*Desalination and Water Treatment*
www.deswater.com

1 (2009) 215–222



# Performance analysis of a trihybrid NF/RO/MSF desalination plant

Osman A. Hamed*, Ata M. Hassan, Khalid Al-Shail, Mohammed A. Farooque

*Saline Water Desalination Research Institute (SWDRI), Saline Water Conversion Corporation (SWCC), P.O.Box 8328, Al-Jubail 31951, Saudi Arabia*
*Tel. +966 (3) 3430333 Ext. 30541; Fax +966 (3) 3431615; email: oahamed@yahoo.com*

Received 23 June 2007; accepted revised 20 August 2008

**ABSTRACT**

The Saline Water Desalination Research Institute (SWDRI) of the Saline Water Conversion Corporation (SWCC), Saudi Arabia has been actively involved in developing the application of nanofiltration (NF) pretreatment to both seawater reverse osmosis (SWRO) and multistage flash (MSF) desalination processes. Full integration of NF, SWRO and MSF processes would result in enhancing the reliability, flexibility, plant productivity and ultimately reduce water production cost. Extensive experimental studies on a pilot-scale were conducted recently by SWDRI to establish the operational boundaries and constraints of the trihybrid NF/RO/MSF desalination system. The system was configured in such a way that the NF unit received seawater feed from the heat rejection of the MSF pilot plant and was able to operate at a fairly constant temperature of about 33°C which produced NF permeate (NFP) at a recovery ratio of about 64%. The SWRO unit which received the NFP as a feed yielded a permeate recovery of about 47%. Average chemical analysis of the RO reject (ROR) revealed that the sulphate and calcium concentrations were only 124 and 281 ppm, respectively, and was subsequently used as a make-up to the MSF pilot plant. The very low concentration of the sulphate and calcium ions in the brine recycle which were below the saturation limits enabled to operate the MSF unit safely up to a top brine temperature of 130°C (unit temperature design limit) and water recovery ratio of about 69%. In this paper, the operational performance of the trihybrid NF/RO/MSF desalination pilot plant will be presented. The established optimum operating conditions can be used as a guide to assess the techno-economic viability of the trihybrid desalination scheme.

*Keywords*: Trihybrid; NF; SWRO; MSF; High temperature

## 1. Introduction

The Saline Water Desalination Research Institute (SWDRI) has been actively involved in the development of nanofiltration (NF) pretreatment technology application for both seawater reverse osmosis (SWRO) and multistage flash (MSF) desalination processes. The technical and economic merits of the combined NF/SWRO have been confirmed both in pilot and commercial plant operation [1–6]. The SWDRI conducted extensive pilot plant testing in which the nanofiltration membrane product (NFP) was sent as a make-up to the MSF pilot plant [8–10]. As the result of the removal of more than 99% of sulfate ions, 86% of calcium ions and 30% of total dissolved solids from the seawater by the NF pretreatment unit, the top brine temperature (TBT) of the MSF pilot was successfully increased up to 130°C with a make-up

* Corresponding author.

*Presented at International Desalination Association World Congress on Desalination and Water Reuse, SP05-172, Singapore, September 11–16, 2005.*

which was entirely formed of NFP [10]. The study revealed that an increase of TBT from 100 to 130°C produces a 48% increase in water production.

Evaluation tests which were carried out using the NF membrane for pretreatment of seawater feed to reverse osmosis desalination unit, revealed that the RO reject consists of a relatively low concentration of scale forming ions as shown in Table 1. Hence, it is worthwhile to explore the possibility of sending the RO reject as make-up to the MSF pilot plant. Such a situation would require the establishment of a trihybrid NF/RO/MSF desalination system. Full hybridization of NF/RO/MSF can be expected to improve the overall product recovery ratio and consequently reduce water production costs. Integration of reverse osmosis with multistage flash distillation offers additional benefits [11–14]. It provides a common and smaller seawater supply system, integration of seawater pretreatment and product post-treatment systems, and the ability to increase the SWRO plant feed water temperature.

This paper discusses the results of extensive pilot plant evaluation testing which determined the operating conditions of the NF/RO/MSF trihybrid system when the MSF pilot plant operates at elevated TBT higher than 120°C.

## 2. The experiment set-up

A schematic flow diagram of the trihybrid NF/SWRO/MSF system is shown in Fig. 1. The seawater supply is first pretreated by passing it through a dual media filter followed by a fine sand filter after addition of about 50 ppm of $H_2SO_4$ to prevent scaling on NF membranes. A micron cartridge filter is used to protect the membrane. The pretreated seawater is then sent to the nanofiltration membrane. The NF product is sent to the RO unit and its brine reject is used as a make-up to the MSF plant.

The MSF pilot plant has a capacity of 20 t/d and consists of a brine heater, four heat recovery stages and two heat rejection stages. The plant is also equipped with an external deaerator as well as a decarbonator and on-line ball cleaning facilities.

## 3. Results and discussion

### *3.1. Operational performance of the NF system*

The NF unit received pretreated seawater and was operating at variable feed water temperature. As shown in Fig. 2, the inlet seawater temperature varies between 24°C and 34°C.  uring the first 540 h of operation the seawater feed to the dual media filter was obtained directly from the seawater intake system. Afterwards, part of the heated seawater leaving the heat rejection section was used as feed for the NF membrane, thus resulting in a higher feed temperature.

Fig. 2 shows that during the first 540 h, during which the operating pressure was maintained at about 24 kg/$cm^2$ and the temperature in the range of 24–27°C, the permeate recovery rate was between 53 and 57%. An increase in pressure to about 28 kg/$cm^2$ and an increase in the temperature of the inlet seawater to 34°C resulted in an increase in the NF recovery rate to about 65%. Average chemical analysis revealed that the nanofiltration pretreatment enabled to reduce the seawater sulphate from 3309 ppm to 75 ppm, calcium ions from 491 to 154 ppm, M-alkalinity of seawater which was initially reduced upstream of the NF membrane by acid addition from 127 ppm to 103 ppm was further reduced to 47 ppm, by NF membrane and TDS was reduced from 45550 to 33500 ppm. It is worth noting that $H_2SO_4$ was dosed into NF feed stream as a precautionary measure primarily due to the high scaling potential of NF reject stream. This may sound ironic since the extremity of NF efficiency in carbonate ions removal had lead to this pressuring measure. That is to say, should one compromise with somewhat lower NF recovery then the use of acid could be totally done away with. Such a decision is left to further optimization

### *3.2. Operating performance of the SWRO system*

The operating conditions and performance of the HFF SWRO unit, which received the NF product as feed, is shown in Fig. 3. The SWRO unit consists of two vessel units, which are connected in series. During the test pe-

Table 1
Average chemical composition of seawater and nanofiltration product (NFP), RO product and $RO_{reject}$

| Parameter | Seawater | NFP | NF reject* | RO product | $RO_{reject}$ |
|---|---|---|---|---|---|
| TDS, ppm | 45,550 | 33,500 | 67235 | 780 | 61,410 |
| Calcium ions, ppm | 491 | 154 | 1097 | 1 | 281 |
| Magnesium ions, ppm | 1556 | 225 | 3951 | 2 | 406 |
| Total hardness as $CaCO_3$, ppm | 7633 | 1310 | 19,012 | 8-5 | 2350 |
| Sulphate ions, ppm | 3309 | 75 | 9129 | ND | 128 |
| Bicarbonate ions, ppm | 155.5 | 57 | 163 | 4 | 101.5 |
| M-alkalinity, ppm | 127 | 47 | 134 | 3 | 83 |
| Chloride ions, ppm | 23,838 | 19,497.5 | 31,648 | 382 | 35,419.5 |

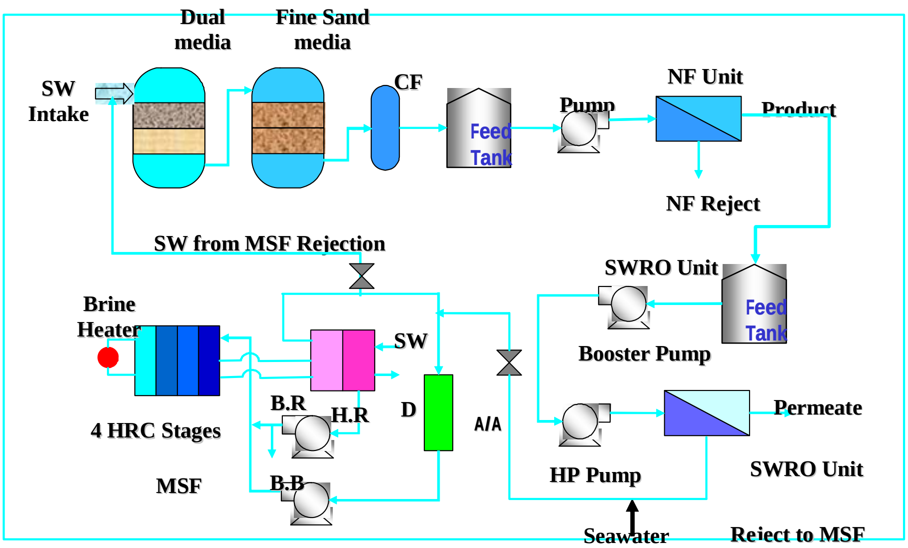


Fig. 1. Schematic flow diagram of the trihybrid NF/RO/MSF system and MSF pilot plants system.

riod, the operating pressure was maintained at 60 kg/cm$^2$ and the temperature ranged from 23 to 34°C. Fig. 3 shows that the average permeate recovery of the first and second vessels were around 30 and 21% respectively and the overall recovery of the integrated SWRO system was about 45%.

Chemical analysis revealed that the majority of the hardness ions and other dissolved salts were concentrated in the brine reject. The RO reject, whose composition is shown in Table 1, was sent to the MSF unit as make-up.

### 3.3. Operational performance of the MSF plant

To prevent alkaline scale formation, the bicarbonate ions in the RO reject which ranged between 98–101.5 ppm, were eliminated by the addition of a stoichiometric amount of sulphuric acid. The RO reject was then sent as make-up to the MSF pilot plant. The top brine temperature was then increased in a stepwise mode from 120°C up to 130°C. The performance of the MSF distiller during a total period of 976 h of operation is shown in Fig. 4. The overall heat transfer coefficient and the fouling factor of the brine heater remained virtually constant. After 728 h of operation at TBT of 128°C, the unit was shut down due to unexpected disturbance in the seawater supply system. The unit then resumed operation for a further 247 h without any sign of scale formation. This fact was further confirmed by the post-test visual inspection. It revealed that the tube ends and sheets of the inlet and outlet water boxes of the brine heater were very clean and that there was no evidence of scale deposits. Fig. 5 shows the effect of the increase of TBT on the water recovery ratio (WRR). An increase of TBT from 120°C to 130°C resulted in an increase in the WRR of about 9%t.

The results of the chemical analysis of the brine recycle stream during this test period are shown in Figs. 6a and 6b. As a result of increase in TBT from 120 to 130°C, the total dissolved solids (TDS) in the brine recycle stream increased from 111,860 to 126,000 ppm, sulphate ions from 344 to 450 and calcium ions from 481 to 621 ppm. Comparison between the observed concentrations of sulphate and calcium ions with the corresponding solubility limits of calcium sulphate hemihydrate are also shown in Figs. 6a and 6b. Fig. 6a shows that the observed concentration of sulphate ions is consistently below the corresponding solubility limits. Fig. 6b shows that the concentration of calcium ions is below the corresponding limits up to TBT of 126°C. When TBT equal or exceeds 128°C, the observed calcium ions concentration exceeds the solubility limits. Based on which, the decision to add acid prior to the NF was found to be a wise action and quite worthwhile. Although the calcium ions solubility limits were exceeded, the relatively low concentration of observed sulphate ions permitted the successful operation of the MSF pilot plant up to a TBT of 130°C. Another parameter that is crucial in studying solubility limits are the residence time compared to hydrate nucleation time. It is, therefore, essential to further study this aspect especially in commercial plants where the residence time is by far longer than that observed in this pilot unit.

### 3.4. Viability and merits

#### 3.4.1. Reliability

In this context, one may say how would such interconnected processes could enhance reliability. Though hard to conceive by mere observation the proposed hy-

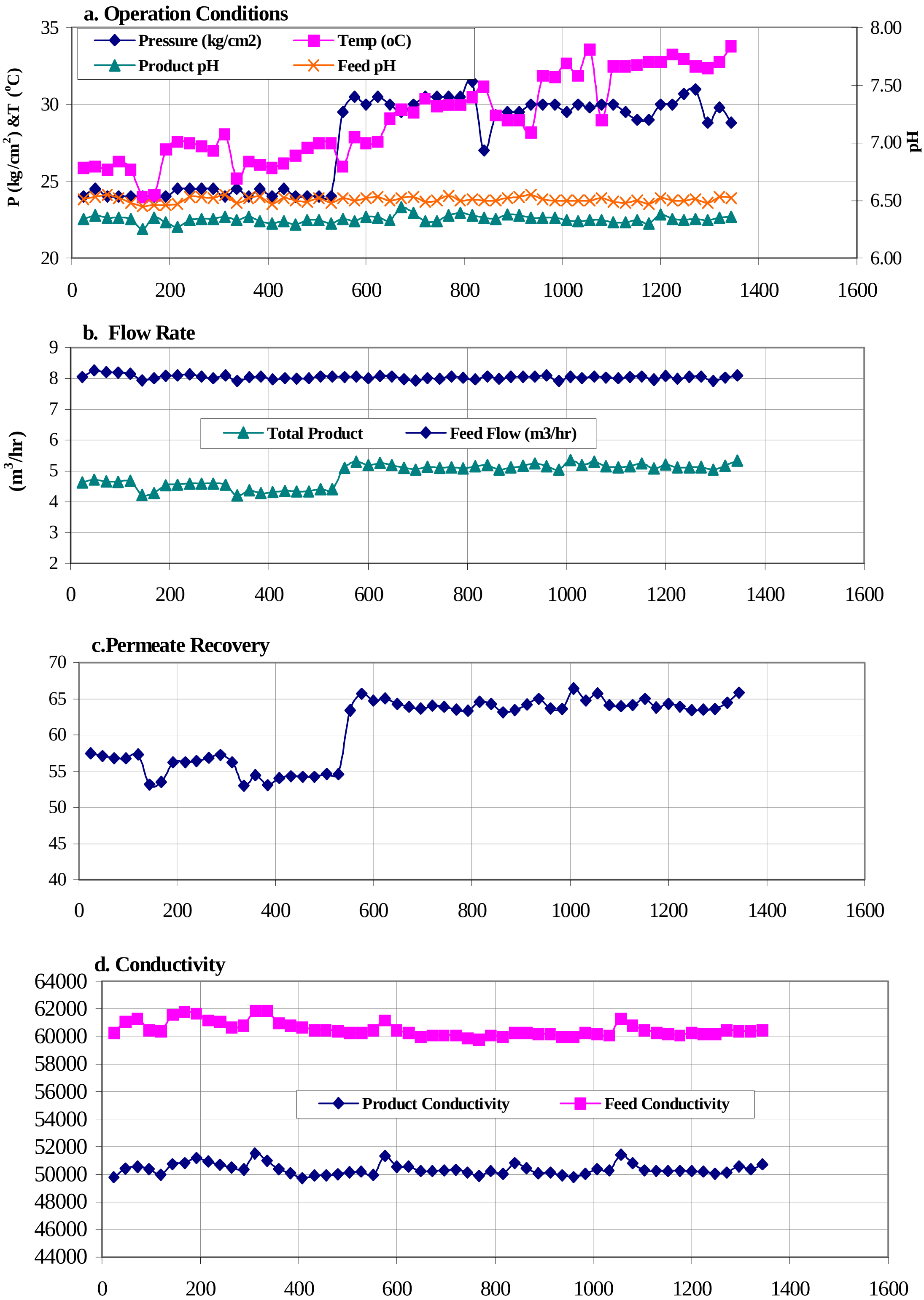


Fig. 2. Performance of NF membrane ( 4 elements in series) coupled to SWRO-MSF pilot plants.

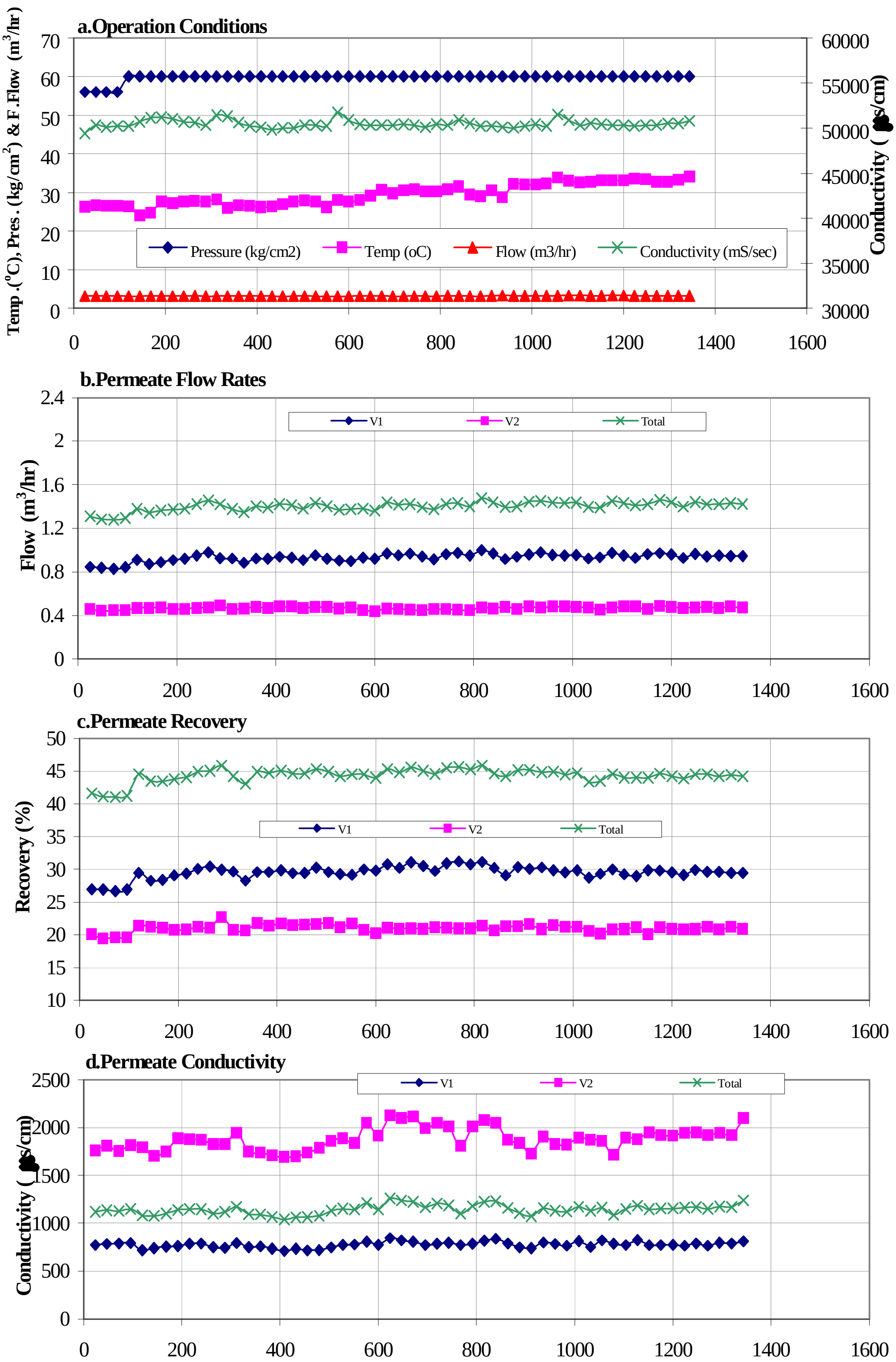


Fig. 3. Performance of HFF SWRO membrane: (a) operating conditions, (b) flow rates, (c) recovery and (d) conductivity vs. operation time. Feed is from NF membrane.

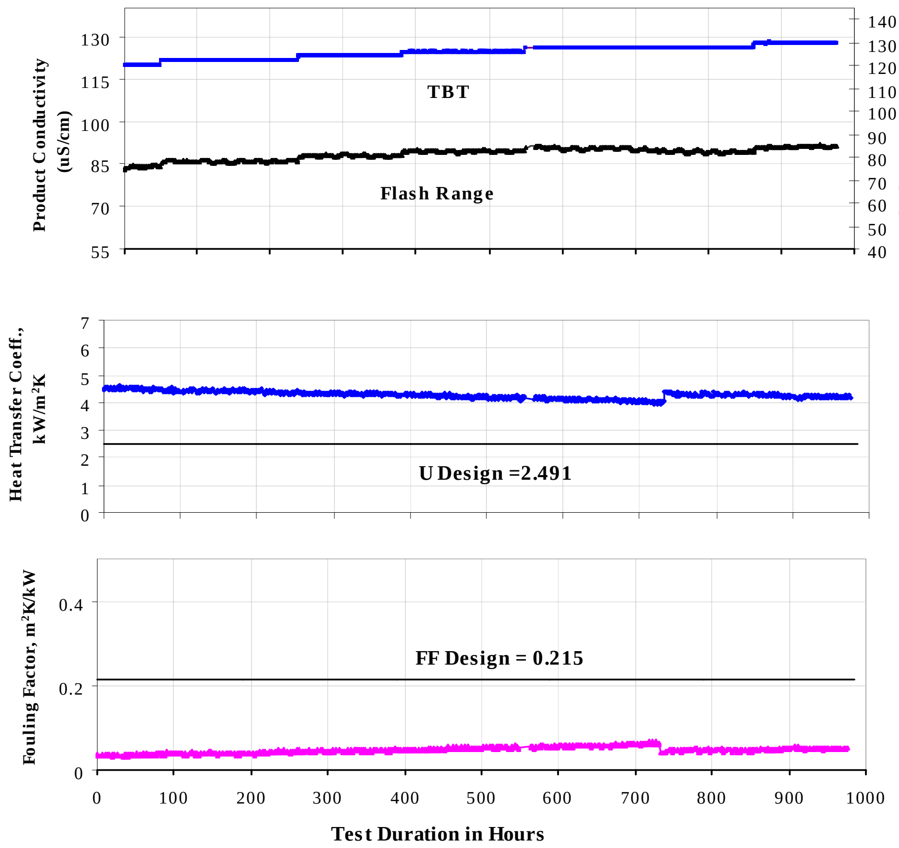


Fig. 4. Performance of MSF pilot plant with nanofiltration feed at TBT range from 120 to 130°C with acid addition and make-up (1.5 RO reject $m^3$/h).

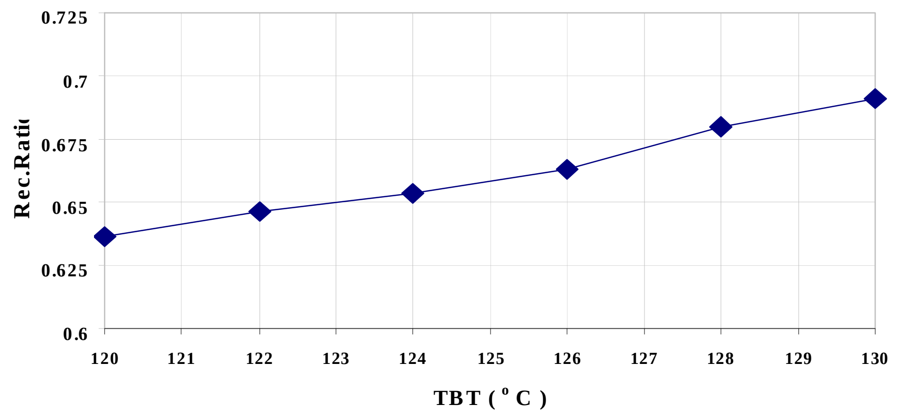


Fig. 5. Impact of TBT on water production and recovery ratio.

bridization would improve on the reliability in a number of ways, most important of which is the "reduced scaling potential throughout the entire processes. Also the opportunity provided in blending of the high purity distillate of the MSF plant with the RO permeate will mitigate the impact of the maloperation of the RO plant.

### 3.4.2. Flexibility

Once again, the same concern could be uttered here. Yet, improved flexibility is primarily related to the availability of more than one process. Hence, any shortcoming or deficit resulting in loss of production would mean

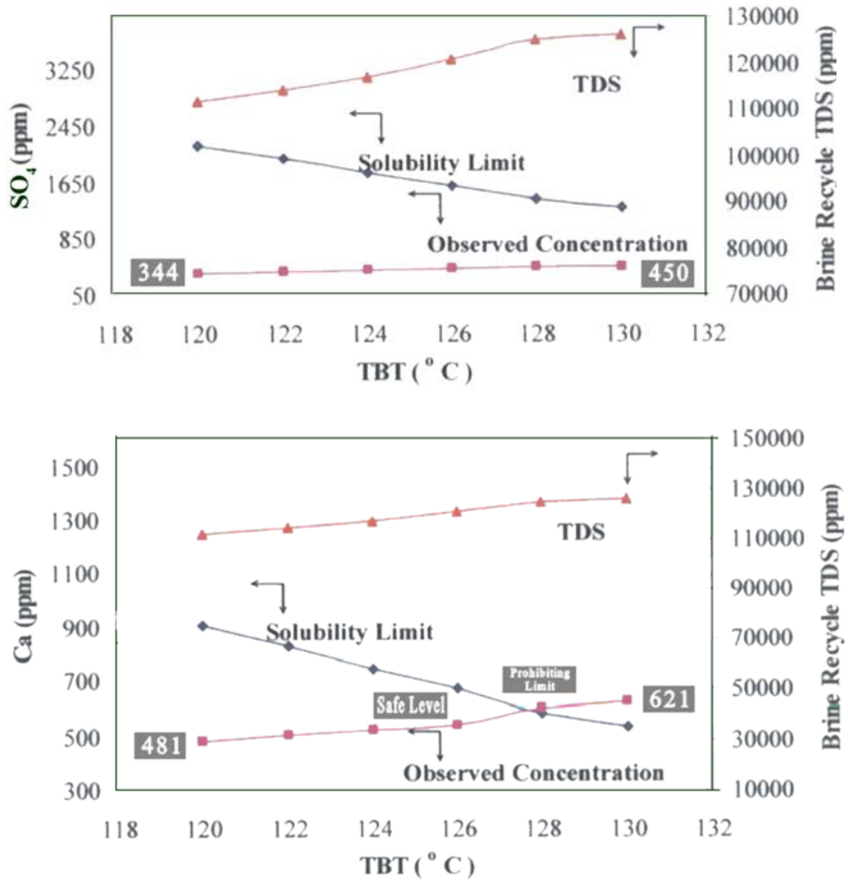


Fig. 6. Vatiation of (a) sulphate and (b) calcium ion concentration with TBT.

that such loss would be partial. Thus part of production of desalinated water is secured.

When the power demand in a conventional dual purpose MSF/power plant is changing, it is essential to provide an auxiliary boiler to provide supplementary fuel for energy to keep water production constant. Conversely, the flexibility inherited in the hybrid RO/MSF configuration provides the prospect for the RO unit to accommodate the power load variation without the need of an auxiliary boiler.

*3.4.3. Plant productivity*

Increasing the TBT of the MSF distiller up to 130°C will increase the distiller's flash range and subsequently will enhance the water production and recovery ratio. Also feeding the RO process with a NF product resulted in the increase of the permeate recovery ratio. Blending the products of the MSF and RO process allows operating the RO unit with relatively high recovery ratio.

*3.4.4. Ultimate cost reduction*

The proposed integration would lead to cost reduction in at least four different components. And these are:

a) Reduced equipment such as MSF brine recycle pump which could become redundant when SWRO reject is used to replace typically circulated brine stream with the MSF process.
b) Improved recoveries would reduce input power for pumping special by the input to SWRO high pressure pump(s).
c) Membrane feed heating especially in winter season and the operation of permeation processes (NF and SWRO) at narrower temperature ranges thus higher recovery and prolonged membrane life.
d) Markable reduction in treatment chemicals.

**4. Conclusions**

1. The operational performance of a trihybrid NF-SWRO-MSF system, where the reject from the SWRO unit, which is fed with NF- product, constituted the make-up to the MSF pilot plant, was established.

2. It has been confirmed experimentally that it is quite safe to operate the MSF pilot with a make-up which is entirely formed of the brine reject from the RO unit at a top brine temperature up to 130°C.

3. The established results of the pilot plant testing of

the trihybrid NF/RO/MSF can be used as a basis to assess its application.

4. The technoeconomic feasibility and commercial viability would require further simulation, evolution and (if possible) actual plant testing.

5. Such evaluation must take into consideration precautions raised in this paper.

## References


[1] A.M. Hassan, M.AK. Al-Sofi, A.S. Al-Amodi, A.T.M. Jamaluddin, A.G.I. Dalvi, N.M. Kither, G. Mustafa and I.R. Al-Tissan, A nanofiltration (NF) membrane pretratment of SWRO feed and MSF make-up, Paper presented at IDA conference, Madrid, October 6–9, 1997.

[2] A.M. Hassan, M.AK. Al-Sofi, A.S.Al-Amodi, A.T.M. Jamaluddin, A.G.I. Dalvi, N.M. Kither, G. Mustafa and I.R. Al-Tissan, A two part article, Part 1, Desalination and Water Reuse Quarterly, 8(1) (1998) 54–59, and Part 2, Desalination and Water Reuse Quarterly, 8(2) (1998) 35–45.

[3] A.M. Hassan, M.AK. Al-Sofi, A.S.Al-Amodi, A.T.M. Jamaluddin, A. M. Farooque, A. Rowaili, A.G.I. Dalvi, N.M. Kither, G. Mustafa and I.R. Al-Tissan, A new approach to membrane and thermal seawater desalination process using nanofiltration membranes, Desalination, 118 (1998) 35–51.

[4] A.M. Hassan, A. Farooque, A.T.M. Jamaluddin, A.S.Al-Amodi, M.AK. Al-Sofi, A.F. Rubian, M.M. Gurashi, A.G.I. Dalvi, N.M. Kither and I. Al-Tissan, Optimization of NF seawater pretreatment, Paper presented at IDA World Congress on Desalination and Water Reuse, San Diego, California, August 29–September 3, 1999.

[5] M.AK. Al-Sofi, A.M. Hassan, G.M. Mustafa, A.G.I. Dalvi and N.M. Kither, Nanofiltration as means of achieving higher TBT of ≥ 120°C, Desalination, 118 (1998) 123–129.

[6] A.M. Hassan, M.AK. Al-Sofi, A.S.Al-Amodi, A.T.M. Jamaluddin, A. M. Farooque, A. Rowaili, A.G.I. Dalvi, N.M. Kither, G. Mustafa and I.R. Al-Tissan, A new approach to membrane and thermal seawater desalination process using nanofiltration membranes, Part 2, Proc. WSTA Conference, Bahrain, February 1999, 2 (1999) 577–594.

[7] A.M. Hassan, M.AK. Al-Sofi, A.S.Al-Amodi, A.T.M. Jamaluddin, N.M. Kither, G. Mustafa and I.R. Al-Tissan, A Nanofiltration(NF) Membrane Pretreatment of SWRO Feed and MSF Make-up (Part-1), Report No. (TR 3807/APP 96008)

[8] M.AK. Al-Sofi, A.M. Hassan, O.A. Hamed, A.I. Dalvi, N.M. Kither, G. Mustafa and K. Bamardouf, Optimization of hybridized seawater desalination process, Desalination, 131 (2000) 147–156.

[9] M.AK. Al-Sofi, A.M. Hassan, O.A. Hamed, G. Mustafa, A.I. Dalvi and M.N.M. Kither, Means and merits of higher temperature operation in dual purpose plants, Desalination, 135 (1999) 213–222.

[10] O.A. Hamed, A.M. Hassan, K. Al-Shail, K. Bamardouf, S. Al-Sulami, A. Hamza, M.A. Farooque and A. Al-Rubain, Operational performance of an integrated NF/MSF desalination pilot plant, Proc. IDA World Congress on Desalination and Water Reuse, Paradise Island Bahamas, 2003.

[11] M.AK. Al-Sofi, A.M. Hassan and E.F. El-Sayed, Integrated and non-integrated power/MSF/SWRO plants, Part 1, Desalination and Water Reuse, 2(3) (1992) 10–16.

[12] M.AK. Al-Sofi, A.M. Hassan and E.F. El-Sayed, Integrated and non-integrated power/MSF/SWRO Plants, Part 2, Desalination and Water Reuse, 2(4) (1992) 42–46.

[13] L. Awerbuch, Power-desalination and the importance of hybrid idea's, Proc. IDA World Congress, Madrid, 1997.

[14] L. Awerbuch, S. May, R. Soo-Hoo and V. Van Der Mast, Hybrid desalting systems, Proc. 4th World Congress on Desalination and Water Reuse, Kuwait, 1989.