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Second law and sensitivity analysis of large ME-TVC desalination units

Anwar Binamer*

Kuwait Foundation for the Advancement of Sciences (KFAS), Research Directorate, Water & Energy Program, P.O. Box 25263, Safat 13113, Kuwait
Tel. +965 22278137; Fax: +965 22278111; emails: aomar@kfas.org.kw; Anwar_Binamer@yahoo.com

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ABSTRACT

Large number of low temperature multi-effect thermal vapor compression (ME-TVC) desalination units have been installed recently in most of the GCC countries. The new trend of combining ME-TVC with conventional multi-effect led to tremendous increase in the unit size more than eight times during a very short period. The unit size capacity of this technology is currently available with 10 million imperial gallons per day (MIGD), and research studies are expected to increase this unit capacity up to 15 MIGD in the near future. Hence, this technology becomes highly attractive and competitive against multi stage flash desalination system. A mathematical model of ME-TVC desalination system is developed in this paper, using Engineering Equation Solver Software. This model is used to evaluate and improve the system performance of some new commercial ME-TVC units with capacities of 2.4, 3.8, and 6.5 MIGD using energy and exergy analysis. A sensitivity analysis is also presented in this paper to investigate the system performance of Al-Jubail ME-TVC unit in KSA, which is considered as the largest ME-TVC desalination plant in the world. Results showed that the first effect was found to be responsible for about 31% of the total effects exergy destruction in Al-Jubail, compared to 46% in ALBA and 36% in Umm Al-Nar. Results also showed that the specific exergy destruction is reduced significantly by increasing the number of effects as well as working at lower top brine temperatures.

Keywords: Desalination; Exergy; Multi-effect; Thermal vapor

1. Introduction

Several low temperature multi-effect thermal vapor compression (ME-TVC) desalination units have been installed recently in most of the GCC countries. The total installed capacity has increased up to 500 million imperial gallons per day (MIGD) between 2000 and 2010. The majority of these units were commissioned in the UAE by SIDEM Company [1]. The unit size capacities of these units were increased exponentially from 1 to 8.5 MIGD between 1991 and 2008 as shown in Fig. 1. The new trend of combining ME-TVC with conventional multi effect units led to this tremendous increase, more than eight times, during a very short period. Moreover, the unit size capacity of this technology is currently available with 10 MIGD, and it is expected to increase up to 15 MIGD in the near future. Hence, this system becomes highly attractive and competitive against multi stage flash desalination system and it is predicted to have a considerable

*Corresponding author.

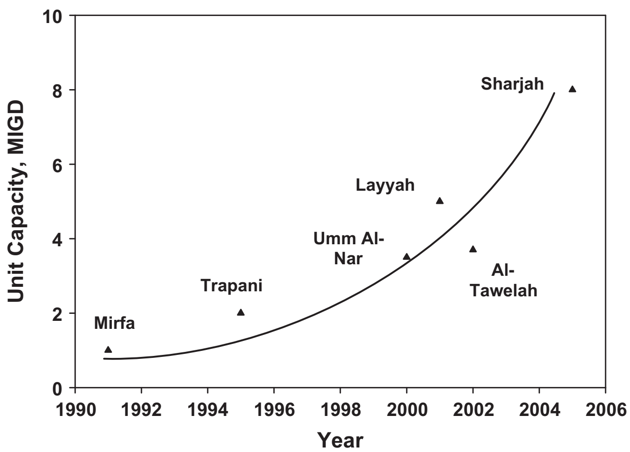

Fig. 1. The increase of unit size capacity of ME-TVC desalination systems.

increase in the desalination market in future, particularly, in the GCC countries.

Several studies have been published since early 1990s concerning ME-TVC desalination system [2,3]. Some include field studies and others describe different conceptual designs. Since then, diverse mathematical models were also developed in most of these publications for simulation and economic evaluation purposes. A summary of literature review of these studies was reported in the literatures [4,5]. On the other hand, limited studies were published handling ME-TVC desalination system from exergy (Second law) point of view since the middle of the last decade, but it has been carried out in several published works recently [6–12].

Hamed et al. conducted and evaluated the performance of a ME-TVC desalination system. An exergy analysis was also performed and compared with conventional multi effect boiling and mechanical vapor compression desalination systems. Results showed that the ME-TVC desalination system is the most exergy efficient compared to the other systems [6].

Al-Najem et al. conducted a parametric analysis using the first and second laws of thermodynamics for single and ME-TVC system. The study revealed that the steam ejector and the evaporators are the main source of exergy destruction in the ME-TVC desalination system [7].

Alasfour et al. developed mathematical models for three configurations of a ME-TVC desalination system using energy and exergy analysis. A parametric study was also performed to investigate the impacts of different parameters on the system performance. The study showed that the decrease in exergy destructions is more pronounced than the decrease in the gain output ratio (GOR) at lower values of motive steam pressure. On the other hand, exergy losses are small at low temperature difference and low at top brine temperature [8].

Choi et al. presented an exergy analysis for ME-TVC pilot plant units; which was developed by Hyundai Heavy Industries Company. The units have different capacities of 1, 2.2, 3.5, and 4.4 MIGD. Exergy analysis showed that most of the specific exergy losses were in thermal vapor compressor and the effects. The amount of exergy destruction represents more than 70% of the total amount. Results also showed that the increase of entrainment ratio to 120% will decrease the total heat transfer area by 12% [9].

Wang and Lior presented the performance analysis of a combined humidified gas turbine plant with ME-TVC desalination systems using Second Law of Thermodynamics. The analysis is performed to improve the understanding of the combined steam injection gas turbine power and water desalination process and ways to improve and optimize it. Results showed that the dual purpose systems have good synergy in fuel utilization, in operation and design flexibility [10].

Sayyaadi and Saffari developed thermo-economic optimization model of a ME-TVC desalination system. The model is based on energy and exergy analysis. A genetic algorithm is used to minimize the water product cost [11].

Bo Zhang et al. investigated five effects of MED experimental unit assisted by a flat plate solar collector. Second law analysis is used to identify the exergy destruction under a series of different operating conditions [12].

A mathematical model of a ME-TVC desalination system is developed in this paper, using Engineering Equation Solver (EES) Software. This model is used to evaluate and improve the performance of some new commercial ME-TVC units, with capacities of 2.4, 3.8, and 6.5 MIGD using energy and exergy analysis. The model results were compared against the actual data [13]. A sensitivity analysis is also presented in this paper to investigate the impact of top brine temperature, temperature difference per effect, motive steam flow rate, and the number of effects on the system's performance of Al-Jubail ME-TVC unit, which is the largest ME-TVC desalination plants in the world. The system performance has been evaluated in terms of GOR, specific heat consumption, specific exergy consumption, specific heat transfer area, and specific exergy destruction.

2. Process description

A schematic diagram of this arrangement is shown in Fig. 2, where two identical ME-TVC units are combined with a single MED unit, whereas the vapor

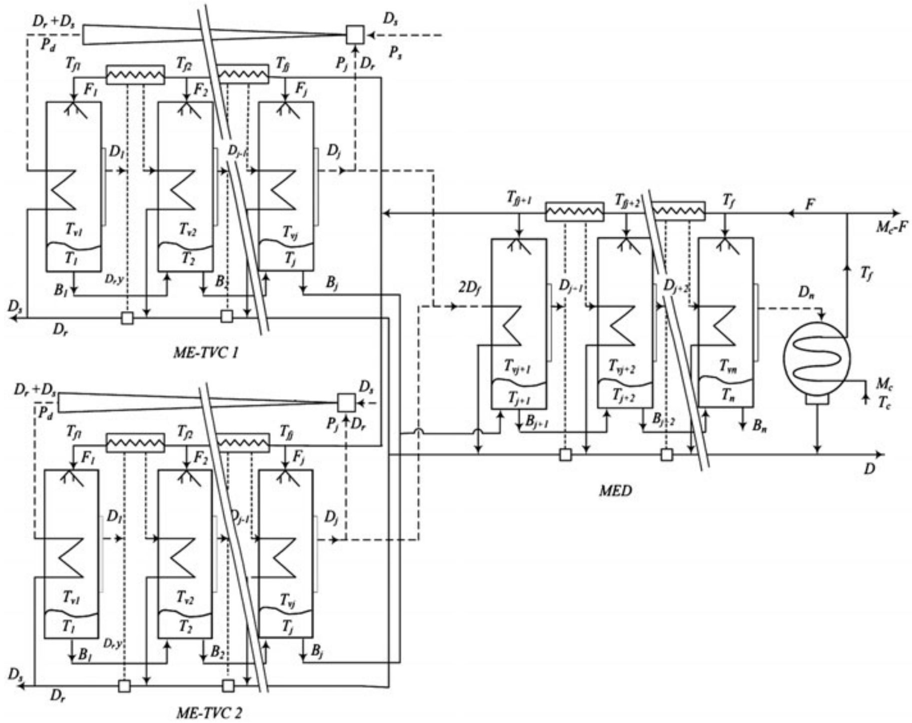

Fig. 2. A schematic diagram of two ME-TVC units combined with a conventional MED unit.

produced in the last effect of each ME-TVC unit (D_j) is split into two streams. The first stream D_r is entrained by a thermo-compressor and other part (D_f) is used as a heat source to operate low temperature multi effect distillation unit (LT-MED).

The configuration consists of the following components: (1) a number of horizontal falling film evaporators (n effects), (2) two thermo-compressors, (3) a number of feed heaters, (4) five main pumps (distillate, feed, condensate, cooling, and brine disposal pumps) to circulate the streams, (5) an end condenser, and (6) a number of flashing boxes.

3. Thermal analysis

The first and second laws of analysis are used in this section to develop a mathematical model of the ME-TVC desalination system. The model is developed by applying mass and energy conservation laws to the thermo-compressor, evaporators, feed heaters, and end condenser. The following assumption were used to simplify the analysis: steady-state operation, negligible heat losses to the surrounding, equal temperature difference across feed heaters, salt free distillate from all effects, and variations of specific heat as well as boiling point elevation with the temperature and salinity are negligible. The number of effects is assumed to be even in this analysis for example n = 4, 6, 8, 10, and 12.

The brine temperature in each effect is less than that of the previous one by ΔT. So, if the brine temperature in the effect i is assumed to be T_i, then the brine temperature in the next effect i + 1 and so on up to the last effect n can be calculated as follows:

$$T_{i+1} = T_i - \Delta T, \quad i = 1, 2, \ldots n \tag{1}$$

The temperature of the vapor generated in the effect i, T_{vi} is lower than the brine temperature by the boiling point elevation plus non equilibrium allowance, where T_{vi} is a saturation temperature corresponding to the pressure in the effect P_i.

$$T_{vi} = T_i - (\mathrm{BPE} + \mathrm{NEA}), \quad i = 1, 2, \ldots n \tag{2}$$

The temperature difference between the effects is assumed to be the same in this analysis and can be calculated as follows:

$$\Delta T = \frac{T_1 - T_n}{n - 1} \tag{3}$$

The feed seawater temperature flowing into each effect (T_{fi}) can be calculated as follows:

$$T_{fi} = T_f + [n - (i+1)] \cdot \Delta T \quad i = 1, 2, 3 \ldots n \tag{4}$$

3.1. Mass and energy balance

The feed seawater flow rate F is distributed equally to all effects at a rate equal to F_i which can be calculated as follows:

$$F_i = \frac{F}{n+j}, \quad j = \frac{n}{2} \tag{5}$$

The brine leaving the first effect enters into the second effect and so on up to the last effect n, and the brine from the last effect is rejected. The brine leaving the first, second, and last effect can be calculated considering mass balance law as follows:

$$B_i = F_i - D_i \tag{6}$$

$$B_{i+1} = \sum_{i=1}^{j} (F_{i+1} - D_{i+1}) \tag{7}$$

$$B_n = 2 \cdot \sum_{i=1}^{j} (F_i - D_i) + \sum_{j+1}^{n} (F_{j+1} - D_{j+1}) \tag{8}$$

The salt mass conservation law is applied, assuming that the distillate is free of salt, to find brine salinity from the first, second, and last effect as follows:

$$X_{bi} = \frac{F_i \cdot X_f}{(F_i - D_i)} \tag{9}$$

$$X_{bi+1} = \frac{F_{i+1} \cdot X_f}{\sum_{i=1}^{j} (F_{i+1} - D_{i+1})} \tag{10}$$

$$X_{bn} = \frac{F_n \cdot X_f}{2 \cdot \sum_{i=1}^{j} (F_i - D_i) + \sum_{j+1}^{n} (F_{j+1} - D_{j+1})} \tag{11}$$

The vapor generated in the first effect by boiling only can be determined from the energy balance of the first effect as follows:

$$D_1 = \frac{[(D_s + D_r) \cdot (h_d - h_{fd})]}{L_1} - F_1 \cdot C \cdot \left(\frac{T_1 - T_{f1}}{L_1} \right) \tag{12}$$

The amount of vapor released from the second up to j can be expressed, respectively, as follows:

$$D_2 = (D_1 + D_r \cdot y - F_1 \cdot y) \cdot \frac{L_1}{L_2} + B_1 \cdot \frac{C \cdot \Delta T}{L_2} - F_2 \cdot C \cdot \frac{(T_2 - T_{f2})}{L_2} \tag{13}$$

$$D_j = \left[\left(D_{j-1} + \sum_{i=1}^{j-2} (D_i + D_r) \cdot y - (j-1) \cdot F_j \cdot y \right) \right] \cdot \frac{L_{j-1}}{L_j} + B_{j-1} \cdot \frac{C \cdot \Delta T}{L_j} - F_j \cdot C \cdot \frac{(T_j - T_{fj})}{L_j} \tag{14}$$

The vapor formed in the last effect of each ME-TVC unit D_j is divided into two streams; one is entrained by the thermo-compressor (D_r) and the other is directed to the MED unit.

$$D_j = D_r + D_f \tag{15}$$

The two streams of D_f are used as a heat source to operate LT-MED unit.

So, the vapor formed in first, second, and last effect of this unit can be calculated as follows:

$$D_{j+1} = 2 \cdot D_f \cdot \frac{L_j}{L_{j+1}} + 2 \cdot B_j \cdot \frac{C \cdot \Delta T}{L_{j+1}} - F_{j+1} \cdot C \cdot \frac{(T_{j+1} - T_{fj+1})}{L_{j+1}} \tag{16}$$

$$D_{j+2} = \left(D_{j+1} + \sum_{i=1}^{j} (D_i + D_r) \cdot y - (j+n) \cdot F_{j+2} \cdot y \right) \cdot \frac{L_{j+1}}{L_{j+2}} + 2 \cdot B_{j+1} \cdot \frac{C \cdot \Delta T}{L_{j+2}} - F_{j+2} \cdot C \cdot \frac{(T_{j+2} - T_{fj+2})}{L_{j+2}} \tag{17}$$

$$D_n = \left[\left(D_{n-1} + \sum_{i=1}^{n-2} (D_i + D_r) \cdot y - (j+n-1) \cdot F_i \cdot y \right) \right] \cdot \frac{L_{n-1}}{L_n} + 2 \cdot B_{n-1} \cdot \frac{C \cdot \Delta T}{L_n} - F_i \cdot C \cdot \frac{(T_n - T_f)}{L_n} \tag{18}$$

The total distillate output from all effects is equal to

$$D = 2 \cdot \sum_{i=1}^{j} D_i + \sum_{j+1}^{n} D_{j+1}, \quad i = 1, 2, \ldots 3 \tag{19}$$

The energy balance of the thermo-compressor is used to calculate the enthalpy of the discharged steam as shown in Eq. (20),

$$h_d = \left(\frac{\left(\frac{D_s}{D_r}\right) \cdot h_s + h_{g(j)}}{1 + \left(\frac{D_s}{D_r}\right)} \right) \tag{20}$$

The most essential part in modeling the ME-TVC desalination system is to determine the ratio of motive steam to entrained vapor (D_s/D_r) in such thermo-compressors. An optimal ratio will improve the unit efficiency by reducing the amount of motive steam [14]. This ratio is a direct function of discharge pressure (P_d), motive steam pressure (P_s), and entrained vapor pressure (P_j) in terms of compression ratio (CR) and expansion ratio (ER) as follows [15,16]:

$$\text{CR} = \frac{P_d}{P_j} \tag{21}$$

$$\text{ER} = \frac{P_s}{P_j} \tag{22}$$

Several methods are available in literature to evaluate entrainment ratios; most of these methods need lengthy computation procedures and use many correction factors [16]. Two simple methods are used to evaluate this ratio in this study: (1) Power's graphical data method [17], (2) El-Dessouky and Ettouney's semi-empirical model [16]. Although Power's method is straightforward, and the entrainment ratio can be extracted directly in terms of CR and ER, it is too difficult to use in such optimization and simulation models. The developed semi-empirical model in method 2 is applicable only if the motive fluid is steam and the entrained fluid is water vapor [15]. The pressure and temperature correction factors were eliminated for simplicity and the model equation is modified as shown in Eq. (23); results were tested and compared with that obtained by Power's graphical method for validity in the following range of motive pressure 3,000 ≥ P_s ≥ 2000 (kPa).

$$\left(\frac{D_s}{D_r}\right) = 0.235 \frac{(P_d)^{1.19}}{(P_j)^{1.04}} (\text{ER})^{0.015} \tag{23}$$

3.2. Exergy balance

An exergy balance is also conducted for the system to find the exergy destruction (I) in each components: in thermo-compressor, effects, condenser, and the leaving streams in kJ/kg according to the following equation:

$$I = T_o \cdot \Delta S = E_{in} - E_{out} \tag{24}$$

where ΔS is the entropy increase, E_{in} is the input exergy and E_{out} is the output exergy.

3.2.1. Thermo-compressor

The exergy destruction in the thermo-compressor can be expressed as follows:

$$\begin{aligned} I_{ej} = & D_s \cdot [(h_s - h_d) - T_o \cdot (S_s - S_d)] \\ & - D_r \cdot \lfloor (h_d - h_{gj}) - T_o \cdot (S_d - S_{gj}) \rfloor \end{aligned} \tag{25}$$

3.2.2. Effects

The exergy destruction in the first, second, and last effect can be expressed, respectively, as follows:

$$\begin{aligned} I_{e1} = & (D_s + D_r) \cdot [(h_d - h_{fd}) - T_o \cdot (S_d - S_{fd})] \\ & - D_1 \cdot L_1 \cdot \left(1 - \frac{T_o}{T_{v1}}\right) - \\ & F_1 \cdot C \cdot \left[(T_1 - T_{f1}) - T_o \cdot \text{In}\left(\frac{T_1}{T_{f1}}\right)\right] \end{aligned} \tag{26}$$

3.2.3. Condenser and leaving streams

The exergy destruction in the condenser and in the leaving streams, D_r, D_f, and B_n can be expressed using the following equations, respectively:

$$\begin{aligned} I_{e2} = & (D_1 + D_r y - F_2 y) \cdot L_1 \cdot \left(1 - \frac{T_o}{T_1}\right) + B_1 \cdot C \cdot \left[\Delta T - T_o \cdot \text{In}\left(\frac{T_1}{T_2}\right)\right] - D_2 \cdot L_2 \cdot \left(1 - \frac{T_o}{T_2}\right) \\ & - F_2 \cdot C \cdot \left[(T_2 - T_{f2}) - T_o \cdot \text{In}\left(\frac{T_2}{T_{f2}}\right)\right] \end{aligned} \tag{27}$$

$$I_{en} = \left[D_{n-1} + \sum_{i=1}^{n-2}(D_i + D_r)\cdot y - (j+n-1)F_i\cdot y\right]\cdot L_{n-1}\cdot\left(1-\frac{T_o}{T_{n-1}}\right) + 2\cdot B_{n-1}\cdot C\cdot\left[\Delta T - T_o\cdot \text{In}\left(\frac{T_{n-1}}{T_n}\right)\right] - D_n\cdot L_n\cdot\left(1-\frac{T_o}{T_n}\right) - F_i\cdot C\cdot\left[(T_n - T_f) - T_o\cdot\ln\left(\frac{T_n}{T_f}\right)\right] \quad (28)$$

$$I_c = D_n\cdot L_n\cdot\left(1-\frac{T_o}{T_n}\right) - M_c\cdot C\cdot\left[(T_f - T_c) - T_o\cdot\ln\left(\frac{T_f}{T_c}\right)\right] \quad (29)$$

$$I_{D_r} = D_r\cdot C\cdot\left[(T_{vj} - T_c) - T_o\cdot\ln\left(\frac{T_{vj}}{T_c}\right)\right] \quad (30)$$

$$I_{D_f} = D_f\cdot C\cdot\left[(T_{vj} - T_c) - T_o\cdot\ln\left(\frac{T_{vj}}{T_c}\right)\right] \quad (31)$$

$$I_{B_n} = D_n\cdot C\cdot\left[(T_n - T_c) - T_o\cdot\ln\left(\frac{T_n}{T_c}\right)\right] \quad (32)$$

3.3. Thermal load

The heat transfer area of an effect can be obtained from the latent heat of condensation (thermal load) of each effect as shown in Eq. (33), where ΔT_e is the temperature difference across the heat transfer surface.

$$Q = U_e\cdot A_e\cdot\Delta T_e \quad (33)$$

Therefore, the heat transfer area for the first, second, and last effect can be obtained as follows:

$$A_{e1} = \frac{(D_s + D_r)\cdot\lfloor h_d - h_{fd}\rfloor}{U_{e1}\cdot(T_d - T_1)} \quad (34)$$

$$A_{e2} = \frac{(D_1 + D_r\cdot y - F_1\cdot y)\cdot L_1}{U_{e2}\cdot(T_{v1} - T_2)} \quad (35)$$

$$A_n = \frac{[(D_{n-1} + \sum_{i=1}^{n-2}(D_i + D_r)\cdot y - (j+n-1)\cdot F_i\cdot y]\cdot L_{n-1}}{U_{en}\cdot(T_{vn-1} - T_n)} \quad (36)$$

The overall heat transfer coefficient (U_e) depends mainly on the type, design, and material of the tubes [16], and for simplicity it can be calculated as [15]:

$$U_{ei} = \frac{(1939.4 + 1.40562\cdot T_i - 0.0207525\cdot(T_i)^2 + 0.0023186\cdot(T_i)^3)}{1{,}000} \quad (37)$$

The cooling seawater flow rate can be obtained by applying the energy conservation law on the condenser as shown below:

$$M_c = \frac{D_f\cdot L_n}{C\cdot(T_f - T_c)} \quad (38)$$

The latent heat of condensation of the un-entrained vapor D_f flowing to the condenser is used to increase cooling seawater temperature to feed seawater temperature. The thermal load of the condenser is used to calculate the condenser heat transfer area as follows:

$$A_c = \frac{D_f\cdot L_n}{U_c\cdot(\text{LMTD})_c} \quad (39)$$

The logarithmic mean temperature difference and the overall heat transfer coefficient of the condenser can be obtained from Eqs. (40) and (41), respectively [16].

$$(\text{LMTD})_c = \frac{(T_{vn} - T_f) - (T_{vn} - T_c)}{\ln\frac{(T_{vn}-T_f)}{(T_{vn}-T_c)}} \quad (40)$$

$$U_c = 1.7194 + 3.2063 \cdot 10^{-2} \cdot T_{vn} - 1.5971 \cdot 10^{-5} \cdot (T_{vn})^2 + 1.9918 \cdot 10^{-7} \cdot (T_{vn})^3 \quad (41)$$

Similarly, the heat transfer area of the feed heaters can be expressed as follows assuming that the overall heat transfer coefficient of the feed heaters is equal to that of the condenser.

$$A_{fi} = \frac{(i)F_i \cdot C \cdot \Delta T_f}{U_f \cdot (T_{fi} - T_{fi+1})} \cdot \ln\frac{(T_{vi} - T_{fi+1})}{(T_{vi} - T_{fi})}, \quad i = 1, 2, \ldots n-2 \quad (42)$$

3.4. System performance

The system performance of the ME-TVC model can be evaluated in terms of the following:

3.4.1. Gain output ratio

The gain output ratio is one of the most commonly characteristic used to evaluate the performance of thermal desalination processes. It is defined as the ratio of total distilled water produced (D) to the motive steam supplied (D_s).

$$\mathrm{GOR} = \frac{D}{D_s} \quad (43)$$

3.4.2. Specific heat consumption, Q_d

This is one of the most important characteristic of thermal desalination systems. It is defined as the thermal energy consumed by the system to produce 1 kg of distilled water, where L_s is the motive steam latent heat in kJ/kg.

$$Q_d = \frac{D_s \cdot L_s}{D} \quad (44)$$

3.4.3. Specific exergy consumption, A_d

The specific exergy consumption is one of the best methods used to evaluate the performance of the ME-TVC based on the Second Law of Thermodynamics. It considers the quantity as well as the quality of the supplied motive steam. It is defined as the exergy consumed by the motive steam to produce 1 kg of distillate, when the steam is supplied as saturated vapor and leaves as saturated liquid at ambient temperature equal to T_o, according to the following Eq. (18):

$$A_d = \frac{D_s}{D} \cdot [(h_s - h_{fd}) - T_o \cdot (S_s - S_{fd})] \quad (45)$$

where h_s and S_s are the inlet motive steam enthalpy and entropy at saturated vapor and h_{fd} and S_{fd} are that of the outlet condensate at saturated liquid.

3.4.4. Specific heat transfer area, A_t

The specific total heat transfer area is equal to the sum of the effect, feed heaters, and the condenser heat transfer areas per total distillate product (m^2/kg/s).

$$\frac{At_d}{D} = 2 \cdot \sum_{i=1}^{j} \frac{A_{ei}}{D_i} + \sum_{j+1}^{n} \frac{A_{ei}}{D_i} + \sum_{i=1}^{n-2} \frac{A_{fi}}{D_i} + \frac{A_c}{D} \quad (46)$$

3.4.5. Specific exergy destruction, I_t

This term shows the total exergy destruction due to heat transfer in the thermo-compressor, evaporators, condenser, and the leaving streams per unit of distillate water.

$$I_t = \sum \frac{I_i}{D} \quad (47)$$

where I_i is the exergy destruction in each component in kJ/kg.

4. Results and discussion

EES software is used to evaluate the ME-TVC system performance. The validity of the model was tested against some available data of the three commercial units having different unit capacities: ALBA in Bahrain (2.4 MIGD), Umm Al-Nar in UAE (3.5 MIGD), and Al-Jubail in KSA (6.5 MIGD). The results showed good agreements as shown in Table 1.

In light of the results shown in Table 1, it can be observed the following:

(1) The available data of Al-Jubail unit is limited in the literature. Hence, the developed mathematical

Table 1
Mathematical model calculations against some commercial plants

Desalination plant	ALBA [17]		UMM Al-NAR [19]		AL-JUBAIL	
Number of effects, *n*	4		6		8	
Operating and design parameters	Model	Actual	Model	Actual	Model	Actual
Motive pressure, bar	21	21	2.8	2.8	2.7	2.7
Top brine temperature, ℃	63	63	63	62	63	NA
Minimum brine temperature, ℃	48	48	44	43	42	NA
Feed sea water temperature, ℃	43	43	40	40	37	NA
Motive steam flow rate, kg/s	8.5 × 2	8.3 × 2	11 × 2	10.65 × 2	17.5 × 2	NA
Temperature drop per effect, ℃	5	5	3.8	3.8	3	NA
Ejector design						
Compression ratio	1.57	NA	1.7	NA	1.75	NA
Expansion ratio	120	NA	18	NA	18.7	NA
Motive to entrained vapor ratio	0.58	NA	0.885	NA	0.98	NA
System performance						
Distillate production, kg/s	123.5	127	184.2	184.38	349	342.22
Gain output ratio	7.26	7.5	8.3	8.6	10	9.8
Specific heat consumption, kJ/kg	346.9	NA	292.1	287.5	223	NA
Specific available energy, kJ/kg	127.2	NA	74.6	NA	56.44	NA
Specific heat transfer area, m^2/kg/s	243.5	NA	335.6	310	452.2	NA
Specific exergy destruction, kJ/kg/s	94.65	NA	54.24	NA	41.16	NA

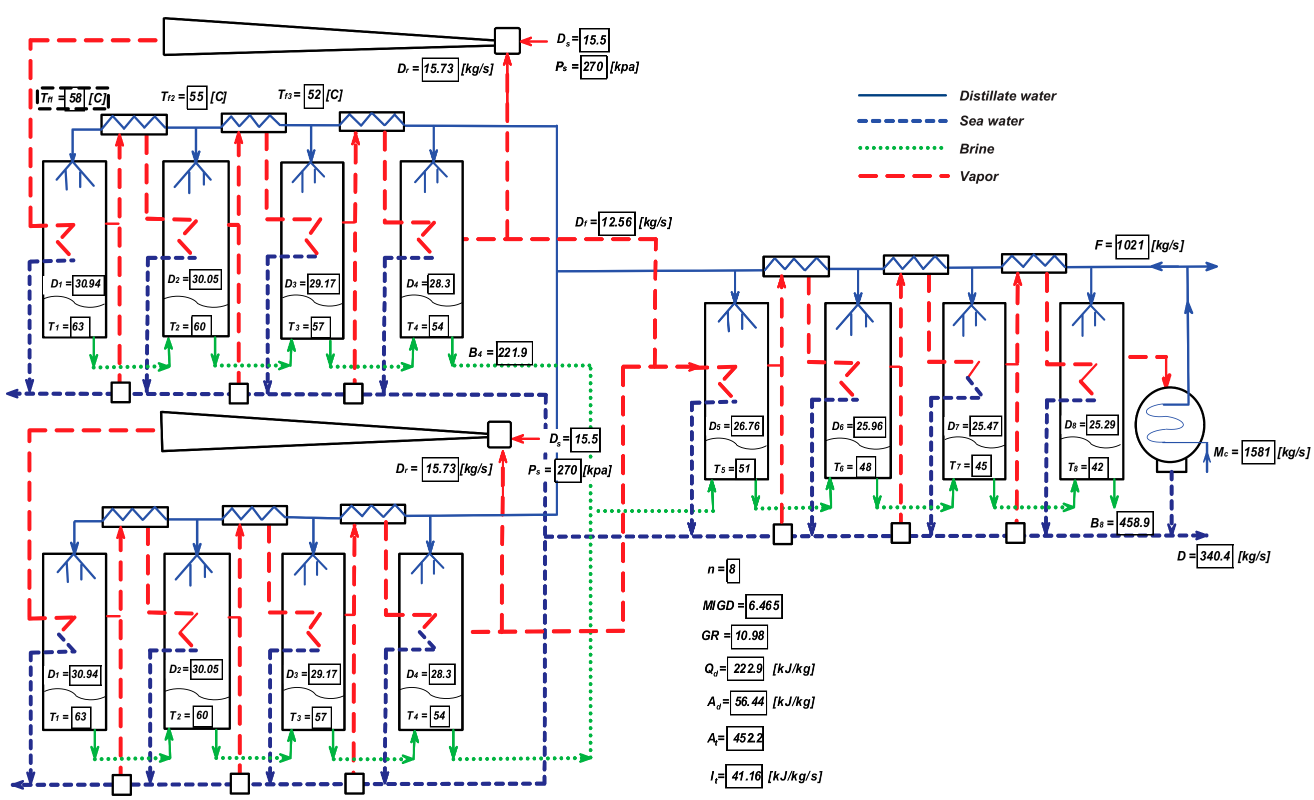

Fig. 3. Flow sheet diagram similar to Al-Jubail (Marafiq) ME-TVC unit, 6.5 MIGD.

model is used to predict the missing values in order to evaluate the system performance of this plant.

(2) The motive steam is supplied directly from boilers at 21 bars in ALBA, while it is extracted from steam turbine (in a combined cycle power plant) at low pressures of 2.8 and 2.7 bars in the case of Umm Al-Nar and Al-Jubail units, respectively.

(3) Al-Jubail unit has the highest GOR as well as the lowest specific heat consumption and the lowest specific available energy.

(4) The specific exergy destruction in ALBA unit (94.65 kJ/kg) is almost twice than that in Umm Al-Nar and Al-Jubail units (54.24 and 41.16 kJ/kg, respectively) because high motive pressure of 21 bars is used in ALBA compared to low motive pressure of 2.8 bars in other units.

(5) The specific exergy destruction can be significantly reduced by increasing the number of effects.

(6) The manufacturer tried to increase the number of effects gradually (4, 6, 8, etc.) in order to increase the size of the units in a compact design.

5. Sensitivity analysis

A sensitivity analysis will be presented in this section to investigate the system performance variations and simulation of Al-Jubail ME-TVC unit in KSA. This project belongs to Marafiq Company and it is currently considered as the largest ME-TVC desalination plants in the world, it consists of 27 units each of 6.5 MIGD as shown in Fig. 3.

Fig. 4 shows the effect of motive steam flow rate on the vapor formed in each effect of this unit, at T_1 = 63˚C and ΔT = 3˚C. The total distillate production can be controlled by adjusting the motive steam flow rate. The reason is when the motive steam flow rate increases the entrained vapor also increases for constant entrainment ratio (D_s/D_r), this will lead to generate more vapor and consequently more distillate water.

The variation of the GOR and the distillate production as a function of top brine temperature is shown in Fig. 5. It is clear that as the top brine temperature increases the distillate output production decreases, and consequently GOR decreases. The reason is when the top brine temperature increases the vapor latent heat decreases and the amount of feed sensible heating increases, and this fact is illustrated in Eq. (12).

The direct dependence of the top brine temperature on the specific heat consumption and the specific exergy consumption are shown in Fig. 6. Both of them increase linearly as the top brine temperature increases, because higher top brine temperature leads to higher vapor pressure and consequently larger

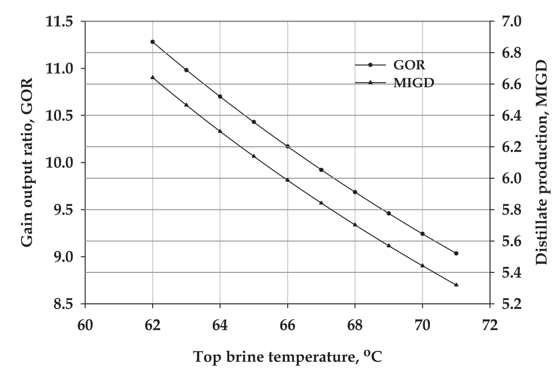

Fig. 5. The effect of top brine temperature on the distillate production and GOR.

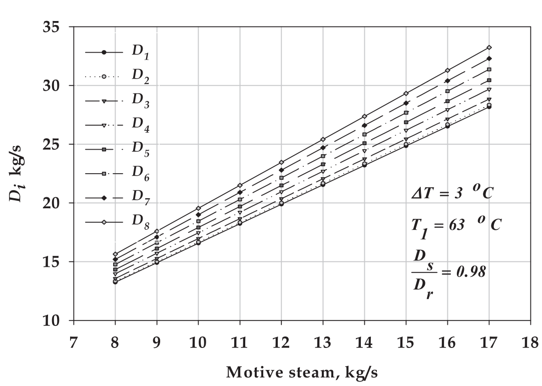

Fig. 4. The effect of motive steam on the distillate production from the effects.

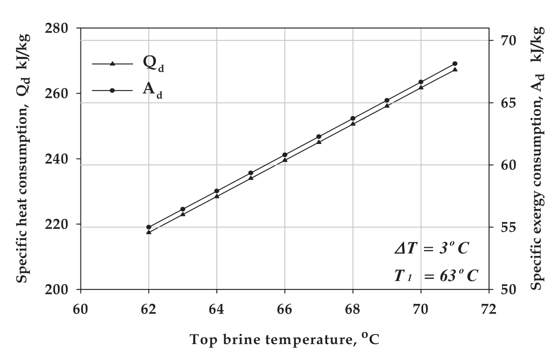

Fig. 6. The effect of top brine temperature on the specific heat consumption and specific exergy consumption.

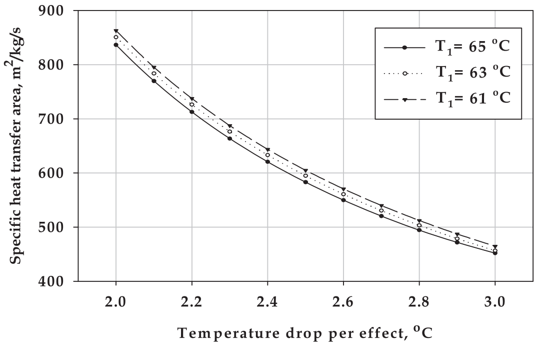

Fig. 7. The effect of temperature drop per effect on the specific heat transfer area at different top brine temperatures.

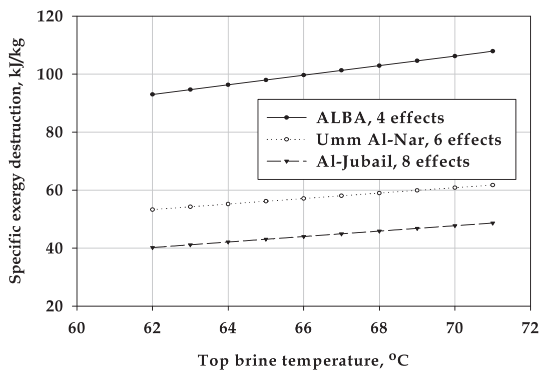

Fig. 8. The effect of top brine temperature on the specific exergy destruction for different units.

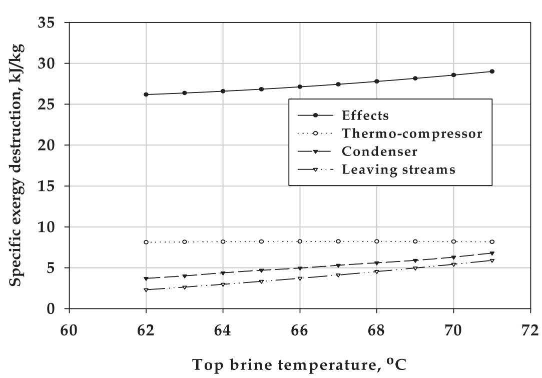

Fig. 9. The effect of top brine temperature on the specific exergy destruction in different components of Al-Jubail ME-TVC unit.

amount of motive steam is needed to compress the vapor at higher pressures.

Fig. 7 demonstrates the variations of the specific heat transfer area as a function of temperature difference per effect at different top brine temperatures.

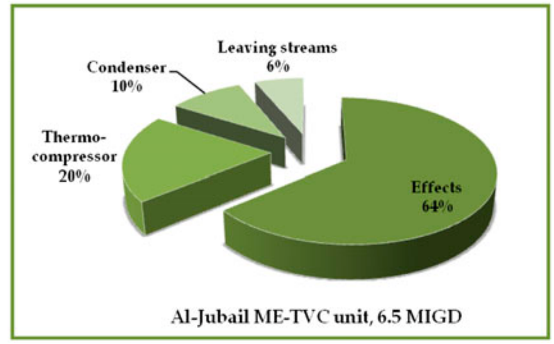

Fig. 10. The exergy destruction in the effects, thermo-compressor, condenser, and leaving streams of Al-Jubail unit.

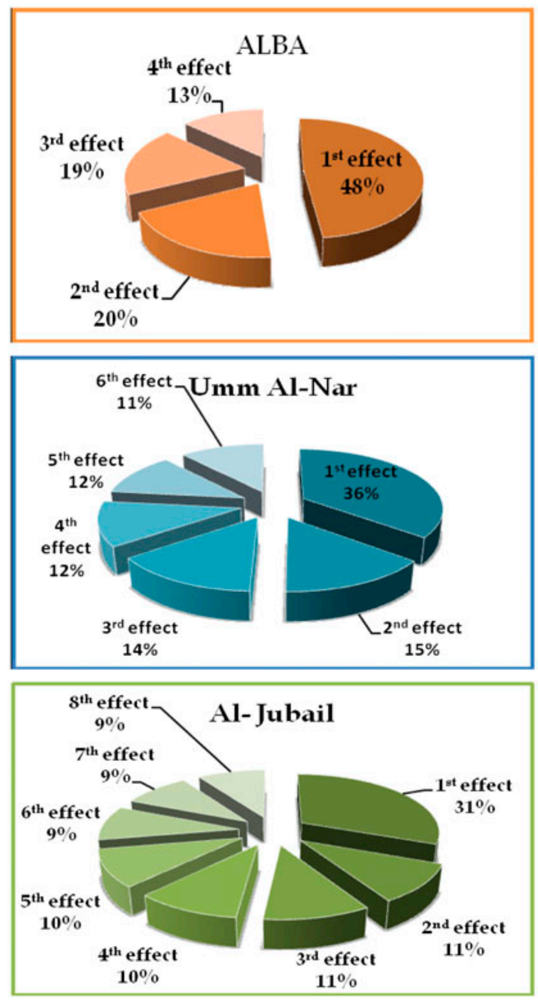

Fig. 11. The exergy destruction in the effects of ALBA, Umm Al-Nar, and Al-Jubail.

The increase in the specific heat transfer area is more pronounced at lower temperature difference per effect than at lower top brine temperatures.

The exergy analysis is also used to identify the impact of the top brine temperature on the specific exergy destruction for different ME-TVC units as shown in Fig. 8. It shows that as the top brine temperature increases, the specific exergy destruction of ALBA, Umm Al-Nar, and Al-Jubail plants increases. It shows also that Al-Jubail unit has the lowest values compared to the other units because it has the highest distillate production. Fig. 9 gives detailed values of exergy destruction in different components of Al-Jubail units, while Fig. 10 pinpoints that the thermo-compressor and the effects are the main sources of exergy destruction. On the other hand, the first effect of this unit was found to be responsible for about 31% of the total effects exergy destruction compared to 46% in ALBA and 36% in Umm Al-Nar as shown in Fig. 11.

6. Conclusions

Exergy analysis shows that the specific exergy destruction in ALBA unit (94.65 kJ/kg) is almost twice that in Umm Al-Nar and Al-Jubail units (54.24 and 41.16 kJ/kg, respectively) because high motive pressure of 21 bars is used in the ALBA compared to low motive pressure of 2.8 bars in the other units. The analysis indicates that thermo-compressor and the effects are the main sources of exergy destruction in these units. On the other hand, the first effect was found to be responsible for about 31% of the total effects exergy destruction in Al-Jubail, compared to 46% in ALBA, and 36% in Umm Al-Nar. The specific exergy destruction can be reduced significantly by increasing the number of effects as well as working at lower top brine temperatures. The manufacturer tried to increase the number of effects gradually (4, 6, 8, etc.) in order to increase the size of the units in a compact design as well as to reduce the irreversibilities.

Symbols

A — heat transfer area, m^2
A_c — condenser heat transfer area, m^2
A_d — specific available energy consumption, kJ/kg
A_f — feed heater heat transfer area, m^2
At_d — specific heat transfer area, m^2/kg
B — brine flow rate, kg/s
BPE — boiling point elevation, ℃
C — specific heat capacity of water, kJ/kg. K
CG-ST — combined gas-steam turbine system
CR — compression ratio
D — distillate, kg/s
D_f — non-entrained vapor, kg/s
D_r — entrained vapor to steam ejector, kg/s
D_s — motive steam flow rate, kg/s
D_s/D_r — entrainment ratio
ER — expansion ratio
F — feed flow rate, kg/s
GR — gain ratio
h — enthalpy, kJ/kg
h_d — enthalpy of the discharged steam, kJ/kg
h_f — saturated liquid enthalpy, kJ/kg
h_{fd} — saturated liquid enthalpy of the discharged steam, kJ/kg
h_g — saturated vapor enthalpy, kJ/kg
h_s — motive steam enthalpy, kJ/kg
HRSG — heat recovery steam generator
L — latent heat, kJ/kg
LMTD — logarithmic mean temperature difference
M_c — cooling seawater flow rate, kg/s
M_c-F — rejection seawater flow rate, kg/s
ME — multi effect
ME-TVC — multi-effect thermal vapor compression
MIGD — million imperial gallons per day
MSF — multi stage flash system
NEA — non-equilibrium allowance, ℃
n — number of effects
P — pressure, kPa
P_d — discharge pressure, kPa
P_n — entrained pressure in the last effect, kPa
P_s — motive steam pressure, kPa
ppm — parts per million
Q — thermal load of condensation, kW
Q_d — specific heat consumption, kJ/kg
S — entropy, kJ/kg. K
S_{fd} — entropy of the discharged steam at saturated liquid, kJ/kg. K
S_g — saturated vapor entropy, kJ/kg. K
S_s — motive steam entropy, kJ/kg. K
T — brine temperature, ℃
TBT, T_1 — top brine temperature, ℃
T_c — cooling seawater temperature, ℃
T_d — discharged temperature, ℃
T_f — feed seawater temperature, ℃
T_o — environment state temperature, K
T_v — saturated vapor temperature, ℃
ΔT — temperature difference per effect, ℃
U — heat transfer coefficient, kW/m^2 K
X — salt concentration, ppm

Subscripts

b — brine
c — condenser or cooling
d — discharge stream
e — effect
f — feed
i — effect number, i
n — last effect
s — motive stream

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