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Features of multi-effect evaporation desalination plants

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ABSTRACT

There are three major types of desalination plants that dominate the desalination market. These are multi-stage flash (MSF), reverse osmosis (RO), and multi-effect evaporation (MEE). MSF dominates the desalination market by more than 73% of units producing 4,000 m^3/d (1.06 mgd) and 51% of units producing more than 100 m^3/d (26,420 gpd). RO has about 17.8% of the total desalting capacity of plants producing more than 4,000 m^3/d and about 32.6% of those producing more than 100 m^3/d. There is a great potential toward installing more MEE plants worldwide and specifically in the Arabian Gulf countries. In Saudi Arabia, Saline Water Conversion Co-operation is currently implementing six projects of satellite plants of MEE type et al. Wajh III, Umluj III, Farasan II, Laith I, Qunfudah I with a capacity of 9,000 m^3/d of water for each plant and 18,000 m^3/d for Rabigh II plant. Besides, three planned plants of MEE types at Al-Khafji III, Haqal III and Duba IV with a capacity of 20,000, 9,000, and 9,000 m^3/d, respectively. Marafiq (the Power and Water Utility Company for Jubail and Yanbu) will have a combined power generation and desalination plant with a capacity of 2,750 MW of power and 800,000 m^3/d of water. The 68,190 m^3/d (15 migd) single MEE unit to be furnished by Doosan at Yanbu could revolutionize the competitiveness of the technology in the Gulf. MEE is more efficient in power consumption among various sea water desalination plants. The MEE process has a highly attractive design and operating features that make it competitive against the dominant MSF process. There are some new innovations and current development work in MEE process that will increase its share in the future desalination market. The major feature of MEE process will be highlighted in this work together with a detailed discussion of recent innovations and developments of this remarkable process.

Keywords: Multi-effect evaporation; MEE; MED; Thermal desalination; Desalination plants

1. Introduction

The multi-effect evaporation (MEE) process is the oldest process in desalination. References and patents have existed since 1840, more than 150 years ago. The SIDEM mother company has been producing MEE plants for ships since 1890. Since then, more than 500 MEE plants have been commercialized by the group [1]. Many works were published on the design, operation, and modeling of MEE plants. EI-Dessouky et al. have made several contributions in the mathematical modeling of MEE plants [2]. Hanbury [3] carried out analytical simulation of MEE plants and Morin [4] made design-and-operating comparisons between MEE and multi-stage flash (MSF) systems. Darwish and El-Hadik [5] investigated the thermal performance of MEE systems and compared it with that of the MSF systems.

MEE with thermal vapor compression is gaining more interest as compared to other thermal desalination processes like MSF desalination due to its low maintenance cost, simple geometry, easer operation, and low-energy consumption. Thermo-compressor plays a major role in MEE systems. It reduces energy consumption and increases system's efficiency. Energy consumption can be significantly influenced by the geometry and operating conditions of thermo-compressor [6,7].

Kouhikamali and Sharifi investigated the influence of thermo-compressors in multi-effect desalination units [8]. They examined the influence of constant area zone on thermo-compressor performance. They changed the throat diameter of thermo-compressor and compared the numerical and experimental results of this modified thermo-compressor with the old thermo-compressor. Overall efficiency of the modified thermo-compressor was increased.

Darwish and El-Dessouky [9] compared the specific available energy, performance ratio, and specific heat transfer area for MEE and MSF. The study showed that MEE is more efficient from thermodynamics' and heat transfer's point of view than MSF's. On the other hand, the multi effect–thermal vapor compression (ME–TVC) system uses less heat transfer surface area compared to MSF and MEE systems for the same energy consumption.

Minnich et al. [10] developed a simple model for the ME–TVC system operating at low-top brine temperature (TBT) of 60˚C. The model was used to compare the performance and the capital cost of the ME–TVC against MSF and MEE. The capital cost for the three systems was compared based on the total heat transfer area. Results showed that operating ME–TVC at low TBT gives a higher heat transfer area than MSF at performance ratios greater than 6. The capital cost of low-temperature ME–TVC exceeds the MSF at a performance ratio greater than eight.

The objective of this paper is to present the remarkable features of MEE process which will make it a promising reliable desalination plant among all commercial desalination processes.

2. Description of MEE process

The MEE plant can be divided into a vertical climbing film tube plant, a rising film vertical tube evaporator plant, or the horizontal tube-falling film spray tube plants, according to the type of heat transfer surface tubes used in each plant. Another configuration in a MEE plant can be used based on brine flow direction regarding the vapor direction from one effect to the other. This type of arrangement includes a forward configuration, backward configuration, and parallel feed configuration.

Based primarily on the arrangement of the heat exchanger tubing there are three arrangements which have evolved for MEE processes. They include the following:

2.1. Horizontal tube arrangement

In this arrangement, the tube bundles are arranged horizontally in the vessel as shown in Fig. 1. The feed water is sprayed over the outside surfaces of the tubing, and the inside tubing surfaces contain the heat to vaporize the feed water. The vapor generated in each effect is directed to the next lower pressure effect.

The full process schematic is shown in Fig. 2. Feed water enters the main condenser. The condenser can be of the conventional shell-and-tube type, as depicted, or it can be designed similar to the effect design. Most of the feed-water flow is for cooling and is returned to the sea.

A small portion of the feed water is used as make-up for the process. The make-up enters the degassifier/deaerator. Normally, there are two vessels at this step: one for removing air and one for removing carbon dioxide if acid is used for pretreatment. A make-up pump is required to pump the make-up from the vacuum condition to the top of the last effect. Here, the feed is pumped through a heat exchanger, where some heat is recovered. The feed stream continues through each recovery heat exchanger of each tube bundle, where a small portion of the feed water is vaporized.

The steam used in the first effect is condensed as the steam gives up its heat to the vaporization process

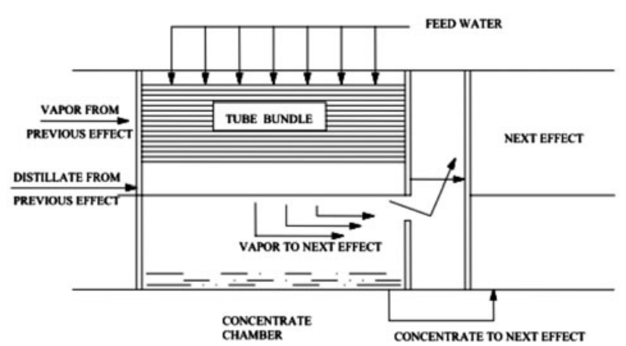

Fig. 1. MEE horizontal tube arrangement [11].

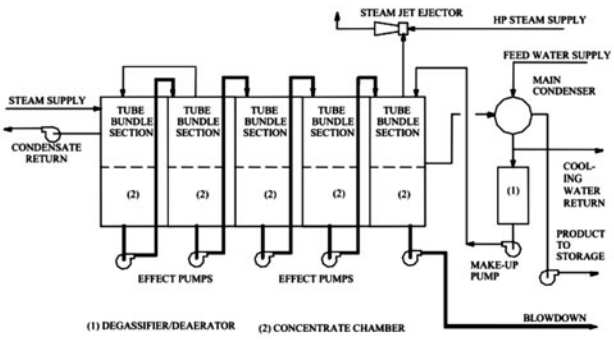

Fig. 2. MEE process schematic—horizontal tube arrangement [11].

and is pumped back to the boiler. The diagram in Fig. 2 shows that the feed from the first effect is collected in the vessel and piped to the second effect, where the vaporization process begins once again. Vapor from the first effect is piped to the second effect, to be used as the heat source. This process continues, through each successive effect, until the vapor from the final effect is condensed in the main condenser.

The distillate produced in each effect is joined with the condensate from the main condenser and becomes the product water, which is then pumped to the post-treatment system prior to storage and pumping to the water distribution system.

2.2. Vertical tube arrangement

The vertical tube bundle arrangement is depicted in Fig. 3. The feed water enters at the top of the effect and flows on the inside surface of the tube. The heat for vaporization is on the outside surface of the tubing. The advantage of this design over the horizontal tube arrangement is higher heat transfer rates. Higher heat transfer rates result from having a thin film on both the inside and outside surfaces of the heat exchanger tubing. One drawback of this design, however, is the difficulty of ensuring that good-flow distribution is achieved for each tube. The design and operation of the vertical tube arrangement are identical to the horizontal tube arrangement's, except that the tubes are arranged vertically.

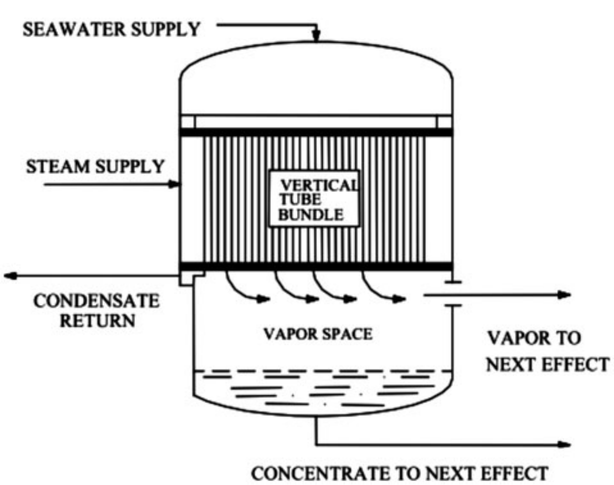

Fig. 3. MEE vertical tube bundle arrangement [11].

2.3. Vertically stacked tube bundles

The tubing arrangement in the vertically stacked unit is depicted in Fig. 4. For this design, the concentrate flows down between effects, thus eliminating the need for pumping. As with the vertical unit described above, the feed water is fed to the inside surface of the tubing, and the heating for vaporization is on the outside surface of the tube bundle. This drawing depicts two sets of bundles, but the unit can consist of many sets of bundles.

There are five types of modern combinations used in MEE plants: conventional low-temperature multi-effect (LT-ME) without any heat pump; LT-ME with mechanical vapor compression; LT-ME combined with thermal vapor compression (ME-TVC), MEE combined with absorption heat pump (ME-ABS), and MEE combined with adsorption heat pump (ME-ADS). The last two combinations can also operate at high-top brine temperature (TBT) and can be considered as a new proposed combination. ME-TVC is already used in many MEE plants in the Arabian Gulf and other countries. ME-TVC with their detailed features is shown in Fig. 5.

The popular configuration used in current MEE plant designs is the horizontal tube, thin-film (HTTF) arrangement in which the brine is distributed as a thin film over the outside of horizontal tubes with condensing steam flowing on the inside of the tubes. MEE plants are almost exclusively of the thin falling film type. High heat transfer coefficients can be achieved due to the fact that brine is boiling outside the tubes and steam is condensing inside. With heating steam entering the tube bundle at one end and distillate being discharged from the other end, non-condensable gases are driven positively and unidirectionally out of the heat transfer zone. This type of evaporator reduces the carry-over and scaling problems and increases the heat transfer coefficient and performance of plant. The performance ratio

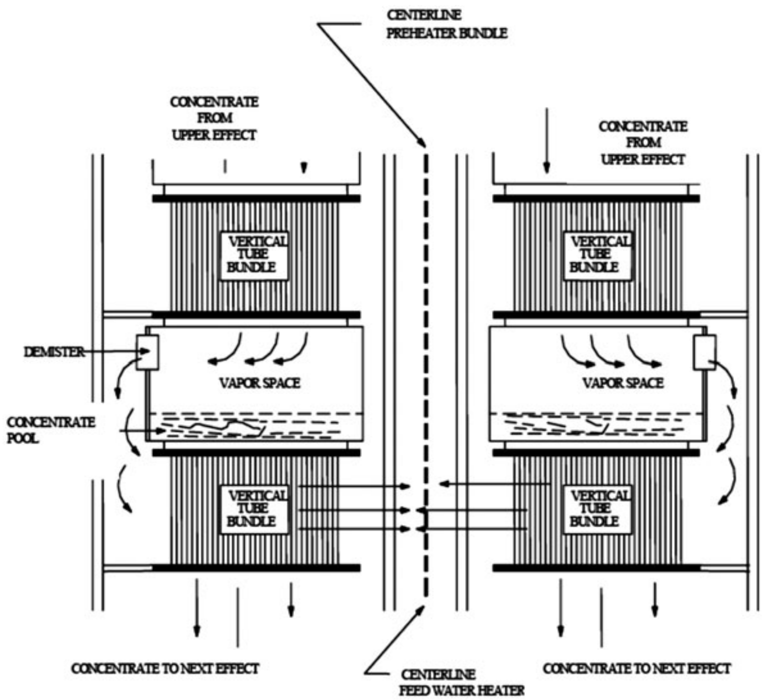

Fig. 4. MEE vertically stacked tube bundles [11].

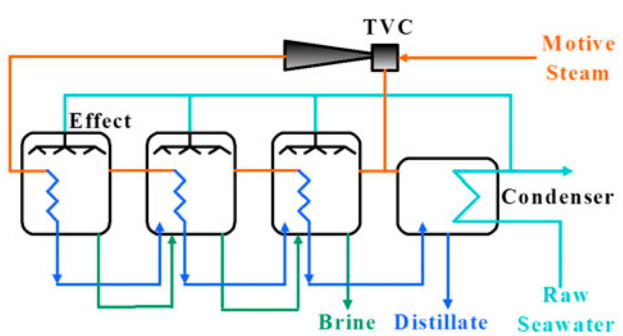

Fig. 5. Schematic diagram of a three-effect ME-TVC plant.

(expressed as GOR; gain output ratio) is directly related to the number of effects in a conventional MEE system; as the number of effects increases, the performance ratio increases, but at a slow rate. This is not the case for other configurations of MEE such as ME-TVC or ME-ABS systems.

MEE plants of the HTTF arrangement can be configured in several ways:

- Horizontal or stacked (vertical) layout of the effects.
- Once-through brine flow or recirculation in each effect.
- Forward feed or backward feed.

3. MEE design concept

The feed sea water and the heating steam are introduced, respectively, into the sea water film on tube surface and tube-side phases. Heat transfer through tube-wall phase causes the heating steam to condense and part of feed sea water to evaporate. The evaporating steam moves into the shell-side phase, and then into the tube-side phase of the next effect. The condensate of tube-side phase called distillate, and the rest sea water of shell-side phase accumulate on the pot of each side, and cascade to corresponding pots of the next stage. The simplified control volume used for the evaporator is shown in Fig. 6.

For mathematically describing the various mass and heat transfer processes in this process, some main assumptions should be made. These include the following:

- vapor and brine are at saturation temperature;
- all steam entering tube side will condense at saturation temperature;
- constant specific heat; and
- negligible heat losses from the evaporator surface.

4. MEE operating principle

In MEE, a series of evaporator effects produces water at progressively slightly lower pressures.

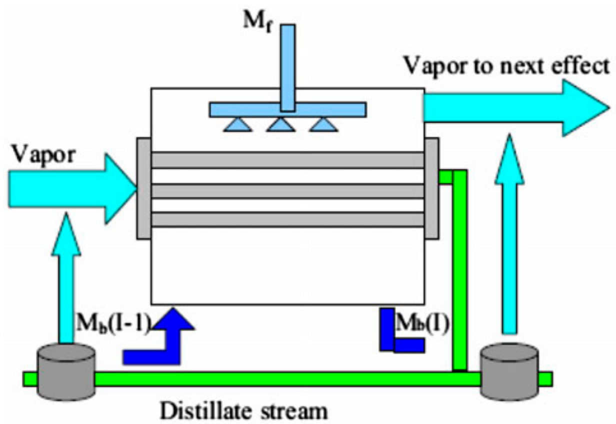

Fig. 6. Evaporator schematic diagram.

Because water boils at lower temperatures as pressure decreases, the water vapor of the first evaporator effect serves as the heating medium for the second evaporator effect, and so on. The more the effects, the higher the performance ratio.

Thus, theoretically (assuming no losses), if a single-effect evaporator produces 2.2 kg per 1.055 MJ (1 lb/1,000 Btu), then three evaporator effects will produce about 1.8 kg (4 lbs) of distillate with the same amount of heat. Fig. 7 shows three effects of a multiple-effect evaporator. Effect 1 is at higher pressure than effect 2, and similarly, the pressure in this effect is higher than that in effect 3. The heat source in effect 1 is enough to boil a portion of the feed water entering at the top of the unit. The vapor formed in this effect heats the next lower pressure effect. The process of producing vapor in each effect, and using it to heat the next lower effect, continues throughout all the effects until the vapor for the last effect is condensed in the main condenser. Brine from each effect can be directed to the next lower effect or it can be taken out at specific points in the process. Distillate, product water, is obtained from the condensate of the vapor in each effect and from the main condenser.

5. MEE process characteristics

Table 1 gives the process characteristics of each of the pre-described MEE processes. Although the main temperature of operation given for the horizontal and vertical arrangements is 76.7˚C (170 ˚F), this type of unit can operate at temperatures upto 110˚C (230 ˚F).

Development of MEE in the last few years has brought this process to the point of competing technically and economically with the MSF process. Major features of the MEE process are low primary energy consumption, low heat transfer area, and high gain ratio.

Al-Shammiri and Safar [12] presented the main features of 22 existing MEE plants with different design parameters such as the capacity, construction year, location, designer, and type of plant according to MEE configuration. Also the gain ratio, number of units, number of effects, operating temperature, using acid, or antiscalant to prevent scale and the duration of acid cleaning were presented as well as the construction material for the evaporator tubes, evaporator tube sheets, condenser tube, and condenser sheet.

Low-temperature (LT) and high-temperature (HT) MEE plant configurations are dictated by TBT. A HT is greater than 90˚C and a LT is less than 90˚C. In 1993, Morin [4] showed that MSF needs about half as much heat transfer surface area required for the Low-temperature multi-effect (LT-MEE) process. This implies that if the plant works at HT, then the required heat transfer area will be less than that used in a LT-ME plant because the low operation temperature results in small heat transfer coefficient, which increases the required heat transfer area and the cooling water quantity.

Operating at high TBT results in a decrease in the specific heat transfer area because of the increase in temperature driving force per effect and the heat transfer coefficient, but the performance ratio of a MEE system is independent of the TBT. However, the low operating TBT results in many other advantages

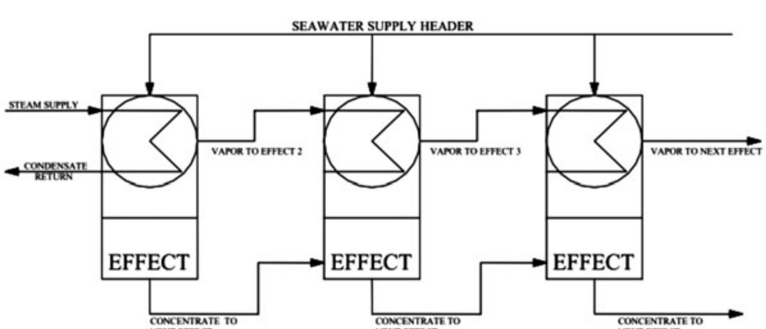

Fig. 7. Three effects of a multiple-effect evaporator [11].

Table 1
Process characteristics of MEE systems

Item	LT horizontal tube design	LT vertical tube design	Stacked vertical tube design	HT horizontal tube design	HT vertical tube design
Maximum operating temperature (°C)	71.7	71.7	110	110	110
Process recovery (percent)	20–35	20–35	67	20–35	20–35
Performance ratio (kg/MJ)	3.44–5.17	3.44–4.30	10.33	3.44–6.46	3.44–6.46
Heat transfer coefficient (w/m^2K)	1,703–3,407	1,703–3,407	4,542–11,356	1,703–4,259	1,703–4,259
Concentrate (mg/l)	54,000	54,000	106,000	54,000	54,000
Electrical consumption (MJ/m^3)	0.00132–0.0026	0.00132–0.0026	0.000528–0.00106	0.00132–0.0026	0.00132–0.0026
Distillate quality (mg/l)	0.5–25.0	0.5–25.0	0.5–25.0	0.5–25.0	0.5–25.0
Pretreatment chemical	Polyphosphate	Polyphosphate	Acid or polymer	Polymer	Acid or polymer
Pretreatment dose rate (mg/l)	0.5–4.0	0.5–4.0	Acid at 140 Polymer at 1–2	1.0–2.0	Acid at 140.0 Polymer at 5–10

such as low-energy consumption (consumption as low as 2.5 kWh/m^3) when using waste heat and upto 5 kWh/m^3 when using prime energy [13].

Almost all the new plants constructed in the 1990s were coupled to thermal vapor compression with a horizontal tube effect, in which these plants were coupled to thermal vapor compression. This combination is used when the available motive steam pressure is above the pressure required in the first effect. The main features of this combination are the increase of performance ratio, less cooling water needed than conventional MEE, and the primary heat source required is reduced because it compresses mostly generated vapor and reuses it as a heating source. Also, the thermal vapor compression system is inexpensive and durable (no moving parts), but it has a low efficiency compared with the mechanical and the absorption heat pump or heat adsorption pump.

The modern MEE plants are designed to switch between two modes of operation, depending on the seasonal variation in power and water demand. The first mode combines ME with a single-stage steam ejector, which compresses the vapor extracted from the last effect. The second mode of operation uses low-pressure heating steam.

The new MEE plants are directed to large scale and large capacity. The LT plant has made possible the utilization of economical and durable materials such as aluminum alloy, but it requires a special feed treatment, large volume evaporator, and a high heat transfer area. Most of the modern plants use titanium in the first three rows of the evaporator, such as in the IDE and SIDEM technology since the harshest operation conditions are in the first three rows. The other evaporator tubes are made from more economical material such as aluminum alloy (AL-brass 76/22/2).

6. New innovations and current development

Al-Shammiri and Safar [12] listed some new innovations and current development work with the potential of increasing MEE process performance. The innovations and developments focus on alternate forms and materials of heat transfer surface, a new range of operation temperatures, and combination with a new type of heat pump. These new innovations and current development are as follows [12]:

- Using more efficient tubes such as corrugated or doubled-fluted tubes (flouted from inside and outside) to increase the surface areas and the heat transfer coefficient. Using evaporators in a vertical arrangement (MES) (as in the southern California project) permits reducing the quantity of tubing by half and the size of the enclosing vessels by the same amount. Also, using a surfactant permits a further 20–30% decrease in tubing [13]. The new method to enhance the overall HTC in ME plants is by suspending a small diameter rod inside each tube and using a mechanism to orbit the rod and in contact with the inside tube walls. The action of the rod results in increased heat transfer coefficient, and a value of 34,000 W/m^2C was obtained [14,15]. This technique also results in high sheer stress inside the tube preventing the adhesion of scale and carrying the microscopic crystals to the bulk film.

- The most important recent change in materials is the understanding of how to use aluminum successfully in the evaporator, condenser and preheater tubes. The aluminum tubes are not only cheaper than any other heat transfer surface but also are more tolerant of both oxygen and acid than Cu–Ni alloys. But aluminum cannot tolerate heavy metals (iron, copper), sulfide and suspended grit or sand.
- A new compact heat exchanger completely welded, called bavex. The bavex plate is corrugated and fitted together to be suited for film evaporation and has been used in a standard unit of 2,500 m^3/d with a 12-stack effect mounted module in a series at the warm end with a four-effect horizontal package arrangement operating with a heat recovery by a thermo-compressor across the first four effects, operated at a TBT below 85˚C. This arrangement results in a high performance ratio of 20 [16].
- Bom [17] proposed suggestions to improve the performance of ME and reduce the cost of plant construction, such as using short tubes with a small diameter, double-flouted aluminum with 25 mm OD, length 0.5 m, instead of conventional tubes of 50 mm OD and 3 m length. These suggestions will result in a reduction of vapor velocity of tube outlet, resulting in much lower pressure loss and a significant improvement of heat transfer.
- The combination of MEE with a heat pump such as absorption or adsorption heat pump can be considered as a new development in the MEE system to improve MEE performance. This type of combination is also proposed by Jacques and Dominique [18] where a 2.5 mgd plant is proposed with a bromide absorption for 14 effects operated at 74˚C. The main feature of this plant is that the predicted cost is US $0.16/$m^3$, which is very competitive compared with that of potable water produced in a MSF, reverse osmosis and even with the cost of distilled water from a classical source (district or river as feed water). El-Dessouky and Alttouney [19] proposed a new, high-performance system for the first time to be coupled with an MEE system. The system includes a combination of zeolite-water adsorption heat pump with MEE system to increase the efficiency of the MEE plant.

The main features of the MEE evaporator are:

(1) Compactness: The evaporator is delivered as a packaged unit, is compact and mounted on a single frame support with the accessories (pipe work, pumps, electrical cubicle, etc.) necessary for its operation. Upon its arrival at the job site, this unit is ready to operate after being set on its foundation and connected to the utility. For transport reasons, bigger units may be shipped in several blocks to be assembled on site.
(2) Low-Operating Temperatures: The sea water is distilled in the evaporator at a very LT, around 40/60˚C. (104/140 ˚F). This minimizes the problem of scaling (which results in a drop of the heat exchanger efficiency) and of its eliminates frequent acid cleanings that over the long term result in materials corrosion.
(3) Reliability: The plant is sturdily built and does not include any rotating parts except for the pumps
(4) Simplified Water Intake: Besides the generally necessary chlorination, the MEE Unit does not require any pretreatment of the raw water. The water intake facilities are thus simplified, and normally consist of a strainer and a pipeline. It should be noted that the absence of any pretreatment procedure is the basic advantage of the MEE process. The cost of the pretreatment plant and the chemicals required by any demineralization system will substantially increase the cost of the produced water. Furthermore, pretreatment requires considerable equipment maintenance in the form of plugged filters, chemical handling, etc.
(5) Simple Operation and Maintenance: The basic rules in designing MEE evaporators have been to minimize erection work at the site, to simplify operation, and to reduce required maintenance. Thus the MEE process is well adapted for use in remote areas where highly trained staff is not available.
(6) Flexible Operation: The quantity of water produced can be adjusted to the customer's actual needs.

Low-temperature multi-effect (LT-MEE) is the most efficient thermal desalination processes currently in use. It incorporates technological advances which have resulted in reliable, durable, and economical desalination plants producing high purity product water. The advantages of LT-MEE are as follows [20]:

(1) Development of a unique design of a falling film horizontal tube evaporator/condenser with high heat transfer coefficient, utilizing only latent-heat transfer, avoiding sensible heat pick-up.
(2) Superior thermodynamic efficiency and very low-pressure drops at high volumetric vapor flows, as prevailing in LT operation. This enabled the optimization of the process for operation at a maximum brine temperature of 70˚C.

Table 2
Yanbu plant design parameters

Parameters	Flow (t/h)	Pressure (barA)	Temp (°C)	TDS (ppm)	Enthalpy (kJ/kg)
HP steam	293.0	65.0	525.0	–	3,476.9
LP steam	371.5	17.0	209.3	–	2,809.4
Condensate return	293.0	9.0	85.0	–	355.9
Sea water intake	20,000.0	4.0	33.0	45,000	130.6
Cooling water discharge	10,055.0	3.0	43.0	45,000	170.2
Distillate production	2,841.0	6.0	45.0	–	188.4
Brine discharge	7,104.0	2.0	46.1	63,000	178.7

(3) The LT operation aided by a comprehensive multidisciplinary development and design approach has made possible the utilization of economical and durable materials of construction such as aluminum alloy for heat transfer tubes, plastic process piping, and epoxy-painted carbon steel shells which show a better resistance when matched with aluminum alloy or titanium.

(4) The economy of using aluminum tubes for heat transfer as compared with copper alloy tubes, which are essential for higher temperature plants (used by other distillation manufacturers), enables the increase of the heat transfer area per ton of water produced in the desalination plant for the same investment costs.

(5) The significant increase in heat transfer area, in addition to the thermodynamic superiority of MEE over the MSF process, results in a very LT drop per effect (1.5–2.5°C), enabling the incorporation of a large number of effects (10–16) even with a maximum brine temperature as low as 70°C, consequently resulting in very high economy ratios (product to steam).

(6) Possibility of using low-cost/low-grade heat available through co-generation schemes to minimize the energy cost component.

(7) Minimal requirements for intake and pretreatment systems.

7. Design parameters of Yanbu plant

The following parameters characterize Yanbu MEE plant:

(1) Performance ratio or GOR

PR/GOR affects the number of stages/effects to produce the required water output. The higher the PR/GOR, the bigger the evaporator size.

(2) TBT

Max operating temperature will make the flash range (TBT–BBT). The high flash range and temperature difference will affect the LMTD to decide heat transfer area. The higher TBT will make the smaller evaporator by high LMTD.

(3) Salinity in sea water

The salinity in sea water is a factor of boiling point elevation. The boiling point elevation is a part of non-equilibrium loss to calculate LMTD. Therefore, lower salinity will make the smaller evaporator at same water output.

(4) Design sea water temperature

The lower design sea water temperature is same, meaning like higher TBT in flash range aspect.

Yanbu MEE unit is designed to produce 2,841 t/h (15 migd), 45°C distillate with 293 t/h HP steam of 65 barA and 525°C condition. Received HP steam is reduced in the steam-reducing station down to 17 barA, 209.3°C and it flows into the steam transformer. Entering LP steam is then condensed and returned back to the power station at the temperature of 85°C. In the meantime, steam transformer receives latent heat from LP steam and it produces saturated process steam at the pressure of 15 barA. Table 2 shows Yanbu major design parameters of Yanbu plant.

8. Conclusions

In this paper, the main features of MEE was highlighted. Some new innovations and current developmental works in MEE process were discussed. Various MEE configurations were reviewed. LT thin-film evaporators proved to be effected. Multi-effect thermal vapor compression (ME-TVC) has been used in many locations and illustrated high efficiency. So MEE process has a highly attractive design and operating features that make it competitive against the dominant MSF process. These features will increase MEE share in the future desalination market.

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