INTEGRATION OF TVC DESALINATION SYSTEM WITH COGENERATION PLANT: PARAMETRIC STUDY

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ABSTRACT

The aim of this research is to perform a parametric analysis on TVC desalination system. The study was based on first and second law of thermodynamics. Four units of thermal vapor compression (TVC) desalting system, from Sidem, with a capacity of 1 MIGD and a gain ratio of 8 were utilized. This system was considered to be integrated with the Azzour South cogeneration plant. Several parameters were investigated in this study; compression ratio, temperature difference across the stages and number of stages. Results showed that the gain ratio, exergy destruction were sensitive to the variations of those parameters. Results also showed that the evaporator and steam ejector are the main sources of exergy destruction occurred in TVC system. The study recommends that efforts should be directed to achieve the best setting for the desalination process to minimize the exergy destruction and increase the gain ratio by improving design of such components.

Keywords: Desalination, Cogeneration, SE-TVC, ME-TVC, Exergy, Gain ratio, Heat consumption

INTRODUCTION

Researchers have continued working for achieving additional improvements to enhance desalination system performance; they are trying to reach a reduction in specific energy consumption, specific heat transfer area, specific cooling water flow rate and specific exergy destruction. On the other side researchers are seeking to find ways to increase desalination gain ratio and performance ratio. Several investigators studied the effect of operational and design parameters using energy and exergy analysis such as:

Darwish and El-Dessouky [6] compared the performance between thermal vapor compression process, conventional multi effect (ME) system and conventional multistage flash (MSF) desalting system. Their results showed that gain ratio of 4 effects TVC is very close to that of 11 ME effects and 24 stages MSF desalting systems. Nevertheless, the MSF and ME are supplied with a steam at low pressure, while the TVC requires a high pressure steam.

Al-Najem *et al.* [1] conducted a parametric analysis for TVC system components; steam ejector, evaporator, and condenser, as well as the system as a whole. The study presented the energy and exergy analysis of individual components for a single and a multi effect thermo vapor compression systems. Results showed that the steam ejector and the evaporator are the main source of exergy destruction in the TVC system. They recommended minimizing theses losses by improving the design of such component.

El-Dessouky and Ettouney [8] evaluated the variations of thermal performance ratio, specific heat transfer area, and specific flow rate of cooling water as a function of brine boiling temperature, vapor compression ratio and motive steam pressure, the study aimed to analyze a single effect thermal vapor compression (SE-TVC) desalination process. They recommended that the single effect vapor compression desalination unit can be operated at intermediate values of evaporation temperature (70 to 80 °C) and low compression ratios (values close to 2). This is necessary to have performance ratios close to or higher than 1.5. They concluded that when the TVC unit operates at intermediate values, a large reduction is observed in the specific heat transfer area and specific cooling water flow rate. This reduction will lower the construction cost of evaporator, condenser, and seawater pump. In addition, they concluded that operating cost would be lower as a result of reduction in the energy required to operate the seawater pumping unit.

El-Dessouky et al. [9] proposed a novel system to increase the performance of a multistage flash desalting process (MSF) by a combination of MSF with thermal vapor compression (TVC). Two schemes, which included vapor entrainment and compression from the heat recovery or rejection sections, were evaluated. They evaluated the performance of the proposed schemes as a function of top brine temperature and location of vapor entrainment. They concluded that thermal vapor compression enhances the performance of MSF system as a result of the increase in the performance ratio and the reduction in the specific flow rate of cooling water and the specific heat transfer area.

Kamali et al. [11] developed simulation model of ME-TVC system for parametric optimization techniques. This model predicts the effect of all parameters on total capacity, performance ratio of the system, temperature difference between effects and pressure on each effect under design and operating conditions. The results showed that by means of parametric study, the computer simulation tool developed will help designers to achieve the best settings for desalination process to increase GOR value and minimize the energy consumption.

Bin Amer [3] developed a Matlab algorithm and used it to solve a mathematical model optimization problem, where different numbers of effects were tested to maximize the gain ratio. The results showed the maximum gain ratio varied between 8.5 and 18.5 for 4 and 12 effects with an optimal top brine temperature ranging between 55.8 to 67.5 ^oC and reasonable specific heat transfer area.

1- Single and Multi Effect Thermal vapor compression desalting system

The main components of the TVC unit are the steam jet ejector, the condenser and the evaporator. The SE-TVC consists of only one evaporator whereas the ME-TVC consists of multi number of evaporators (effects). Multi effect thermal vapor compression desalting systems is shown in figure 1; the motive steam at a medium pressure is used to compress some of the vapor generated in the last evaporator (the lowest temperature effect) by the steam ejector. The recompressed vapor discharged from the ejector is used (along with the expanded motive steam) as a heating source. The expanded motive steam and recompressed vapor leaving the steam ejector are directed to and condensed in the first and highest temperature effect. The vapor generated in the first effect (D_1) at (P_1) is directed to the second effect where it condenses. This vapor (D_1) acts as a heat source for this second effect and heats the feed (F_2) to that effect from its feed temperature (T_f) to its evaporation temperature (T_2) and generates vapor by evaporation and flashing at a rate equal to ($D_2 = D_{e2} + D_{fl2}$) at (P_2). Similarly, the vapor (D_2) generated in the second effect is used as a heat source for the next effect and so on to the last effect. The vapor generated in the last effect (D_n) is divided to (D_{ev}) and (D_c). The stream (D_{ev}) is directed to the steam ejector where it is recompressed and returned to the first effect, along with the motive steam (S) as a heating medium. The stream (D_c) is directed to the end of the condenser where it condenses and heats the seawater feed from seawater temperature (T_{cw}) to the feed temperature (T_f). The brine leaving the first effect (B_1) is directed to the second effect where its temperature is spontaneously decreased from (T_1) to (T_2) where ($T_1 - T_2 = \Delta T$) by flashing a part of this brine equal to ($B_1 C \Delta T / L$) into a vapor in the second effect. The vapor generated in the second effect (D_2) consists of the part obtained by evaporation (D_{e2}) and the part obtained by flashing (D_{fl2}). Similarly, the brine leaving the second effect (B_2) is directed to the third effect and so on to the last effect. The brine leaving the last effect (B_n) is the brine blow down. Part of the condensate returns to the boiler, and the other part join the product water. The energy and exergy analysis for each components of multi effect system will be presented in this section. In the following analysis, some assumptions will be made, whenever adequate, to simplify the analysis such as: the specific heats C_f, C_d and C_{br} are averaged as C, the latent heats $L_1, L_2, ...L_n$ are assumed to be equal to L and temperature drop across evaporators, $T_i - T_{i+1}$ are assumed to be equal to ΔT_e.

- **Steam ejector**

The energy balance and exergy destruction (irreversibility) in the steam ejector are expresses, as the following:

$$Sh_s + D_{ev}h_{gn} = (S + D_{ev})h_{dc} \tag{1}$$

$$I_{ej} = \Delta\Psi_{ej} = S[(h_s - h_{dc}) - T_o(s_s - s_{dc})] - D_{ev}[(h_{dc} - h_{gn}) - T_o(s_{dc} - s_{gn})] \tag{2}$$

- **First effect**

The energy balance and exergy destruction (irreversibility) in the first effect are expresses, as the following:

$$(S + D_{ev})(h_{dc} - h_c) = F_1C(T_1 - T_f) + D_1L_1 \tag{3}$$

$$I_1 = \Delta\Psi_1 = (S + D_{ev})[(h_{dc} - h_c) - T_0(s_{dc} - s_c)] - F_1C\left[(T_1 - T_f) - \left(T_0 \ln\frac{T_1}{T_f}\right)\right] - D_1L\left(1 - \frac{T_0}{T_{v1}}\right) \tag{4}$$

- **Second effect**

The energy balance and exergy destruction (irreversibility) in the second effect are expresses, as the following:

$$D_1L + (F_1 - D_1)C(T_1 - T_2) = F_2C(T_2 - T_f) + D_2L \tag{5}$$

$$I_2 = \Delta\Psi_2 = D_1L\left(1 - \frac{T_0}{T_1}\right) + (F_1 - D_1)C\left[(T_1 - T_2) - T_0\ln\frac{T_1}{T_2}\right] - D_2L\left(1 - \frac{T_0}{T_2}\right) - F_2C\left[(T_2 - T_f) - T_0\ln\frac{T_2}{T_f}\right] \tag{6}$$

- **n-effect**

The energy balance and exergy destruction (irreversibility) in the n-effect are expresses, as the following:

$$D_{i-1}L_{i-1} + [(F_1 - D_1) + (F_2 - D_2) + \ldots(F_{i-1} - D_{i-1})]C\Delta T = F_iC(T_i - T_f) + D_1L_1 \tag{7}$$

$$\begin{aligned} I_i = \Delta\Psi_i = D_{i-1}L_{i-1}\left(1 - \frac{T_o}{T_{v(i-1)}}\right) + \left(\sum_1^{i-1}(F_i - D_i)\right)C\left[\Delta T - T_o\ln\frac{T_{i-1}}{T_i}\right] \\ - D_iL\left(1 - \frac{T_o}{T_{vi}}\right) - F_iC\left[(T_i - T_f) - T_1\ln\frac{T_i}{T_f}\right] \end{aligned} \tag{8}$$

- **End condenser**

The energy balance and exergy destruction (irreversibility) in the n-effect are expresses, as the following:

$$D_cL_n = (M_{cw} + F_t)C(T_f - T_{cw}) \tag{9}$$

$$I_c = \Delta\Psi_c = D_c L_n\left(1-\frac{T_o}{T_n}\right)-\left(M_{cw}+F_t\right)C\left[\left(T_f - T_{cw}\right)-T_o \ln\left(\frac{T_f}{T_{cw}}\right)\right] \quad (10)$$

The total product distillate output is expressed by

$$D_t = \sum D_i = D_1 + D_2 + ...+ D_n \quad (11)$$

2- Thermal vapor compression desalting system performance parameter

In this section, some of important parameters that have significant effect on the performance of TVC system will be presented.

- **Specific energy consumption**

The specific energy consumption per unit distillate is expressed by:

$$\frac{Q}{D} = S\left(h_s - h_c\right) \quad (12)$$

- **Gain ratio**

The amount of fresh water product per unit mass of motive steam or the gain ratio is expressed by:

$$GR = \frac{D}{S} \quad (13)$$

- **Specific exergy destruction**

The specific exergy destruction per unit distillate is expressed by:

$$\Delta\psi = \frac{\Delta\Psi}{D} \quad (14)$$

- **Specific heat transfer surface area**

The specific heat transfer surface area of whole system is expressed by:

$$\frac{A}{D} = \frac{A_e + A_c}{D} \quad (15)$$

The heat transfer area of evaporator (first effect) is expressed by:

$$A_e = \frac{Q_e}{U_e\left(T_{dc} - T_1\right)} = \frac{\left(S + D_{ev}\right)\left(h_{dc} - h_c\right)}{U_e\left(T_{dc} - T_1\right)} \quad (16)$$

The heat transfer area of the second effect to the last effect is expressed by:

$$A_i = \frac{D_{(i-1)}L}{U_i\left(T_i - T_{i+1}\right)} \tag{17}$$

The heat transfer area of condenser is expressed by:

$$A_c = \frac{D_c L}{U_c\left(LMTD\right)_c} \tag{18}$$

The log mean temperature difference is expressed by:

$$LMTD = \frac{T_f - T_{cw}}{\ln \dfrac{T_{vn} - T_{cw}}{T_{vn} - T_f}} \tag{19}$$

AZZOUR DESALINATION PLANT

One of Kuwait cogeneration power desalting plants is the Azzour South cogeneration plant, which consists of 8 steam turbines with a 300 MW nominal capacity each. Each turbine is designed to supply extracted steam from cross tube connecting the IP and LP turbines to two MSF units of 7.2 MIGD capacities each. Table 1 in Appendix -A presents a comparison based on specific energy consumption by three analytical methods for four different desalting systems (MEE, TVC, MSF and RO). Based on results showed in Table 1 in Appendix- A, TVC was selected to be integrated with Azzour south cogeneration plant.

A parametric study using first and second law of thermodynamics is applied to an existing and operating TVC designed and manufactured by Sidem of France (Table 2 in Appendix- A). This system is considered to be integrated to an existing Azzour South power desalting plant. The considered system is similar to the four units of 1 MIGD capacity each, built by Sidem in the western remote area of Abu-Dhabi in the UAE. Each unit has four effects and an end condenser. It is directly operated by a boiler generating saturated steam at 25 bar pressure. The top brine temperature (T_1) at about 58.8 °C in the first effect; (P_1) = 0.8159 bar and last effect temperatures (T_4) at about 46.8 °C, (P_4) = 0.8159 bar. The data shown in Table 2 in Appendix-A is designed for units directly operated by the boiler, where in Azzour south power desalting plant, the steam is extracted from cross over tube connecting the intermediate and low pressures turbines. So to add the Sidem system to Azzour plant, the steam supply condition must be changed to the conditions of extracted steam: P = 3 bar, T = 264.4 °C (actual condition of Azzour plant at 75% load).

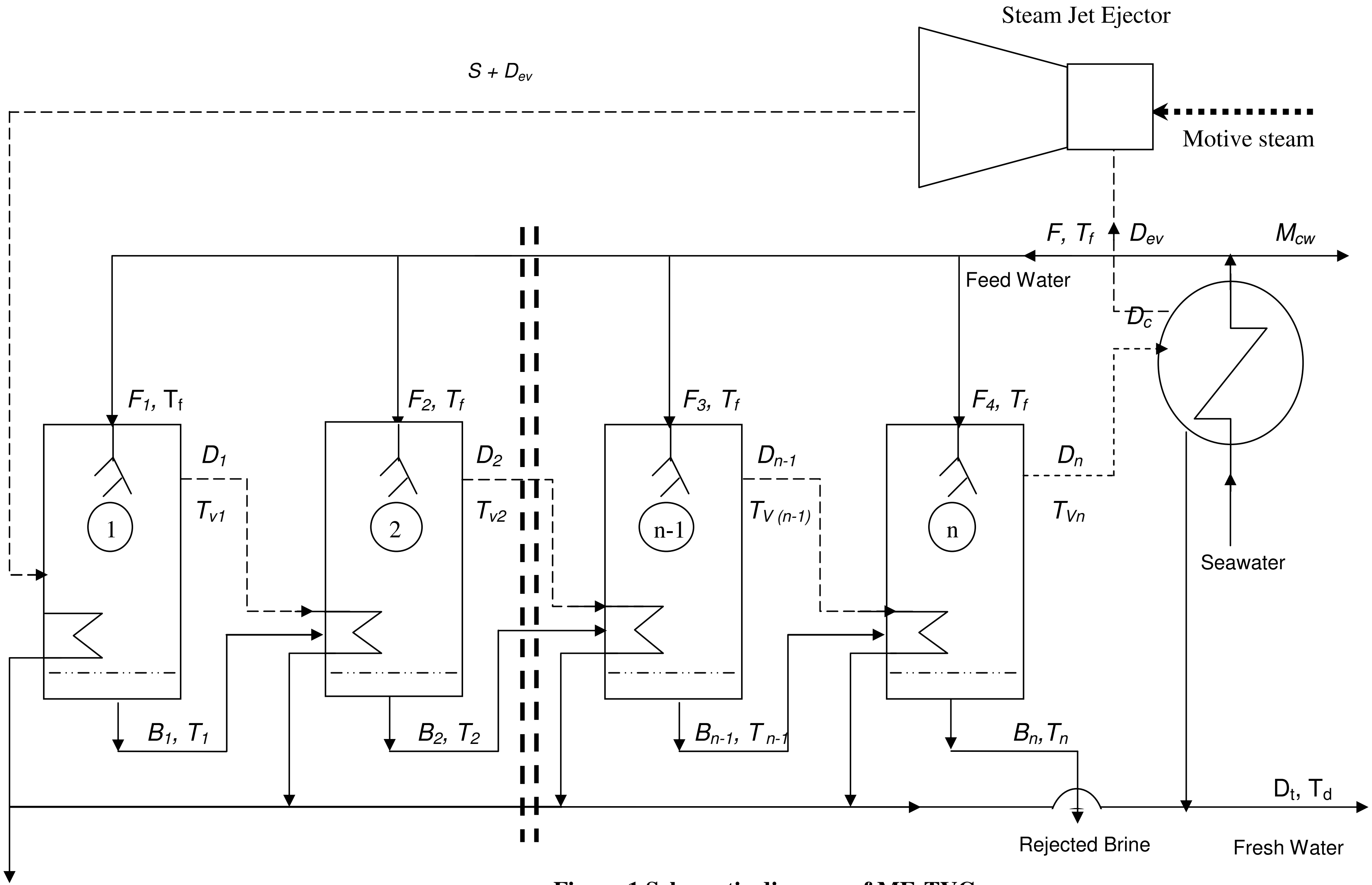

Figure 1 Schematic diagram of ME-TVC

RESULTS AND DISCUSSION

Results are presented in terms of variations in the system design parameters as a function of temperature difference across the evaporator *(ΔT_e)*, compression ratio *(Cr)*, top brine temperatures *(T_1)* and number of effects (*N*). The system parameters include variations in specific heat transfer area per unit distillate *(A/D)*, specific heat consumption per unit distillate *(Q/D)*, gain ratio *(D/S)*, Specific exergy destruction per unit distillate ($\Delta\Psi / D$) in evaporator, condenser, ejector and the whole system The results are examined both the single effect and multi effect thermo-vapor compression desalting systems

Figure 2 showed the variation of the specific heat transfer area per unit distillate *(A/D)* as a function of temperature difference across the evaporator *(ΔT_e)* in the evaporator, condenser and the whole system. Results are obtained at a temperature difference *(ΔT_e)* ranging from 2 to 16 °C. As *(ΔT_e)* decreases, the heat transfer area of the evaporator (and that of the whole system) is increased and consequently the unit cost. The decrease of *(ΔT_e)* is insensitive in the condenser whereas it is sensitive in the case of the evaporator. The drop in the specific heat transfer area of the evaporator from, *(ΔT_e)* = 2 to 8 is about 83% while from, *(ΔT_e)* = 8 to 16, the drop is small, only 9%.

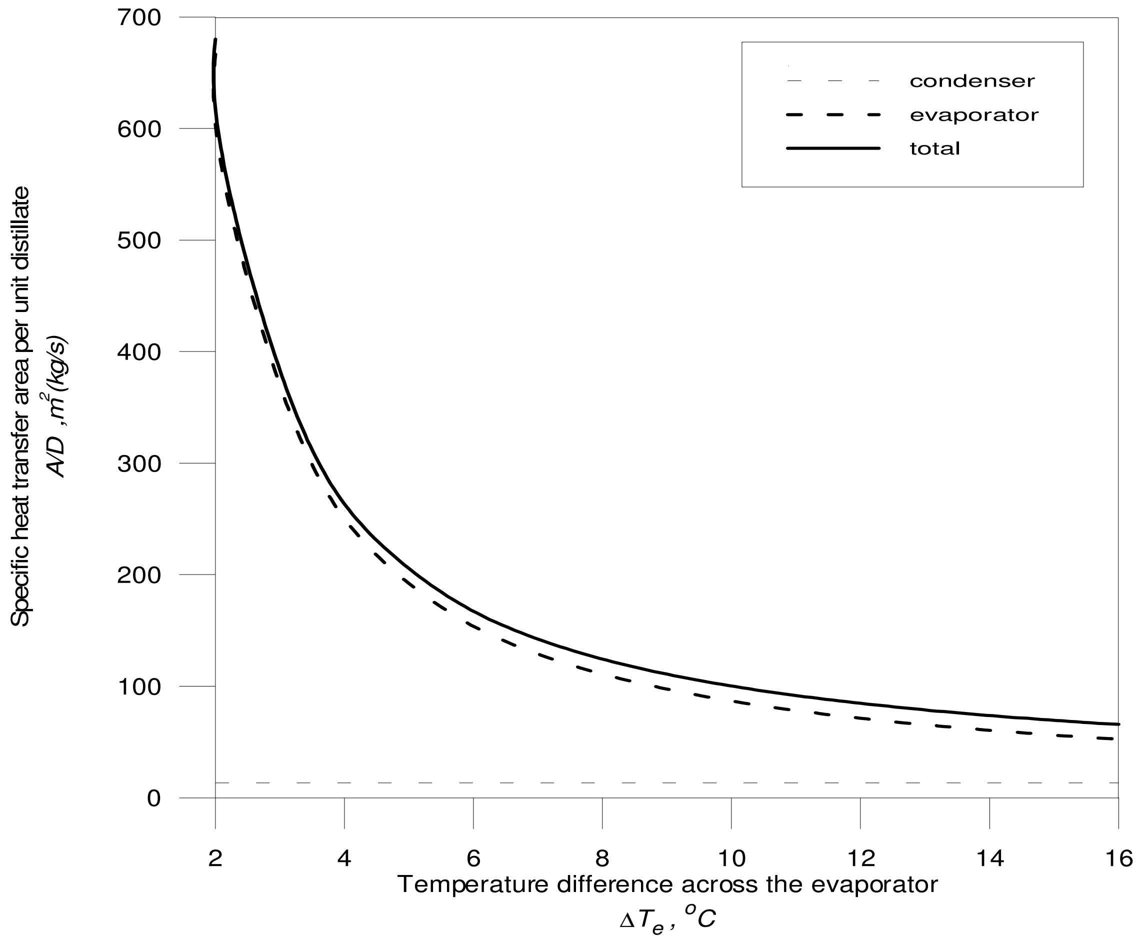

Figure 2 Effect of temperature difference across the evaporator on the specific heat transfer area of the evaporator and condenser (SE-TVC)

Figure 3 showed the variation of specific heat transfer area per unit distillate *(A/D)* as a function of compression ratio *(Cr)* under four different top brine temperatures. The results are obtained at motive steam pressure of 3 bar and top brine temperature range of 46 to 70 °C. Results showed that the specific heat transfer area decreases drastically as the compression ratio is increased and the top brine temperature is increased. At constant top brine temperatures and at higher compression ratios, the pressure of the discharge vapor is greater. This is because the pressure of the entrained vapor does not change at constant top brine temperatures. Simultaneously, the temperature of the discharge vapor is also increased as the compression ratio is elevated. The increase in the temperature of the discharge vapor enhances the rates of heat transfer. This is caused by the increase of the driving force for the heat transfer across the evaporator (ΔT_e). As a result, the evaporator heat transfer area is reduced at higher compression ratios. Regardless, the heat transfer area increases in the condenser. This is because of the increase in the condenser load, which is caused by the reduction in the amount of entrained vapor at higher compression ratios. However, the decrease in the evaporator area is more pronounced than the increase in the condenser area. The net result of the above is the decrease in the specific heat transfer area upon the increase of the compression ratio.

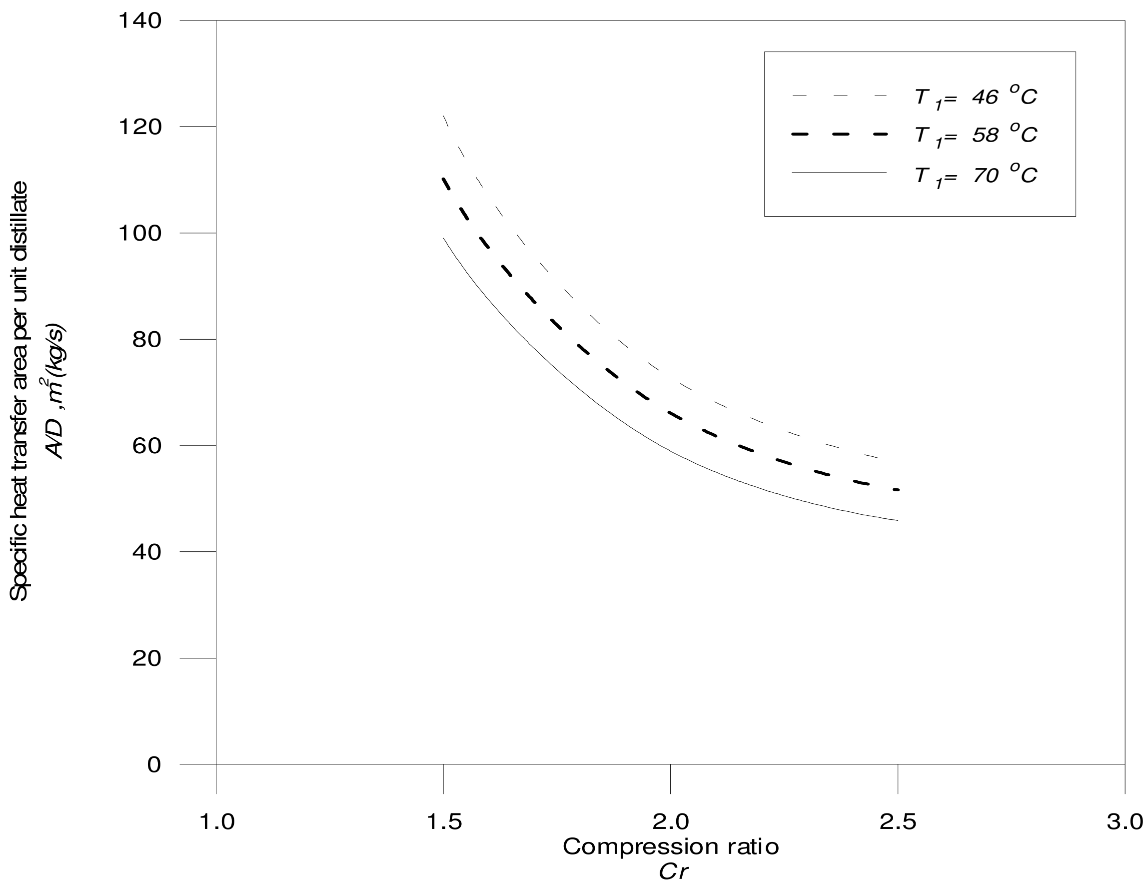

Figure 3 Effect of compression ratio on the specific heat transfer area at different top brine temperatures

Figure 4 shows the specific heat consumption per unit distillate *(Q/D)* and gain ratio *(GR)* as a function of temperature difference across the evaporator (ΔT_e). The results are obtained at temperature differences ranging from 2 to 16 °C. The results showed that the value of the specific heat consumption per unit distillate is sensitive to variations in temperature difference, where it is increased from 359.2 [kJ/(kg/s) of distillate] for (ΔT_e). = 2 °C to 1443 [kJ/(kg/s) of distillate] for (ΔT_e) = 16 °C. The drop in gain ratio is 65% for (ΔT_e) ranges from 2 to 8 °C, whereas from (ΔT_e) = 8 to 16 °C, the drop is relatively less it is about 11% only. The drop that occurred is due to the increase of compression ratio as (ΔT_e), increases which yield to an increase the amount of motive steam consumed to compress the entrained vapor. Therefore, the system gain ratio is reduced.

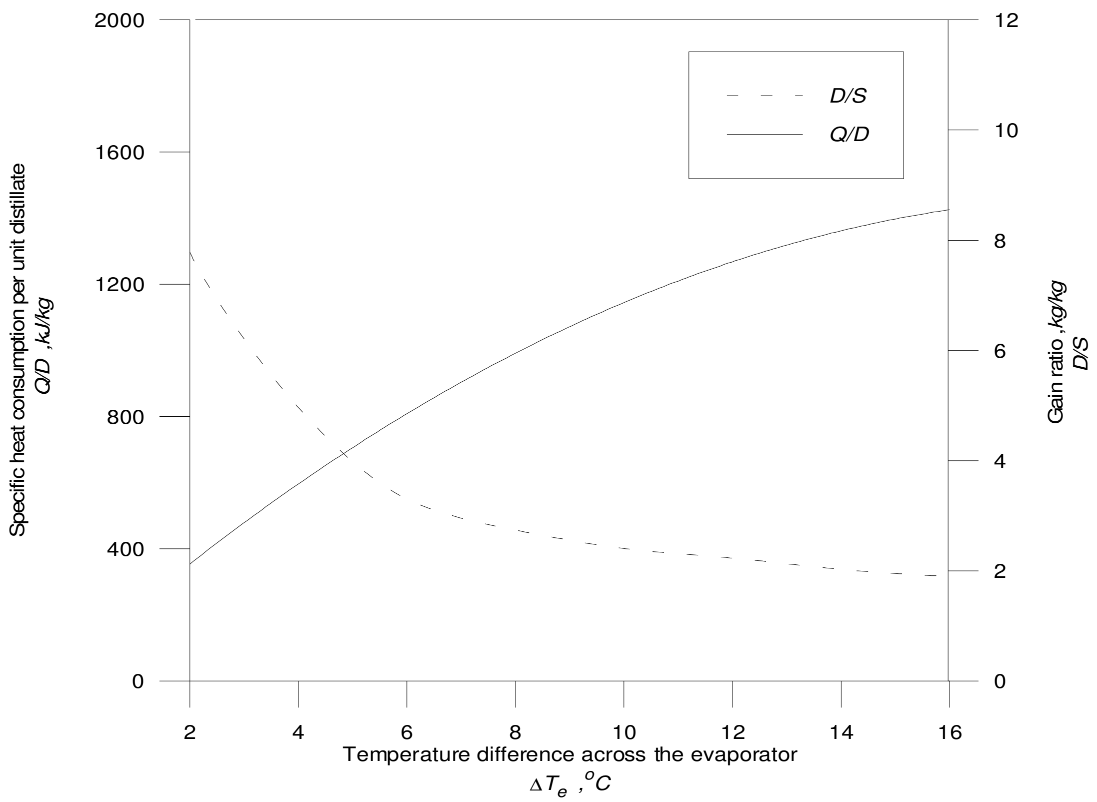

Figure 4 Effect of temperature drop across heat transfer surfaces in the evaporator on the specific heat transfer consumption per unit distillate and gain ratio

Variations in the gain ratio *(D/S)* as a function of number of effects *(N)* under different top brine temperatures, (T_1) are shown in Figure 5. The results were obtained for the same temperature difference between the top brine temperature (T_1), (evaporating temperature of the first effect) and (T_n), (of the evaporating temperature in the last effect), whereas the evaporation temperature in the last effect assumed to be (T_n) = 46 °C. The increase in the number of effects reduces the temperature across each evaporator (effect), and consequently decrease compression ratio. At low compression ratios, the amount of motive steam consumed to compress the entrained vapor is small. Therefore, the system gain ratio increases.

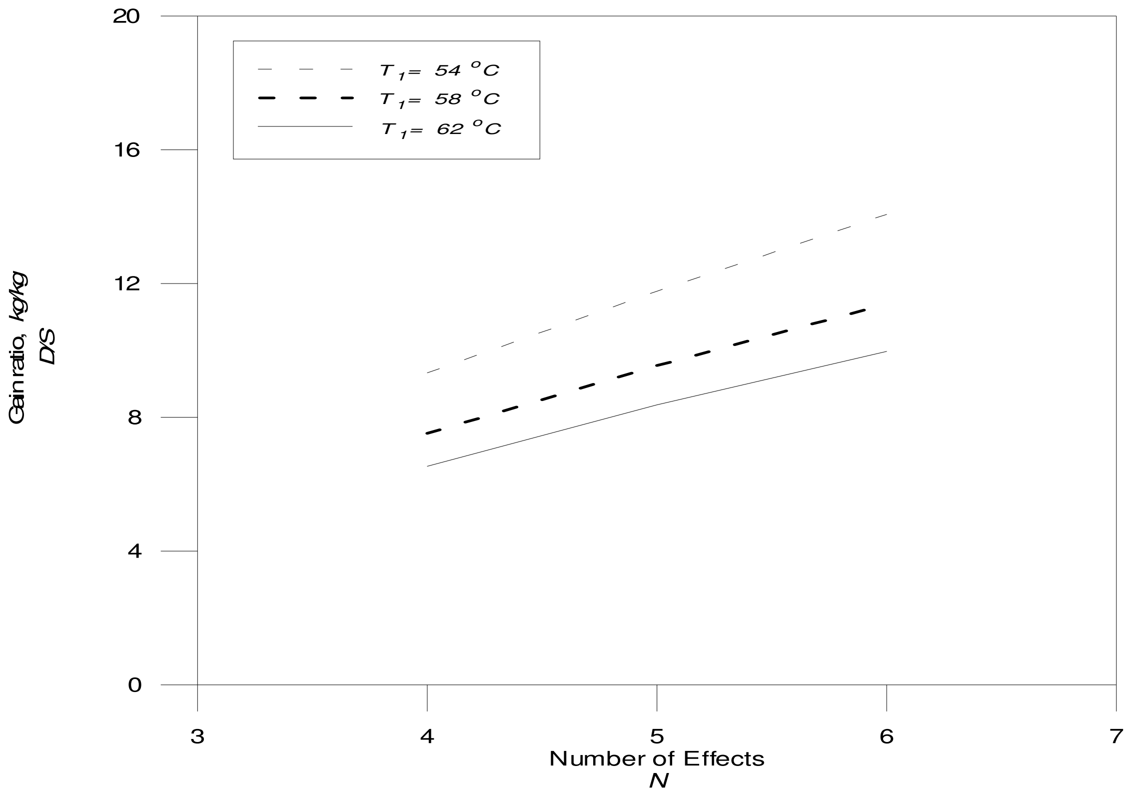

Figure 5 Effect of increasing the number of effects for the same T_n on the gain ratio at different top brine temperatures

The variations in the specific heat transfer area per unit distillate, *(A/D)*, as a function of number of effects (*N)* at different top brine temperatures, (T_1) is shown in Figure 6. The evaporation temperature in the last effect assumed to be T_n = 46 °C. The results showed that the heat transfer area increases by adding more effects. The heat transfer area for the four effect units, for example, is more than four times than the area of tehg single effect unit producing the same distillate and working between same (T_1) and (T_n).

The variations in the exergy destruction per unit distillate; in the condenser, evaporator, steam ejector, and the system as whole, as a function of top brine temperature is shown in Figure 7. Results are obtained at motive steam pressure of 3 bar and with four effects. The results showed that the increase of the top brine temperature, while keeping the same (T_n), increases the exergy destruction per unit distillate. The results indicated that the main exergy destruction occurs in the evaporator and steam ejector.

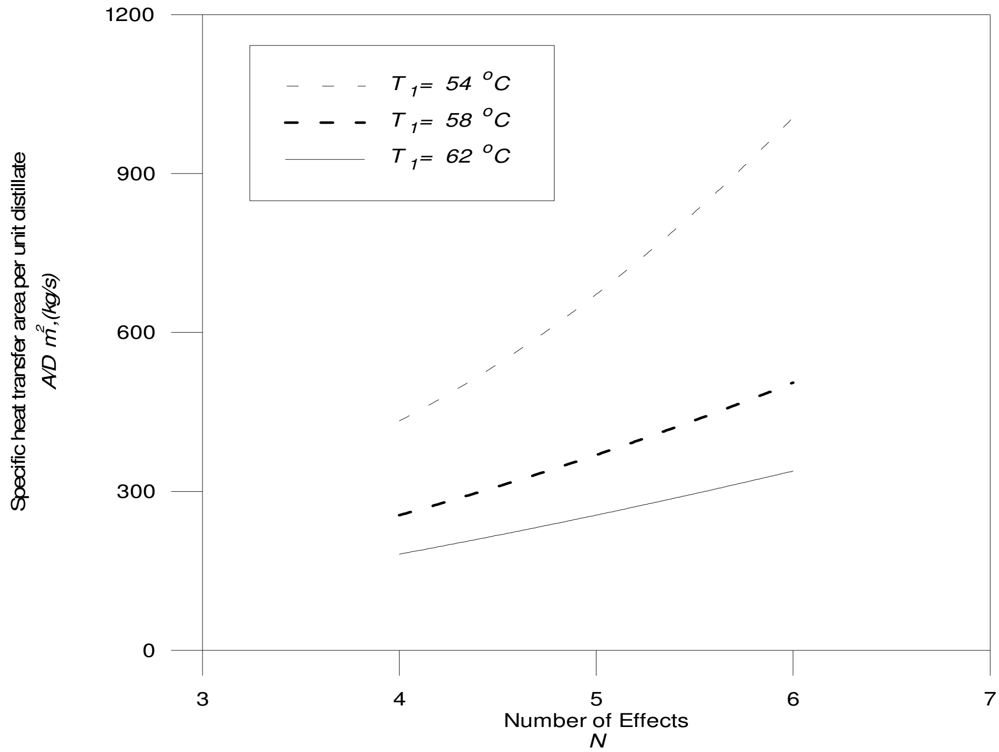

Figure 6 Effect of the number of effects on the specific heat transfer area at different top brine temperatures

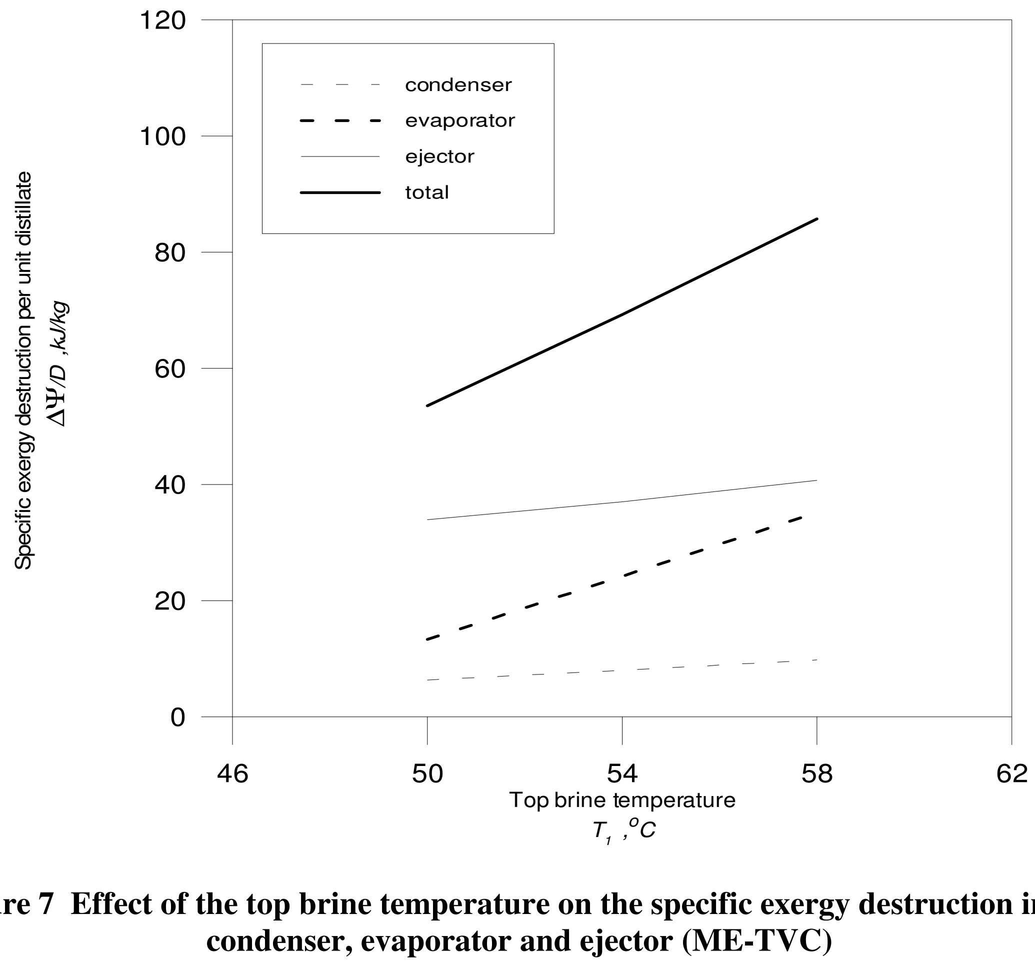

Figure 7 Effect of the top brine temperature on the specific exergy destruction in the condenser, evaporator and ejector (ME-TVC)

CONCLUSION

A parametric study based on first and second law analysis was applied on a suggested TVC system, which was considered to be integrated with an existing Azzour South cogeneration plant. Results showed that the specific energy consumption per unit distillate and the gain ratio are sensitive to variations in temperature difference across evaporator. The gain ratio is also sensitive to variations of number of effects.

Moreover, results showed that the specific exergy destruction per unit distillate is sensitive to the variations in temperature difference across evaporator, and top brine temperature.

The parametric analysis of TVC desalting system combined with Azzour South plant showed that the steam ejector and the evaporator are the main sources of exergy destructions in TVC system. Therefore efforts should be directed to minimize these losses by improving design of such components. The exergy analysis enables us to develop a systematic approach that can be used to identify sites or real losses of valuable energy in thermal devices.

NOMENCLATURE

A	Heat transfer area, m^2
B	Brine flow rate, kg s^{-1}
C	Liquid (distillate, feed and brine) specific heat kJ kg^{-1} K^{-1}
C_r	Compression ratio
D	Distillate flow rate, kg s^{-1}
E_r	Expansion ratio
F	Feed flow rate, kg s^{-1}
GR	Gain ratio
h	Specific enthalpy, kJ kg^{-1}
I	Irreversibility rate, MW
L	Specific latent heat, kJ kg^{-1}
$LMTD$	Low pressure, bar
m	Mass flow, kg
M	Mass flow rate, kg s^{-1}
$MIGD$	Million imperial gallons per day
N	Number of effects
P	Pressure, bar
Q	Motive steam supply flow rate, kg s^{-1}
s	Saturation temperature, °C
S	Temperature, °C
ST	Top brine temperature, °C
T	Overall heat transfer coefficient, kW m^{-2} °C
TBT	Top brine temperature, °C
U	Overall heat transfer coefficient, kW m^{-2} °C

Greek symbols

ψ	Specific exergy, kJ kg^{-1}
Ψ	Exergy rate, kJ s^{-1}
ΔT_e	Temperature difference across the evaporator, °C
ΔT_i	Temperature drop of the flashing stream per stage, °C

Subscripts

1	First effect
br	Brine
c	Condensate or condenser
d	Distillate
dc	Steam ejector discharge condition
e	Evaporator or evaporation
ej	Ejector
ev	Entrained vapor
f	Feed
fl	Flashing
g	Gain
gn	Saturated vapor generated in the evaporator
i	Stages numbers
l	Loss
n	Last effect
o	Surroundings
s	Steam
t	Total
v	Vapor

Appendix-A

Table 1 Specific energy consumption by four different desalting systems at design and actual data [5]

Desalting System	**Thermal Energy kJ/kg**		**Equivalent Mechanical Due to Thermal kJ/kg**		**Pumping Energy kJ/kg**		**Total Equivalent Mechanical kJ/kg (kWh/m^3)**		**Specific Fuel Energy kJ/kg**	
	Design	Actual	Design	Actual	Design	Actual	Design	Actual	Design	Actual
MSF	258	258	57.07	55.36	14.4	14.4	71.47 (19.85)	69.76 (19.38)	198.53	193.78
TVC	178.8	178.8	37.6	36.31	7.2	7.2	44.8 (12.44)	43.51 (12.09)	124.44	120.86
MEE	217.4	217.4	22.03	20.97	7.2	7.2	29.23 (8.12)	28.16 (7.82)	81.19	78.22
RO	-	-	-	-	23.055	23.055	23.00 (6.40)	23.00 (6.40)	64.00	64.00

Table 2 Data of Sidem system built in UAE [1]

Parameter	Delivery	Effect 1	Effect 2	Effect 3	Effect 4
T(saturation), °C	62	58	54	50	46
P, bars	0.21851	0.18159	0.15012	0.12344	0.100938

Distillate output, MIGD (kg/s)	1 (52.6)
Motive steam	Saturated at 25 bar
Top brine temperature, °C	58.8
Last effect brine temperature, °C	46.8
Average boiling point elevation, °C	$BPE = T_i - T_{vi} = 0.8$
Number of effects	4
Temperature drop/effect (4 °C)	$\Delta T = T_1 - T_2 = T_2 - T_3 = T_3 - T_4 = T_d - T_1 = 4°C$

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