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Multi-effect boiling systems from an energy viewpoint

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Abstract

All desalting systems consume energy, either thermal or mechanical or both. In the search for energy-efficient desalting systems, it is clear that the reverse osmosis (RO) desalting system is more efficient than the widely used multi-stage flash (MSF) desalting system. For seawater in the Gulf area, as an example, RO consumes about 5 kWh/m^3 of mechanical work, while MSF desalting units consume about 4 kWh/m^3 pumping energy, besides thermal energy. The thermal energy input to large MSF units is in the range of 250–300 kJ/kg, and is usually in the form of slightly superheated steam extracted from steam turbines at about 2–3 bar. The equivalent work of this thermal energy is in the range of 17 kWh/m^3. The conventional multi-effect boiling (MEB) desalting system uses about half of the MSF pumping energy, and almost the same amount of thermal energy used by the MSF, if both have the same gain ratio. However, a recent trend of using low-temperature MEB (LTME) allows the use of low temperature (in the range of 70°C) steam as heat source, and consequently of low exergy and low equivalent work. This can bring the LTME consumed equivalent mechanical energy close to that consumed by the efficient RO system. The conventional multi-effect desalting system was revisited to show that thermal energy input to LTME is low, and can bring the equivalent mechanical energy, and thus the consumed fuel energy, to low values close to those of a seawater RO desalting system.

Keywords: Multi-effect boiling; Gain ratio; Equivalent mechanical energy; Falling film evaporator

1. Introduction

In practice, the efficiency of distillation desalting systems, in terms of consumed energy, is usually measured by some terms defined by:

1. Gain ratio (GR): $GR = D/S$ where D is the distillate output and S is the steam supplied to the desalting system (both have the same units). This rating method does not account for the steam enthalpy difference across the desalting unit, the supply steam quality (temperature and pressure), or the pumping work.

2. Performance ratio (PR): PR is the amount of desalted water produced by condensing 1 kg of steam at an average temperature corresponding to 2330 kJ/kg latent heat.

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$$PR = \frac{D}{(Q_d/2330)} = \frac{2330}{(Q_d/D)} = \frac{2330\,D}{\Delta h_s S_d} = \frac{2330\,GR}{\Delta h_s}$$

where Q_d is the heat supplied to desalting unit, and Δh_s is the enthalpy difference of the steam across the unit. When steam is supplied as saturated vapor and leaves as saturated liquid, then

$$Q_d = S\,L_s$$

where L_s is the steam latent heat, and the PR becomes

$$PR = \frac{2330}{L_s}\frac{D}{S} = \frac{2330}{L_s}(GR)$$

It is more rational to use PR than GR since it accounts for the enthalpy drop of the supplied steam, but still does not account for the steam availability or the mechanical work used by the pumps.

3. Specific heat consumption (Q_d/D): The specific heat consumption is the heat energy consumed to produce 1 kg distillate:

$$q_d = \frac{Q_d}{D} = \frac{2330}{PR}$$

Although the previous three expressions are widely used, they are not really appropriate to evaluate the performance of the desalination system for two reasons:

- the pumping energy, $W_{(pump)}$, is not accounted for, and
- the quality (or the availability) of the used thermal energy is not considered.

As an example, the condensation of 1 kg of saturated steam at 1 MPa (T_{sat} = 180°C ≅ 453 K) gives 2015.3 kJ/kg heat, while at 40 kPa (T_{sat} 76°C = 349 K) gives 2319.2 kJ/kg. Counting only by the amounts of thermal energy, one can conclude that 1 kg of steam at 40 kPa gives more condensation heat than that at 1 MPa. However, this is not true when the steam quality (pressure and temperature) is considered. The value of the steam is measured by its ability to produce work. The reversible (maximum) work, w_r, produced by 1 kg of saturated steam at temperature, T_s, and ambient temperature, T_e = 300 K is

$$w_r = L_s\left(1 - \frac{T_e}{T_s}\right)$$

The term w_r is called the specific exergy or the availability.

- For 1 kg of steam at 1 MPa

w_r = 2015.3 [1−(300/453)] = 680.7 kJ/kg

- For 1 kg of steam at 40 kPa

w_r = 2318.55 [1−(300/349)] = 325.6 kJ/kg

This clearly shows that the real value of steam at 1 MPa is almost twice that at 40 kPa.

Other meaningful criteria can be considered in the rating of the desalting systems such as:

- Specific fuel energy: The amount of fuel energy used to produce the thermal energy Q_d and mechanical energy $W_{(pump)}$ required to produce 1 kg of distillate.
- Specific consumed available energy: The available energy W_r of the supplied steam plus the pumping work $W_{(pump)}$ required to produce 1 kg of distillate.
- Equivalent specific mechanical energy: The work W_d equivalent to the thermal energy and the pumping work $W_{(pump)}$ required to produce 1 kg of distillate.

This paper revisits the multi-effect desalting system through examples from operating units and presents its main characteristics. The suggested terms used to evaluate the efficiency of thermal desalting systems (specific consumed fuel, specific consumed available energy, and specific equivalent work) are applied to evaluate the real performance of the multi-effect desalting system.

2. Conventional multi-effect desalting system

The conventional multi-effect desalting system (MEB) is the oldest method used to desalt seawater in large quantities. It has many variants such as forward feed (Fig. 1), parallel feed

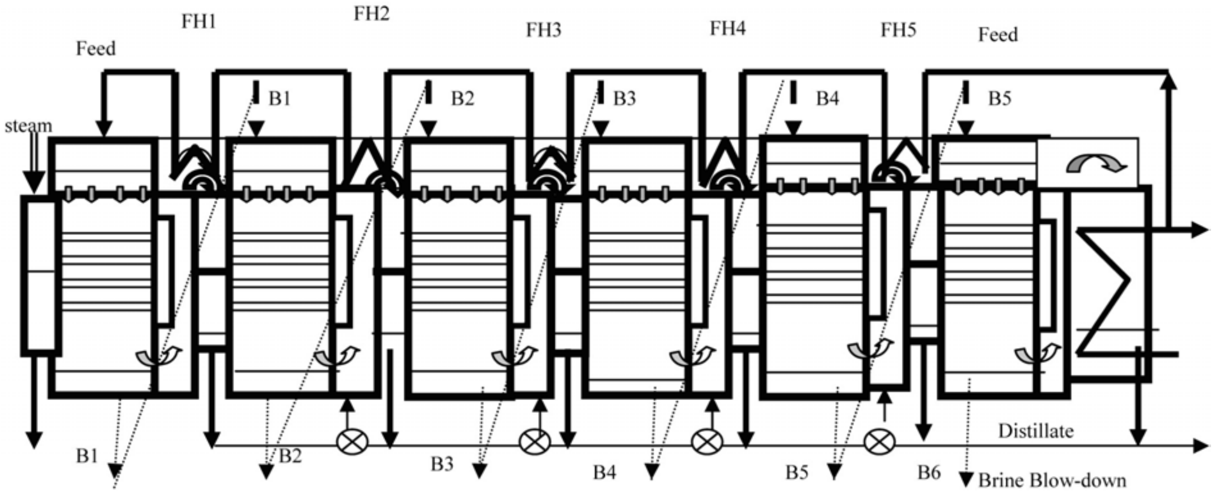

Fig. 1. Forward feed multi-effect boiling with regenerative feed heaters.

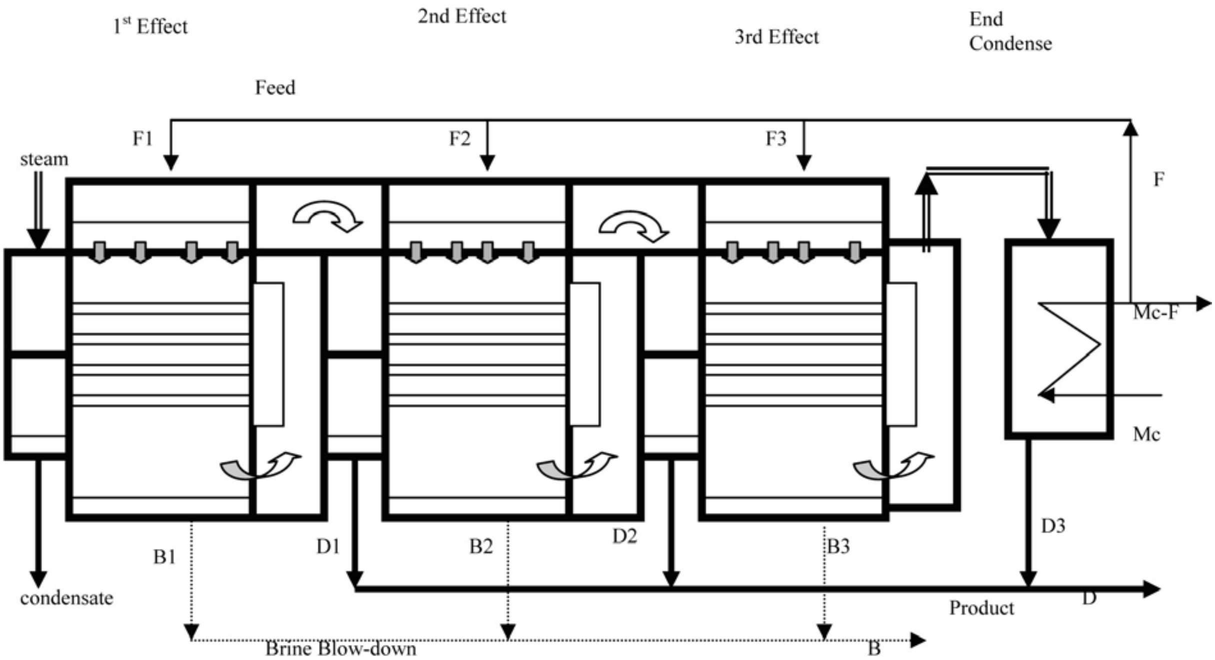

Fig. 2. Parallel feed multi-effect desalting unit with no pre-feed heaters.

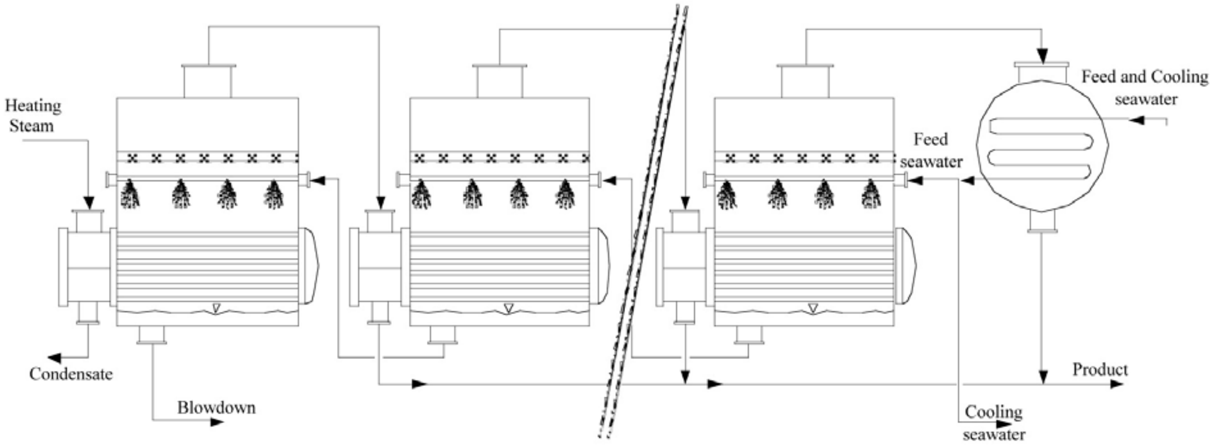

Fig. 3. Backward feed multi-effect desalting system using horizontal tube evaporators.

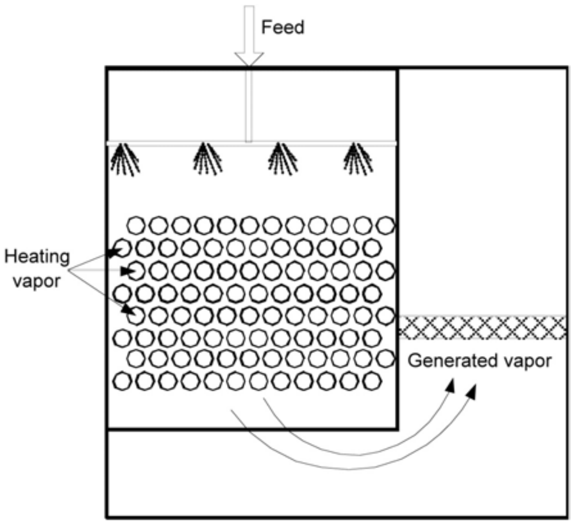

Fig. 4. Horizontal falling film tube evaporator.

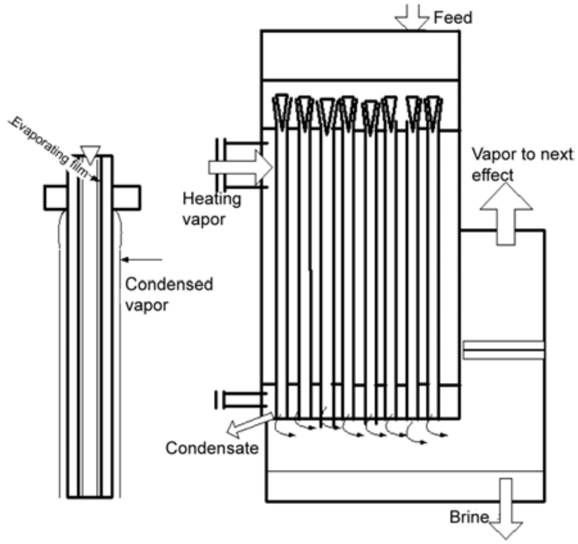

Fig. 5. Falling film vertical tube evaporator.

(Fig. 2), mixed feed, and backward feed (Fig. 3). In the forward feed, both water feed and heating vapor to the evaporators flow in the same direction; hence the least salinity is at the highest temperature in the first effect. The backward feed system where heating vapor and feed flow are opposite to each other is rarely used in desalination since the first effect has the highest temperature and salinity.

Early MEB units used submerged tube evaporators. In these evaporators the heating coils are submerged in a pool of boiling seawater and were known to have low heat rates and high scale formation [1]. Modern MEB units use falling film evaporators (either horizontal as in Fig. 4 or vertical as in Fig. 5 and feed heaters between effects as in Fig. 1. Parallel feed is used when partial or no feed heaters are used between

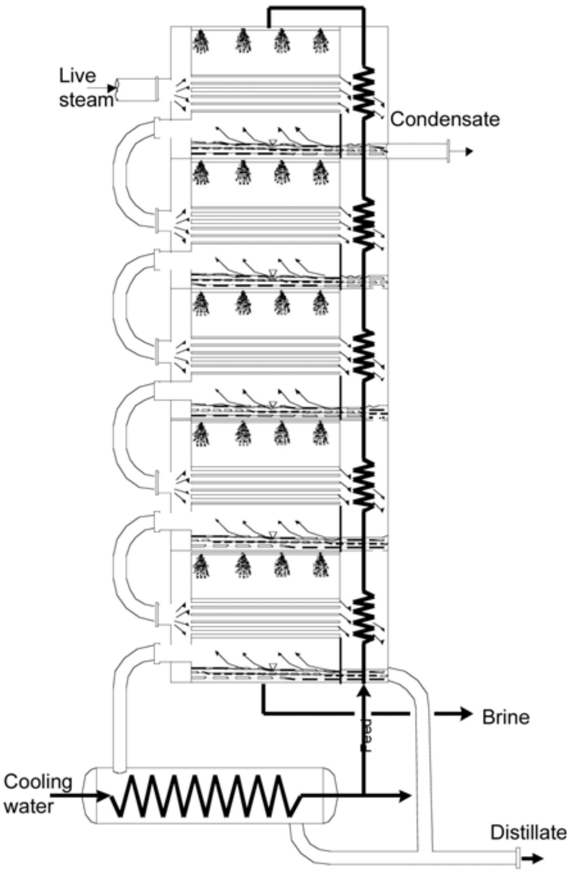

Fig. 6. Multi-effect desalting system with evaporators stacked vertically [2].

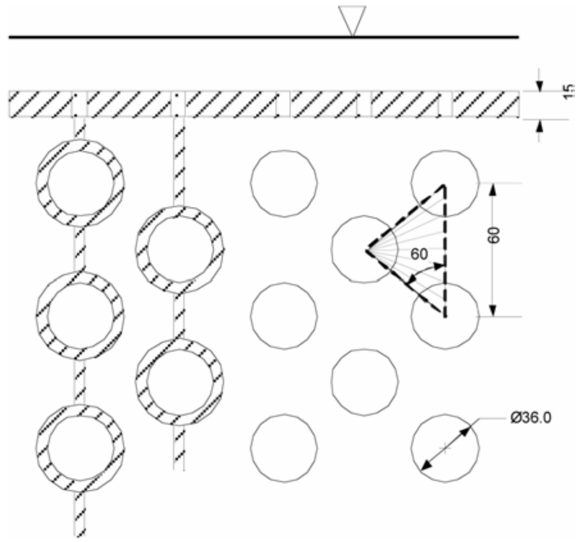

Fig. 7. Typical arrangement of a sieve tray over a tube bundle.

the effects. The evaporators can be placed horizontally next to each other as in Fig. 1 or stacked vertically as in Fig. 6 [2]. Falling film evaporators are characterized by their high overall heat transfer coefficients (3.5 kW/m^2 °C).

In horizontal tube evaporators, the heating vapor flows and condenses inside the horizontal tubes. The feed is sprayed by nozzles or perforated trays and flows as film around the outer surface of the tubes and is evaporated by heat transfer across the tube wall from the condensing vapor (Fig. 7).

In vertical tube evaporators, the feed flows as a film flowing down next to and concentric with the inside surface of the vertical tubes while heating vapor is condensed on the outer surface of the tubes and its condensate flows down.

3. Simple analysis of forward feed with feed heaters

In the forward feed shown in Fig. 1, cooling water (M_c) enters an end condenser at t_c to condense D_n (last effect vapor output) and leaves at t_n. Part of the pre-treated M_c becomes feed (F) and is heated successively as it flows in the feed heaters from t_n to t_1 before entering the first effect. The balance ($M_c - F$) is rejected back to the sea.

The supplied steam (S) to the first effect heats the feed from t_1 to boiling temperature T_1, and boils D_1 out of F (D_1 is the first effect distillate). The steam condensate returns back to the steam supply source. If the steam enters the first effect as saturated vapor and leaves as saturated liquid, then:

$$SL_s = FC\left(T_1 - t_1\right) + D_1 L \tag{1}$$

Vapor D_1 enters the first feed heater FH_1, preheats F from t_2 to t_1, and then flows as heating vapor to the second effect. The process is repeated to the last effect. The vapor formed in the last effect flows to the end condenser to be condensed. The condensate leaves and joins the distillate of other effects.

Brine B_1 from the first effect enters the second effect as feed, and brine B_2 from effect 2 is fed to effect 3, and so on to the last effect. Brine B_n from the last effect is rejected to the sea.

The feed to distillate ratio (F/D) is determined by the maximum allowable salinity, X_b, of B_n and feed salinity, X_f, by:

$$\frac{F}{D} = \frac{X_b}{(X_b - X_f)} \tag{2}$$

A simplified analysis for the MEB system is given here by assuming:

- equal vapor generated by boiling in each effect (other than first effect) = βD
- equal boiling temperature difference ΔT between effects
- equal increase Δt of the feed in feed heaters, and $\Delta T = \Delta t$
- equal specific heat C for the brine and feed, and
- equal latent heat L and BPE.

Part of D_1 (vapor) equals yF where $y = (C\Delta T)/L$ is condensed in the first FH as it heats F from t_2 to t_1, and the balance ($D_1 - yF$) enters the second effect to boil the same amount. Since vapor boiled in each effect, except the first, is the same and equal to βD, then

$$D_1 = yF = \beta D \quad \text{or } D_1 = yF + \beta D \tag{3}$$

Brine $B_1 = F - D_1 = (1-y)\,F - \beta D$ becomes the feed for the second effect. Its temperature T_1 drops to T_2, by flashing yB_1 (equal to the second effect flashed vapor D_{f2}). Thus, $D_2 = \beta D + yB_1$. Then

$$B_2 = B_1 - D_2$$

$$B_2 = B_1 - (\beta D + yB_1)$$

$$B_2 = B_1(1-y) - \beta D$$

$$B_2 = (1-y)\left[F(1-y) - \beta D\right] - \beta D$$

$$B_2 - (1-y)^2 F - \frac{\beta D}{y}\left[1 - (1-y)^2\right]$$

And similarly,

$$B_n = (1-y)^n F - \frac{\beta D}{y}\left[1 - (1-y)^n\right] \tag{4}$$

Notice that $[1-(1-y)^n]$ can be approximated by

$$\left\{ny\left[1 - \frac{(n-1)y}{2}\right]\right\} \qquad \text{for } y \ll 1.$$

The vapor generated in the first effect, D_1, is condensed partially in FH_1 and in the second effect. Part of condensate D_1, equal to yD_1, flashes by its temperature drops from T_{v1} to T_{v2}, and enters FH_2 by the flash-pot in the distillate line. Thus, the vapor inlet to FH_2 is equal to:

$$D_2 + yD_1 = [\beta D + y\,(F - D_1)] + yD_1 = \beta D + yF$$

and vapor exit = βD, after condensing yF to heat F from t_3 to t_2. Therefore, boiling the vapor in each effect, except effect 1, is βD, and generates the same amount of βD by boiling.

Since

$$D = F - B_n$$

then

$$D = F\left[1 - (1-y)^n\right] - \frac{\beta D}{y}\left[1 - (1-y)^n\right]$$

$$D = \left[1 - (1-y)^n\right]\left(F - \frac{\beta D}{y}\right)$$

Then

$$\frac{F}{D} = \frac{1}{\left[1 - (1-y)^n\right]} - \frac{\beta}{y} \tag{5}$$

and

$$\frac{\beta}{y} = \frac{1}{\left[1 - (1-y)^n\right]} - \frac{F}{D}$$

Since

$$\left[1 - (1-y)^n\right] = \left\{ny\left[1 - \frac{(n-1)y}{2}\right]\right\},$$

$$\frac{\beta}{y} = \frac{1}{\left[1 - (1-y)^n\right]} - \frac{F}{D}$$

Then

$$\beta + \frac{yF}{D} = \frac{1}{n\left[1 - (n-1)y/2\right]}$$

This is practically proportional to $1/n$.

The gain ratio is determined from:

$$SL = FC\left(T_1 - t_1\right) + D_1 L$$

$$SL = FC\left(T_1 - t_1\right) + \left(yF\,\beta D\right) L$$

$$\frac{S}{D} = \beta + \frac{yF}{D} + \frac{FC\left(T_1 - t_1\right)}{DL} \cong \frac{1}{n} + \frac{FC\left(T_1 - t_1\right)}{DL} \tag{6}$$

D/S is approximated by

$$\frac{D}{S} = \frac{n}{\left[1 + nFC\left(T_1 - t_1\right)/DL\right]} \tag{7}$$

This shows that the gain ratio is always less than n, but close to it.

4. Typical conventional MEB units

Most of the new MEB units are designed with low T_1 (TBT), around 65°C, to minimize the risk of scale formation and corrosion. Since the brine temperature in the last effect T_n is in the range of 40°C, $(T_1 - T_n)$ does not allow the use of a large number of effects (typically 6–8) to have reasonable $\Delta T = (T_1 - T_n)/(n-1)$ between effects, typically 4°C. The decrease of ΔT increases the specific heat transfer area $\Sigma A/D$. To keep the MEB system competitive with the MSF, its $\Sigma A/D$ should be in the same range as a typical MSF unit: 200–300 $m^2/(kg/s)$. One of the main merits of the MEB system is its ability to use a low-temperature heat source (steam or water as a heat source) since T_1 is relatively low.

Table 1 shows samples of MEB plants including two low-temperature (LT) plants. The Sidem 1 plant [3] uses saturated steam at 70°C and has 12 effects, but the Ashdod plant [4] uses hot water at 62.5°C and has six effects. The use of relatively large (n = 12) effects as in the Sidem 1 plant (Fig. 8) significantly increases the heat transfer surface areas for low T_1, as shown later.

However, some designs of high T_1, large n, and high gain ratios utilize energy sources of high temperatures. As an example, Sidem 2 [5] in Table 1 has a 5.5 MIGD capacity with a steam supply at 110°C, 16 effects, T_1 = 106°C (TBT), parallel feed, and GR = 12.4. Another example is the Barge unit [6] shown in Fig. 9, which has a high TBT of 135°C, which allows a large number of effects (n = 22). It is worth mentioning here that the use of a TBT higher than 110°C is risky as reliable high temperature additives only allow a TBT up to 110°C.

This mounted barge unit consists of two desalting units: the first is a two-stage mechanical vapor compression (MVC) unit, and the second is a 24-effect MEB unit with a GR of 22.3. High-pressure steam of 50 bar and 505°C drives a steam turbine operating the MVC unit and a generator, which produces power for the pumps

Table 1
Examples of conventional multi effect desalting units

Location [ref.]	Ashdod [4]	Sidem 1 [3]	Eilat [4]	Barge unit [6]	Sidem 2 [5]
Evaporator type	THE	THE	THE	THE-stacked	THE
No. of effects	6	12	12	24	16
Capacity (kg/s)	201	139	N/A	50	290
GR	5.7	9.8	10.1	22.3	12.4
Heat source	Water 2778 kg/s 63–55.4°C	Steam 14.17 kg/s, 0.31 bar	N/A	Steam	Steam
Feed TDS (g/l)	42	36	N/A	33.5	50
Feed (kg/s)	611	45.6	N/A	N/A	1502
TBT (°C)	50	64	70–74	99	106
Minimum T, (°C)	34.5	37.5	N/A	N/A	46.6
Ejector steam (kg/s), P (bar)	0.25 kg/s at 6.6 bar	0.7 at 8 bar	N/A	N/A	N/A
Pump energy (kWh/m^3)	2.2	2	N/A	N/A	N/A
Equivalent energy (kWh/m^3)	9.1	8.14	N/A	N/A	N/A
Treatment	Poly-phosphate	N/A	Poly-phosphate	Anti-scale	N/A

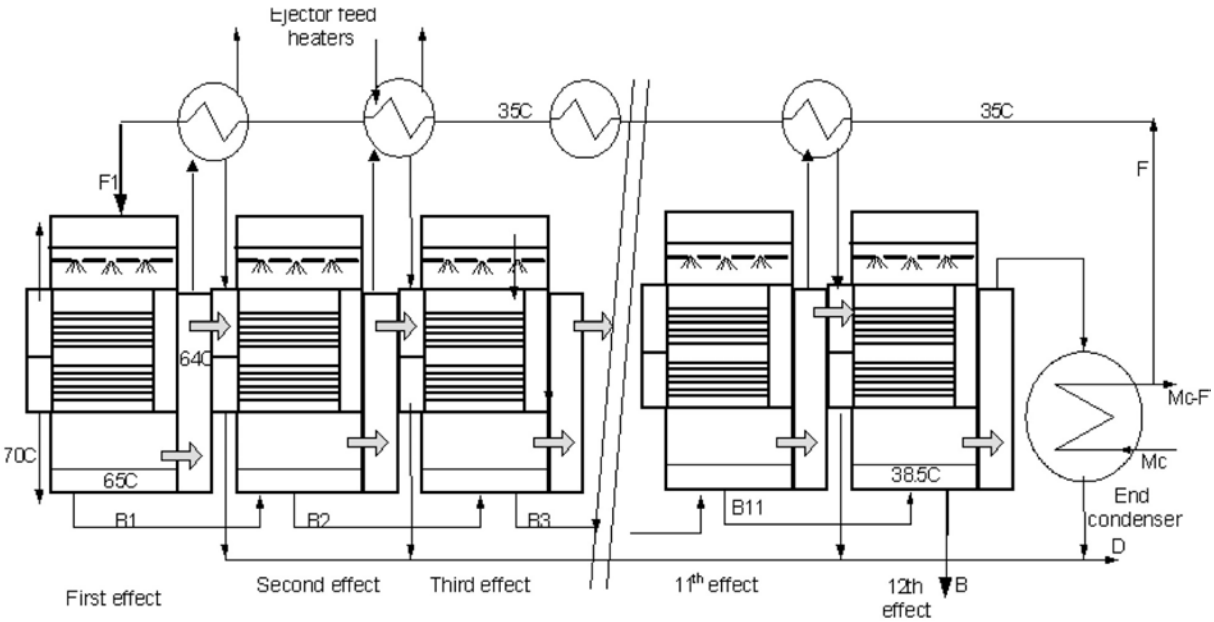

Fig. 8. Forward feed of 12 effects similar to the Sidem 1 plant.

of the desalting units and other barge requirements. The steam exhausted from the turbine is supplied to the MEB unit. The total nominal plant output of both MVC and MEB units is 5000 m^3/d (57.87 kg/s). No details were given on the product of each desalting unit. However, the MVC

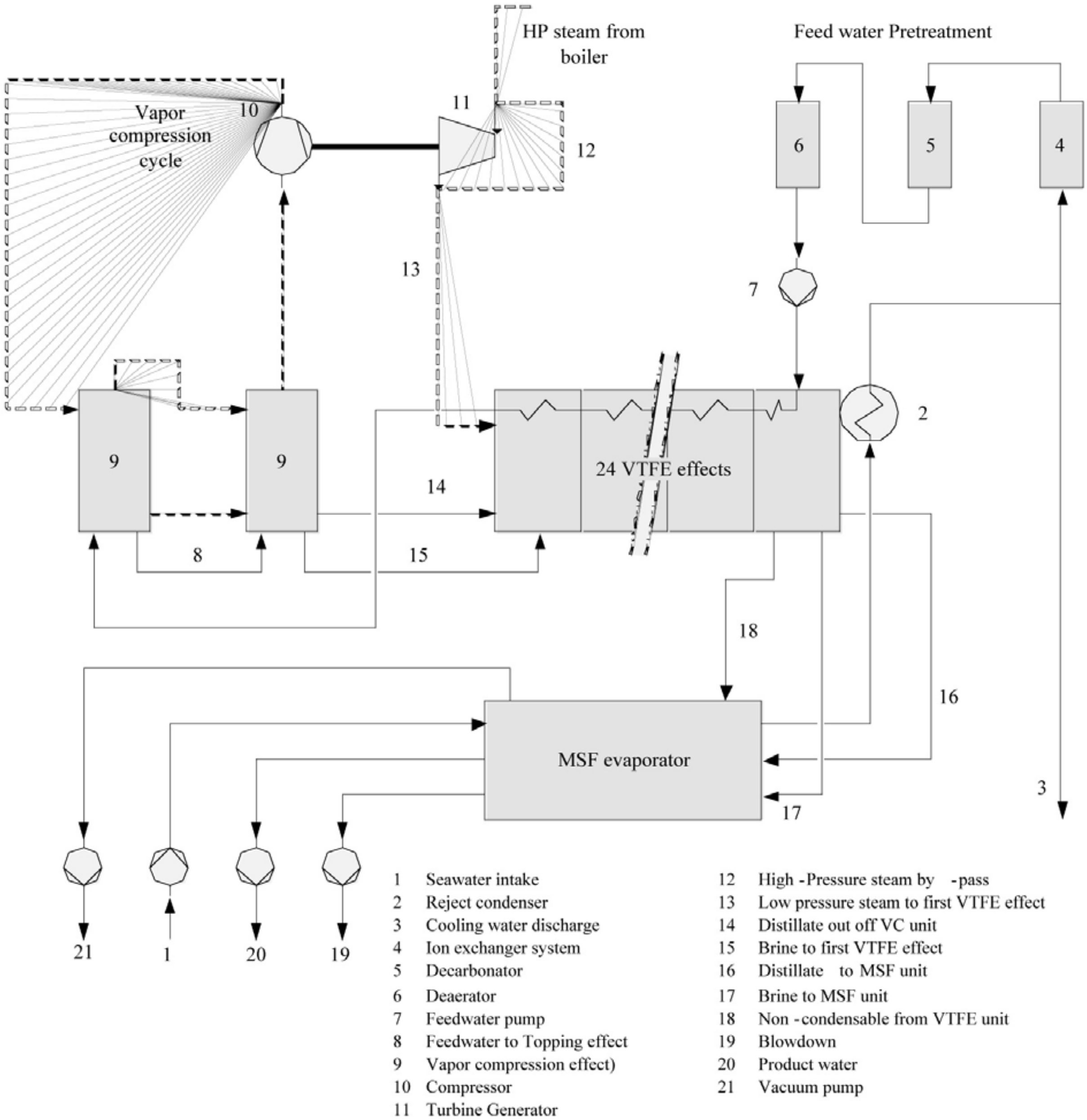

Fig. 9. Barge-mounted combined MEB of 22 effects and a two-effect MVC section, reproduced from Ohlemann and Emmermann [6].

compressor suction flow rate is given as 6.2 m^3/s at 128.8°C saturation temperature, or a mass flow rate of 6.2/0.693 = 8.95 kg/s (0.693 is the vapor specific volume). Since the MVC has two stages, its MVC product output is estimated by 17.9 kg/s. Thus, the MEB output is 39.97 kg/s, and its steam flow rate is 39.97/22.3 = 1.792 kg/s.

The Ashdod MEB unit (Table 1) uses hot water coming out of a power plant condenser at 62.5°C as heat source, and the TBT = 50°C.

Vapor is generated from this hot water by flashing as it enters a flash chamber upstream the first effect. The same idea can be used to utilize the hot water produced by the phosphoric acid fuel cells at 60–65°C as heat source to operate the MEB system. The six-effect Ashdod plant Table 1) has a GR of 5.7 and the 12-effect Eilat plant has a GR of 10.1; thus, as given before, the GR is directly proportional to the number of effects. The use of feed heaters also affects the product output and the GR as shown below by examples. The Ashdod plant has a $T_o = 50$°C and $T_n = 34.5$°C (low), and this gives $\Delta T = 3.1$°C for six effects. If the BPE = 1°C, the potential for heat transfer per effect is $\Delta T_e = \Delta T - 1 = 2.1$°C is real small and tends to increase the heat transfer area. The heat transfer area of a typical MSF of 6 MIGD is 86,661 m^2, and the specific heat transfer area is 275 m^2/(kg/s). For the MEB system to remain competitive with MSF, the specific heat transfer area should be in the same range as the MSF system.

5. Energy consumed by the MEB system

Calculations of plants similar to Ashdod and Sidem MEB plants are used here as examples to show the main characteristics of the MEB system and to calculate roughly its consumed energy, as well as its feed to distillate ratio (F/D), cooling water to distillate ratio (M_c/D), and specific heat transfer areas. Work energy is used for pumping and is in the range of half that used by MSF units.

5.1. Example 1

Consider a plant similar to the Sidem 12-effect units of 11 feed heaters shown in Fig. 8, and use the assumptions of the given simplified analysis to find: temperature and salinity distribution, the gain ratio D/S, feed to distillate ratio F/D, cooling water to distillate ratio M_c/D, and the specific heat transfer area of effects and feed heaters if the overall heat transfer coefficient U_e (effect) = 3kW/m^2 °C, and U_f (in feed heaters and condenser) = 2.6 kWh/m^2 °C. The unit given data are: n (number of effects) = 12, output D = 500 ton/h (139 kg/s), TBT = 65°C, $T_n = 38$°C, $t_c = 28$°C, t_{12} (feed temperature at condenser exit) = 35°C, brine and seawater specific heat C = 4 kJ/kg °C, average latent heat L = 2333 kJ/kg, feed salinity $X_f = 46$ g/kg, and maximum salinity $X_b = 72$ g/kg.

Solution

For $n = 12$, $\Delta T = \Delta t = (65-38)/11 = 2.45$°C, then $t_1 = t_n + (n-1)\,\Delta t = 35 + 11\,(2.45) = 62$°C, $F/D = X_b/(X_b - X_f) = 72/(72-46) = 2.77$, $F = 139 \times 2.77 = 385$ kg/s, $y = C\Delta T/L = 0.004$, $\beta/y = 1/[1-(1-y)n] - F/D$, $\beta = 0.074$, $\beta D = 10.234$ kg/s, $D_1 = \beta D + yF = 11.854$ kg/s, $S = D_1 + FC(T_1 - t_1)/L = 13.83$ kg/s, $D/S = 10.05$.

These calculations were used to establish Table 2 by using

$$B_1 = F - D_1$$

$$D_2 = \beta D + yB_1$$

$$X_2 = X_1\, F/B_1$$

$$D_i = \beta D + yB_{i-1}$$

$$X_i = X_{i-1}\, B_{i-1}/B_i$$

To obtain M_c, D_{12} should be known (see Table 2).

$D_{12}(L) = M_c(4)\,(35-28)$, $M_c = 935.7$ kg/s, $M_c/D = 6.73$.

The heat transfer areas of the effects are calculated by: thermal load = $U_eA_e(\Delta T - \text{BPE})$. The first effect thermal load = SL, and of all other effects = $D_b(L) = 2333\,\beta D$.

The area of each feed heater is calculated by $FC\Delta t = U_f(A_f)$ (LMTD), and LMTD = $\Delta t/\ln[(T_{vi} - t_{i-1})/(T_{vi} - t_i)]$. As example for the first feed heater, $T_{vi} = 65-1 = 64$°C, $\Delta t = 2.454$°C, $t_i = 62$°C, $t_{i-1} = 59.55$°C, and LMTD = 3.065°C, $A_{f1} = 474.36$ m^2. The results for each effect are shown in Table 2.

Table 2
Stream temperatures, flow rates, and salinity in the MEB unit similar to the 12-effect Sidem plant and 11 feed heaters with D = 139 kg/s

Effect #	T_i	t_i	F	D_b	D_f	D	B	X	A	A_f
1	65.00	62.00	385.03	11.85	0.00	11.85	373.18	47.46	7396.8	
2	62.55	59.55	373.18	10.23	1.57	11.80	361.37	49.01	5469.6	474.3
3	60.09	57.09	361.37	10.23	1.52	11.75	349.62	50.66	5469.6	474.3
4	57.64	54.64	349.62	10.23	1.47	11.71	337.91	52.41	5469.6	474.3
5	55.18	52.18	337.91	10.23	1.42	11.66	326.26	54.29	5469.6	474.3
6	52.73	49.73	326.26	10.23	1.37	11.61	314.65	56.29	5469.6	474.3
7	50.27	47.27	314.65	10.23	1.32	11.56	303.09	58.44	5469.6	474.3
8	47.82	44.82	303.09	10.23	1.28	11.51	291.58	60.74	5469.6	474.3
9	45.36	42.36	291.58	10.23	1.23	11.46	280.12	63.23	5469.6	474.3
10	42.91	39.91	280.12	10.23	1.18	11.41	268.71	65.91	5469.6	474.3
11	40.45	37.45	268.71	10.23	1.13	11.36	257.34	68.82	5469.6	474.3
12	38.00	35.00	257.34	10.23	1.08	11.32	246.03	71.99	5469.6	474.3
Total						139			67562.4	5217.3

D_b, vapor generated by boiling; D_f, vapor generated by flashing from brine; B, brine; X, salinity in g/kg.

The results show that the total heat transfer area is 72,779 m^2, and the specific heat transfer area A/D is 523.6 m^2/(kg/s), which is 90.4% more than that of the typical MSF unit, where $A/D \approx$ 275 m^2/(kg/s). The high specific heat transfer area of the MEB can be tolerated for two reasons: the heat supply here is at lower availability (has a lower value) compared to the heat source for the MSF units; and the MEB unit has 25% more GR than the MSF, but A/D is still high. The main reason for this high A/D is the low heat transfer temperature difference in the evaporator: ΔT− BPE = 2.45−1 = 1.45°C due to the large number of the used effects (n =12).

5.2. Doubling the output same MEB unit by increasing the heating steam

One of the main advantages of the MEB system is its operation flexibility. As an example, the Sidem plant output can be more than doubled if it operates as six effects only, but the GR drops to almost half its original, as shown in example 2. The potential temperature difference for heat transfer in the evaporator is more than doubled for the case of example 1.

Example 2

Assume that the steam supply to the Sidem MEB unit is increased to increase the unit output as follows: steam is supplied to evaporator 1 (area A_1 = 7396.8 m^2) and 2 (area A_2 = 5469.6 m^2) as the first effect; vapor leaving this effect is supplied to evaporators 3 and 4 (5469.6 m^2 each) as the second effect; and so on to the last sixth effect consisting of evaporators 11 and 12. Similarly, feed heaters 1 and 2 (474.3 m^2 each) serve effect 1, and feed heaters 3 and 4 serve effect 2, and so on; but the condenser size should be enlarged after considering that feed heater 11 is part of the condenser. Also the feed should be increased to match the distillate increase. Simply, it is operating as two parallel units, and each has six effects with its feed heaters as shown in Fig. 10.

Consider the overall heat transfer coefficients and the areas are almost the same as in example

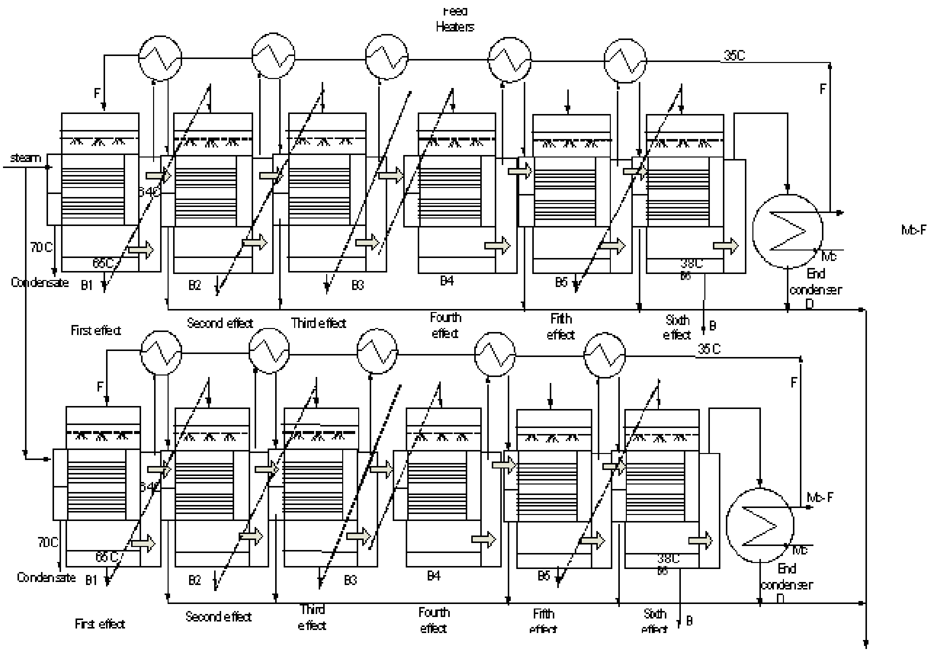

Fig. 10. Operation of the Sidem forward feed with regenerative heaters, and 12 evaporators as only six effects.

1, find the new steam supply, distillate output, cooling water, and the gain ratio for the same T_o = 65°C and T_n = 38°C.

Solution

T_o = 65°C and T_n = 38°C. The first effect heat transfer area is 7396.8 + 5469.6 = 12,866.4 m^2. The temperature difference across each effect is (65−38)/5 = 5.4°C. The first effect thermal load $SL = U A\ (\Delta T - \mathrm{BPE})$, and $S = (3)(12{,}866.4)(5.4-1)/2333$ = 72.8 kg/s.

By assuming the GR = 5.4, then D (to be checked later) = 393.1 kg/s, and $F = 2.77\times D$ = 1090 kg/s. $SL = D_1L + F(C)(T_1-t_1)$, for T_1 = 65°C, t_1 = 62°C, S = 72.8 kg/s, F = 1090 kg/s, D_1 = 67.1935 kg/s, $D_1 = yF + \beta D$, $y = C\Delta T/L$ = 0.00926, βD = 57.1 kg/s.

Check if the heat transfer area A_{e2} of the second effect is enough to carry the new thermal load. The second effect thermal load $\beta DL = UA_{e2}$ $(\Delta T-\ \mathrm{BPE})$ = 57.1 × (2333) = 3 (A_{e2}) (5.4−1). The required A_{e2} = 10,092 m^2 is slightly lower than the available area of the two evaporators: 2 × 5469.6 = 10,939.2 m^2. Thus, evaporators 3 and 4 can do the job of the second effect in the new arrange-ment. The calculations are carried as before and the results are given in Table 3.

The calculations show that the plant output almost tripled, D = 394 kg/s, but the GR decreased from 10.05 to 5.4 (almost half), and the required heat transfer area, 72,833 m^2, is almost the same as the available 72,780. The specific area $\Sigma A/D$ = 185 m^2/(kg/C) is only 35% of the 12-effect case, and 33% lower than the reference MSF unit. The cooling water requirement if t_c = 26°C is calculated by: $D_6(L) = M_cC\,(t_n-t_c)$. If t_c = 26°C, t_n = 35°C, and D_6 = 64.14 kg/s; then M_c = 4157 kg/s, and M_c/D = 10.55 kg/s is 56% more than in the 12-effect case.

The results show that the required heat transfer area of the effects, 63,326.4 m^2, is lower than the available effects area of 67,562 m^2, but the required feed heater area is 9507 m^2, while the available area is only 5217 m^2. There should be no problem as the effect area can do the job of feed heaters in the effects.

Table 3
Calculations of the stream temperature, flow rate, and salinity for the Sidem plant when operated as six effects

Effect #	T_i	t_i	F	D_b	D_f	D	B	X	A_e	A_f
1	65.0	62.0	1090.0	67.19	0.00	67.19	1022.8	49.0	12,866.4	
2	59.6	56.6	1022.8	57.10	9.47	66.57	956.2	52.4	10,092.0	1901.4
3	54.2	51.2	956.2	57.10	8.85	65.95	890.3	56.3	10,092.0	1901.4
4	48.8	45.8	890.3	57.10	8.24	65.34	824.9	60.7	10,092.0	1901.4
5	43.4	40.4	824.9	57.10	7.64	64.74	760.2	65.9	10,092.0	1901.4
6	38.0	35.0	760.2	57.10	7.04	64.14	696.1	72.0	10,092.0	1901.4
Total				352.69	41.24	393.94			63,326.4	9507.0

5.3. Effect of top brine temperature on the heat transfer area

Example 3

Show the effect of low ($T_o - T_n$) as in the Ashdod plant on the heat transfer specific area, and compare it with the Sidem 1 plant when it is operated with the same number of effects ($n = 6$) as the Ashdod plant. The Ashdod plant data are: $T_o = 50$°C, $T_n = 34.5$°C, $D = 201$ kg/s, $F = 611$ kg/s, $X_f = 42$ g/kg.

Solution

$\Delta T = \Delta t = (50-34.5)/5 = 3.1$°C; then, $t_1 = t_n + (n-1)\,\Delta t = 32.5 + 5(3.1) = 48$°C, $F/D = 611/201 = 3.04$, $y = C\Delta T/L = 0.005322$, $\beta/y = 1/[1-(1-y)n] - F/D$, $\beta = 0.1514$, $\beta D = 30.4326$ kg/s, $D_1 = \beta D + yF = 34$ kg/s, $S = D_1 + FC(T_1 - t_1)/\mathrm{L} = 36.09$ kg/s, $D/S = 5.57$. To get M_c, D_6 should be known (see Table 4).

$D_6(L) = M_c(4)\,(32-26)$

$M_c = 3214$ kg/s

$M_c/D = 16$

Due to the low $T_o = 50$°C, the specific area is 323.26 m^2/(kg/s), which is almost 75% more than that of the Sidem plant (185 m^2/(kg/s) when operated with six effects at $T_o = 65$°C. Also the decrease of T_n to 34.5°C, and even $t_c = 26$°C, $M_c/D = 16$, which is very high compared to the Sidem 1 plant with six effects, and $T_n = 38$°C. Results are shown in Table 4.

5.4. Effect of using feed heaters on the gain ratio

Example 4

Consider the Sidem plant but with parallel feeding and only two feed heaters: one before the first effect and another before the second effect as shown in Fig. 11. The feed is heated (in the two feed heaters) by an outer heat source (usually the steam coming from steam ejector used to reject the non-condensable gases of flow rate S_2). Other plant data are: TBT = 65°C, $T_n = 38$°C, t_1 (feed to the first effect) = 62°C, t_2 (feed to the second effect) = 56.2°C, t_i (feed to effects 3 to 12) = 35°C, $X_f = 46$ g/kg and $X_b = 72$ g/kg.

Find the temperature and salinity distribution, vapor generated by boiling D_b, and by flashing D_f in each effect, and D/S, F/D, and M_c/D.

Solution

Mass, salt, and energy balances are made to all effects. The feed flow rate F_i to effect i is calculated to keep X_b of the brine leaving each effect X_i less than 72 g/kg. $X_f = 46$ g/kg. $F_1/D_1 = X_1/(X_1 - X_f)$, $F_1 = 2.77\,D_1$. Then for the first effect: $SL = D_1(L) + F_1(C)(T_1 - t_1)$, $S = 13.8345$, $D_1 = 13.64$ kg/s, $F_1 = 37.8$ kg/s, and $B_1 = 24.16$ kg/s.

Table 4
Stream flow rates, temperatures and salinity for the Ashdod plant and effects and feed heaters calculated heat transfer surface areas

Effect #	T_i	t_i	F	D_b	D_f	D	B	X	A_e	A_f
1	50	47.5	611.0	33.95	0.00	33.95	577.1	44.5	11,284.5	1053.4
2	46.9	44.4	577.1	30.70	3.07	33.77	543.3	47.2	9,474.1	1053.4
3	43.8	41.3	543.3	30.70	2.89	33.59	509.7	50.3	9,474.1	1053.4
4	40.7	38.2	509.7	30.70	2.71	33.41	476.3	53.9	9,474.1	1053.4
5	37.6	35.1	476.3	30.70	2.53	33.23	443.1	57.9	9,474.1	1053.4
6	34.5	32	443.1	30.70	2.35	33.06	410.0	62.6	9,474.1	1053.4
						201.00			58,654.9	6320.4

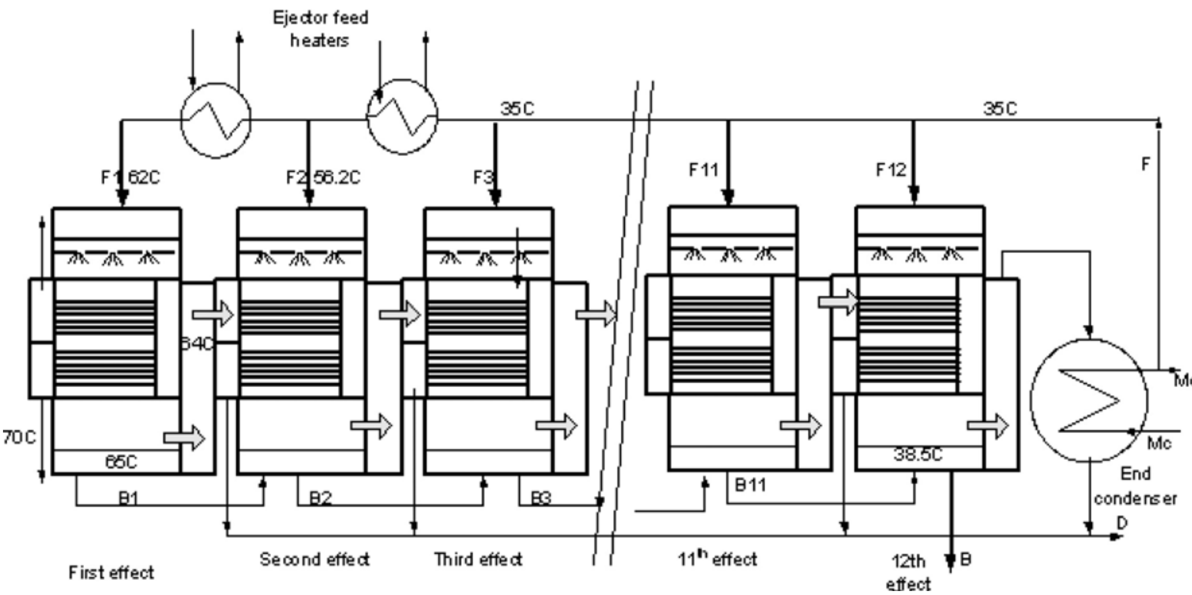

Fig. 11. Parallel feed 12-effect desalting system with only feed heaters.

For the second effect: $D_1(L) = D_{b2}(L) + F_2(C)(T_2-t_2)$, and $D_{f2} = B_1(C)\Delta T/L = 0.1017$ kg/kg, D_{b2} and D_{f2} are the vapors generated by boiling and flashing in effect 2, respectively. In effect 2, salt in $F_2(X_f) + B_1(X_1)$ = salt out $B_2(X_2)$, or $F_2(X_f) + B_1(X_1) = (B_1 + F_2-D_2)(X_2)$.

Since $X_{b1} = X_{b2} = X_b$, $F_2/D_2 = X_{b2}/(X_{b2}-X_f)$, and $F_2 = 2.77\ D_2$. $D_1(L) = (D_2-D_{f2})L + 2.77\ D_2(C)(T_2-t_2)$, and $D_2 = (D_1+D_{f2})/[1+2.77(C)(T_2-t_2)/L]$.

The last equation is generalized to give: $D_i = (D_{i-1} + D_{if})/[1 + 2.77\ (C)(T_i-t_i)/L]$.

Table 5 gives the temperature and salinity distribution, feed ($F_{i)}$ to each effect, and distillate generated by boiling D_{bi} and by flashing D_{fi}. The results show that $D = 137.86$ kg/s and total feed is $F = 383.53$ kg/s. The steam supply to the two feed heaters (S_2) is calculated by: $S_2(L) = (F_1+F_2)(C)(t_2-35) + F_1(C)(t_2-t_1)$, $S_2 = 3.1$ kg/s, total $S = 16.93$ kg/s; $D/S = 7.78$, and $F/D = 2.784$. This example shows that the use of feed heaters increases the GR by 29% (from 7.78 to 10.05) compared to the case when no feed heaters were used.

Table 5
Temperature, salinity, feed, distillate by boiling D_b and by flashing D_f, and brine from effects of example 4

Effect #	T_i	T_{vi}	F_i	T_i (feed)	D_b	D_f	D	B_i	X_i
1	65.00	64.00	37.80	62.00	13.64	0.00	13.64	24.16	71.97
2	62.55	61.55	37.12	56.20	13.24	0.10	13.40	48.56	71.98
3	60.09	59.09	33.82	35.00	11.95	0.20	12.21	73.47	71.98
4	57.64	56.64	31.44	35.00	10.99	0.31	11.35	95.94	71.98
5	55.18	54.18	29.84	35.00	10.32	0.40	10.77	116.61	71.98
6	52.73	51.73	28.91	35.00	9.90	0.49	10.44	136.02	71.99
7	50.27	49.27	28.56	35.00	9.69	0.57	10.31	154.61	71.99
8	47.82	46.82	28.75	35.00	9.68	0.65	10.38	172.79	71.99
9	45.36	44.36	29.45	35.00	9.85	0.73	10.63	190.91	71.99
10	42.91	41.91	30.67	35.00	10.22	0.80	11.07	209.29	71.99
11	40.45	39.45	32.42	35.00	10.77	0.88	11.71	228.25	71.99
12	38.00	37.00	34.75	35.00	11.53	0.96	12.55	248.13	71.99
Total			383.53		131.76	6.10	137.86	385.99	

6. Equivalent work consumed by the MEB system

The Sidem 1 unit is designed to operate by low-pressure steam extracted from steam turbines at 0.3 bar (saturation temperature of 70°C). The plant capacity is 2.64 MIGD. The thermal energy consumed by the system according to design is 51 t/h (14.17 kg/s) steam of 2498 kJ/kg enthalpy and 0.3 bar; the leaving condensate has 294 kJ/kg enthalpy. The distillate output is 500 t/h (138.89 kg/s), and this gives a specific thermal energy of 217.4 kJ/kg distillate. If this MEB unit is combined with one of the steam power plants in Kuwait, shown in Fig. 12, it can be supplied with steam at 70°C extracted from the LP steam turbine as the heat source. This steam can produce work if it expands to the condensing pressure in the LP turbine. This work is considered as work loss due to steam extraction to the desalting unit, or work equivalent to the thermal energy supplied to the unit.

This work loss is equal to the steam enthalpy difference between the extraction point (2580 kJ/kg) and at the condenser inlet (2346 kJ/kg), as shown in Fig. 13. Thus, the work loss due to extraction per kg of steam is equal to 234 kJ/kg. Since the GR calculated in example 1 is 10.05, then the specific equivalent work is 23.3 kJ/kg distillate. By adding 7 kJ/kg pumping energy, the total specific equivalent work becomes 30.3 kJ/kg distillate (equivalent to 8.4 kWh/m^3 distillate). This is almost 40% of the work equivalent consumed by a typical MSF system (about 21 kWh/m^3), but still 40–60% higher than that of the very efficient RO system (about 5–6 kWh/m^3).

Table 6 [7] shows the enthalpy of steam at the extraction point (at 70°C); at the condenser inlet, the work loss per kg of steam and per kg distillate and the total specific equivalent work at different power loads of the power plant.

The Ashdod plant operates at a lower temperature heat source, 62.5°C, and its GR = 5.6 [4]. The work equivalent to the thermal energy supplied to the unit is 7.65 kWh/m^3, and the pumping energy is 2.5 kWh/m^3 (based on 1800 kW pumping energy), a total of 10.15 kWh/m^3. This is less than half of the work equivalent used by a typical MSF unit, although its GR is 5.7, and that of MSF is 8.0. This shows that the Ashdod plant of 5.7 GR is 100% more efficient than the MSF unit of 8.0 GR.

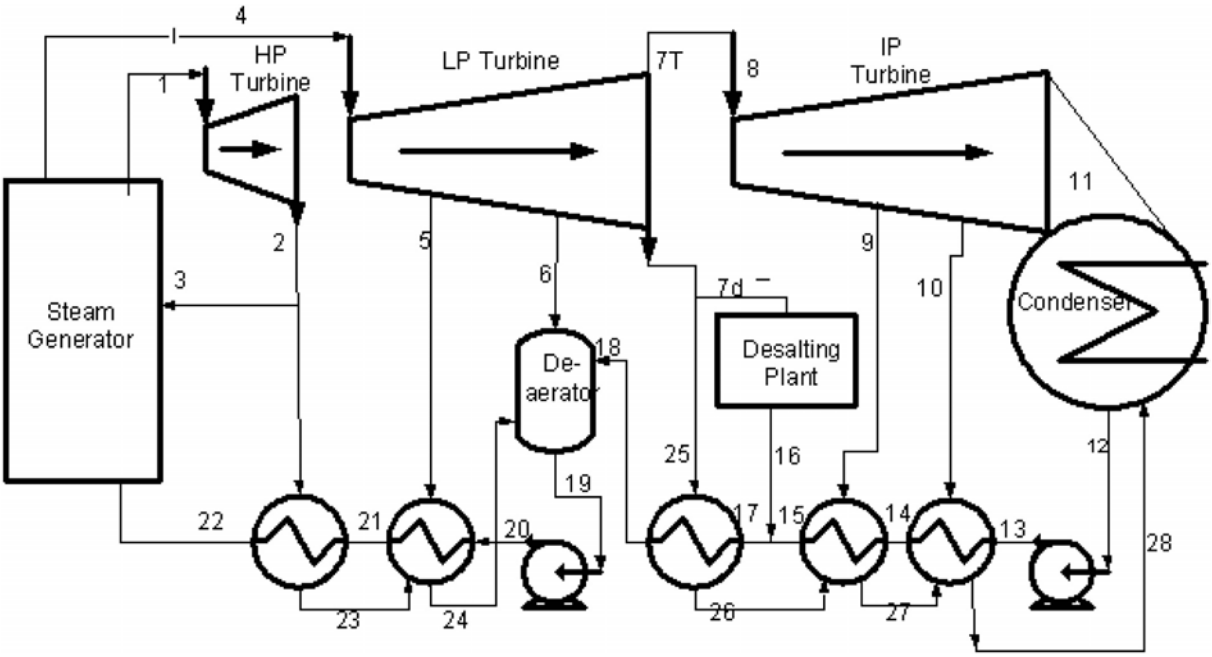

Fig. 12. Cogeneration power desalting plant used to supply steam to MSF units, the expected supply to the MEB from point 10.

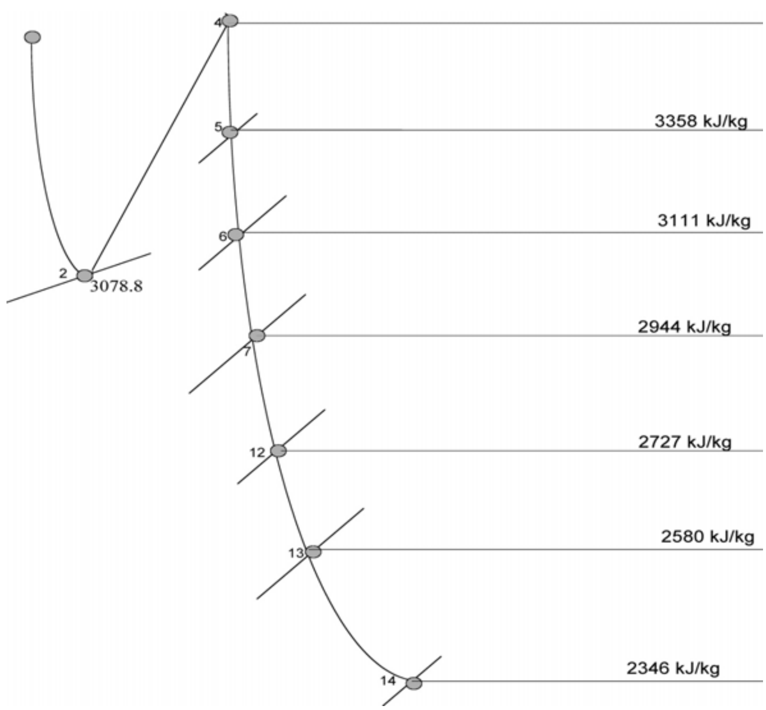

Fig. 13. Enthalpy of extracted steam from the cogeneration power desalting plant at different electric loads.

Table 6
Enthalpy of steam extracted from the turbine to the MEB at different loads of the turbine and corresponding equivalent work, and specific fuel energy

	Load, %			
	100	80	50	25
$h_{extraction}$, kJ/kg	2550	2550	2630	NA
$h_{condenser}$, kJ/kg	2340	2335	2500	NA
Work loss, kJ/kg_{steam}	210	215	130	NA
Specific equivalent work, $kJ/kg_{distillate}$	20.89	21.39	12.93	NA
Total specific equivalent work, $kJ/kg_{distillate}$	27.89	28.39	19.93	NA
Total specific equivalent work, $kWh/m^3_{distillate}$	7.75	7.89	5.54	NA
Specific fuel energy input, kJ/kg	77.5	78.9	55.4	

Pumping energy is used by the MEB system to move its streams, and is usually about half that used in the MSF system. The reported specific electric power consumed for three MEB units operated in St. Thomas (209.4 m^3/h capacity), St. Croix (207 m^3/h), and St. Thomas II (213 m^3/h) are 1.75, 1.8, and 1.75 kWh/m^3, respectively, while the design figure for the three units is 2.5 kWh/m^3 [8].

The specific fuel energy can be calculated by multiplying the specific work equivalent in kWh/m^3 by 3.6 to convert to kJ/kg work, and divided by 0.36 (the typical efficiency of power plant to get the specific fuel energy in kJ/kg).

The available energy of steam supplied at 0.3 bar can be calculated by:

$$2336.1\ [1-(25 + 273)/(69 + 273)] = 300\ \text{kJ/kg}$$

where 2336.1 is the latent heat in kJ/kg for P = 0.3 bar. For GR = 10.05, the specific available energy per kg distillate A_d/D_{is} 300/10.05 = 29.9 kJ/kg or 8.3 kWh/m^3.

7. Conclusions

In conclusion, the conventional MEB has the advantage of using a low-temperature heat source (steam or hot water) when it operates at low TBT, and this can give much lower equivalent work or available consumed energy than MSF units. The decrease of ΔT to less than 2°C significantly increases the heat transfer areas. The use of feed heaters enhances the GR, but adds more complexity, capital cost, and pumping energy. This system consumes about half the pumping energy of the MSF. The MEB can be arranged to give much more product when needed, but at lower GR.

References

[1] M.A. Darwish and A.A. El Hadek, The multi effect boiling desalting system and its comparison with the MSF, Desalination, 60 (1986) 251–265.

[2] R. Rautenbach and B. Artz, The performance of high performance distillation plants, Desalination, 56 (1985) 261–275.

[3] C. Temster and J. Laborie, Dual purpose desalination plant — high efficiency multi-effect evaporator operating with turbine for power production, Proc. IDA World Conference on Desalination and Water Science, Abu Dhabi, 3 (1995) 297–308.

[4] U. Fisher, A. Aviram A. and A. Gendel, Ashdod low temperature multi-effect desalination plant, Desalination, 55 (1985) 13–32.

[5] B. Franquelin, F. Murat and C. Temstet, Appli-

cation of multi-effect process at high temperature for large seawater desalination plants, Desalination, 45 (1983) 81–92.
[6] B. Ohlemann and D. Emmermann, Advanced barge mounted VTE/VC seawater desalting plant, Desalination, 45 (1983) 39–47.
[7] M.A. Darwish, F. Al Asfour and N. Al Najem, Energy consumption in equivalent work by different desalting methods: case study study for Kuwait, Desalination, 152 (2002) 83–92.
[8] U. Fisher, One year of operation of Israel Desalination Engineering's multi-effect distillation U.S. Virgin Island, Desalination, 44 (1983) 73–84.