128 – 134.
[12] Euvrard, M, Membrey, F., Filiatre, C. & Foissy, A., 2004, "Crystallization of calcium carbonate at a solid/liquid interface examined by reflection of a laser beam," *Journal of Cyrstal Growth*, **265**, 322 – 330.
[13] Gryta M., 2009, "Calcium sulphate scaling in membrane distillation process," *Chemical Papers*, **63** (2), pp. 146-151.
[14] Gryta M., 2007, "Effect of iron oxides scaling on the MD process performance," *Desalination*, **216**, pp. 88-102.

[15] Gryta M., 2009, “Scaling diminution by heterogeneous crystallization in a filtration element integrated with membrane distillation module,” *Polish Journal of Chemical Technology*, **11**, pp, 60-65.
[16] Zhang J, Duke M, Ostarcevic E, Dow N, Gray S, Li J, 2009, “Performance of new generation membrane distillation membranes,” *Water Science & Technology: Water Supply*, **9**, pp. 501-508.
[17] Al Obaidani S., Curcio E., Di Profio G., Drioli E., Ji X., et al, 2010, “Membrane distillation - crystallization of seawater Reverse osmosis brines,” *Separation and Purification Technology*, **71**, pp. 76-82.
[18] Zhang, J., Dow, N., Duke, N., Ostarcevic, E., Li, J., Gray, S., 2009, “Identification of material and physical features of membrane distillation membranes for high performance desalination,” *Journal of Membrane Science*, **349**, pp. 295-303.
[19] Xu, Z., Pan, Y., Yu, Y., 2009, “CFD simulation of membrane Distillation of NaCl solution,” Frontiers of Chemical Engineering in China, **3**, pp. 293-297.
[20] Kullab, A., Martin, A., 2007, “Membrane Distillation and Applications for Water Purification in Thermal Cogeneration – Pilot Plant Trials,”