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The MSF: Enough is enough

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ABSTRACT

The energy consumed by the predominantly used multi stage flash (MSF) desalting system in Kuwait and other Gulf Co-operation Countries GCC are discussed in detail. The MSF consumed energy in the range of 5–6 times that of the latest preferred seawater reverse osmosis (SWRO) desalting system. The gravity of the consumed high energy of MSF is felt by the $2185M estimated cost of energy used for the year 2008 to produce 550 Mm^3 of water distillate in Kuwait. This cost was compared with that off the SWRO, if used, and estimated to be $261M. The suggestion of increasing MSF performance by nano-filtration (NF) pretreatment is also discussed. This can remove some of the scale-forming constituents from feed water, which allows raising the top brine temperature (TBT) and the flashing range and thus the capacity. While the capacity increase is badly needed in Kuwait, the high energy cost heavily overweighs the benefits of the MSF capacity increase by using NF. The MSF drains these countries energy resources. Building new MSF units should be stopped.

Keywords: MSF; SWRO; Energy cost; Nano-filtration; Energy consumption

1. Introduction

Multi stage flash (MSF) (Fig. 1), is the predominantly used desalting system in the Gulf Co-operation Countries (GCC) to desalt seawater. There is no doubt that MSF is the simplest, easy to operate and maintain, reliable and robust desalting system. The MSF unit capacity is much higher than that of the most used, worldwide, seawater reverse osmosis (SWRO) desalting system. MSF can deal with the worst seawater quality to produce almost pure water. Coupling the MSF units with steam turbines in steam power plants (PP) (Fig. 2), reduces the MSF indirectly used fuel energy to more than 50% of that used when it is directly operated by fuel fired boilers. The same applies when the MSF is combined with heat recovery steam generators HRSG of gas turbine (GT) in GT PP. Consequently, all large MSF units are combined with steam or GT PP. Tables 1a and 1b present examples of the MSF units used in the GCC and in one of the cogeneration power desalting plant (CPDP) in Sabbiya, Kuwait respectively; and show the MSF desalination unit capacity and combinations with combined gas/steam turbines cycle CG-ST or steam turbines power plants PP.

Despite this energy reduction compared to MSF operation with fuel fired boilers, the MSF consumed fuel energy is much more than that of the SWRO system. The MSF is widespread in the GCC due to the low cost of fuel used in calculating the cost of produced electrical energy and desalted water, compared to the international fuel cost. Energy subsidies distort the choice of desalination processes in favor of energy-inefficient technologies.

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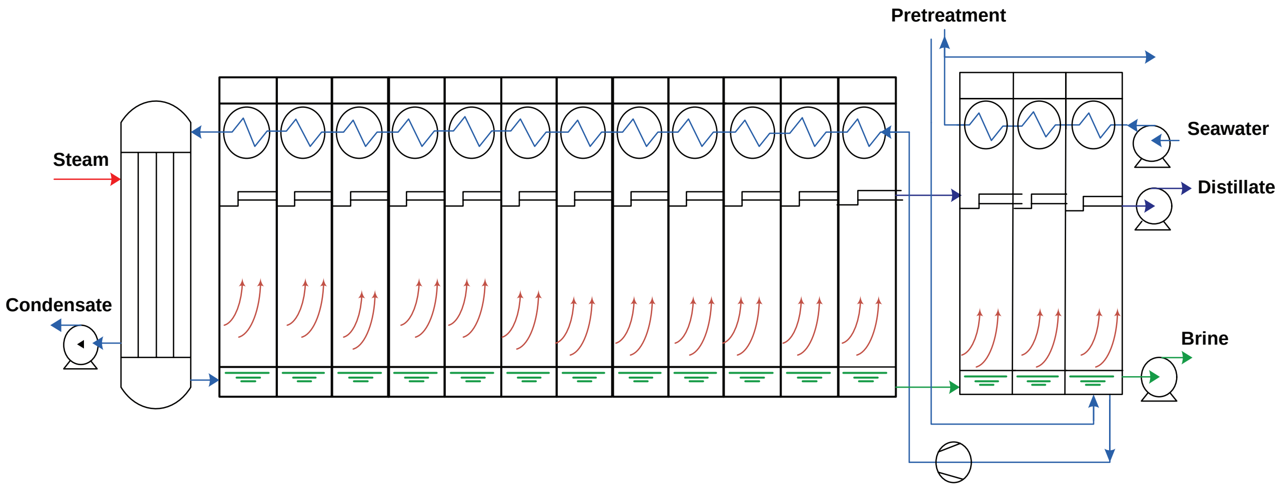

Fig. 1. The multi stage flash MSF desalting system.

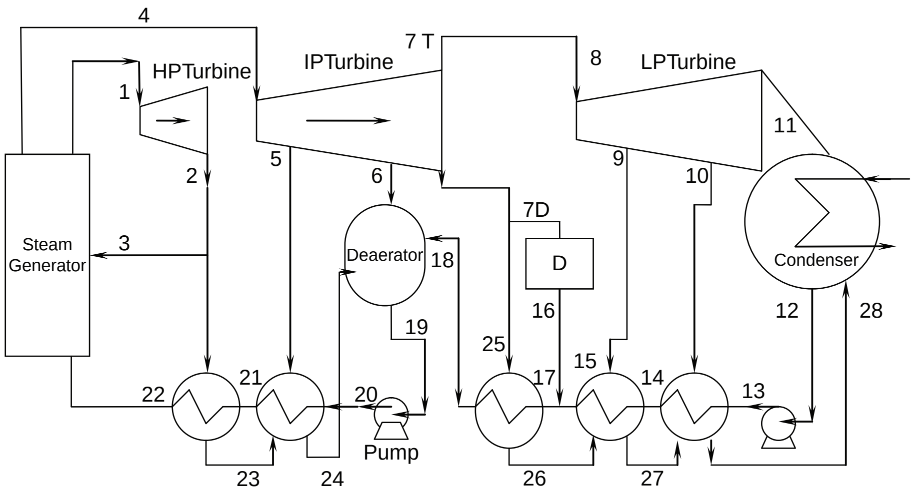

Fig. 2. Arrangement for combining MSF desalting unit with steam turbine in Kuwait.

Table 1a
Some MSF desalination plants in GCC countries

PWR	MW	Power plant	MIGD	Desalination	Year	Contractor	Project
7	656	CG-ST	12.5 × 5/37.5	MSF/RO	2002	Doosan	Al-Fujairah
14	710	CG-ST	12.5 × 4	MSF	2001	Siemens	Al-Taweelah A2
10	720	CG-ST	12.5 × 6	MSF	2004	Siemens	Al-Taweelah B
15	1500	CG-ST	17 × 6	MSF	2002	Siemens	Al-Shuweihat S1
14	850	CG-ST	12.5 × 5	MSF	2000	Hanjung	Umm Al-Nar B
22	880	CG-ST	13.5 × 3	MSF	2003	Fisia Itali.	Jabel Ali K II
5	500	CG-ST	10 × 10	MSF	2003	Doosan	Shuaiba II
2.2	164	BP-ST	10 × 4/36	MSF/RO	2000	NA	Yanbu-Medina

PWR is the power water ratio in MW(e)/MIGD; CG-ST Combined gas turbine steam cycle; BP-ST Back pressure steam turbine cycle.

Table 1b
Commissioning Dates Al Sabbiya

Power units	Commission date	Steam turbine capacity	Distiller	Distillers capacity	Commission date
Unit#1	9/2/1998	300 MW	D 5	12.5	11/8/2006
Unit#2	21/09/1998	300 MW	D 6	12.5	1/10/2006
Unit#3	6/2/1999	300 MW	D 7	12.5	29/10/2006
Unit#4	26/04/1999	300 MW	D 8	12.5	30/11/2006
Unit#5	24/07/1999	300 MW	D 4	12.5	25/05/2007
Unit#6	1/5/2000	300 MW	D 3	12.5	5/7/2007
Unit#7	7/3/2000	300 MW	D 2	12.5	7/9/2007
Unit#8	10/4/2000	300 MW	D 1		25/10/2007

Table 2
Some large SWRO plants around the world

Location, country	Installed/planned capacity, m^3/d	Seawater, mg/l, recovery ratio %	Comments	Ref.
Barcelona, Spain	200,000	Mediterranean, 39,700, (45%)	20% potable water for Barcelona	[1]
Aguilas/Guadalentin, Spain	180,000–210,000	Mediterraenean, 39,700, (45%)	Two output phases, and 2 stages RO	[2]
Palm Jumerah, Dubai, UAE	32,000	Arabian Gulf AG, 45,000, (38%)	Ultra filteration UF pretreatment	[3]
Sidney, Australia	250,000, can extend to 500,000	Ocean water, 35,000 (53.2%)	15% Sydney water demand, $ B1.9 cost, run by renewable energy	[4]
Tenes, Algeria	200,000	Mediterraian, 39,700, (45%)	Very low consumed energy by pressure exchanger	[5]
Perth, Australia	143,000	Ocean 35,407–37,459 %	Powered by wind energy, Perth II use UF pretreatment	[6]
Fujirah, UAE	170,000	Gulf of Oman	–	[7]
Torrevieja, Spain	240,000	–	–	[8]
Mekka region, Barge	2 × 25,000	Red sea	Barge mounted plant	[9]
Hamriyah, Sharjah	90,920	Arabian Gulf 42,000 (40%)	UF used as pretreatment	[10]
Sinspring in Tuas, Singapore	136,000	–	–	[11]
Point Lisas, Trindad	163,410	Ocean, 35,000, (53.2%)	Micro and ultrafiltration were used as pretreatment	[12]
Shuquaiq, Saudi Arabia	216,000	Red sea, 44,000 (36%)	Two pass RO for Boron removal	[13]
Rabeigh, Saudi Arabia	170,000–190,000	Red sea, 41,200 (43% first stage)	Less than 5 mg/l chloride limit, 3 stages RO system	[14]
Tampa, Florida, USA	95,000	Ocean,35,000 (riginal 60%)	Modified after first failure	[15]
Hamma plant, Algiers	200,000	Mediterraian, 39,700, (44%)	25% capital city needs	[16]
Barka phase 2, Oman	120,000	–	–	[17]
Maris Palmachim, Israel	120.000	–	–	[18]
Bajo Almanzora, Spain	60,000	39,700 (44%)	Beachwells	[19]
Valdelentisco, Spain	200,000	Seawater	–	[20]
Ashkelon, Israel	348,000	–	–	[21]

Meanwhile, there are concerns about the reliability of the SWRO feed water pretreatment system, which is site dependent. This should not be an excuse to avoid the SWRO use and development, as the MSF system similarly experienced many failures in its early development.

In the 2009 International Desalination Association (IDA) conference in Dubai, there was no single paper about any new or planned MSF desalting plant anywhere, outside the GCC. It was clear that reverse osmosis is the preferred technology for large brackish and seawater desalting plants.

Examples of large SWRO plants, installed or under installation, reported in IDA 2007 and 2009 conferences are given in Table 2. Some in the GCC are also included.

Table 3
Seawater desalination projects in Southern California [22]

Projected cost of water (US $/m^3)	Target completion date	Intake type	Capacity, m^3/d	Desalination plant/developer
0.7–0.75	2010	Collocated with AES Power plant	200,000	
0.7–0.75	2010	Collocated with Encina Power plant	200,000	
0.85–1	2015	Collocated with Scattergood Power plant	45,000	
0.8–0.9	2012	Collocated with El Segundo Power plant	76,000	
0.9–1.1	2015	Collocated with San Onofre Nuclear PP	95,000	
0.85–0.95	2013	Slant beach well	100,000	
0.75–0.95	2012	Beach well	34,000	

Table 4
Seawater desalination projects in Northern California [22]

Projected cost of water (US $/m^3)	Target completion date	Intake type	Capacity, m^3/d	Desalination plant/developer
0.85–1.2	2011	Unknown May Be Collocated with Mirant Power plant	76,000–303,000	Bay Area Regional Desalination project/ EBMUD, CCWD, SFPUC and SCVWD
0.95–1.15	2010	Collocated with C&H Sugar plant in Crockett	5,700	Low energy application of desalination (LEAD) project/EBMUD
01.1–1.3	2008	Beach Wells	1,000	Sand City Water Supply Project/City of Sand City
0.8–0.9	2012	New Open Surface Intake	38,000–57,000	Sand Rafael Bay Water Seawater Desalination Project/Marin Municipal Water District Monterey Bay Regional

There are 11 desalination plants planned to be installed in California, USA as shown in Tables 3 and 4 [22], 20 plants in Spain, and 4 plants in Algiers. All these plants are seawater reverse osmosis SWRO plants [22].

The main reason that all countries in the world, except the GCC, avoid using MSF is clear, the MSF has too high energy consumption. MSF consumes pumping energy in the range of 4 kWh/m^3 (almost the same total energy consumed by the SWRO) plus thermal energy. This thermal energy is usually in the form of steam, extracted from steam turbines to the MSF units in steam PP. This steam can produce more electric power if not extracted to the MSF units. For example, when a steam turbine in Kuwait's Azzour PP produces 300 MW electric power and supplies 77.22 kg/s of extracted steam to two MSF units producing 14.4 MIGD (757.8 kg/s). the consumed fuel energy is 933.67 MW. When the same turbine produces 300 MW power, and no steam is extracted to the MSF units (a conventional PP), the consumed fuel energy is 811 MW (~0.37 overall efficiency). Hence the consumed fuel energy to produce distilled water of 758 kg/s is 122.6 MW, or 162 MJ fuel energy per 1 m^3 desalted water.

2. Energy consumed by the MSF units

An MSF unit (Fig. 1), consumes both thermal and mechanical energy. The thermal energy (ThE) in the form of moderately low pressure (1–3 bar) steam is usually extracted from steam turbine (Fig. 2). Typical specific consumed heat is in the range of 300 kJ/kg of distilled water. The mechanical (or electrical) energy (ME) consumed by the unit's pumps to move its streams is in the range of 14.4 kJ/kg (4 kWh/m^3). The thermal energy (ThE) is expressed in terms of its equivalent mechanical energy (EMETh) in order to compare the MSF consumed energy with that of mechanically driven desalting systems such as reverse osmosis RO. Wangnick [23] showed that the mechanical energy required to drive the pumping of MSF is 4 kWh/m^3, and that for SWRO is 6 kWh/m^3 (with no energy recovery), and that for multi-effect thermal vapor compression ME-TVC system is 2 kWh/m^3, see Fig. 3. The minimum equivalent mechanical energy to the MSF consumed thermal energy (EMETh) was given as 14 kWh/m^3 (Fig. 4). In Fig. 4, the harmonized energy is related to the (theoretical) production of electrical energy by the steam (used for heating in a

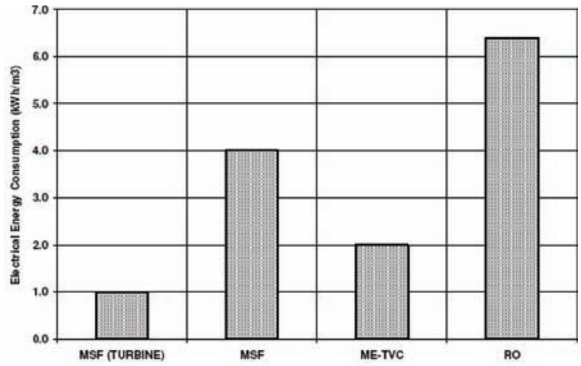

Fig. 3. Consumption of electrical energy by desalination processes [kWh/m^3]; (Turbine) means the drive of the brine recirculation pump is a back-pressure steam turbine [23].

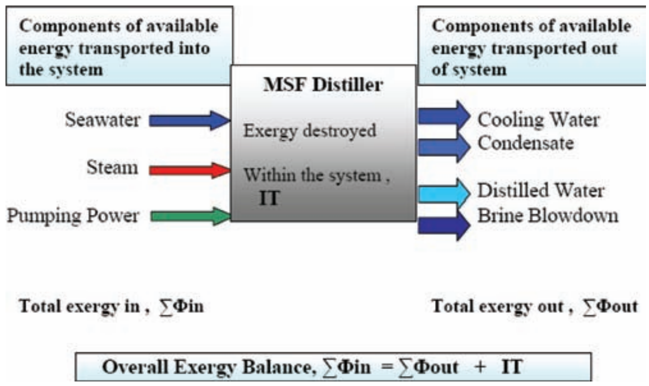

Fig. 5. The overall exergy balance of an MSF distiller [24].

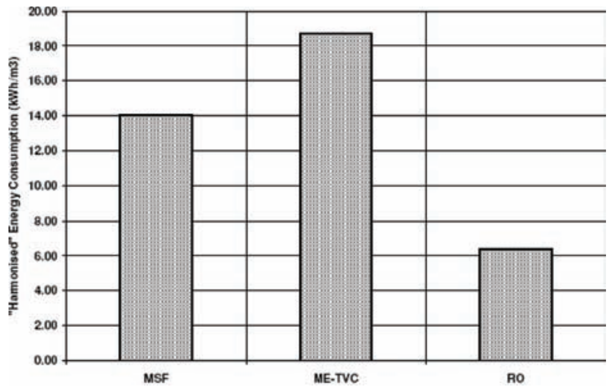

Fig. 4. Harmonized energy consumption of desalination processes [kWh/m^3][23].

thermal plant) in a steam turbine, in order to compare thermal energy with electrical energy, and therefore processes such as RO and MSF [23]. This makes the minimum total consumed equivalent mechanical energy EME by the MSF as 18 kWh/m^3 (14 for ThE and 4 for pumping). This is to be compared with 4 kWh/m^3 total ME consumed by SWRO using energy recovery.

Hamed [24], conducted comprehensive second law thermodynamic analysis to calculate the inherited (exergy loss) irreversibility for some of the MSF units operating in Saudi Arabia. He reported that the total exergy losses are in the range of 15.2 to 23.7 kWh/m^3. These losses are less than the exergy input, and should be supplied by, equivalent mechanical energy (EME) to these units, see Fig. 5.

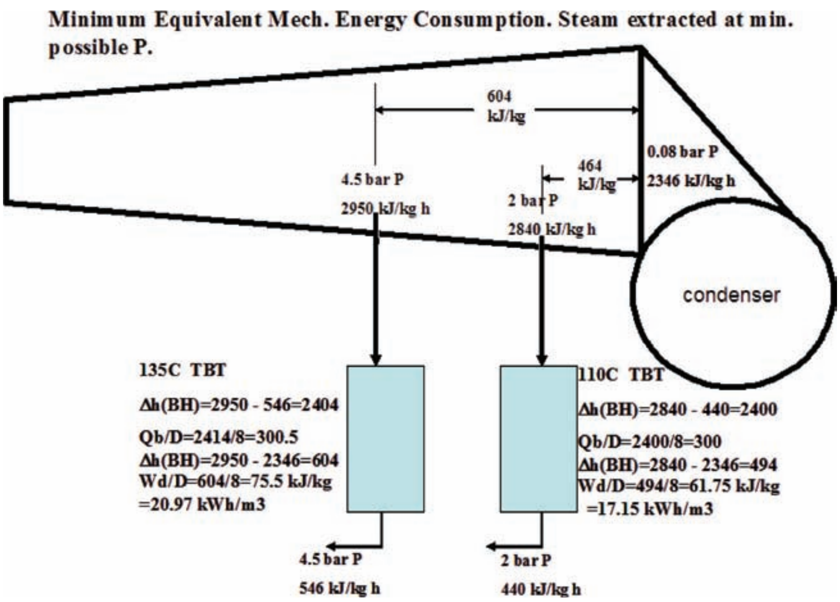

Fig. 6. The enthalpies of steam extracted to the MSF desalting units at different extraction points.

In Kuwait cogeneration power desalting plants (CPDP), if the steam supply to the MSF unit was extracted at 2 bar, the minimum pressure required by an MSF operated with 110 °C top brine temperature TBT, the minimum EMETh can be calculated from the enthalpy difference Δh(T) between the extraction point (2840 kJ/kg) and at condenser inlet (2346 kJ/kg), see Fig. 6. This Δh(T) is the turbine work loss due to extraction of one kg steam to the MSF unit, thus:

Δh(Turbine) = 2840 – 2346 = 494 kJ/kg steam

Since in this plant, each kilogram of steam produces 8 kg distilled water, the minimum turbine loss to produce one kilogram distillate is 494/8 = 61.75 kJ/kg (= 17.15 kWh/m^3 distillate). The ratio of the distillate output D and the supplied steam S, (D/S), is called the gain ratio GR. The enthalpy of the heating steam condesate leaving the MSF unit is 440 kJ/kg, and thus the heating steam enthalpy difference across the MSF unit is Δh_d = 2400 kJ/kg steam, and the specific heat per kg of distillate is Q_b/D = 300 kJ/kg. The pumping energy is 4 kWh/m^3.

Then, the minimum consumed equivalent mechanical (EME) energy is 21.15 kWh/m^3 (17.15 for the thermal energy, and 4 kWh/m^3 for pumping).

This is less than the actual energy consumed by the MSF operating in Kuwait. The pressure of the steam expanded along the turbine decreases as the turbine load decreases. In fact, the steam pressure at the same extraction point to the MSF unit varies from 4.5 to 2 bar as the turbine load decreases from 300 to 80 MW. As example, an MSF unit in Doha West PP is operating with the conditions of 110 °C TBT, 8 gain ratio, 42 °C T_n (brine temperature in the last stage n), and specific thermal energy consumption Q_b/D = 315 MJ/m^3 of distillate product. The $Q_b = S \times \Delta h_d$ is the heat supplied to the brine heater BH, and S is the steam flow rate to the BH in kg/s. The unit consumes 4 kWh/m^3 pumping energy to move its streams. The steam flowing in the extraction-condensing turbine has enthalpy difference Δh(T) between the extraction point to the MSF at 3.5 bar (when turbine load is 225 MW) and the condenser inlet, Δh(T) = 2944 – 2346 = 598 kJ/kg. For 8 gain ratio, the turbine wok loss per kg of distillate output is 598/8 = 74.75 kJ/kg (20.76 kWh/m^3). This is the EMETh to the thermal energy of 315 kJ/kg, or EMETh = 20.76 kWh/m^3.

So, the acual equivalent work EME consumed the MSF unit in Kuwait is 24.76 kWh/m^3 (20.76 for thermal, and 4 for pumping).

3. Availability of the heat consumed by the MSF

More rigorous analysis to count for the (EMETh) consumed by thermal desalting system (here the MSF) is to find the availability (exergy) of the heating steam supplied to the desalters. This represents the theoritical maximum work obtained from this steam if it is supplied to reversible Carnot heat engine cycle. When Carnot cycle receives heat from heat source at T_s (heating steam temperature to the MSF), and rejects heat to heat sink at low temperature T_c, the exergy W_{th}/D of the specific heat supplied to the MSF unit (Q_b/D) is

Table 5
The available energy of the steam supplied to the MSF unit at different TBT

TBT	Ts	Carnot efficiency	Ws of Qb/D
90	97	0.149	44.59
110	117	0.192	57.69
125	132	0.222	66.67
130	137	0.232	69.51
135	142	0.241	72.29
140	147	0.250	75.00

$$W_{th}/D = (Q_b/D)(1 - T_c/T_s)$$

Here $(1 - T_c/T_s)$ is the Carnot cycle efficiency, the heat sink temperature T_c is considered, for practical reasons, the same as the PP condenser, which is almost as T_n (brine temperature of the MSF last stage) = 42 °C = 315K. If saturated steam is supplied to the MSF unit at T_s = 117 °C (390K), 7 °C above TBT, T_c = 315K, then $(1 - T_c/T_s)$ = 19.23%, and theoritical specific avaiable work output W_{th}/D is 57.69 MJ/m^3 (16.03 kWh/m^3) for Q_b/D = 300 MJ/m^3.

It is noted here that the increase of the MSF top brine temperature (TBT) requires the increase of T_s of the heating steam temperature, and its availability, see Table 5. For example if TBT = 135 °C, and T_s = 143 °C (416K), and same T_c = 42 °C, and Q_b/D = 300 MJ/m^3, the W_{th} = 72.84 MJ/m^3 (20.23 kW/m^3). So, the EME is 24.23 kWh/m^3.

4. Energy consumption in terms of money

The gravity of the high consumed energy in MSF is felt by this energy cost and its impact on environment. In Kuwait, the daily (and annual) production of distilled water in 2008 was 1.5 Mm^3/d, (or 550 Mm^3/y). The 2008 equivalent mechanical energy (EME) energy cost to produce this 550 Mm^3/y distillate by the MSF can be simply calculated as:

550 Mm^3 × 24.23 kWh/m^3 = 13,326.5 GWh

Fuel energy consumed to produce this energy by an efficient PP of 0.36 efficiency (i.e. each GWh is produced by 10,000 GJ fuel energy) is 133.265 million GJ (MGJ). This is equivalent to 21.847 million barrels (Mbbl) of oil, which cost \$1,529.3M if the cost/bbl is \$70. This \$1,529.3M is only the fuel energy cost and the electrical

Table 6
Comparison of the parameters affecting the environment for both MSF and SWRO systems, and their numeric values when 550 Mm^3 are produced

	MSF	Mm^3/y	SWRO	Mm^3/y
Relative flow rate through intake	7 P	3850	3 P	1650
Relative flow rate through outfall	6 P	3300	2 P	1100
Brine salinity relative to seawater salinity	1.5		1.5	
Relative salinity in outfall	1.2		1.5	
Temperature relative to seawater in outfall	Same + 11.2 °C		Same + 1.2C	
Heat rejected $/m^3$ to sea	(6/7)(300 + 14.4) MJ		(2/3)14.4 MJ	
Heat rejected due to desalting 550 Mm^3	148.33 MGJ		5.28 MGJ	

Table 7
Comparison of the parameters involved in the 2008 desalted water production of 550 Mm^3/y and hypothesis if SWRO was used to produce the same quantity

Parameter	MSF	SWRO
Specific energy consumption, kWh/m^3	24.23	4
Total mechanical energy consumption, GWh	13,327	2,200
Consumed fuel energy, MGJ	133.3	22
Consumed fuel, Mbbl	21.85	3.6
Consumed fuel cost, $ M	1529	252.5
Consumed energy cost, $ M	2185	260.7
Produced CO_2, in million ton	9.7	1.603
Produced NO_2, in 1000 ton	29.97	4.9
Produced SO_2, in 1000 ton	194.59	32.0

energy EE (or EME) cost becomes $M 2185 if the fuel cost is 70% of the EME cost.

Now, suppose the same desalted water of 550 Mm^3 were produced by SWRO system with specific consumed EME of 4 kWh/m^3, the total EME: 2200 GWh, consumed fuel energy is 22 MGJ (3.6 Mbbl). The fuel cost would be $252.5M, and the EME cost $360.7M. Hence the energy cost of the SWRO is approximately equal to 1/6 of the MSF energy cost. Table 6 shows a comparison between the parameters involved in the production of 550 Mm^3 in 2008, by both MSF and SWRO systems. The consumed fuel energy is associated with polluted gas emission such as NO_2 and SO_2, and greenhouse gas emission (GHG) of CO_2 and NO_2 due to fossil fuel combustion is shown in Table 7.

5. The MSF and SWRO impact on environment

Both the MSF and SWRO have negative impact on the environment; with more severe impact of MSF compared to that of SWRO. This is shown by calculating the parameters affecting the environment for the case of producing 550 Mm^3 distillate in 2008 by the MSF and SWRO systems. Fossil fuel (mainly heavy oil and a small percentage of natural gas) is used by the CPDP to produce the EME required for operation of both desalting systems. The fuel oil combustion leads to emission of CO_2, CO, NO_x (mainly NO and NO_2) and SO_2. While CO_2 and NO_2 are (GHG) causing global warming, the CO, NO_x, and SO_2 gases are air polluting gases. In calculations of the emitted gases, it was assumed that heavy oil is used with typical 41,200 kJ/kg calorific value, and typical mass percentage content of 87.4% carbon C, 3.2% sulfur, 8.9% hydrogen, 0.3% nitrogen, 0.01% ash, and the mass of one bbl is 139 kg [25]. The emitted NO_x per million British thermal units (MBtu) is assumed to be equal to 0.5 lb/Mbtu (typical value for NO_x emitted in steam generators with no NO_x control). Hence the emission due to burning one barrel of oil is calculated as 445.45 kg/bbl CO_2, 1.37 kg/bbl NO_2, 8.896 kg/bbl SO_2 and the calculated emitted gases due to desalting 550 Mm^3 in 2008 by the MSF system are 9.732 million tons (M ton) CO_2, 29.97 thousand tons of NO_2, and 194.59 thousand tons of SO_2. If the SWRO was used to desalt the 550 Mm^3 produced in 2008, the emitted gases would have been equal to 1.423 M-ton CO_2, 4.948×10^3 tons NO_2 and 32.124×10^3 tons SO_2. The gases negatively affecting the air environment in both cases are given in Table 7. The gases emitted in the case of MSF system are more than 6 times those of the SWRO case.

Desalting seawater by either MSF and SWRO systems badly affects marine environment due to their discharge of high salinity brine with chemicals used for pre-treating the feed water to these plants; and at higher seawater temperature in case of the MSF. When both systems have the same recovery ratio of the make up water, say 1/3, or 1 m^3 product (P) is produced from 3 m^3 feed water (F), it is noted that:

1. The SWRO, the seawater intake to the plant is the same as the make up water F, 3 m^3 for each 1 m^3 P, and brine B rejected through the outfall is of 2 m^3 for each 1 m^3 P, at almost the same seawater temperature, but with high salinity equal to 1 ½ times the seawater salinity.

2. In the MSF system, the make up water F (3 m^3 for each 1 m^3 P) is only a part of the intake seawater supply to the heat rejection section as cooling water M_c (M_c is in the range of 7 m^3 for each 1 m^3 P). So, the intake to the MSF is more than double that of SWRO plant. Part of M_c (after being heated) is treated to become the makeup F (3 m^3 for each 1m^3 P). The balance (M_c – F), 4 m^3 for each 1m^3 P, is discharged back to the sea through the outfall, say at 10°C higher than seawater temperature and same seawater salinity. As part of F becomes the distillate D, the balance is the brine B (2 m^3 for each 1 m^3 P) rejected back to sea through the outfall. The rejected brine B has, say at 10 °C higher than seawater temperature and 1½ seawater salinity. So, the MSF outfall flow rate is 6 times that of the distillate and at 10°C higher than that of the seawater. So, the outfall for the MSF is about 3 times more than the SWRO outfall. In the MSF, the brine B and returning part cooling seawater (M_c – F) are mixed in the outfall. This reduces the rejected mixture salinity to about 1.2 seawater salinity compared that of 1½ in the SWRO. The high flow rates of seawater intake in MSF case (as compared to the SWRO intake) intensify the negative effect on marine species by impingement; increase the chlorine discharge due to chlorination of seawater at the intake, and its overall negative effect on marine life. The gravity of high seawater intake and discharge in the case of MSF can be shown for year 2008 by the intake of 3,850 Mm^3 (44,000 m^3/h), and discharge of 3300 Mm^3 (377,000 m^3/h) at 11.2°C higher than seawater temperature. The heat rejected to sea in case of MSF is 148 MGJ, almost 50 times that in the SWRO case.
3. The energy consumed by both processes is rejected back to the sea. The pumping energy for each process is 4 kWh/m3 (14.4 MJ/m3). The thermal energy to the MSF is in the range of 300 MJ/m3 and zero for SWRO system.
4. Both systems use anti-scalants and chlorination for pretreatment which have negative effects on marine species.

6. Prospect of improving the MSF system by NF pretreatment

A relatively new MSF improvement was suggested to pre-treat the MSF feed water, fully or partially by nano-filtration, e.g. [26–33] to remove some of its scale constituents such as sulphate, calcium, carbonate and magnesium. This allows an increase in its TBT, To, and its flashing range (To – Tn), and thus the unit output, (proportional to (To – Tn)). The NF is also sometimes used as SWRO pretreatment to remove scale consituents

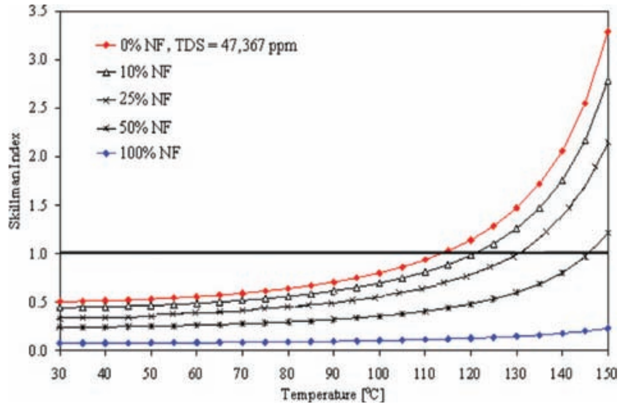

Fig. 7. Influence of NF on sulfate scale potential in BR-MSF plant.

and raise its recovery ratio. The use of NF pretreatment for both systems was suggested and extensively studied in Saudi Arabia. Similarly related work was presented by Awerbuch [32] showing the benefit of using NF membranes in the removal of scale elements from seawater. He suggested that using NF permeate and seawater as a mixture feed (partial feed pretreatment) to thermal process would reduce the cost of NF pretreatment. Al-Rawajfah et al. [26] reported influence of NF on sulfate scale potential in recirculation-MSF plant (Fig. 7).

This figure shows the sulfate scale potential, expressed by Skillman index (SI), for seawater with 0, 10, 30, 50 and 100% NF-treated make-up in a recirculation MSF reference plant. SI is a simple sulfate solubility index for estimating the likelihood of calcium sulfate scaling. SI is a ratio between the actual concentration of either calcium or sulfate and its theoretical or equilibrium concentration whichever is the limiting species, [34]. The Skillman index was first published in [35].

The scale potential increases with increasing the TBT and decreasing the percentage of NF-treated feed. For seawater with no NF feed pretreatment, the scale can start deposit at 115°C. The maximum top brine temperature (TBT), at which sulfate scale begins to precipitate, is shifted to 120, 135 and 145°C when the NF-treated portion of the make up water increased from 10, 25 and 50%, respectively. Combination of the MSF unit with NF pretreatment is not at free cost as shown in the following section.

6.1. Modification required to combine the MSF unit with NF to increase its capacity

The maximum daily consumption of distillate water is equal (or oven little higher) than the installed desalting capacity in Kuwait. So, there is definitely a need to increase the installed capacity. The MSF modifications to raise its TBT and thus its capacity by using NF is a viable solution that has already been put into practice in Sharjah, UAE. This requires the following:

1. The NF feed requires the same stringent pretreatment system of the SWRO system, besides adding the NF membranes system with its pumps. This eliminates the MSF main advantage of having very simple pretreatment.
2. The MSF unit also has to be modified to deal with the anticipated production increase. This includes increasing the recirculation stream flow rate and its delivery pressure, adjusting the weirs between stages, raising the saturation temperature of the steam supplied, dealing with the increasing vapor generated in stages especially the last stages.
3. The increase of generated vapor in a stage without the ability to condense it completely can build higher pressure in the stage, decreases the flashing brine flow, and resulted in capacity decrease instead of increase. Venting system should be modified, and the heat transfer areas should be checThe increase of vapor velocity in any stage increases the entrained brine droplets with the generated vapor and deteriorates the product quality. So, the demisters should be modified to increase their areas and efficiency.

The improvement of the MSF system by increasing its TBT through NF pretreatment is discussed here through an example. If any of the 7.2 MIGD capacity MSF unit operating in Kuwait is modified to operate with NF as pretreatment to 30% of its feed, its TBT can be raised to 135 °C. Then distillate output is expected to increase 35%, from 7.2 to 9.72 MIGD, or 2.52 MIGD increase. The required capacity increase can be achieved, everywhere nowadays, by adding SWRO system of the needed capacity increase. The case of 2.52 MIGD capacity increase by modifying an MSF is compared by adding SWRO system of same increased capacity (2.52 MIGD). These two systems are compared here if both are operated with capacity factor CF equal to 0.9.

The MSF modification to raise its capacity by NF is justified if its modifications cost plus the cost of NF treatment costs are less than the cost of another desalting system (SWRO or multi effect MED or MSF) of same added capacity. The cost of desalting systems in $/(m^3/d)$ are in the range of: $800, 900, and $1000/(m^3/d)$ for SWRO, MED, and MSF respectively [36]. The cost of adding SWRO of 2.52 MIGD (or 11.456×10^3 m^3/d), is in the range of $ 8.95M.

Raising the MSF unit TBT from 110 to 135 °C should increase its output (proportional to the flashing range, (TBT − T_n)), 35% output increase, i.e from 7.2 to 9.72 MIGD, 2.52 MIGD capacity increase. The steam supply to the MSF unit should have increased saturation temperature from 117 to 143 °C.

The plant gain ratio GR (D/S) is going to remain almost the same. The GR depends on the number of stages, and heat transfer areas of the stages condensers, and expressed, (when the steam is supplied as saturated vapor and leaves as saturated liquid) by:

$$D/S_d = \eta(L_s/L)(\mathrm{TBT} - T_n)/(\mathrm{TBT} - t_1) = \eta(L_s/L)(1 - D/2\mathrm{R})[\mathrm{n}\Delta T/[\Delta T + (T_1 - t_1)]$$

The terms given in this equation represent: D distillate output, S_d steam supplied, η the efficiency of the BH (heat gain/heat added) and has typical value of 0.99, L_s latent heat of the steam, L average latent of vapor generated in the MSF unit, T_n is vapor saturation temperature in the last stage, t_1 brine temperature leaving the 1st recovery stage to the BH, n number of stages, ΔT is the temperature difference across the stage, and R is the recirculation flow.

Although Q_b/D in the case of TBT =135 °C is almost the same as the case of TBT = 110 °C The availability of the heat supplied at TBT = 135 °C is 20.23 kWh/m^3, which is higher than that at TBT=110 °C (16.03 kWh/m^3).

More mechanical energy is consumed by pumping 30% of the feed F, through the NF system. The feed to the MSF unit F is in the range of 3 times the desalted water output D, and if 30% of this feed is pretreated by NF, then 0.9 m^3 will be pumped to the NF unit for each m^3 distilled water. The reported feed pressure to the NF membrane is 20 bar. Then, the specific pumping energy (per 1 m^3 of distilled water) consumed by NF for pumping efficiency of 0.8 is:

$$W_p\,(\mathrm{NF}) = 0.9 \times 2000/0.8 = 2250\ \mathrm{kJ/m^3}\ (0.625\ \mathrm{kWh/m^3}).$$

Then pumping energy increases from 4 to 4.625 kWh/m^3 to count for the NF pumping energy.

The minimum specific mechanical energy for the modified case is 25.595 (20.97 for heat and 4.625 for pumping).

6.2. Comparison of raising the MSF capacity by NF and by installing SWRO system

Case 1: Using SWRO system to augment the existing MSF.

The unmodified 7.2 MIGD MSF unit will produce 10.75 Mm^3/y (if CF = 0.9), and consumes 227.4 GWh (based on 21.15 kWh/m^3) EME energy. The 2.52 MIGD (11.46×10^3 m^3/d) SWRO system can produce 3.76 Mm^3/y (CF = 09), and consumes 15.05 GWh (based on 4 kWh/m^3). This gives total consumed electric energy of 242.5 GWh, consumed fuel energy of 2.42 MGJ (0.3975

Table 8
Cost comparisons for Case 1 and Case 2

Parameter	SWRO + MSF at TBT = 110 °C	Modified MSF for TBT = 135 °C
Ts	117 °C	143 °C
Qb/D kJ/kg	300	300
EMEth	17.15	20.97
W(pump)	4	4.6
EME	21.15	25.6
D MIGD	2.52 + 7.2	9.7
Fuel energy cost, $M/y	27.823	42.6
Cost of adding SWRO, $M	9.165	0
Cost of modifying MSF	0	3 (assumed)
Consumed EE cost, $M/y	39.75	60.94
First year cost, $M	48.915	63.49
Second year cost, $M	39.75	60.94

Mbbl) based on 10,000 kJ/kWh heat rate, and fuel cost of $27.8M. When the fuel cost represents 70% of electrical energy cost, the later cost is $39.75M. The capital cost of the SWRO system is in the range of $800/(m^3/d), and the SWRO of 2.52 MIGD will cost $$ M 9.165.

Case 2: Modifying the MSF unit by raising its TBT from 110 to 135 °C to produce 9.72 MIGD (14.515 Mm^3/y). In this case the consumed EE is 371.51 GWh (25.595 kWh/m^3), consumed fuel energy is 3.7151 MGJ (0.609 Mbbl), costing $ 42.632M, and electric energy cost is $60.904M.

The annual consumed electric energy in case 2 is (371.51 – 242.455) 129.055 GWh more than case 1, and its electric energy cost is $ M21.154 more than case 1. So, adding an SWRO train to produce 2.52 MIGD to the existing MSF without modifications will save electric energy cost almost 3 times the cost of adding the SWRO unit.

Table 8 shows the first year cost for case 1 (including the energy cost and adding SWRO) is only $ M48.9, and for case 2 (including energy cost and MSF modification) is $ M63.94. In the consequent years, the added capital cost can be neglected, and the energy cost for case 1 is 39.75, while that for case 2 is $M60.94.

7. Conclusion

Kuwait and the GCC should stop installing any new MSF units, as they consume much more energy (at least 5 times) than that consumed by the SWRO system. There is no waste or cheap heat source as claimed. The MSF system drains much of the energy resources. Meanwhile, the improvements of the MSF to raise its capacity or for better performance do not solve the real problem of very high energy consumption.

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