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Desalination experience in Kuwait

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Abstract

This paper evaluates the desalination experience in Kuwait. Review of the desalination data in Kuwait shows that the multistage flashing (MSF) process dominated and remains to dominate the desalination market in Kuwait. The start in the 1960s included small MSF units, each with a capacity of 454.6 m^3/d (0.1 MIGD). In 2006/2007, eight MSF plants each with a capacity of 56,826 m^3/d (12.5 MIGD) will be commissioned. This will increase the total MSF capacity in Kuwait to 1.92×10^6 m^3/d (423 MIGD). Review of MSF progress and developments in its design features are discussed. The review shows that several of the old units build in the 1970s have been refurbished (instead of being demolished). These units are expected to continue operation for the next 10 years. In addition, careful selection and modification of the construction materials have been implemented in various parts of the plant. This has resulted in selection of materials with higher resistance to corrosion and erosion. A simple model is developed for system design and performance evaluation. The model predictions are validated against field data of existing units. Model results are well within known values for various design parameters that include stage dimensions, performance ratio, heat transfer area, and flow rates of various stream. The current desalination status in Kuwait indicates that the MSF would remain to dominate the desalination industry in Kuwait for the next two to three decades.

Keywords: Seawater desalination; Multistage flashing; Modeling

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1. Introduction

The desalination industry started during the early part of the 20th century with few small capacity units that had submerged tube evaporators. This design had inefficient operational features that required continuous cleaning of the tubes. Rapid growth in the desalination industry occurred during the 1960s. Since then, water desalination provided a sustainable and reliable source of fresh water. In arid areas such as the Gulf States, Mediterranean and Caribbean islands, water desalination is the main source of fresh water. Other alternatives of water transportation are proved to be less reliable, more expensive, and insufficient.

The MSF process was designed in the late 1950s; however, the first installation was not made until the 1960s. During the same period, several desalination technologies did emerge; however, few of these technologies remain to be found on the market. These technologies include RO, MED, and electrodialysis (which is only used for brackish water desalination). The MSF process remains to have a sizeable share of the seawater desalination market, which is close to 50%. The MSF process is found in several countries around the world, including the Gulf States, the Caribbean islands, Italy, Spain, Cyprus, and Malta.

The success of MSF is mainly due to its simple layout and reliable performance over the years. Although the MSF process as well as the MED process consumes a larger amount of energy than the RO process, about 18 kWh/m^3 for MSF, 15 kWh for MED, and 5 kWh/m^3 for RO, the reliable performance of the thermal desalination processes MSF and MED made highly competitive against the RO process. Recent reports on unit product cost [1] show that the unit product cost for the three processes is almost the same — \$0.5/m^3. In addition, previous literature reports [2–4] show that MSF plant life has exceeded 20–30 years. Several old units installed in the 1970s and 1980s remain in operation and have been rehabilitated to continue operation for the next 10–20 years. This further reduces the unit product cost, taking into consideration that plant capital may account for 30–40% of the unit product cost.

At present the large MSF units with production capacity that ranges between 50,000–75,000 m^3/d are being installed in several countries including Kuwait, Saudi Arabia, and United Arab Emirates. The large increase in unit capacity contributes further to reduction in the unit product cost.

The following sections give a review of progress and developments in the MSF industry in Kuwait. Also, a mathematical model is developed for design and analysis of large scale MSF units. The model predictions are validated against the design data for a number of existing MSF units. Finally, discussion is presented of the future outlook for the MSF industry in Kuwait.

2. Progress of the MSF desalination industry in Kuwait

Progress of the MSF desalination industry was the topic in a number of previous publications [5,6]. The study by Al-Zubaidi [5] in 1987 reviewed the MSF desalination experience in Kuwait since the mid-1950s. The study by Al-Zubaidi [5] was motivated by the large-scale MSF installations in the Doha East and Doha West stations. At that time, both stations were considered to be the largest desalination plants in the world. Ten years later, a second review of the MSF desalination industry in Kuwait [6] showed that most of the older and smaller MSF units constructed in 1960s were demolished. The study by Al-Shuaib et al. [6] was motivated by construction of 16 MSF units, each with a capacity of 32,732 m^3/d (7.2 MIGD) in the Az-Zour South Station in Kuwait.

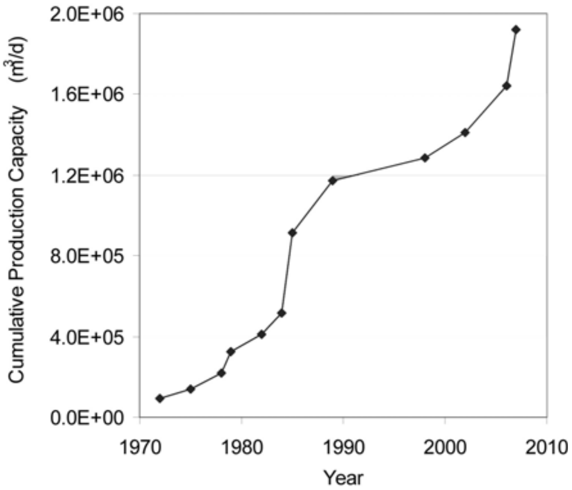

Fig. 1. Cumulative production capacity of MSF plants in Kuwait.

An update for the progress of the MSF desalination industry is summarized in Fig. 1 and Tables 1 and 2. The data shown in Fig. 1 are for existing units. Data for demolished units are given in Table 3. As is shown in Fig. 1, by 2007, the production MSF production capacity will reach more than 1.92×10^6 m^3/d (423 MIGD).

The MSF progress data given in Tables 1 and 2 are summarized below:

- In the early 1970s, the MSF total production capacity was slightly above 90,920 m^3/d (20 MIGD). By 1980, this value increased to 318,220 m^3/d (70 MIGD). A decade later, more than a threefold increase occurred and the production capacity increased to 1.17×10^6 m^3/d (258 MIGD). This expansion continues and it is estimated to reach 1.92×10^6 (423 MIGD) in 2007.
- The unit capacity experienced drastic increase over the years. As shown in Table 1, the very first units installed in 1960 had a production capacity of 4546 m^3/d (1 MIGD). The unit production capacity was then doubled in 1968 to reach a value of 9092.2 m3/d (2 MIGD). Two years later, in 1970, another doubling occurred in the unit production capacity to reach 18,184 m^3/d (4 MIGD). Subsequently, and in 1971, the unit capacity increased to 22,730 m^3/d (5 MIGD). By the end of the 1970s, the well known 27,276.6 m^3/d (6 MIGD) unit was constructed.
- The 6 MIGD unit capacity was slightly increased in 1984/1985 to 7.2 MIGD by increasing the top brine temperature to 110°C.
- The 6 MIDG and 7.2 MIGD units dominated the MSF market through the period from 1980 until the end of the 1990s. However, in 1996, an MSF unit with a capacity of 57,735 m^3/d was commissioned in the UAE. Further enlargement in the MSF unit capacity occurred in 2004 when a unit with a capacity of 77,000 m^3/d was commissioned in Shuweihat, UAE. Reliable performance of these large units has resulted in construction of eight MSF units, each with a capacity of 56,826 m^3/d (12.5 MIGD) in Sabiya, Kuwait. These units will be commissioned in 2006/ 2007.
- Progress in the MSF process has also occurred in its performance ratio where the performance ratio of the earlier units was limited to values below 5. The performance ratio was increased to a value of 8 in 1968. Since then the performance ratio increased slightly to higher values of 8.65 and up to 10.
- Use of motor-driven and large-capacity pumps instead of turbine-driven pumps occurred at an early stage of MSF development. This feature has improved system operation and maintenance since pumps are known to cause major breakdowns during operation [7].
- Careful review of the data shown in Table 2 indicates an increase in the use of either solid stainless steel or carbon steel plates cladded with stainless steel. These materials have been used for various parts within the system including evaporator shell plates, partition plates, ceiling plates, and tube support plates.
- Copper nickel alloys (Cu-Ni 70-30) tubes

Table 1
Progress of the MSF industry in Kuwait

Year	Number of units	Unit capacity, m^3/d (migd)	Total capacity, m^3/d (migd)	Type	*n*	*PR*	Location	Status	Manufacturer
1953	10	454.6 (0.1)	4,546 (1)	Submerged tube	4	2.5–3.1	Shuwaikh	D	Westinghouse, USA
1954/1955	10	454.6 (0.1)	4,546 (1)	Submerged tube	4	2.5–3.1	Shuwaikh	D	Westinghouse, USA
1959	4	2,273 (0.5)	9,092 (2)	Flash evaporator	4	3.3	Shuwaikh	D	Westinghouse, USA
1960	2	4,546 (1)	9,092 (2)	MSF	30	5.6	Shuwaikh	D	Weirwestgarth, GB
1965	2	4,546 (1)	9,092 (2)	MSF	30	8	Shuwaikh	D	Weirwestgarth, GB
1965	3	4,546 (1)	13,638 (3)	MSF	30	7.65	Shuaiba North	D	Weirwestgarth, GB
1968	2	9,092 (2)	18,184 (4)	MSF	24	8.33	Shuwaikh	D	Westinghouse, USA
1968	2	9,092 (2)	18,184 (4)	MSF	25	8	Shuwaikh	D	IHI, Japan
1968	1	9,092 (2)	9,092 (2)	MSF	24	8	Shuaiba North	D	Westinghouse, USA
1968	2	9,092 (2)	18,184 (4)	MSF	25	8	Shuaiba North	D	IHI, Japan
1970	1	18,184 (4)	18,184 (4)	MSF	26	8	Shuwaikh	D	IHI, Japan
1971	1	22,730 (5)	22,730 (5)	MSF	25	8	Shuaiba North	D	Alsthom, France
1971/1972	4	22,730 (5)	90,920 (20)	MSF	25	8	Shuaiba South	O	Alsthom, France
1975	2	22,730 (5)	45,460 (10)	MSF	26	8	Shuaiba South	O	IHI, Japan
1978	3	27,276 (6)	81,828 (18)	MSF	26	8	Doha East	O	IHI, Japan
1979	4	27,276 (6)	109,104 (24)	MSF	26	8	Doha East	O	IHI, Japan
1982	3	27,276 (6)	81,828 (18)	MSF	24	8	Shuwaikh	O	Hitachi, Japan
1985	1	4,546 (1)	4,546 (!)	MSF	28	10	Doha East	S	Reggina, Italy
1984	4	27,276 (6)	109,104 (24)	MSF	24	8	Doha West	O	Reggina, Italy
1985	12	32,731.2 (7.2)	392,774.4 (86.4)	MSF	24	8.65	Doha West	O	Sasakura, Japan
1989	8	32,731.2 (7.2)	261,849.6 (57.6)	MSF	24	8	Az-Zour South	O	Sasakura, Japan
1998	4	27,276 (6)	109,104 (24)	MSF	24	8.65	Az-Zour South	O	Mitsubishi, Japan
2001/2002	4	32,731.2 (7.2)	130,924.8 (28.8)	MSF	24	8.8	Az-Zour South	O	DHIC, Korea
2006/2007	4	56,825 (12.5)	227,300 (50)	MSF	23	9.5	Sabiya	UC	DHIC, Korea
2007	4	56,825 (12.5)	227,300 (50)	MSF	23	9.5	Sabiya	UC	DHIC, Korea

D, demolished; O, operational; S, out of service; UC, under construction.

Table 2
Progress of the MSF desalination industry in Kuwait

Year	Description
1953	First multi-effect submerged-tube type distillation plant was installed in Shuwaikh station. The station included 10 units each with a capacity of 454.6 m^3/d (0.1 MIGD). These units have been demolished.
1957/1958	Construction of the first flash type distillation plant in Shuwaikh station. The installation included four units each with a capacity of 2,273 m^3/d (0.5 MIGD). System features included Installation of stainless steel demisters in stages to reduce carry over of brine droplet in the distillate vapor. This resulted in good control over the product salinity and maintaining it values below 30 ppm. Installation of a strainer for the feed seawater makes up to reduce fouling and tube clogging in the condenser tubes in the heat recovery section and the brine heater by debris from the sea. These units have been demolished.
1960	Installation of two MSF units in Shuwaikh station, worlds first MSF desalination plant, each with a capacity of 4,546 m^3/d (1 MIGD). The new units had a performance ratio of 5.6. The system included a single input/single output controller on the heating steam flow rate. The controller measured the temperature of the outlet brine stream from the brine heater. This improved system operation and maintained the outlet temperature at the desired value to maintain constant production capacity. These units have been demolished.
1965	Installation of two MSF units in Shuwaikh station each with a capacity of 4,546 m^3/d (1 MIGD). The new units had a performance ratio of 8. The tube material in the first and second stages in the heat recovery section were made of 70/30 Cu/Ni alloy. The tubes in all other stages were made of aluminum brass tubes. The intake seawater temperature was controlled by mixing with part of the outlet cooling seawater. The entire system had a remote control room. Brine blow down flow rate was controlled with the brine level in the last stage. This prevented reduction in the brine level in the last stage, which may result in vapor flow through across the stages. These units have been demolished.
1965	Installation of three MSF units in Shuaiba North station each with a capacity of 4,546 m^3/d (1 MIGD). The new units had similar features to those installed in Shuwaikh in the same year.
1968	Installation of four MSF units in Shuwaikh station each with a capacity of 9,092 m^3/d (2 MIGD). The new units had a performance ratio of 8. The flow rate of the seawater make up stream to the last stage was controlled by the salinity of the brine recycle stream. Increase in the feed seawater makeup would result in reduction of the conversion ratio; while, its decrease would result in increase in the brine recycle salinity. These units have been demolished.
1968	Installation of three MSF units in Shuaiba North station with a unit capacity of 9,092 m^3/d (2 MIGD). The units had the same characteristics as those installed in Shuwaikh in the same year. These units have been demolished.
1970	Installation of one MSF unit in Shuwaikh station with a capacity of 18,184 m^3/d (4 MIGD). The main achievement in this new installation was to double the production capacity. These units have been demolished.
1971	Installation of one MSF unit in Shuaiba North station with a capacity of 22,730 m^3/d (5 MIGD) and four MSF units in Shuaiba South Station. The main achievement in these new installations is the increase in the unit production capacity by 25%. The system had two methods for brine blow down, the first through the use of the brine blow down pump and the second by a discharge line installed on the brine recirculation line. Previous installation had brine blow down through the brine circulation discharge line. Installation of the pump gives better control on the system performance. Another new system feature was the use of pumps driven by electric motors instead of turbines. Also, stainless steel was used to construct distillate trays in stages 1–4, distillate ducts in all stages, distillate box in the last stage, and distillate pumps suction piping. The Shuaiba North unit was demolished, while the Shuaiba South units remain operational.

Table 2, continued

Year	Description
1975	Installation of two MSF unit in in Shuaiba South Station with a capacity of 22,730 m^3/d (5 MIGD). The units had the same characteristics as those installed previously installed in 1971 in Shuaiba South station. These units remain operational. Refurbishment of the Shuaiba south units was started in 2005. This will extend the life of the units for an additional 10 years. Also the unit capacity is increased from 5 MIGD to 6 MIGD. This is achieved by increasing the top brine temperature to 110 ºC.
1978/1979	Installation of seven MSF units in Doha East Station with a capacity of 27,276 m^3/d (6 MIGD). The main achievement is the increase in the unit capacity to 27,276 m^3/d (6 MIGD), which remained to be the standard unit capacity for all MSF installations over the next 15 years. These units remain operational.
1982	Installation of three MSF units in Shuwaikh Station with a capacity of 27,276 m^3/d (6 MIGD). These units remain operational. The units have been converted to operate at a higher top brine temperature of 110°C, in 2005. This has resulted in the increase in the total production capacity of the station to 19.5 MIGD instead of 18 MIGD.
1983/1984	Installation of four MSF units in Doha West Station with a capacity of 27,276 m^3/d (6 MIGD). For the first time in Kuwait, these units utilized the on-line ball cleaning system. These units remain operational.
1984/1985	Installation of 12 MSF units with a maximum capacity of 32,731.2 m^3/d (7.2 MIGD). A new feature in these units is the increase in the top brine temperature to 110°C in the units with the 32,731.2 m^3/d capacity. This has resulted in the increase in the performance ratio to 8.65. Also, the units utilized new antiscalent polymer to withstand the high temperature. Similarly, stainless steel cladding is used to protect the plates in stages 1–6 and 24. Also, the ceiling plates in stages 1–12 were made of carbon steel and cladded with stainless steel. The water boxes in stages 1–5 was made of carbon steel and cladded with 90/10 Cu/Ni alloy.
1985	An experimental MSF unit with a capacity of 4,546 m^3/d (1 MIGD) was installed in Doha East Station. The unit is designed to operate at top brine temperature of 138°C and a performance ratio of 10. The unit is out of service.
1988/1989	Eight MSF units each with a capacity of 32,731.2 m^3/d (7.2 MIGD) are installed in Az-Zour south Station. The units had a stainless steel bottom for stages 1–12, which is the roof of the lower stages. The boxes for the brine blow down outlet and the brine recirculation are made of carbon steel cladded with stainless steel. A distributed control system is used together with a back-up analogue control unit. The system included a CO^2 supply system for product recarbonation.
1998	Four MSF units each with a capacity of 27,276 m^3/d (6 MIGD) are installed in Az-Zour south Station. The units had titanium tubing for the heat rejection stages and the brine heater. The system included self cleaning filter for the feed seawater.
2001/2002	Four MSF units each with a capacity of 32,731.2 m^3/d (7.2 MIGD) are installed in Az-Zour south Station. The system had shell plates made of carbon steel cladded with stainless steel. All tube supports in evaporators and brine heater are made of stainless steel. Water boxes in the high temperature section are made of carbon steel cladded with copper nickel alloy (Cu-Ni 90/10). Shell material for vent condenser, ejector condenser, and vent gas condenser are made of 904L stainless steel instead of 316 L stainless steel.
2006/2007	Installation of eight MSF units in Sabiya station each with a capacity of 56,825 m^3/d (12.5 MIGD). The main feature of these units is use of a single deck for all flashing stages. The unit width is limited to 20 m; however, the brine load per stage width is increased by 50% to 333.3 kg/(m s).

which have been used in the brine heater and heat rejection section in a number of installations have been replaced with titanium. Although titanium is more expensive than Cu-Ni 70-30, it has better mechanical and corrosion-resistant properties. Therefore, the wall thickness of titanium tubes is almost one-half that required for Cu-Ni 70-30. In addition, the specific weight of titanium is almost one-half that of Cu-Ni 70-30. As a result, the material cost of titanium tubes is almost the same as Cu-Ni 70-30. However, their performance is superior and resulted in reduction of corrosion problems or in the number of tube replacements during overhauls.

- Use of demisters was adopted during the 1960s. This design feature considerably improved product quality since demisters remove more than 99.9% of the entrained brine droplets in the flashed-off vapor. In addition, demisters are inexpensive and are simple to clean. Demister fouling can cause an increase in product salinity. This is because demister fouling reduces the vapor flow area and, as a result, the entrainment rate of brine droplets increases. Frequent demister fouling might be caused by a small demister area, short distance between the demister and the top of the brine pool, or an increase in brine temperature.
- On-line ball cleaning was another milestone in MSF design. This feature resulted in increase in the total operation time of MSF plants and reduction in the frequency of acid cleaning and overhauls. Cleaning cycles are performed at fixed intervals to remove soft fouling and scale. Also, it would disrupt and delay formation of nucleation sites. Proper design of on-line ball cleaning system is characterized by the rate of ball loss or damage. The MSF cross-tube configuration proved to be well suited for on-line ball cleaning. Field experience indicates a considerable reduction in the frequency of acid ball cleaning [7].
- Rehabilitation and upgrading have been made to a number of the old units. Examples include: (1) Refurburishment and upgrading of six MSF units in Shuaiba North have started in 2005. Their life expectancy is going to be increased by 10 years. Upgrading included increase in unit capacity to 27,276 m^3/d (6 MIGD). This was achieved by increasing the top brine temperature to 110°C instead of 90°C. Completion of the refurbishment is expected to be completed in 2007. (2) The Shuwaikh unit installed in 1982 was converted to operate at a top brine temperature of 110°C. This has resulted in the increase of the total plant capacity to 88,647 m^3/d (19.5 MIGD). A similar modification has been also applied to the 27,276 m^3/d (6 MIGD) units installed in Az-Zour South. Therefore, the 27,276 m^3/d (6 MIGD) unit capacity is increased to 32,731.2 m^3/d (7.2 MIGD).

3. Analysis of large-scale MSF plants

Analysis of the MSF process can be made by simple or detailed mathematical models [8–10]. Detailed models solve a large number of equations and generate much greater information on system variables and properties [11–13]. However, simple models always proved to be efficient and accurate in generating main design parameters of the system. The following simple analysis is adopted to calculate the main design features of large-scale MSF systems, which include the brine recycle flow rate, the flow rate of cooling seawater, the stage length, and the stage height. The following is a summary of the model equations:

The brine recycle flow rate is obtained from the brine heater energy balance where

$$M_s \lambda_s = M_R C_p \left(T_{b_o} - T_{f_1} \right) \tag{1}$$

Division of Eq. (1) by the production capacity (M_d) gives

$$\left(M_R / M_d\right) = \left[\left(M_s / M_d\right)\lambda_s\right] \Big/ C_{p_h}\left(T_{b_o} - T_{f_1}\right) \tag{2}$$

In Eq. (2) the term (M_d/M_s) gives the system performance ratio (*PR*). Therefore, Eq. (2) is reduced to the following form:

$$\left(M_R / M_d\right) = \left(\lambda_s / PR\right) \Big/ C_p\left(T_{b_o} - T_{f_1}\right) \tag{3}$$

The cooling water flow rate is obtained by performing overall energy balance on the system shown in Fig. 2. The balance is given by

$$M_{cw} = \left[M_x\lambda_s - M_f C_p\left(T_{b_n} - T_{cw}\right)\right] \Big/ \left[C_p\left(T_{b_n} - T_{cw}\right)\right] \tag{4}$$

Division of Eq. (4) by the production capacity (M_d) gives

$$\begin{gathered}\left(M_{cw} / M_d\right) = \Big\{M_s / M_d\lambda_s - \left(M_f / M_d\right) \\ C_p\left(T_{b_n} - T_{cw}\right) \Big/ \left[C_p\left(T_{b_n} - T_{cw}\right)\right]\Big\}\end{gathered} \tag{5}$$

In Eq. (5) the term (M_d/M_s) gives the system performance ratio (PR) and (M_d/M_f) gives the conversion ratio (CR). Therefore, Eq. (5) is reduced to the following form:

$$\begin{gathered}\left(M_{cw} / M_d\right) = \left[\left(\lambda_s / PR\right) - \left(1 - CR\right)C_p \right. \\ \left.\left(T_{b_n} - T_{cw}\right)\right] \Big/ \left[C_p\left(T_{b_n} - T_{cw}\right)\right]\end{gathered} \tag{6}$$

In Eq. (5) the conversion ratio (CR) is obtained through a simple material balance, which is given by

$$CR = \left(X_b - X_f\right) \Big/ X_b \tag{7}$$

Demister length is obtained from definition of the vapor velocity across the flashing stage. This gives the following relation:

$$L_p = \left(D_{vv}\right) / \left(V_v\, W_{st}\right) \tag{8}$$

The stage length is obtained from

$$L_{st} = L_p + L_{tb} \tag{9}$$

The tube bundle length is obtained as a function of number of tubes, tube diameter, and the tube spacing. The tube bundle length is obtained from

$$L_{tb} = n\, t^{1/2} d\; S_t \tag{10}$$

The number of tubes is obtained as a function of the stream flow rate and velocity. These equations are given by

$$n\, t_r = 4MR / \left(\rho\, VR\, dr^2 \pi\right) \tag{11}$$

$$nt_r = 4\left(M_{cw} + M_f\right) \Big/ \left(\rho V_{cw}\, dj^2 \pi\right) \tag{12}$$

The stage height is obtained from the following relation:

$$H_{st} = H_b + H_{pb} + L_{tb} \tag{13}$$

The following illustration shows the use of the above simple model for analysis of large MSF systems. The following parameters are defined to solve the model equations:

- Number of flashing stages, $n = 24$
- Plant capacity, $M_d = 655$ kg/s (56,600 m^3/d)
- Heating steam temperature, $T_s = 120$°C
- Top brine temperature, $T_{b_o} = 110$°C
- Temperature of brine recycle entering the brine heater, $T_{f1} = 102$°C
- Temperature of brine blowdown, $T_{b_n} = 37$°C
- Intake seawater temperature, $T_{cw} = 30$°C
- Salinity of feed seawater, $X_f = 40{,}000$ ppm
- Salinity of brine blow down, $X_{b_n} = 70{,}000$ ppm

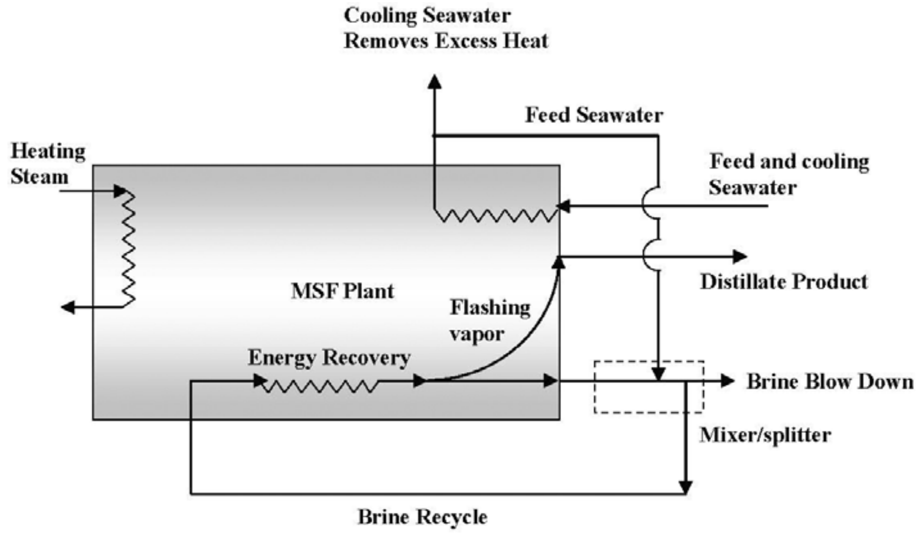

Fig. 2. Heat and mass transfer in MSF brine circulation plant.

- Outer diameter of condenser tubes, $d_r = d_j$ = 0.0312 m
- Specific heat at constant pressure, C_p = 4.2 kJ/kg K
- Vapor velocity in demister in first stage, v_{v1} = 2 m/s
- Vapor velocity in demister in last stage, v_{v24} = 12 m/s
- Stage width, W_{st} = 20 m
- Liquid density, ρ = 1000 kg/m^3
- Tube velocity of brine recycle stream, VR = 2 m/s
- Tube velocity of intake seawater, V_{cwf} = 2 m/s
- Height of brine pool, H_b = 0.2 m
- Distance between demister and brine pool, H_{pb} = 2 m
- Performance ratio, PR =9.5
- Latent heat of heating steam at 120°C, λ_s = 2202.6 kJ/kg

Table 3
Illustration results

Design parameter	Value
Brine recycle flow rate (M_R), kg/s	4519.7
Conversion (CR)	0.429
Cooling seawater flow rate (M_{cw}), kg/s	3637.09
Demister length in first stage (L_{p1}), m	0.826
Vapor specific volume in first stage (V_{v1}), m^3/kg	1.21
Demister length in last stage (L_{pn}), m	2.56
Vapor specific volume in last stage (V_{v_n}), m^3/kg	22.74
No. of tubes in heat recovery section (n_{tr})	2956
No. of tubes in heat rejection section (n_{tj})	3378
Length of tube bundle in heat recovery section (L_{tr}), m	2.54
Length of tube bundle in heat rejection section (L_{tj}), m	2.72
Length of heat recovery stage (L_{str}), m	5.13
Length of rejection stage (L_{stj}), m	5.31
Height of heat recovery stage (H_{str}), m	4.74
Height of heat rejection stage (H_{stj}), m	4.92

Results of the above illustration are shown in Table 3. As is shown, the demister length in the first stage is smaller than that in the last stage. This is because of the increase in the vapor specific volume. Irrespective of this, other design characteristics of the heat rejection and heat recovery stages are quiet similar. This includes the stage height and length.

4. Design characteristics of large- and medium-scale MSF

A comparison of model predictions against field data is made for a number of existing MSF units in the Gulf States. The model results are shown in Table 4. The input design data include the number of flashing stages, the system capacity, top brine temperature, and stage width. The calculated variables include the performance ratio, stage length, stage height, demister length, and specific flow rates of the cooling water and brine recycle.

The results shown in the table are for small, medium, and large production capacity systems which vary from 15,000 to 75,670 m^3/d. The stage width for these systems varies over a range of 8–23.8 m as the system capacity increases. As is shown, the MSF performance ratio varies between 8–9.5. This is except for the unit with a capacity of 15,000 m^3/d, which has a performance ratio of 6. Also, it should be noted that specific flow rate of the cooling seawater and brine recycle varies over a range of 8–9. Similarly, the stage length and height varies over a range of 3.5–7 m.

The results shown in Table 2 indicate that stage dimensions of the MSF system are strongly dependent on stage width. The stage width is set to maintain the weir loading within a range of 200–300 kg/(m s). A lower weir loading would imply a high residence time for the brine stream within the stage, which would result in high brine levels. In this case, the minimum distance between the top of the brine pool and the demister will not be achieved. As a result, brine entrainment in the distillate vapor will increase and would result in higher product salinity. Higher weir loading is also not desirable because it may result in increased vibrations within the system and subsequent damage to the weir components.

Although no actual field data were available for some of the design parameters, the predicted values are well within known field practice although several of the design data for the Kuwait Sabiya station compared well with the model predictions. For example, stage height and length are known to vary between 4–6 m. Also, the specific flow rate of the brine recycle is known to vary over a range of 9–10. Similarly, the specific flow rate of the heat transfer area is reported in several studies to vary between 200–300 m^2/(kg/s).

5. Future outlook

The immediate future outlook for desalination in Kuwait, which includes a major part of the first half of this century, is rather simple to predict. Inspection of the data presented in the previous sections indicate that a relatively new, modern, and well-maintained MSF plant with a capacity of close to 2×10^6 m^3/d exists in Kuwait. Based on the MSF operational experience in Kuwait, it is suggested that these MSF plants will form the backbone of the Kuwait desalination industry up to 2030. This assumes a plant life time of 30–40 years, which has already been experienced for several existing units in Kuwait. Simultaneously, the MSF plants remain operating in fossil fuel co-generation power plants. The MSF will extract the required heating steam from the back-pressure steam turbines. However, more efficient cogeneration systems that include use of combined cycle and gas turbines are planned to be installed in the Shuaiba North Station. Tenders for the power and the desalination plants for the Shuaiba North Station are expected to be issued in 2006. Field experience and literature studies show the higher efficiency of these configurations [14–16].

Close to the end of the first half of this century, several factors may affect the desalination policy in Kuwait. These factors may include the following:

- Current desalination technologies show equal unit product cost for the main three desali-

Table 4
Comparison of model predictions against field data

Plant	No of stages	Capacity (m^3/d)	Top brine temp. (°C)	Stage width (m)	PR	Stage length (m)	Stage height (m)	Weir loading [kg/(m s)]	Demister length (m)	Specific heat transfer area [m^2/(kg/s)]	sM_{CW}	sM_R
Al Taweelah "B" (Abu Dhabi-UAE)	20	57,600	112	19	8	5.58	6.2	293	2.3	174	9.53	8.36
Al Hidd (Bahrain)	21	37,000	107–112	14.2	9	4.66	5.6	260	2.1	198	8	8.6
Ruwais (UAE)	15	15,000	105–112	8	6	3.64	4.7	193	2.3	141	12.82	8.85
Jebel Ali "G" (Dubai UAE)	21	34,080	115	14	8.8	4.25	5.4	226	2	184	8.88	8
Jebel Ali "K" (Dubai UAE)	21	45,480	105	17.8	9	4.7	5.8	237	2	189	8.6	8
Jebel Ali "K" 2 (Dubai UAE)	19	60,530	105	23	8	5.7	6.4	282	2.5	194	8.57	9.27
Mirfa (Abu Dhabi-UAE)	21	34,000	110	14	8.9	4.4	5.5	242	2	197	8	8.6
Ras Laffan (Qatar)	21	45,400	105	18	8.6	5	5.9	270	2.2	199	7.9	9.3
Shuweihat (Abu Dhabi-UAE)	21	75,670	111	23.8	9	6	6.6	311	2.3	199	8	8.45
Subyia (Kuwait)	23	56,818	110	19	9.5	4.5	4.5	288	1.34–2.09	253.44	8	9

nation technologies, which includes MSF, MED, and RO [1]. Future progress, development, and accumulated experience may upset this balance towards one of the three processes or another new technology, which may prove to be more efficient, reliable, and gives lower product cost.

The present design of the MSF and MED processes requires close to 20 kWh/ m^3 of total power, which includes electricity and heating steam. This value is close to four times that required by the RO process. However, the membrane replacement cost, extensive feed treatment, and lower plant factor for the RO process offset this large difference in energy consumption.

The present drawbacks of the RO process may be resolved during the coming decades through the development of more efficient and less expensive membranes and antiscalent chemicals. If this situation occurs, then the RO unit product cost might be reduced by more than one-half. In addition, accumulated experiences in construction, operation, and maintenance of large RO plants may make the RO process highly attractive.

The Kuwaiti state will continue to experience an increase in its population and demand for desalinated water and generation of electric power. Currently, Kuwait consumes less than 10% of its oil production for various industrial sectors, motor vehicles, and electric power generation. However, population increase and expansion in the industrial sector (including desalination) will eventually result in an increase of the oil consumption rate. This situation may call for the adoption of the RO process instead of the MSF process.

Environmental problems generated by combustion of fossil fuel may become more serious. In the need for switching to a sustainable form of energy may call for the use of various forms of renewable energy, which may include solar collectors, photovoltaic panels, or wind energy. Use of renewable energy may be adopted in hybrid form together with existing fossil fuel power plants. This choice might be necessary to accumulate experience in construction, operation, and maintenance of renewable power generation plants on a large scale.

6. Conclusions

The Kuwaiti desalination experience extends over more than 50 years. The study shows that the entire experience deals with MSF thermal desalination, which started with small MSF units with a capacity of 454.6 m^3/d (0.1 MIGD) and gradually progressed to reach much larger MSF unit capacity of 56,818 m^3/d (12.5 MIGD). The starting total production capacity was only 4546 m^3/d (1 MIGD). By 2007, the total production capacity will reach 1.92×10^6 m^3/d (423 MIGD). In addition to an increase in the unit production capacity, other achievements have been made in unit design, including the use of more efficient and less expensive materials, adoption of on-line ball cleaning, use of demisters, motor-driven pumps, and high-temperature antiscalants.

The future outlook indicates that the MSF process will remain dominant in the desalination market in Kuwait during the first half of this century. However, important issues such as environmental considerations, progress in renewable energy, population increase and simultaneous growth in power consumption and water demand may result in reevaluation of current policies of power generation and desalination.

7. Symbols

C_p — Specific heat at constant pressure, kJ/kg K
CR — Conversion ratio, $= M_d/M_f$
d — Tube diameter, m
H — Height, m
H_{pb} — Distance between demister and top brine pool, m

L — Length, m
M — Mass flow rate, kg/s
nt — Number of tubes
PR — Performance ratio, = M_d/M_s
St — Tube spacing, m
T — Temperature, °C
v — Specific volume, m^3/kg
V — Velocity, m/s
W_{st} — Stage width, m
X — Salinity, ppm

Greek

λ — Latent heat, kJ/kg
ρ — Density, kg/m^3

Subscripts

1 — First stage
b — Brine
cw — Cooling seawater
d — Distillate product
f — Feed stream
j — Heat rejection section
n — Last stage
p — Demister
r — Heat recovery section
R — Brine recycle
s — Heating steam
st — Stage
t — Tube
tb — Tube bundle
v — Vapor

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