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MSF challenges and survivals

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ABSTRACT

Thermal desalination processes prevailed over other desalination processes. In the Gulf Cooperation Council (GCC) countries, multistage flash (MSF) plants are the predominant method since 1960. MSF produces about 94% of the total water production of thermal desalination processes in the GCC countries. MSF desalination technology is the vast producer of desalinated water in Middle East and North Africa (MENA), representing 53% of total capacity. About 85% of water production by the Saline Water Conversion Corporation of Saudi Arabia is provided by large MSF plants. MSF is a well-established technology for seawater desalination. It has long plant working times of more than 30 years. MSF has experienced enormous technical improvements in various major desalination issues; scaling and fouling, high energy requirements, and severe corrosion especially on the vapor side. Successful developments were achieved in scale formation control, selection of appropriate materials, increase of evaporator production capacity, reduction in water production cost and decrease in environmental impacts for better operation, maintenance and maintain higher plant life time. In this work, the present trend and the future outlook of MSF plant will be discussed. The paper will focus on the main challenges that are faced by MSF desalination plants and analyse the competition promoted by other desalination processes, such as reverse osmosis (RO) and multi-effect distillation.

Keywords: Desalination; Thermal desalination; Multistage flash; Future of desalination; Large MSF; MSF improvements

1. Introduction

There were about 18,000 desalination plants globally by the end of 2015, with an overall installed production capacity of 86.55 Mm^3/d (22,870 mgd). The production capacity is expected to reach 120 Mm^3/d by 2020. About 27.7 Mm^3/d of potable water is produced by thermal desalination, accounting for 31% of all installed desalination capacity in the world. About 75% of all thermal desalination plants are located in the GCC, where Saudi Arabia produces 12.9 Mm^3/d and UAE of 7.8 Mm^3/d. The trend in the desalination plant in the GCC is 30% RO and 70% thermal. However, these percentages vary from one to another country depending on feed water quality and expertise.

Thermal desalination and in particular multistage flash (MSF) process has been for long time the major desalination process used. In the Arabian Gulf, the MSF desalting system has been the prevailing method since 1960. Almost 88% of the Saudi Saline Water Conversion Corporation (SWCC) water production is provided by large MSF desalination plants which are operating within the context of power/water cogeneration plants. MSF produced about 94% of the total production of thermal desalination processes in the Arabian Gulf region.

The first Saudi MSF plant was built in 1928 in Dhuba and Al-Wajh with a capacity of 227 m^3/d. Two other MSF plants were constructed in 1968 in Dhuba and Al-Wajh with a capacity of 200 m^3/d each. Currently, MSF makes up 81% of

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the total capacity of 7.6 million m^3/d of the total SWCC water production. Membrane processes mainly reverse osmosis (RO) cover only 19%. This is primarily due to the availability of oil as cheap primary energy and slightly unfavorable conditions (such as salinity, temperature, relative abundance of aquatic life) for the membrane processes.

Due to the large number of running MSF units in the world having different capacities, design, materials and chemical treatment, there are extensive data and experience available – more than those available for other desalination processes [1]. There is no doubt that MSF is the simplest, easy to operate and maintain, reliable and robust desalting system [2]. MSF is the most reliable, mature desalting process, representing more than 50 years of experience in design, operation, material selection, and maintenance [3]. It has the largest unit capacity among all desalting systems, exemplified by the 20 migd (90,921 m^3/d) plant recently installed in Ras Al Khair in Saudi Arabia.

Certainly, MSF technology has been confronted with very strong competitors in recent years. Nevertheless, MSF is still a strong player in this competition. MSF process was in operation for about 50 years ago. However, the development in MSF process was evolutionary rather than revolutionary [4]. The main efforts in research and development were mainly focused on scale control and formation on heat transfer tubes utilizing scale inhibition chemicals and on-line sponge ball cleaning. Selection of optimum construction materials, increase of plant unit capacity and improvements of the water quality were among the other area of research and development.

Some facts and features of MSF include the following [5]:

- It is a major thermal desalination process—90% of all thermal production and 42% total world desalination production. Thus, it is among the most commonly used desalination technologies.
- It is the most robust of all desalination technologies.
- It can process water at a very high rate with relatively less maintenance.
- It is capable of very large yields. Plants with design capacities of 600,000–880,000 m^3/d are in operation in Saudi Arabia and the UAE.
- It operates using a cascade of chambers, or stages, each with successively lower temperature and pressure, to rapidly vaporize water, which is condensed afterward to form freshwater. The number of stages may be as high as 40.
- MSF operates at top brine temperature (TBT) of 90°C–120°C. The highest temperature to which the seawater is heated in the brine heater by the low-pressure steam in a cogeneration system. Higher temperatures than this lead to scaling, the precipitation, and formation of hard mineral deposits such as magnesium and calcium sulfates, carbonates, and hydroxides with low concentrations of manganese oxides and aluminum hydroxide.
- Its capital and energy costs are quite high, the latter being crucial for sustainability.
- 25%–50% recovery takes place in high-temperature recyclable (recirculate) MSF plant.
- It gives high-quality product water. The total dissolved salts (TDS) of the product of MSF processes are less than 50 mg/L.
- Minimal pretreatment of feed water required for it.
- Plant process and cost are independent of salinity level.
- Heat energy for MSF can be sourced by combining it with power generation; this is called cogeneration.
- However, MSF is an energy-intensive process.
- MSF requires large capital investment.
- MSF has a larger footprint in terms of land and materials.
- Corrosion problems arise if materials of lesser quality are used.
- It has slow startup rates.
- Its maintenance requires shutdown of the entire plant.
- High level of technical knowledge required.
- Its recovery ratio (product rate/seawater feed rate) is relatively low.

The following is a discussion of the present trend and the future prospect of MSF desalination plant emphasizing the main challenges that faces the survival MSF desalination plants.

2. MSF process description

Multi-stage flash (MSF) commercial desalination systems have two major process configurations; once-through MSF (MSF-OT) and brine recirculation MSF (MSF-BR). In MSF-OT [6], feed seawater passes throughout the process once through at a time while in MSF-BR process a small amount of seawater feed is mixed with major recycling flow of rejected brine exist from the last stage.

Once-through MSF plants include an evaporation section (called heat recovery section) and a brine heater as an energy input and the condenser tubes arrangement. Brine recirculation MSF plants have three sections: brine heater, heat recovery and heat rejection sections. Heat rejection section is used to remove excess thermal energy from the plant, to cool the produced distillate and the rejected brine to the lowest possible temperature. For large-scale desalination process, brine circulation system is most widely used. MSF plants normally consist of 15–40 stages. Once through configuration is generally limited to small-scale plants. The majority of the commercial operating MSF plants are based on brine recirculation system with cross flow configuration [7].

In MSF-BR, raw seawater is screened and chlorinated before passing through the heat exchanger tubes in the heat rejection section where it is heated by the flashing brine. Part of the heated seawater (make up water) is chemically pretreated with either acid (sulfuric acid) or antiscalent additives to suppress the formation of alkaline scale in heat transfer tubes.

The dissolved oxygen content of the makeup water is stripped to a level below 20 ppb in a de-aerator to minimize the corrosion. For acid-treated MSF desalination plant a de-carbonator unit in the form of a packed tower is employed to remove the carbon dioxide. Carbon dioxide may affect the heat transfer performance and corrodes heat transfer tubes. Further reduction of oxygen content to a level below 10 ppb is carried out by a chemical scavenger treatment such as sodium bisulfite. The makeup water is then mixed with the recirculation brine from the heat rejection section to form the feed.

The feed is then introduced to a series of heat exchanger tubes in a heat recovery section. The feed temperature rises gradually due to the transfer of heat with the vapor generated by flashing of brine. Vapor condenses outside the heat transfer tube and is collected on the distillate tray. The feed water then goes to the brine heater where its temperature rises to the maximum plant operating temperature (top-brine temperature, TBT). Heated feed enters the flash chamber, maintained slightly below the saturation vapor pressure of water. A fraction of its water content flashing into steam goes through the demister and condenses on the outside of the tubes as distillate water which is collected in trays and passes through all stages via special inter-stage transfer orifices. The un-flashed brine enters the second stage, which is at a lower temperature, and pressure.

The same steps are repeated, until the last stage in the heat rejection section, where part of the brine is rejected as blow down. The balance is re-circulated back along with the makeup water to enter the recovery section. The non-condensable gases formed by flashing are vented to the atmosphere. The distillate water is subjected to post treatment which includes a re-carbonation and or alkalization for increasing carbonate, calcium content and pH correction before it is sent to the consumers.

3. Operational experience of MSF plants

Scale formation represents a major operational problem encountered in thermal desalination plants in general. There are two types of scales: alkaline scale and non-alkaline scale. Alkaline scale consists of calcium carbonate and magnesium hydroxide separately or in mixtures. Non-alkaline scale is mainly due to calcium sulfate [8].

The scale formed in evaporators running below 80°C is primarily calcium carbonate. As heat is applied to the brine, bicarbonate alkalinity decomposes to form carbonate ions:

$$2HCO_3^- + \text{heat} \rightleftarrows H_2O + CO_2 + CO_3^- \tag{1}$$

The carbonate ions then react with calcium in the seawater to form calcium carbonate

$$Ca^{++} + CO_3^- \rightleftarrows CaCO_3 \tag{2}$$

The solubility of calcium carbonate $CaCO_3$ decreases as temperature rises, reduced pressure and release of CO_2. At higher brine temperatures, the carbonate further decomposes to yield hydroxyl ions.

$$CO_3^- + H_2O \rightleftarrows CO_2 + 2OH^- \tag{3}$$

The magnesium in the water can then react with the hydroxyl ions to form magnesium hydroxide.

$$Mg^{++} + 2OH^- \rightleftarrows Mg(OH)_2 \tag{4}$$

Formation of magnesium hydroxide usually proceeds slowly, but accelerates in the presence of nucleation sites. A rough estimate of calcium sulfate scaling can be found from Skillman sulfate solubility index [9]. Skillman index is a ratio between the actual concentration, $[i]_{\text{actual}}$, of either calcium or sulfate and its theoretical or equilibrium concentration whichever is the limiting species:

$$\text{Skillman Index} = \frac{[i]_{\text{actual}}}{\left(\sqrt{x^2 + 4K_{\text{sp}}} - x\right) \times 10^3} \tag{5}$$

where x is the absolute value of the excess common-ion concentration of calcium and sulfate ions which can be devalued from:

$$x = \left|2.5\left[Ca^{2+}\right] - 1.04\left[SO_4^{2-}\right]\right| \times 10^{-5} \tag{6}$$

The solubility product constant (K_{sp}) for calcium sulfate in g/L, as function of temperature can be determined from the following equation [10]:

$$K_{\text{sp}} = 2.091 + 0.003173T - 8.193 \times 10^{-5} T^2 \tag{7}$$

An important strategy to reduce the formation of inorganic scales depends on the limitation of the operating conditions and on the addition of small quantities of scale prevention additives.

De-carbonation or CO_2 removal is accomplished in a vacuum de-aerator or an atmospheric de-carbonator followed by a vacuum de-aerator. Separate de-carbonation with CO_2 release to the atmosphere is generally preferable for large plants to reduce the size of the vacuum system and decrease corrosion in the vent system.

Feed water is typically de-aerated (the de-aerator is often integrated in the evaporator) and treated with polyelectrolytes for scale and foam control, plus sodium bisulfite for scavenging oxygen (after a de-aerator) and residual chlorine.

Scale in heat exchanger tubes is additionally controlled by on-line sponge ball cleaning systems. Anti-scale additive dosing and ball cleaning systems ensure an operating period between acid cleaning of up to several years.

Addition of a threshold chemical such as polyphosphate retards alkaline scale formation by preferentially combining the calcium and magnesium into a soluble complex. These compounds are usually added to the extent of 2–4 ppm to the seawater makeup ahead of the de-aerator and allow operation higher temperature without severe scaling if properly controlled. Unfortunately, these chemicals are not wholly stable in water solutions and revert to sludge with time. Conventional acid cleaning techniques are used to remove the sludge fouling that forms.

Calcium sulfate scale can form in seawater evaporators when its inverse solubility limit is exceeded. This limits evaporator temperature and restricts the brine concentration factor in distillation plants. Three forms of calcium sulfate prevail. Precipitation temperature depends upon concentration and generally commences near 110°C for the anhydrite form at a concentration factor of 1.0.

In practice, the efficiency of thermal desalination plants is usually measured by either the gain output ratio (GOR) or performance ratio (PR). Performance ratios vary between 5.6 and 10.6 kg/2,326 kJ (2.39–4.57 kg/1,000 kJ). GOR is the ratio of kg of water produced per kg of steam used. Values of GOR are often between 8 and 10 with a practical maximum of 12, which corresponds to about 55 kWh/m^3 of thermal energy.

Large MSF plants work in dual-purpose status for the simultaneous production of power and water. Such co-generation configuration utilizes either backpressure or extraction condensing turbine. The power to water ratio (PWR) indicates the ratio between the generated power and the fresh water produced. It is considered a key parameter in dual-purpose plants. PWR is selected to meet the demand of the power and water in a region. Rated PWR depends on the design of the power cycle, part-load and supplementary firing systems.

Mussati et al. [11] studied MSF plants coupled to five power plant configurations: extraction steam turbine, combined cycle gas turbine with backpressure steam turbine (CC-BST), gas turbine (GT), BST and gas turbine with heat recovery steam generator. They found that lower specific cost of water can be achieved with lower PWR.

Table 1 shows the characteristics and operational history of Saudi MSF plants. Extraction condensing turbines were used in MSF plants in Saudi Arabia in the co-generation cycles till 1982. The PWR was ranging between 10.2 and 17.5 MW/migd [6]. Since 1983 backpressure turbines were utilized in all new Saudi dual-purpose MSF plants. Backpressure turbines have lower PWR which are suitable for high water demand. They have high thermal efficiencies. They are employed to efficiently utilize low-grade heat.

In large MSF plants having back-pressure steam turbines to drive the main pump, the electrical power consumption will be minimized significantly. The electrical power consumption will be as low as 1 kWh per m^3 [4]. The reduction in the electrical power consumption of brine recirculation pump in large MSF plants having back-pressure steam turbines can be achieved by better specification of pumps with very high efficiency as well as minimization of the friction losses. Pressure head and geometrical head have significant contribution to the overall brine recirculation pump power consumption. Back-pressure steam turbines in large MSF plants enable the improvement of thermal efficiency and better adoption of steam turbine driven motor for driving the pump. Appreciate motor-driven equipment accounts for about two-thirds of electricity consumption. Consumption of power can also be further reduced by reduction of speed for fixed load and use parallel system for highly variable loads. The abatement of the pipe work and system losses due to friction utilizing the optimal routing and proper choice of the equipment geometry can have major roles in pump power consumption [12].

MSF distillers are described by various design features and performance characteristics [13]. MSF has a current modular capacity up to 90,000 m^3/d which can treat very salty water up to 70,000 mg/L. It has high energy use: from 3 to 5 kWh/m^3 electricity and 233 to 258 MJ/m^3 heat required. For example, Ras Al Khair MSF plant has eight identical cross tube MSF evaporators with brine recirculation. At 100% of design rating, each desalination unit produces 92,582 m^3 of distillate per day. The evaporator in Ras Al Khair plant measures 123 m long, 33.7 m wide and weighs 4,150 ton. Product has less than 25 ppm TDS.

Table 1
Characteristics and operational history of Saudi MSF plants

				1st Generation						
Plant	Conf.	Power, MW	Type	Water, m^3/d	PWR	Chem.	TBT	Comm.	Reti.	PR
Jeddah-1	LT	50	ST,EC	1,893	10:01	Ac	120	1972	1980	10
Khobar-1	LT	–	GT	37,850	–	Ac	120	1974	1982	10
Jeddah-2	LT	25 × 3	ST,EC	37,850	5:01	Ac	120	1978	2007	10
Jeddah-3	CT	62 × 3	ST,EC	75,700	10:01	Ac/Ad	107	1979	2005	7
Jeddah-4	LT	118 × 5	ST,EC	189,250	10.3:1	Ac/Ad	110	1981	–	7
Yanbu-1	LT	69.4 × 5	ST,EC	95,000	12.5:1	Ac/Ad	120	1980	–	10
Jubail-1	CT	60 × 6	ST,EC	137,729	10:01	Ad	90	1980	–	8.5
Jubail-2	CT	122.5 × 10	ST,BP	947,890	4.7:1	Ad	112	1983	–	8.5
Khobar-2	CT	142 × 5	ST,EC	223,000	–	Ad	115	1982	–	–
				2nd generation						
Shuaiba-1	CT	52.56 × 5	ST,BP	230,000	5:01	Ad	102	1988	–	8.5
Shuqaiq-1	CT	54 × 2	ST,BP	106,000	5.3:1	Ad	102	1989	–	8.5
Yanbu-2	CT	75 × 2	ST,BP	144,000	4.4:1	Ad	110	1998	–	9
Khobar-3	CT	119.7 × 4	ST,BP	280,000	–	Ad	115	1999	–	–
				3rd generation						
Shuaiba-2	CT	104 × 5	ST,BP	455,000	17.9:1	Ad	110	2000	–	9.5
RasAl Khair	CT	600 × 4	GT,CC	770,000	9.5:1	Ad	112	2014	–	9.5

Note: Ac: acid treatment; Ad: additive treatment; LT: long tube configuration; CT: cross tube configuration, ST: steam turbine, BP: back pressure, EC: extraction condensing, CC: combined cycle.

As an example of the design details of MSF evaporator tubes in different plant sections, Table 2 shows tube information in Al-Jubail II MSF Plant. Table 3 summarizes the major design parameters of the two modes of MSF operations; low temperature operation (LTO) at 90.6°C and high temperature operation (HTO) at 112.8°C.

Non-condensable (NC) gases are essentially oxygen (O_2), nitrogen (N_2), argon (Ar), and carbon dioxide (CO_2). They form from the evaporating brine in desalination distillers and affect the heat transfer for condensation, energy consumption, operation, and material lifetime of the distillers.

The first generation of MSF plants largely employed carbon steel as a material for the evaporator shell and internals. The initial duration of the equipment was planned for a maximum of 15 years. These plants experienced long operational life-time longer than what were originally anticipated. Several routine rehabilitation and refurbishment projects were performed for extending the original life-time for 20 years and beyond.

Noble materials were economically adapted as results of developments in material science and technology and better knowledge of the corrosion issues in seawater environment. The second generation of the large Saudi MSF desalination plants which were installed in the last 10 years are expected to last for more than 40 years with minimum maintenance.

The following is a list of typical materials used in MSF plants [14]:

- Titanium is used for evaporator tubes at temperatures below 80°C with small wall thickness of 0.5 mm.
- Cu/Ni 70/30 with a wall thickness of 1–1.2 mm is used to construct tubes at operating temperatures above 80°C. Its main disadvantage results from contamination of the rejected brine with the copper element, which has effects on the environment.
- Cu/Ni 90/10 with 1 mm wall thickness is used to construct tubes in lower temperature evaporators. Also, it is used for cladding carbon steel in water boxes as well as partition walls and floors in evaporators.
- Aluminum brass tubing for evaporators operating below 80°C.
- Stainless steel, SS 316L, is used to manufacture partition walls, distillate trays, and evaporator internals (limited to 80°C to avoid pitting and crevice corrosion temperature threshold).

Carbon steel is used for construction of steam and condensate piping. Cladding materials such as stainless steel, CuNi 90/10, or polyurethane are used together with carbon steel to construct evaporator partition walls and floors, de-aerator shell, water boxes, and seawater, distillate and brine piping.

Table 3
Operational design parameters of Al-Jubail II MSF plant

Item	LTO	HTO
Max. brine temp., °C	90.6	112.8
Max. brine conc., ppm	64,900	61,800
Distillate capacity, m^3/h	985.0	1,163.3
Performance ratio, kg/MJ	3.44	4.09
Average energy consumption, kW	3,873.3	3,729.2
Brine velocity in tube, m/s	1.98	1.58
Recovery fouling, m^2 K/W	0.000176	0.000146
Brine heater fouling, m^2 K/W	0.000176	0.000176
Scale cont. add. dosing rate, ppm	5	7
Scale control additive type	Polyphosphate	Polymers

4. Future prospects of MSF desalination plants

MSF desalination process will continue to be the dominant technology for seawater desalination in the Arabian Gulf region. MSF plant reliability and performance were outstanding, with recorded historical on-line times exceeding 90% at design capacity and product purity. The past 50 years of successful operation made a refinement of the MSF technology in terms of materials, unit sizes and scale prevention techniques. So MSF distillation has become a mature technology giving reliable operation for seawater desalination and expected plant lifetimes of more than 30 years.

Although it is capital and energy intensive process, MSF is still a desirable alterative for high plant capacity. Existing MSF plant productivity can be increased by adapting one or more of the following paths [15]:

- Increasing the TBT leads to an increase in the flashing range.
- Increasing the recycle stream flow rate. This option overloads the recycle pump and reduces its energy efficiency. In addition, if the TBT is to be increased simultaneously, steam amount to the brine heater as well as steam temperature will have to be increased accordingly. In this contest, a novel idea in the process pretreatment is to couple the MSF process with a nanofiltration membrane unit, NF, for partial elimination of the bivalent scale forming ions, namely: SO_4^{--}, Ca^{++} and Mg^{++} as well as HCO_3^- from part of the makeup stream. This pretreatment step

Table 2
Evaporator tube information in Al-Jubail II MSF plant

Item	Brine heater	Recovery section	Rejection section
Tube material	66 Cu/30 Ni/2 Fe/2 Mn	90–10 Cu/Ni	Titanium
Tube wall thick, mm	1.25	1.25	0.71
Tube OD, mm	39.0	39.0	29.0
Tube length, m	14.3	19.9	19.9

will enable plant operation at a TBT beyond 125°C. This increase in TBT will increase the flashing range and hence plant productivity without the threat of scale formation at the high temperature end of the plant. The process will be expected to run at lower anti-scalant doses, results in lower chemicals and operational costs in general.

The design modifications of the pre-described work [15] are characterized by utilizing two different distillate product lines, namely the recovery section distillate line and the rejection section product line. The distillate corridor in the rejection stages has been removed in the modified plant design. The distillate trays have been replaced by longer ones. Larger area demisters have replaced the old ones in the rejection section. Additional pumps over those normally found in the conventional plants were utilized [15].

The most significant change in the design of MSF-cross tube evaporators over the past 30 years may be the increase of unit capacities from about 5 migd (22,730 m^3/d) to a current maximum of about 20 migd (90,922 m^3/d). Ongoing investigations on different MSF plant designs were along the flowing direction [16]:

- Once through MSF type is suggested instead of brine recycle one.
- Long tube instead of cross tube.
- Single tier instead of double tier. In single tier design all chambers are arranged at the same elevation whereas in double tier design half the stages are arranged on the top floor and the rest on the bottom floor.
- A blow down pump can be canceled by elevation of MSF plant about 11 m above sea level.
- Placing the brine heater on ground (under head) to protect against boiling in brine heater.
- Others such as improved interstage orifice devices, specific weir loads up to 2,000 t/h m, improved condenser design without stagnant areas.

TBT is expected to increase from 110°C to 130°C by increasing the flow rate of the recycle stream by 85% of the maximum recycle pump capacity [15]. The total plant capacity will then increase by 49% [15].

Helal [17] considered that the simple design of long tube (LT) once-through (OT) MSF evaporators will represent the future design of super-large MSF plants. The main features of these future plants are outlined in Table 4 according to Rautenbach and Schafer [18],

SWCC and Doosan Heavy Industries and Construction, a subsidiary of Doosan Group, is a heavy industrial company headquartered in Changwon, South Korea, to once through long tube (OT-LT) MSF configuration [19]. High temperature once through long tube (HT OT-LT) MSF pilot plant was designed with 20 stages and built in SWCC-Desalination Technology Research Institute (DTRI) in Jubail Saudi Arabia. The pilot plant was operated at the TBT of 130°C. It was found that HT OT-LT MSF is considered as competitive large capacity and high energy efficiency desalination plants. OT-LT MSF plant has significant improvement in heat transfer coefficient and reduction in CAPEX and OPEX.

Modifications in MSF process will include venting system readjustment, increase of temperature and steam rate and capital investment for the evaporator engineering modifications. This is worth investigating to examine its technical feasibility and to study its cost effectiveness as well. For example, Sommariva et al. [20] reported that about 45% increase in productivity can be obtained through increased flashing range and recycle flow rate in conjunction with the design modification of the heat rejection section. Enthalpy

Table 4
Comparison of conventional and future MSF design

Feature	Conventional	Future design
Mode	Brine recycle	Once-through
Stages	<21	>40
GOR	7–9	>12
TBT, °C	110	110–130, maximum
Bundle	Cross-tube	Long-tube arrangement
Condenser	Dead spots with accumulation of non-condensable	No dead zones; bundle higher height transfer; better gases venting
Evaporator	Double tier	Single tier
Brine loading	1,000 ton/h m width	Up to 2,000 ton/h m width
Elevation above sea level, m	Approx. 4 above ground + BD pump	Approx. 11, no BD pump
Brine heater protection	Control valve.	Hydrostatic, non-valve variable speed pump.
Shell material	Cast steel with Cu-Ni clad	Stainless steel
Tubes/support	Cu-Ni	Stainless steel + titanium
De-aerator	Separate	Stage l and 2
Pumps, valves	Redundant	Single
Flow control	Throttling valve + constant speed pump	Variable speed pump
Ejector condensers	Surface condensers	Spray condensers of smaller size by direct venting to atmosphere in stage 1

of the distillate stream leaving the heat recovery section of the MSF plant can be utilized to operate a low grade energy process.

Alt [21] described an optimized MSF-cross tube evaporators with an increased range of performance ratios with traditional proven process parameters. These include TBT, brine concentration, flash chamber liquid loading, feed water treatment, etc. The optimized evaporators have performance ratio up to 16 kg/2,326 kJ. Within this optimized system, cross tube evaporators can be built with unit capacities significantly above 20 migd (90,922 m^3/d) with a reduction in space requirements.

It is possible for dual-purpose MSF plants to utilize the low grade energy of the condensate, which is returned to the power plant at relatively high temperature with a thermal vapor compressor. According to Alt [22], the compressed vapor released from flashing down the condensate to a lower temperature can be used as part of the required heating steam. This can reduce the annual steam consumption of MSF desalination plant by about 5% or more [22].

Within the same concept Jiping et al. [23] proposed an enhanced-MSF (E-MSF) seawater desalination system. This system has two modifications: (1) an extraction of part of the flash vapor in flash room to heat the flashing brine in the following stage; (2) the use of cooling seawater from power plant as an MSF makeup water to utilize the waste heat of the power plant. By extracting maximum value of 0.773 of flash vapor, calculations yield an increase of the GOR by 74.1%, reduction in brine concentration in each stage 21.8% on an average and expected reduction on the desalinated water production 10.7% with respect to a conventional MSF system [23].

Al-Weshahi et al. [24] proposed the enhancement of MSF desalination performance by utilizing the heat from stage distillate to warm up the make-up stream or brine recycle using an internal heat exchanger as shown in Fig. 1. This extracted distillate could increase water production by 2% and reduce steam consumption by 5%. Reduction in pump power consumption is also expected since seawater feed flow is reduced [24].

Barbe et al. [25] investigated the improvement of the existing MSF cogeneration plants. They mentioned that adding reverse osmosis unit using the cooling water of the power plant condensers and/or MSF seawater reject as RO feed water looks attractive in terms of capital cost since no additional intake has to be installed. This water may need to be cooled with an existing seawater source to maintain RO feed temperature below maximum allowed values.

The following efforts are ongoing to enhance the MSF's performance [26]:

- changes in construction, such as different designs of the brine gate orifices, demisters [27].
- stripping methods to improve evaporation without increasing heat inputs [27].
- brine heater condensate cooler located downstream of the brine heater condensate pump.
- better antiscalant characteristics for higher TBTs [28].
- acid dosing also to achieve higher TBT.
- reduction in MSF manufacturing lead time [29].
- nanofiltration as pretreatment to raise TBT.

It seems that increasing the TBT draws the attention of most of the researchers.

An increase in TBT from 110°C to 120°C will lead to 15.8% increase of water production and to 6.4% decrease in the specific energy consumption [30]. For better recovery and energy utilization, development of hybrid configurations, recirculate brine streams, and reuse of waste heat could improve the exergy efficiency in the MSF plants. Table 5 shows a list of some approaches for improving exergy efficiency in the MSF process [31].

Darwish et al. [2,3] claimed that installation of new MSF units should be ceased since the improvements of the MSF do not match with its high energy consumption. This is based on their estimation of the equivalent mechanical energy of MSF as 18 kWh/m^3 (14 for thermal energy and 4 for pumping) compared with 4 kWh/m^3 consumed by SWRO using energy recovery. The primary energy use in RO plants is the power required to drive the high pressure pump to provide hydraulic pressure in excess to the osmotic pressure. Thermal processes are normally driven by low pressure steam (most typically extracted or back pressure steam from a power plant) or any other waste heat available at similar

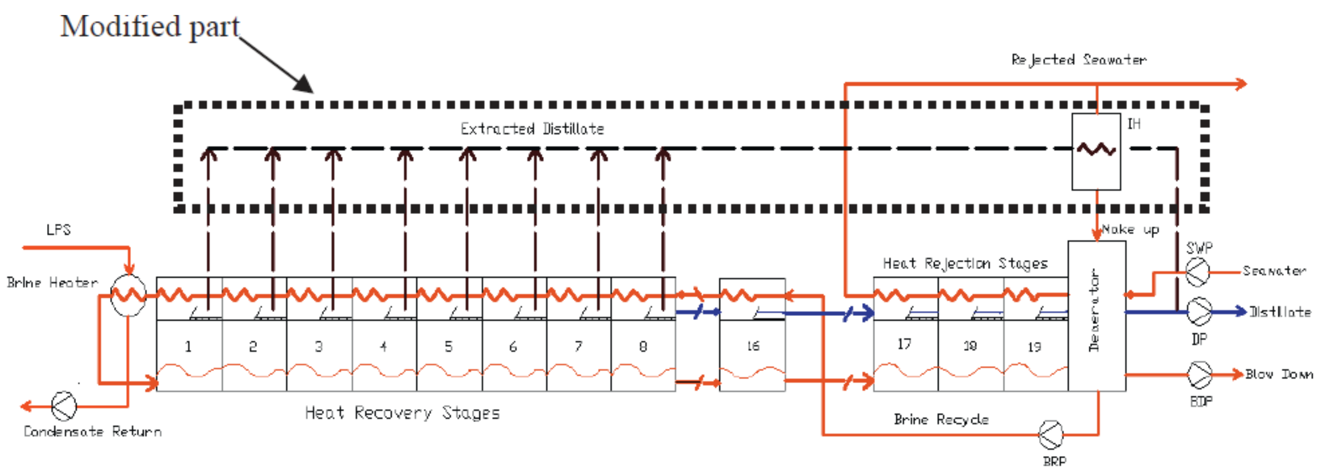

Fig. 1. Modified MSF desalination model with internal heat exchanger [24].

Table 5
Exergy performance in MSF process [31]

Process	Description	Performance
Solid oxide fuel cell–gas turbine (SOFC–GT) hybrid system integrated with a multi stage flash (MSF) desalination unit	Heuristic optimization method, namely, multi-objective genetic algorithm (MOGA) Desalination capacity - 256 m^3/d; performance ratio of 8.8	Maximum achievable exergy efficiency of 46.7% with optimal design MSF system exergy efficiency—3.49%
MSF with heat recovery from hot distillate water stages	IPSEpro software was used. Capacity – 91,200 m^3/d; # of stages 19 (16 heat recovery + 3 heat rejection) with a performance ratio of 8.43.	Overall exergy efficiency – 5.8%. Exergy destroyed: Heat recovery stages – 55.0%. brine heater – 17.0% Heat rejection stages – 10.0% Pumps – 4.3% Brine streams disposal – 14.0% With heat recovery – 14.0%.
Recirculating MSF plants in Saudi Arabia, namely, Al-Khobar II, Al-Jubail II, and Shuaibah	Quantitative assessment of MSF desalination plants. *Al-Khobar II:* Capacity – 194,200 m^3/d; # of stages – 16 (10 identical units). *Al-Jubail II:* Capacity – 940,000 m^3/d; # of Stages – 22 (40 identical units). *Shuaibah:* Capacity – 181,818 m^3/d; # of Stages – 19 (10 identical units).	TBT – Exergy efficiency 87°C – 4.61%. 106°C – 5.21% 115°C – 5.35%. 90.6°C – 10.02% 90.8°C – 10.38% 112.8°C – 7.61%. 76.5°C – 3.57% 90.0°C – 1.78%. 101.5°C – 1.12%.

temperatures. So common platform of standard primary energy consumption is necessary in providing an effective comparison of all desalination processes [32].

Evaluation of various desalination technologies should be performed at a common platform as suggested by Shahzad et al. [32]. They proposed a new and most suitable desalination processes performance evaluation method based on primary energy called universal performance ratio (UPR) [32]. The UPR is given by evaporative energy divided by primary energy input. The performance of desalination plants, conventionally reported based on their derived energies. Since different derived energies are not the same in terms of quality (work potential). The derived energies are multiplied with respective conversion factors be transformed equitably on a common platform based primary energy.

The thermodynamic limit represents the ideal work for separation of dissolved salts in seawater. The thermodynamic limit is calculated based on minimum separation work theory which revealed that the minimum energy required for separation at 35,000 ppm concentration is 0.78 kWh/m^3 [32]. The existing desalination processes are still far from the thermodynamic limit.

It can be seen from Table 6 that MSF, RO and multi-effect distillation processes are only operating at 7%–10% of the thermodynamic limit (TL) of UPR. So these processes will be comparable within the common energy consumption viewpoint. However, for generalizing the comparison between various desalination processes, other parameters should be considered; such as environmental impact, water quality, amount of energy required, and water production cost.

The statement that MSF is obsolete and should be ceased is unfair to be drawn since increasingly improvement and modifications are in progress. A clear answer to the question

Table 6
Primary energy of MSF, RO and MED processes and universal performance ratio (UPR) [32]

Desalination processes	Derived energy, kWh/m^3		Conversion efficiency exergy proportion of primary energy		Primary energy, kWh/m^3	UPR	% of thermodynamic limit (TL)
	Electrical	Thermal	Electrical	Thermal			
RO	3.5	NA	47%	NA	7.45	86	10.4%
MSF	3.0	80.6	–	5.4%	10.73	60	7.2%
MED	2.3	71.7	–	3.4%	7.32	88	10.6%

"is the multi stage flash evaporator obsolescent?" is given by Torzewski and Müller [26] as "it is not possible".

5. Conclusions

The evolutionary developments in MSF process were discussed. In the future respective, it can be said that the thermal plant and especially the MSF technology will still lead in the Arabian Gulf countries. It is evident that MSF is still a strong player and will survive for the nearest future. It has robust and matured design, consume low amounts of chemicals, ideal for coupling to thermal power plants, very large unit sizes possible and produces water with high quality. The main possible improvements may focus on optimized use of materials, optimized mechanical design of the evaporator, optimized thermodynamic design parameters and optimized hydraulic design. There is also room for developing a more effective and economical antiscale treatment.

MSF may have further increase in the unit production capacity with more efficient association with cogeneration power plants. The construction of MSF hybrid systems with other thermal and membrane processes is being viable specially with the use of waste heat and the utilization of renewable energy.

Improvement of the performance ratio by an increase in the heat exchange surface or the number of stages or both of them will inevitably increase the capital cost. This option should be studied carefully.

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