ELSEVIER

Desalination 126 (1999) 45–59

DESALINATION

www.elsevier.com/locate/desal

Multi-effect distillation plants: state of the art

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Abstract

The multi-effect distillation (MED) process is the oldest process in desalination. References and patents have existed since 1840, more than 150 years ago. Vertical tubes, horizontal tubes and different types of submerged tubes have been commercialized and were used until 1960 when multi- stage flash (MSF) dominated the desalination market. MSF plants are presently the most widely used and are considered as reliable sources for the production of fresh water from the sea in Middle East countries, in general, and in the Gulf region, in particular. Development of MED 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 MED process are low primary energy consumption, low heat transfer area and high gain ratio. This paper discusses the general features of existing commercial MED plants and associated technical aspects related to steam, condensers, evaporators, pumps and capacity. It also discusses gain ratio, operating temperature, materials of construction, operation and maintenance of these plants, associated problems, and other available information. Attempts to identify areas of development are also presented.

Keywords: Multi-effect plant; Gain output ratio; Construction material; Heat pump; Scale; Seawater

1. Introduction

There are four different types of desalination plants in existence: multi-stage flash (MSF), multi-effect (ME), multi-effect vapor compression (MEV), and reverse osmosis (RO). The selection of dependable, efficient and economic desalination methods is of great importance, especially in the Arabian Gulf countries.

Kuwait's first experience with desalination was the triple-effect submerged tube evaporator that was built in the 1950s to produce distilled water. This plant suffered from hard scale that formed on the tubes; therefore, when MSF was

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Presented at the Conference on Desalination and the Environment, Las Palmas, Gran Canaria, November 9–12, 1999. European Desalination Society and the International Water Services Association.

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PII: S0011-9164(99)00154-X

introduced in the 1960s, it dominated the desalination market because scaling was slow and easier to remove on MSF than in the old ME. Since the 1960s, the MSF process has proved to be more reliable and simpler to operate and maintain than other desalination systems. As a result, MSF became the leading method of seawater desalination.

The SIDEM mother company has been producing ME plants for ships since 1890. Since then, more than 500 ME plants have been commercialized by the group [1]. In 1995 the MSF share of world capacity was 69%, whereas the RO share is about 23% and the ME is about 8% [2]. These numbers indicate the present status of desalination in the world and show that MSF popularity is decreasing in the desalination market, and new processes such as RO and ME are beginning to take the lead. Over the years ME has been developing and has reached a stage at which many researchers predict that it will take a large portion of the desalination market in near future.

This paper discusses the general features of 22 commercial MED plants and their capacity; construction year; location; designer; type of plant according to ME configuration; gain ratio; number of units; operating temperature and the construction material for the evaporator, condenser, preheaters and demister. Associated operational and maintenance problems of these plants are provided. Attempts to identify areas of development to improve ME plant performance are also presented.

2. Multi-effect boiling distillation plant

The conventional type of dual-effect plant normally consists of a steam supply, a number of effects, a series of preheaters, a train of flashing boxes, a condenser and a venting system [3]. The motive steam is always extracted from a power generation turbine, a special boiler or by flashing steam from a waste energy source. ME plants have many limitations, i.e., as a top brine temperature (TBT) of 120°C by calcium sulfate scaling, and the temperature at the bottom end condenser is limited to the normal temperature of seawater used as a cooling water. The plant effects must be operated at specific vacuum pressure according to boiling point elevation, saturation pressure, salt concentration and others parameters. The number of effects in ME is restricted by the temperature difference between the condensing temperature at the first hot plant effect and the condensing temperature at the final condenser.

The ME evaporation process can be considered the only process that can have many possible configurations. The ME 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 ME 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.

There are two ways to link the effects together to form an ME plant. The first one is the horizontal effect where the effects are linked together horizontally, and the second is the stacked layout where the effects are linked vertically. Almost all the larger ME plants tend to be arranged horizontally because of their stability and simplicity in operation and maintenance. The stack layout already exists in many small ME plants. A multi-effect stack (MES) plant can be arranged in two ways: simple MES where the evaporators are stacked one on the top of the other as in the Al-Ain plant, or a double stack configuration where the effects are arranged in a double stack configuration, i.e., effect 1,3,5.., one on the top of the other in one stack and effects 2,4,6,...above each other in the other stack as in the Nagoya and Um-Al-Naar plants. The main difference between the horizontal and stack arrangement is that the brine in MES flows by gravity from the top effect to the next effects without pumps.

Morsy et al. in 1993 [4] compared the horizontal and stack arrangement of ME and found that the heat transfer area required for the horizontal arrangement is about double the area for the stack arrangement, and the number of packing per cell is ten for horizontal and six for stack arrangement. The capital and maintenance costs of the MES plants are lower than other designs since a pump is used only for feed water, acid injection, brine down blow and product water. The other main features of an MES plant are the compactness in plant area; high heat transfer coefficient (HTC), for example, a 3000 W/m^2.K was obtained at a 60°C TBT [5]; and stability in part load without any serious problems under Arabian Gulf conditions [6].

3. LT–ME and HT–ME plant

Low temperature (LT) and high temperature (HT) ME plant configurations are dictated by TBT. A high temperature is greater than 90°C and a low temperature is less than 90°C. In 1993 Morin [7] showed that MSF needs about half as much heat transfer surface area required for the LT–ME process. This implies that if the plant works at high temperature, 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 HTC, 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 ME system is independent of the TBT [8].

Operation at low temperature will avoid scaling and corrosion problems that might cause a serious problem in a HT–ME plant. TBT is limited to about 75°C with antiscalant treatment, but by using acid treatment of the feed water, one can operate at a higher brine temperature [9]. a thermo-economic assessment of a dual-purpose plant in the Arabian Peninsula was carried out by Breidenbach et al. [10] for a high-temperature vertical tube evaporator (HT–VTE) with a gain ratio of 17 to 21 as well as three different low-temperature horizontal tube (LT–HTE) ME plants with a gain ratio of 9.5 to 13.5. The study showed that the lowest production cost is provided by the HT–VTE plant. However, the low operating TBT results in many other advantages such as low energy consumption (consumption as low as 2.5 kWh/m^3) when using waste heat and up to 5 kWh/ m^3 when using prime energy [11]. The ability of a LT plant to make effective use of low-cost, low-grade heat or even zero-cost waste heat, reduces the motive team required to a minimum [12], and with the flexibility of a LT–ME plant, specific power consumption is not changed markedly when operating on partial load [13]. Utilization of economical and durable construction material such as aluminum alloy tubes, plastic piping and epoxy painted steel shells increases the performance ratio due to their high thermal conductivity and decreases the capital cost due to their low cost.

4. Modern combination of ME system and heat pumps

There are five types of modern combinations used in ME plants: conventional LT–ME without any heat pump; LT–ME with mechanical vapor compression (ME–MVC); LT–ME combined with thermal vapor compression (ME–TVC) (this type of combination is already used in many ME plants in the Arabian Gulf and other countries); ME combined with absorption heat pump

(ME–ABS); and ME combined with adsorption heat pump (ME–ADS). The last two combinations can also operate at high TBT and can be considered as a new proposed combination.

El-Dessouky and Alttouney [3] found, through a mathematical simulation model for a ME–ABS system, that this system can reach a performance ratio of 25 with only 12 effects at 110°C, and the ME–ADS system can reach a performance ratio of 20 at the same number of effects and operating temperature. The performance ratio of a conventional ME system with the same number of effects cannot exceed 10.

5. Survey of existing ME plants

Table 1 presents the main features of 22 existing ME plants with different design parameters such as the capacity, construction year, location, designer and type of plant according to ME configuration. Table 2 presents the gain ratio, number of units, number of effects, operating temperature, using acid or antiscalant to prevent scale and the duration of acid cleaning. Table 3 presents the construction material for the evaporator tubes, evaporator tube sheets, condenser tube and condenser sheet. Associated problems are provided (Tables 4 and 5). A brief description of each plant and performance is also provided.

5.1. St. Thomas 1,2 and St. Croix 1

Three LT–ME plants with thermal vapor compression, horizontal tube falling film (LT–ME–TVC–HTE–FF) with a design capacity of 1.25 mgpd were installed in St. Thomas and St. Croix by Israel Desalination Engineering (IDE), coupled to an existing power plant using extraction steam from the power plant turbine of 38 psia (3 bar) previously fed to the MSF plant located on the same site. After 1 year of operation, the production of these plants was reported to be always above the design capacity. The real production was 1.34, 1.327 and 1.364 mgd, whereas the design is 1.25 mgd. Also the gain ratio of these plants is 13, 12.4 and 14.7, all above the nominal gain output ratio(GOR) of 10. The acid cleaning of these plants is predicted to be carried out only every 2 years, but in real operation, it is only needed after 6 years of operation, which reflects the reliability of a LT–ME–TVC plant as a reliable desalination source. After 10 years of operation, guaranteed capacity has always been met; the availability of the plant has exceeded 97%, and the purity of the product water is 16 ppm.

5.2. Mirfa, Sila and Jebel Dhanna, UAE

Mirfa, Sila and Jebel Dhanna are four identical dual-purpose plants. The plants are LT–ME–TVC coupled to a diesel oil-fired boiler. Each plant has four units with four cylindrical effects per unit with the following dimensions: 4.8 m diameter, 12 m length and 60 t of weight, to reach the required GOR of 8 [1], but this type of plant (with say 12 effects) can reach a PR of 17 when using TVC without any excessive investment costs when working with the thermal vapor compression as a second mode of operation.

The construction period was only 2 years. The four plants are located at three different sites. Although the plants are located on high turbidity, salinity, and high biological activity sites, they were always kept in operation, and a remarkable stability of monitored parameters was observed. The electric consumption of the evaporator is only about 1 kWh/m^3 of distillate produced. After more than 3 years of continuous operation, tubes are clean, the fouling factor has never exceeded the design fouling value, and the performance test results have shown a 10% higher production and 10% better GOR over the design [26].

Table 1
List of survey ME plants

Plant	Capacity, mgd	Type	Design	Const year	Location
Mirfa	2.0	LT–TVC–SF	SIDEM	1991	UAE
Jebel Dhanna	1.0	LT–TVC–SF	SIDEM	1991	UAE
Sila	1.0	LT–TVC–SF	SIDEM	1991	UAE
Trapani	14.5	LT–TVC–SF	SIDEM	1992	Italy
Ashdod	4.6	LT–TVC–HTE–SF	IDE	1983	Israel
St. Thomas.1	1.25	LT–TVC–HTE–FF	IDE	1981	USVI
St. Thomas 2	1.25	LT–TVC–HTE–FF	IDE	1981	USVI
St. Thomas 3	2.25	HT–VT–FF	Envirogenc	1974	USVI
St. Croix 1	1.25	LT–TVC–FF	IDE	1982	USVI
St. Croix 2	1.0	HT–VT–FF	Stearns Rogers	1968	USVI
St. Croix 3	2.25	HT–VT–FF	Envirogenc	1973	USVI
Curacao	3.2	LT–TVC–HTE–FF	SIDEM	1989	Netherlands
St. Marteen	2.0	LT–TVC–HTE–FF	SIDEM	1990	French West Indies
Tunisia	0.032	LT–VTE–FF		1987	Tunisia
Eilat	1.0	LT–HTE–SF	IDE	1974	Israel
Al-Ain	0.1319	HT–MES–HTE–SF			UAE
Umm-Al-Naar	0.032	LT–MES–SF	Sasakura	1984	UAE
PSA–I	0.019	LT–MES–TVC–SF	ENTROPIE	1988	Spain
PSA–II	0.019	LT–MES–ABS–SF	ENTROPIE	1994	Spain
So. California[a]	75.0	HT–MES–VTE–FF	Metropoln	1997	So. California
Nagoya	0.264	HT–MES–FF	Sasakura	1974	Japan
Ebeye	3.9	LT–TVC–FF–HTE	IDE	1987	Marshall Island

[a]Not yet constructed. SF, spray film; MES, multi-effect stack; ABS, absorption heat pump; FF, falling film; VTE, vertical tube evaporator; LT, low temperature; TVC, thermal vapor compression; HT, high temperature; HTE, horizontal tube evaporator.

5.3. St. Thomas 3, St. Croix 2,3 and Eilat

The three plants of St. Thomas 3 and St. Croix 2,3 in the Caribbean have vertical falling film tubes, whereas Eilat, Israel, has a spray horizontal tube evaporator at 55°C in Israel. The three Caribbean plants were all dual-purpose plants with an oil-fired boiler. St. Thomas 3 and St. Croix 3 were designed for a GOR of 13, but they were functioning at a ratio of 7–8 with many corrosion problems. Eilat had a performance ratio of 10.1, with no corrosion problems during operation due to low operation temperature. Some scaling problems were observed in St. Thomas 3 and no scaling problems in the Eilat plant.

Table 2
Main features of survey ME plants

Plant	Top brine temp., (°C)	No. unit	No. effect	GOR	Dosing type	ACF. (month)	Reference
Mirfa	58.5	4	4	8–17	B	6	1,26
Jebel Dhanna	58.5	4	4	8–17	B	6	1,26
Sila	58.5	4	4	8–17	B	6	1,26
Trapani	55.0	4	12	16.6	B[a]	12[c]	14
Ashdod	62.9	1	7	5.7	B[b]	15	15
St. Thomas 1	71.2	1	17	13–14	A	24	13,27
St. Thomas 2	71.2	1	17	14.7	A	24	13,27
St. Thomas 3	121	1	17	7–8	A		28
St. Croix 1	71.2	1	17	12.4	A	24	13,27
St. Croix 2	121	1	11		A		28
St Croix 3	121	1	17	7.8	A		28
Curacao	70	1	12	9.8–13.4	B	12	11,16,29,30
St. Marteen	70	3	4	17	B	12	16
Tunisia	60	1	6		B		31
Eilat	70–74	1	12	10.1	B[b]	12	28
Al-Ain	115	1	55				5
Umm-Al-Naar	99	1	18	12.7	B		18,20
PSA–I	69	2	14	9.4-14	B		19,31,33
PSA–II	69	1	14	24	B		19,31,33
So. California	110	18	30	23	A, B		32
Nagoya	110			6	A	18	17
Ebeye	70	1	12		B[b]		30

[a]Belegrad (2–3);
[b]Phosphate
[c]Clean only first two effects.
A, acid; B, antiscale; ACF, acid cleaning frequency.

5.4. Ebeye

This plant is LT–HTE–FF–ME operating at 70°C as TBT. Seawater is supplied to the plant from two salt wells drilled to a depth of 75 ft. The feed is treated with a polyphosphate additive. This plant utilizes low-grade waste heat from diesel engines. The others main feature of this plant is the capability to follow the power station

Table 3
Material construction of ME plants

Plant	Evaporator tube			Condenser	
	Sheet	First row	Other rows	Tubes	Sheet
Mirfa	SS316L	Titanium	Al-brass 76/22/2	Al-brass 76/22/2	SS316L
Jebel Dhanna	SS316L	Titanium	Al-brass 76/22/2	Al-brass 76/22/2	SS316L
Sila	SS316L	Titanium	Al-brass 76/22/2	Al-brass 76/22/2	SS316L
Trapani	SS316L	Titanium	Al-brass 76/22/2	Al-brass 76/22/2	SS316L
Ashdod	Aluminum	Titanium	Al-alloy	Al-alloy	Steel
St. Thomas 3	S316/B[a]	90/10 Cu/Ni	90/10 Cu/Ni	90/10 Cu/Ni	S316/B[a]
St. Croix 2	90/10 Cu/Ni	90/10 Cu/Ni	90/10 Cu/Ni	90/10 Cu/Ni	90/10 Cu/Ni
St. Croix 3	90/10 Cu/Ni	90/10 Cu/Ni	90/10 Cu/Ni	70/30 Fe/Mn	90/10 Cu/Ni
Curacao	SS316L	Titanium	Al-brass 76/22/2	Al-brass 76/22/2	SS316L
St. Marteen	SS316L	Titanium	Al-brass 76/22/2	Al-brass 76/22/2	SS316L
Eilat	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
Um-Alnar	Steel	70/30 Cu/Ni (first effect all tubes)	AL-Br (naval brass[b])	Titanium	Steel
So. California[c]	Concrete		Al-alloy		
Nagoya	Steel	Al-brass	Titanium	Titanium	Steel
Las Palmas	Al-#5052	Titanium	Al-#5052,	Al-#5052	Al-#5052

[a]Inside, 90/10 Cu/Ni; outside, cladding on steel.
[b]Tube sheet material.
[c]Not yet constructed.

load without any instability. The final assembly of the plant and testing took place in January 1987. The performance test showed a 19.2% increase in the production over the design and 100% gain in water quality of 25 ppm, which exceeded the guarantee of the plant.

5.5. Trapani

The Trapani ME plant represents one of the latest and the largest examples of the application of the ME process at low temperature for seawater desalination. The plant is LT–ME–TVC with a parallel brine configuration [14].

The Trapani ME plant consists of four identical units, and each has 12 effect evaporators arranged in six blocks with a diameter of 4.8 m, 17.5 m length and 110 t weight, with a GOR of 16.6 per unit and electrical power consumption of 1 kW/m^3, which represents the most remarkable features of this plant. The motive steam fed to the plant is at 45 bar, and condenses at 64.5 °C. The

Table 4
Failure in evaporator tubes

Plant	Corrosion type	No. of corroded tubes	Metal used	Types, location
St. Thomas 3		6	90/10 Cu/Ni	Fluted, evaporator
St. Thomas 3			90/10 Cu/Ni	Roped, preheater
St. Croix 2	Pitting	70	90/10 Cu/Ni	First effect evaporator
St. Croix 2		190	90/10 Cu/Ni	Remaining effects
St. Croix 2		240	90/10 Cu/Ni	Stage 1, preheater
St. Croix 2		40	90/10 Cu/Ni	Stage 2, preheater
St. Croix 2		3	90/10 Cu/Ni	Stage 3, preheater
St. Croix 3		40	90/10 Cu/Ni	First effect evaporator
St. Croix 3		25	90/10 Cu/Ni	2 effect evaporator
Eilat	Erosion	150	Aluminum	Condenser

Table 5
Conversion in ME plants

Plant	Feed rate	Feed to ME (make up)	Production	Conversion, %
PSA	20 m^3/h	12 m^3/h	3 m^3/h	15
Mirfa and Sila	1300 t/h	572 t/h	158 t/h	12
Bahrain plant (MES)	569 m^3/h	426 m^3/h	150 m^3/h	26
Ashdod	8600 t/h	2200 t/h	725 t/h	8.4
Trapani	1200 t/h	1130 t/h	375 t/h	31.2

other main advantages of this plant are the low seawater operation temperature (about 55 °C as a TBT) a very high efficiency and low power consumption (5.5 kWh/m^3). The construction material was selected according to SIDEM's standard material for seawater. The plant has an excellent conversion, which is about 31.2%. The antiscalant used is Belegrad EV at a rate of 2–3 ppm. The plant has been in operation since the end of March 1995. Each unit gives full satisfaction of production, and the product salinity is around 15–20 ppm. Acid cleaning is limited for the first two effects only each 12 months.

5.6. Ashdod

The plant is LT-TVC-HTE-FF-ME [15] and is coupled to a 50 MWE power plant. This plant consists of a LT steam generating unit (flash chamber), six heat recovery effects, and a condenser, which are contained in a single cylindrical horizontal vessel. The running-in of the plant was completed in March 1983, and during the first 12 months, the plant was operated almost continuously following the turbine load from its nominal capacity (about 45 MW) down to above 35% of this load. The thermodynamic efficiency of the plant is higher than expected in the design. The total operating and maintenance staff was 14. The only chemical used was ID-104, a polyphosphate scale inhibitor at a dosage of 15 ppm.

In April 1984, the plant was opened for inspection. The tubes of heat transfer surface were found to be relatively scale free, and a slightly calcium carbonate thin layer of scale (0.1 mm) was observed in warm effects. The clean state of the heat transfer surface of the plant was the reason for the high and constant performance during the first 15 months of operation with no need for chemical cleaning; no corrosion on the aluminum tubes at the condenser or evaporator parts could be observed, and the coating and paint were found in good condition, although the plant availability is 61%, which is low due to electrical breakdown failure.

5.7. Curacao (LT-ME-TVC)

The Curacao desalination plant is a dual-purpose plant designed for the Kompania di Awa Electrisidat (KAE) [16]. The plant produces 20,000 m^3/d of distillate water. The evaporator has 12 effects arranged in six adjacent cylindrical models. This plant is designed to operate with two modes of operation: one if no electrical power is needed, where the plant is fed with 2.55 bar steam at 155°C through a thermal compressor with GOR of 12.5–13.4; and one if electrical power is needed, where a turbine is fed with 2.5 bar steam, which will be expanded to 0.34 bar to generate 3.1 MW before passing to the evaporator. Thus, it is a classical ME with a GOR of 9.8.

In both modes of operation the plant produces to full capacity, and the design is such that there is no need to stop the plant to change from one mode to the other. The new feature used in the design to suit the dual-mode operation is that the design of the first six hot effects is different to that of the second six cold effects to accommodate the additional amount of vapor; when operating in the recycle mode, more and longer tubes, but with a smaller diameter, are used in the first hot effects. The seawater pre-heaters are conceived as separate objects outside the modules. The materials of the plant were selected according to SIDEM's standard material. The plant is supplied with a data acquisition system. During all operation years, the evaporators gave full satisfaction [16], and the frequency of acid cleaning was very low (once per year). The success of this plant led to the purchase of a new identical unit commissioned in June 1990. This new unit has a net power consumption for desalination below 5 kWh/m^3.

5.8. Nagoya (HT-MES)

This MES plant was developed through development research to prove the features of MES over the conventional MSF or VTE plants [17]. This plant has a GOR of 6 and a capacity of 1000 m^3/d.

The main feature of this plant is its high heat transfer efficiency, where it ranges between 4000–5000 Kcal/m^{2}h°C at a temperature of 110°C of condensing vapor. This high performance is due to elimination of brine depth to zero because of spraying the brine onto the outer surface of evaporator tubes in a thin film, reduction of volume and weight by using small-diameter tubes in the evaporator, and a minimal number of direction changes and a short vapor pass are employed since the vapor flows from each effect directly to the other end of the next effect.

The Nagoya MES plant, since it is compact with a vertical design, requires about one-half the plot area of a conventional distillation plant. This particular MES plant has been in operation for 16 months with no acid cleaning. Its capacity, performance ratio, temperatures and pressure have not deviated from the initial start-up and commissioning test data.

5.9. Umm Al-Naar solar desalination plant (MES)

This solar desalination plant is located in Umm Al-Naar, Abu Dhabi, in the United Arab Emirates. It was commissioned in November 1984 [18]. This plant continued operation from 1985 until 1995. During the first 7 years of operation, the evaporator did not show any deterioration in its performance; however, during the last 3 years (1992–1994), a decline in distillate production and a rise of specific heat consumption were observed and attributed to scale formation on heat exchange tubes, pre-heater and the condenser tubes due to the high operating temperature.

Although Belgard for anti-scale was used regularly, acid cleaning at low pH was used to overcome this problem and, as a result, the performance of the evaporator improved. No tube leaks were inspected during the 10 years of operation, whereas most of isolating valves and bolts used in the evaporator experienced moderate corrosion. No problem has been encountered with any tube bundle, and distillate salinity has been in the range of 10–20 ppm.

5.10. Plataforma Solar De Almeria MES plant

The Plataforma Solar De Almeria (PSA) developed a unique experience in desalination of seawater with solar energy using a MES LT system. This system was developed in 1988 and is still running. It is composed of two phases using the same ME plant with a small capacity of 72 m^3/d. The first phase operated from 1988 until 1991, when the second phase was developed. The evaporator is designed as a vertical shell with equal pre-heater areas shell and tube condenser. Sieve trays distribute the brine onto top rows of the tube bundle [19].

This plant has two modes of operation. The performance ratio is 10.4 to 9.4 when the plant operates in the low-pressure steam mode, but GOR can be increased up to 12–14 when the plant operates in the steam ejector mode. This system shows high reliability, and the only problem detected was the blocking of the spray device by silt deposition. During the second phase, the same system was improved by adding a double effect absorption heat pump, and this improve-ment was evaluated. The cost analysis of this new system showed that the cost is reduced to about of \$2/m^3 of distillate for large plants. The only problem during the second phase was the difficulty in achieving a steady-state condition with a heat pump and corrosion of carbon steel elements in contact with the working fluid of the heat pump (Li–Br solution). The main advantages characteristic of this new system are the reduction in the thermal consumption of the plant by 44% from 63 to 36 kW/m^3, the reduction of electricity consumption by 12% from 3.3 to 2.9 kWh/m^3, and the increase in performance ratio to 24 from 14 in the previous phase [19].

5.11. Major problems

The two main problems are scaling and corrosion. Scaling was observed in Umm Al-naar where some scale deposition was detected on the pre-heaters and condenser tubes due to the high operating temperature. Carbonate scaling was found in Mirfa, Sila and Jebel Dhanna, and the quantity of scale at 63 °C was observed to be four times the quantity of scale at 46 °C.

The hot effects of the Ashdod plant caused a thin layer of calcium carbonate scale, 0.1 mm, that slightly increased in thickness from effects 3 to 1. At the St. Thomas 3 plant, a scale problem was also reported. Scaling problems were observed to be combined with decreases in distillate production and a rise of specific heat consumption. Although antiscalant was used regularly, acid cleaning at low pH was used to overcome this problem. The SIDEM designed Trapani plant is cleaned routinely only for the first two effects every 12 months to avoid any scale accumulation.

Corrosion is considered the second major problem in ME plants. Cost of materials in the ME system represents 25% of the plant cost, and using low-cost materials would represent a large difference in overall cost, but the material must be carefully selected for high overall transfer coefficient, i.e., good thermal property and low corrosion rate, to avoid the high cost of replacing any plugged tubes. Materials used in some plants (Table 3) show very good performance without any serious problems in Sila, Mirfa, and Jebel Dhanna where no tube failure was indicated. The same was observed in Trapani with the same material, which was selected according to the SIDEM standard material for seawater. At Umm Al-naar after 10 years of operation, no corrosion was detected in tubes (90/10 Cu/Ni) with a 99 °C operation temperature. Other plants such as St. Thomas 3, St. Croix 2 and St. Croix 3 suffered from serious corrosion problems and high cost for replacement of tubes. Table 4 presents the numbers and locations of tube failures in some of the older plants.

Another problem observed in the surveyed plants was that the water produced had a relatively high salt content due to carrying some brine by vapor through the demister to the condenser, or due to leaks from feed heaters and in the main condenser as in the Ashdod plant. This problem can be decreased if the brine level is reduced to a minimum or a spray film technique is used; in this technique the brine depth was eliminated to almost zero. The fouling problem of the orifices at Mirfa, Jebel Dhanna and Sila was found to create a difficulty for the operators. This problem is caused by the accumulation of very fine silt on the distribution system as also observed at the Umm Al-Naar plant. The operator recommended using adequately sized spray nozzles and testing the nozzles to guarantee a homogenous flow density to overcome this problem. Interlock problems at Umm Al-Naar imposed restrictions on operating the equipment until the condition set in the design was fulfilled, such as a vacuum interlock for seawater intake pump, seawater pit level low, feed water flow rate, high conductivity of product water, and vacuum problem of the evaporator. These problems can be overcome by choosing the suitable set point for all the control parameters in the control system. Very low conversion in a MED plant (Table 5) compared to 35% of the RO system, where 80% of the cooling water in the condenser in the Ashdod plant is discharged to the sea and the remaining 20% becomes feed for evaporators, which results in about a 8.4% conversion. The conversion for Mirfa and Sila is 12%, , PSA is 15%, Bahrain MES is 26% and the Trapani plant, a modern one, has the highest conversion through the survey plant at 31.2%.

6. Discussion

MED plants are almost exclusively of the thin falling film type (Table 1) in which the brine runs down under the effect of gravity and is sprayed onto a bank of horizontal tubes in the form of a thin film. This type of evaporator reduces the carry-over and scaling problems and increases the HTC and performance of plant.

The performance ratio GOR is directly related to the number of effects in a conventional ME system (Table 2); as the number of effects increases, the performance ratio increases, but at a slow rate. This is not the case for other configurations of ME such as ME–TVC or ME–ABS systems.

The MES plant was always designed for small capacity, except for the new proposal project for southern California in which the stack arrangement for large capacity (75 mgd) is chosen for a first time. This plant is a new metropolitan program including 30 multi-effects and using double-fluted vertical aluminum tubes in a concrete tower.

There are 17 out of 22 plants operated at low temperature (Table 2). This indicates that the new generation of ME effects will be mostly operated at LT, despite the advantages of a HT–ME plant.

Almost all the new plants constructed in the 1990s were coupled to thermal vapor compression with a horizontal tube effect, in which 12 plants (Tables 1 and 2) 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 ME, 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 ME 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 as in the St. Marteen, Curaçao and Trapani plants.

The new ME plants are directed to large scale and large capacity as in Trapani. The projected plant at southern California was planned to be constructed with a capacity of 75 mgd.

The LT plant has made possible the utilization of economical and durable materials such as aluminum alloy (Table 3), 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 (Table 3) 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). There are eight out of 14 plants using these materials. Only St. Thomas 3 and St. Croix use a SS316 inside and 90/10 Cu/Ni outside clouded on steel and both suffer from a serious corrosion problem (Table 4).

Although Eilat uses aluminum alloy in the evaporator, preheater and condenser, the only corrosion noticed in this plant was in the condenser and it was erosion type (Table 4).

There is a strong relationship between corrosion and operating temperature. Although the same material is used in different plants (Tables 1 and 4), the plants with high temperature show greater corrosion problems, while the same materials did not suffer from any corrosion at the LT plants. Also, roped tubes tend to corrode more than the smooth ones.

All the surveyed plants proved the reliability of an ME plant where almost all the plants show acceptable performance and a production rate higher than the design. Although for long periods of operation, the product salinity remained at 16 ppm for St. Thomas 1, 2 and St. Croix after 10 years of operation, and the acid cleaning is done only 6 six years of operation on these plants with high availability. The same was noticed in Mirfa, Sila and Jebel Dhanna, which proves that ME is an alternative process for Gulf conditions, and that ME will be a large portion of desalination in the next decade.

7. New innovations and current development work underway in ME

Some new innovations and current development work with the potential of increasing ME process performance are listed below. 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.

- Using more efficient tubes such as corrugated or doubled-fluted tubes (flouted from inside and outside) to increase the surface areas and the HTC. 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 [21]. 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 HTC, and a value of 34,000 $W/m^2.C$ was obtained [22]. 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 (1993) 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 2500 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 thermocompressor across the first four effects, operated at a TBT below 85°C. This arrangement results in a high performance ratio of 20 [4].
- Bom [24] 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 ME with a heat pump such as absorption (Table 1) or adsorption heat pump can be considered as a new development in the ME system to improve ME performance. This type of combination is also proposed by Jacques and Dominique [9] 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, RO and even with the cost of distilled water from a classical source (district or river as feed water). El-Dessouky and Alttouney [3] proposed a new, high-performance system for the first time to be coupled with an ME system. The system includes a combination of zeolite-water adsorption heat pump with ME

system to increase the efficiency of the ME plant.

8. Conclusions

1. According to the latest technology used in the ME system, there are two ways to increase the GOR: increase the number of effects, which are limited to the maximum brine temperature due to risk of scaling; or couple the ME system to a heat pump. There are three types of heat pumps that can be coupled to the ME system: a Li-bromide/water absorption heat pump, an adsorption pump and a thermal vapor compression pump.

2. Combination of ME with a solar power plant is one of the most promising techniques, especially in Arabian Gulf countries where this source of energy is abundant.

3. The LT plant had reduced scaling and corrosion rates at acceptable levels, overcoming the main problems plaguing conventional HT distillation plants.

4. In designing a water plant to meet modern conditions, higher efficiency will be a major goal; this means efficiency not only in energy consumption, but also in operation costs, reliability and maintenance.

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