A Simulation Model and Parametric Study of Triple-Effect Desalination Plant

Maha BenHamad, Ali Snoussi, Ammar Ben Brahim

***Abstract*—**A steady-state analysis of triple-effect thermal vapor compressor desalination unit was performed. A mathematical model based on mass, salinity and energy balances is developed. The purpose of this paper is to develop a connection between process simulator and process optimizer in order to study the influence of several operating variables on the performance and the produced water cost of the unit. A MATLAB program is used to solve the model equations, and Aspen HYSYS is used to model the plant. The model validity is examined against a commercial plant and showed a good agreement between industrial data and simulations results. Results show that the pressures of the last effect and the compressed vapor have an important influence on the produced cost, and the increase of the difference temperature in the condenser decreases the specific heat area about 22%.

***Keywords*—**Steady-state, triple effect, thermal vapor compressor, MATLAB, Aspen HYSYS.

I. INTRODUCTION

THE number of desalination industry increases around the world to solve the water shortage problems. Desalination technologies can be divided in two categories; membranes and thermal units [1]. The multi-effect desalination with thermal vapor compression (MED-TVC) is considered as one of the important technologies in thermal systems.

El-Dessouky and Ettouney developed a detailed analysis in mathematical modeling and design of the different types of thermal systems [1]. Several works [2], [3] have been investigated on the analysis of MED-TVC systems based on energetic and exergetic equations and using several algorithms developed with MATLAB. On the other hand, other works [4]-[7] focused on the numerical simulation to optimize the desalination units and studied the influence of operating parameters on the performance of some industrial MED-TVC plants. Therefore, authors presented different software such as Aspen Custom Modeler, CFD, gPROMS simulator.

This paper presents a new method to study the influence of operating parameters and minimize the product unit cost of a triple effect coupled with TVC desalination plant using a connection between MATLAB software and the process simulator Aspen HYSYS. The mathematical and economic equations which defined the unit are implemented in MATLAB, and the flowsheet of the unit is doing with Aspen HYSYS.

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II. DESCRIPTION OF DESALINATION UNIT

Fig. 1 shows a simplified schematic of the desalination unit. The seawater enters in the tubes of condenser in which the increase in temperature for a few degrees due to condensation of an amount of steam comes from the last effect. Then, the seawater flow rate is divided into two parts; the first part is rejected to the sea called cooling water and the second passes to effects and is disturbed equally with mass flow rate F_i.

The effects are three simple evaporators with horizontal tubes collected successive in which the pressures decrease from the first effect to the last. In each effect, the steam introduces inside the tubes, and the feed seawater is sprayed with nozzles outside the tubes which create the evaporation of seawater. The last effect is connected with the TVC. The motive steam comes from an external heat source in the factory and entrains an amount of steam from the last effect in the TVC. The mixture steam enters in the tubes of the first effect. Finally, the brine forms and distillate product water is collected and rejected using pumps.

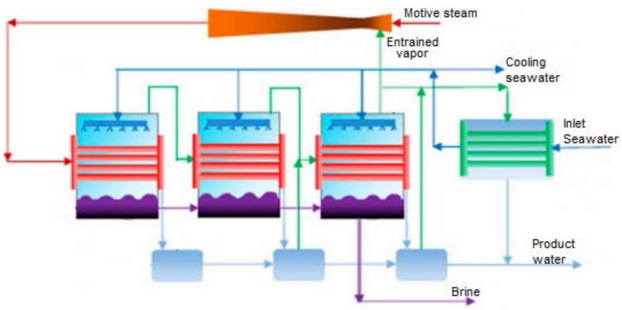

Fig. 1 Scheme of triple-effect desalination system

III. SYSTEM MODELING

A. Mathematical Model

The mathematical model present in this paper can be derived with the following assumptions:

- The desalination plant operates in steady state.
- The product water is considered to be free of salts.
- Thermodynamics losses include just the boiling point elevation (BPE).
- Heat losses from desalination to the surroundings are negligible.
- Pressure drops across the demister and during the condensation are neglected.
- The vapor formed in effect is salt-free.
- The dimensions of equipment are not including in the model.

- The temperature difference between effects is assumed to be equal as:

$$\Delta T = \frac{T_1 \text{-} T_n}{n \text{-} 1} \quad (1)$$

where T_1 and T_n are the temperature of first and last effect, respectively and n is the numbers of effects.

The temperatures of the first effect and the i[th] effect are given as:

$$T_1 = T_{cv} \text{-} \Delta T \quad (2)$$

$$T_{i+1} = T_i \text{-} \Delta T \quad (3)$$

In the i[th] effect, the brine temperature (T_{bi}) is assumed to be equal to the effect temperature (Ti), while the vapor temperature (T_{vi}) can be calculated as:

$$T_{vi} = T_i \text{-} BPE \quad (4)$$

where the BPE is the increase in the boiling temperature due to the salts dissolve in the water and can be calculated with the correlation presented in [2] as:

$$BPE = X\left(B + CX\right)10^{-3} \quad (5)$$

The variables C and D are functions of temperature as:

$$B = \left(6.71 + 6.34\times10^{-2}T + 9.74\times10^{-5}T^2\right)10^{-3} \quad (6)$$

$$C = \left(22.238 + 9.59\times10^{-3}T + 9.42\times10^{-5}T^2\right)10^{-8} \quad (7)$$

where BPE and T are in °C and X in ppm.

The mass, salinity and energy balances for the first effect are as:

$$F_1 = V_{cv} + B_1 \quad (8)$$

$$X_{f1}F_1 = X_{b1}B_1 \quad (9)$$

$$V_{cv}\lambda_{cv} = F_1 C_{p1}\left(T_1 \text{-} T_f\right) + V_1\lambda_1 \quad (10)$$

Therefore, mass, salinity and energy balances for each effect can be calculated as:

$$F_i = V_i + B_i \quad (11)$$

$$X_{fi}F_i = X_{bi}B_i \quad (12)$$

$$V_{i\text{-}1}\lambda_{i\text{-}1} = F_i C_{pi}\left(T_i \text{-} T_f\right) + V_i\lambda_i \quad (13)$$

in which C_{pi} is the specific heat capacity for seawater. λ_i and λ_{cv} are the latent heat of vaporization at the effect temperature and at the compressed vapor temperature, respectively. These parameters can be calculated with the following correlations presented in [1]:

$$C_p = \left[A + BT + CT^2 + DT^3\right]\times10^{-3} \quad (14)$$

The variables A, B, C and D are a function of the water salinity as:

$$A = 4206.8 - 6.6197X + 1.2288\times10^{-2}X^2 \quad (15)$$

$$B = -1.1262 + 5.4178\times10^{-2}X - 2.2719\times10^{-4}X^2 \quad (16)$$

$$C = 1.2026\times10^{-2} - 5.3566\times10^{-4}X + 1.8906\times10^{-6}X^2 \quad (17)$$

$$D = 6.8777\times10^{-7} + 1.517\times10^{-6}X - 4.4268\times10^{-9}X^2 \quad (18)$$

where C_p in kJ/kg.°C, T in °C and X in g/k.

The Latent heat of vaporization in kJ/kg:

$$\lambda = 2589.583 + 0.9156T \text{-} 4.8343\times10^{-2}T^2 \quad (19)$$

The heat transfer area of each effect and the total heat transfer area can be written as follows:

$$A_{ei} = \frac{Q_{ei}}{U_{ei}\left(LMTD\right)_i} \quad (20)$$

$$A_t = \sum_{i=1}^{n} A_{ei} \quad (21)$$

In addition, the overall heat transfer coefficient Uei and the logarithmic mean temperature difference (LMTD)i can be calculated using the following correlations presented in [1]:

$$U_{ei} = 1.9394 + 1.40562\times10^{-3}T_{bi} \text{-} 2.07525\times10^{-5}\left(T_{bi}\right)^2 + 2.3186\times10^{-6}\left(T_{bi}\right)^3 \quad (22)$$

$$(\mathrm{LMTD})_i = \frac{(\mathrm{T_i}\text{-}\mathrm{T_f})}{\ln\left(\dfrac{\mathrm{T_{v_{i\text{-}1}}}\text{-}\mathrm{T_f}}{\mathrm{T_{v_{i\text{-}1}}}\text{-}\mathrm{T_i}}\right)} \quad (23)$$

The energy balance and the heat transfer area of the condenser can be calculated as follows:

$$V_c\lambda_n = \left(M_f + M_{cw}\right)C_p\left(T_f \text{-} T_{sw}\right) \quad (24)$$

$$A_{cd} = \frac{V_c\lambda_n}{U_{cd}\left(LMTD\right)_{cd}} \quad (25)$$

The logarithmic mean temperature difference and the overall heat transfer coefficient of the condenser can be calculated using the following equations [1]:

$$\left(\mathrm{LMTD}\right)_{cd}=\frac{\left(T_{vn}-T_{sw}\right)-\left(T_{vn}-T_{f}\right)}{\ln\left(\frac{T_{vn}-T_{sw}}{T_{vn}-T_{f}}\right)} \quad (26)$$

$$U_{con}=1.7194+3.2063\times10^{-2}\left(T_{vn}\right)+1.5971\times10^{-5}\left(T_{vn}\right)^{2}+1.9918\times10^{-7}\left(T_{vn}\right)^{3} \quad (27)$$

To evaluate the performance of the thermo-compressor, the Entrainment Ratio (Ra) is defined by a semi-empirical model presented by El-Dessouky and Ettouney in [1] as follows:

$$Ra=0.296\frac{\left(P_{cv}\right)^{1.19}}{\left(P_{ev}\right)^{1.04}}\left(\frac{P_{m}}{P_{ev}}\right)^{0.015}\left(\frac{PCF}{TCF}\right) \quad (28)$$

$$\mathrm{PCF}=3\times10^{-7}\left(P_{m}\right)^{2}-0.0009\left(P_{m}\right)+1.6101 \quad (29)$$

$$TCF=2\times10^{-8}\left(T_{ev}\right)^{2}-0.0006\left(T_{ev}\right)+1.0047 \quad (30)$$

where P is in kPa and T is in °C.

B. Economic Model

The Total Annualized Cost (TAC) of the SIDEM unit is defined as the sum of the capital costs of equipment ($C^{capital}$) and the operational expenses ($C^{operational}$) [8].

$$TAC=C^{capital}+C^{operational} \quad (31)$$

The total capital cost $C^{capital}$ consists of the effects evaporator, the condenser and the thermo-compressor, and it is given by the following equation [8]:

$$C^{capital}=a_{f}\cdot\left(\frac{CEPCI_{2015}}{CEPCI_{2001}}\right)\cdot\left((C_{p}^{0}F_{BM})_{evaporator}+(C_{p}^{0}F_{BM})_{condenser}+(C_{p}^{0}F_{BM})_{compressor}\right) \quad (32)$$

where a_f represents the amortization factor which is given by:

$$a_{f}=\frac{i_{r}\left(i_{r}+1\right)^{y}}{\left(i_{r}+1\right)^{y}-1} \quad (33)$$

where i_r refers to the interest rate per year and y is the number of years.

In the above equations, C^{0}_{p} indicates the purchased cost of a unit of equipment, in US$. C^{0}_{p} of the evaporator and the TVC are estimated using the correlations presented in [9]. For the condenser, the cost has been calculated using the correlations presented in [10]. F_{BM} represents the correction factor for the equipment unit cost. Furthermore, the cost correlations were updated using the Chemical Engineering Plant Cost Index (CEPCI).

The operational expenditure accounts for the steam cost and is expressed as:

$$C^{operational}=C_{steam}Q_{s} \quad (34)$$

in which C_{steam} is the specific steam cost given by the GCT factory data, and Qs is the consumption steam by the unit.

The cost of produced water per cube meter can be written as:

$$C_{porduction}\left(\$/m^{3}\right)=\frac{TAC\left(\$/year\right)}{3600\times24\times350\times Q_{p}\left(m^{3}/s\right)} \quad (35)$$

where Q_p is the product water volume flow rate.

C. System Performance

The following parameters are used to analyze the performance of system [1]:

- The gain output ratio, GOR, is the ratio between the mass flows rates of the distillate product water and motive steam.
- The specific heat transfer area, sA, is the ratio between the sum of the heating surface area of equipment (effects and condenser) and the mass flow rate of produced water.
- The specific heat consumption, sQ, is the thermal energy consumed by the system to produce 1 kg of distilled water and can be obtained as:

$$sQ=\frac{V_{m}\lambda_{m}}{M_{d}} \quad (36)$$

- The specific exergy, Sex, is the exergy consumed by the motive steam to produce 1 kg of distillate water [7] and can be calculated as follows:

$$S_{ex}=\frac{V_{m}}{M_{D}}\left[\left(h_{m}-h_{fd}\right)-T_{0}\left(S_{m}-S_{fd}\right)\right] \quad (37)$$

IV. Simulation Method

The main goal of this work is to study the sensitivity analyses of several parameters on the systems performance in order to minimize the product unit cost of the desalination unit. The purpose of this paper is to use a combination between Aspen HYSYS as a process simulator and MATLAB as a process optimizer. The process simulator does not include optimization algorithms, in this case the connection with a process optimizer is necessary to find good results and control the parameters with lower and upper bounds and under limits constraints. This connection is done via ActiveX/COM server of Microsoft [11]. MATLAB sends the initial values to Aspen HYSYS which is employed to simulate the system operation. The simulator returns the simulation results to MATLAB; further, the objective function is calculated and process convergence is verified. The iterations are repeated until we obtain a final result. Fig. 2 shows the process of MATLAB – HYSYS connection.

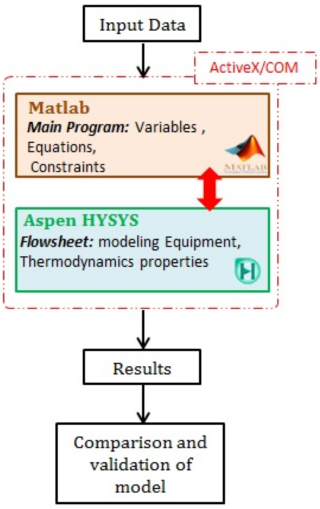

Fig. 2 Schema of MATLAB-HYSYS connection

MATLAB R2013a is used to implement the equations model, and the function '*fmincon*' has been integrated to find the minimum of a function from several variables starting at initial estimates using successive iterations [11], [12]. Aspen HYSYS V8.4 is considered as process simulator due to their flexibility in the design and operating problems of chemical processes [13]. A steady-state model has been developed for the desalination unit using the NRTL-electrolyte as the thermodynamic model for the simulation. The following constraints are taken into consideration during the simulation which guarantees the convergence of the solutions and to obtain logical results: $T_i > T_{i+1}$ and $P_i > P_{i+1}$. For environmental limit, the salt concentration of the rejected brine is limited with upper value as: $X_B \leq 70{,}000$ ppm. The constraints for compressor vapor are the entrainment ratio as $Ra \leq 4$ and the compression ratio as $1.81 \leq CR \leq 6$.

V. Case Study and Results

A. Case Study

The validity of the proposed model was tested with available data of a commercial desalination unit located in the Phosphoric Acid Plant owned by the Tunisian Chemical Group (GCT) installed in the industrial area of Gabes (south of Tunisia). The unit is composed by three effects coupled with a thermo-compressor and a condenser in which known by the name "SIDEM" in the factory. The input parameters and the economic data used are given in Tables I and II.

In this work, the minimization of the TAC is considered as the principal function, and the selected decisions variables are the temperature difference in the condenser, the motive steam pressure, the compressed vapor pressure (output of TVC) and the last effect pressure. Fig. 3 shows the Aspen HYSYS flow sheet of the unit.

TABLE I
PARAMETERS FOR SIMULATION

Parameter		*Value*	*Unit*
Seawater	Mass flow rate	220	ton/h
	Temperature	28	°C
	Pressure	3	bar
	Salinity	39,000	ppm
Motive Steam	Mass flow rate	3	ton/h
	Temperature	170	°C
	Pressure	5	bar
Condenser	Pressure drop tube	0.3	bar
	Pressure drop shell	0	bar
	Temperature drop	6	°C
Ejector	Pressure output	0.25	bar
Effects	Temperature E1	60	°C
	Temperature E2	50	°C
	Temperature E3	40	°C
Cooling seawater	Mass flow rate	160	ton/h
Feed to effects	Mass flow rate	20	ton/h

TABLE II
ECONOMIC PARAMETERS

Parameters	Value
Cost of Steam Csteam, $/ton	16.61
Amortization year y, year	10
Interest rate ir, %	10
Annual Operating Hours	24×350

B. Results and Discussion

The feasible solutions of the simulation model for the unit and the three effects are presented in Table III. A comparison with the industrial data is doing which shows an accuracy of ±10%. The performance parameters of the plant are illustrated in Table IV. The results show that the product cost is 4.1712 $\$/m^3$ and less than the cost presented by the GCT factory which is 4.8 $\$/m^3$. This difference could be explained by different effects as the economic assumptions used in this model.

The influence of the variation in operating conditions for the actual desalination plant on the minimization of the product cost, product fresh water, and the system performance was performed by the developed combination and shown below.

1. Effect of the Temperature Difference in the Condenser

The influence of increasing the input seawater temperature inside the condenser (ΔT_c) is investigated. It should be noted that the actual value used in the factory is equal to 4 °C. Fig. 4 shows the variation ΔT_c from 1 to 8 °C causes 22% increase in the specific heat and 26% rise in the specific exergy consumption. However, the product water decreases by 18 % so consequently the GOR value decreases from 8.26 to 6.77, as shown in Fig. 5. As seen in Fig. 6, the increase of ΔT_c caused the increase in the cost value with 7% (4.07 to 4.36 $\$/m^3$), while the specific heat transfer area sA decreases.

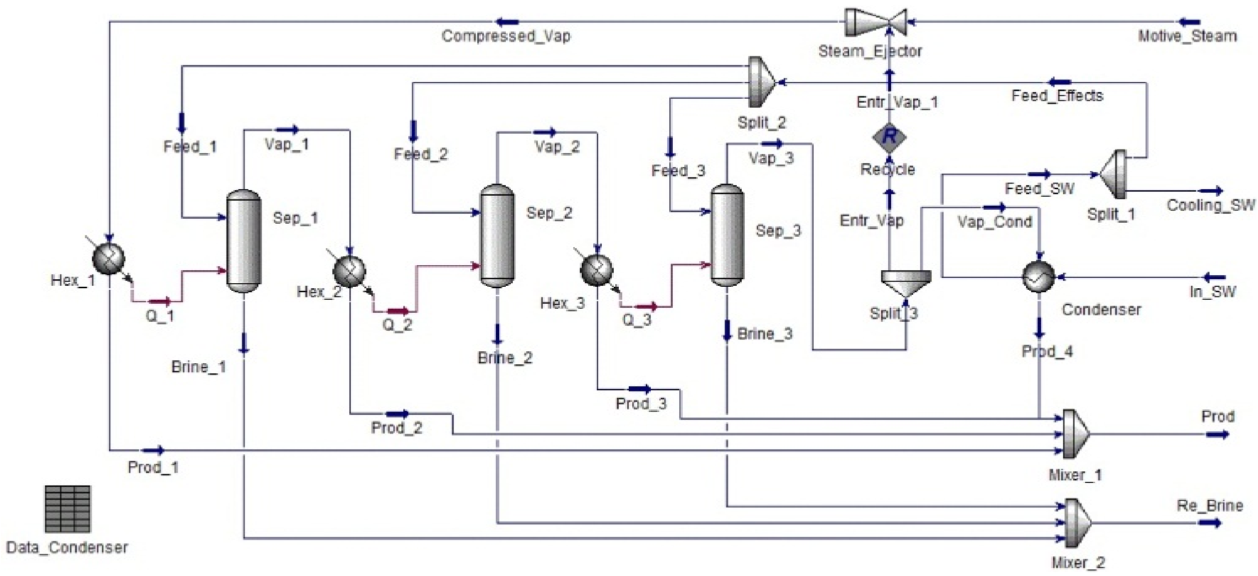

Fig. 3 Aspen HYSYS flowsheet of the desalination unit

TABLE III
COMPARISON BETWEEN SIMULATION RESULTS AND INDUSTRIAL DATA

Parameters (unit)	Calculated	Actual	Deviation
Total distillate product water M_D (ton/h)	22.870	21.67	+5.54%
Temperature of product water T_D (°C)	39.65	NA[a]	-
Pressure of last effect P_3 (bar)	0.07248	0.074	-2.054%
Salinity of rejected brine X_B (ppm)	58,300	NA[a]	-
Entrained vapor flow rate V_{ev} (ton/h)	4.946	4.55	+8.712%
Vapor enter to condenser V_c (ton/h)	1.504	NA[a]	-
Temperature of compressed vapor T_{cv} (°C)	84.5	90	-6.11%
The Entrainment Ratio Ra	2.31	-	-

[a]: Not Available

TABLE IV
SYSTEM PERFORMANCE

Parameter (unit)	Model
Gain output ratio GOR	7.623
Specific heat transfer area sA (m^2/kg/s)	96.791
Specific heat consumption sQ (kJ/kg)	268.802
Specific exergy consumption Sex (kJ/kg)	320.719
Unit water cost (\$/m^3)	4.171

2. Effect of Motive Steam Pressure

As shown in Fig. 7, the variations of the motive steam pressure (P_m), from 1 to 7 bar, lead to increase the product cost from 4.12 to 4.2 \$/m^3, also cause the increase of the specific heat transfer area sA about 5%. Moreover, this increase gives a slight increase on the specific heat and exergy consumptions (less than 1%) also a slight decrease in the mass flow rate of product water and the GOR value (less than 1%). On the other hand, the pressure of compressed vapor increases about 8% and the temperature of the compressed vapor decreases by 8° C as shown in Fig. 8.

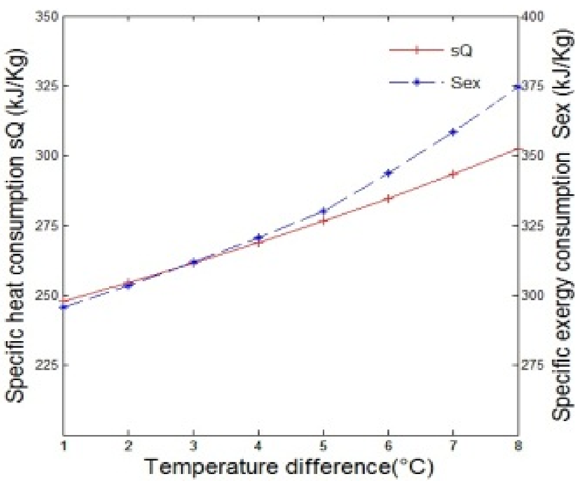

Fig. 4 Effect of temperature difference on the specific heat consumption and specific exergy consumption

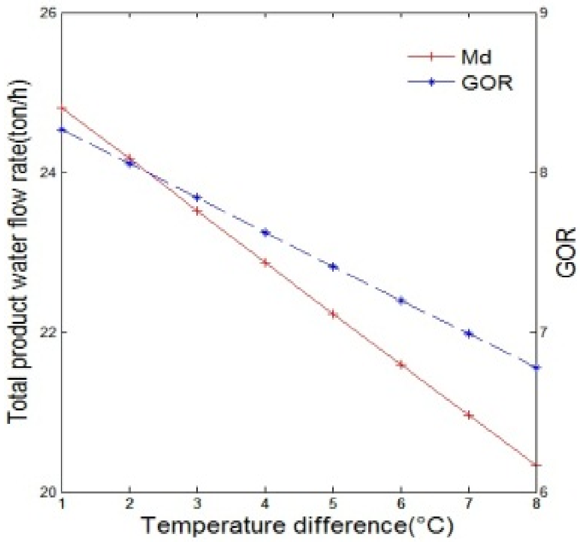

Fig. 5 Effect of temperature difference on the total product water flow rate and GOR

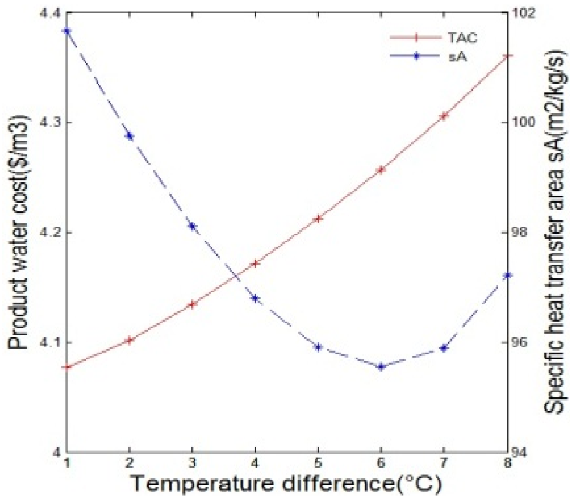

Fig. 6 Effect of temperature difference on the unit product water cost and the specific heat transfer area

3. Effect of Compressed Vapor Pressure and the Last Effect Pressure

The effect of variation in compressed vapor pressure and the last effect pressure on the product unit of the desalination unit are presented in Fig. 9. As it is shown in this figure, if the two pressures increase, the product water cost increases from 3.69 to 5.75$/m^3. As results of these variations, the compressed vapor temperature increases from 70 to 110 °C which causes the decrease of the heat transfer area in all effects. Also, the mass flow rate of the distillate production decreases and consequently the GOR value decreases. Therefore, the specific heat transfer area decreases about 20% and the salinity of rejected brine decreases from 69,800 to 47,200 ppm.

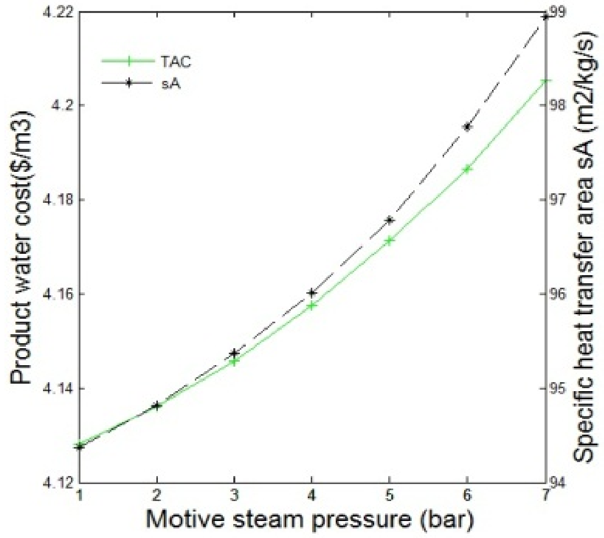

Fig. 7 Effect of motive steam pressure on the unit product water cost and the specific heat transfer area

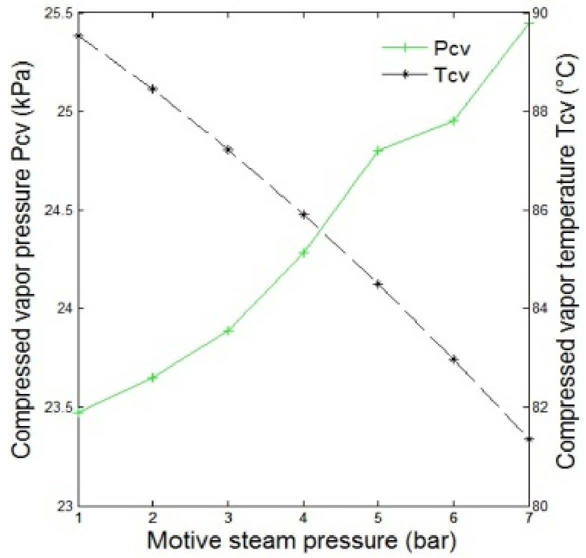

Fig. 8 Effect of motive steam pressure on the compressed vapor pressure and temperature

VI. Conclusion

This work presents a parametric study of a MED-TVC desalination unit in a steady-state operation. A MATLAB algorithm was developed and used to solve mathematical and economic models, and a flow sheet of the desalination unit is done with Aspen HYSYS. A novel connection between MATLAB and Aspen HYSYS is presented to study the influence of decisions variables under several constraints on the system performance and the product cost of the unit. An industrial plant installed in the industrial zone of Gabes (Tunisie) presented as a case study to verify the accuracy of the proposed solution. Effects of different parameters including the temperature difference in the condenser, the motive steam pressure, the compressed vapor pressure (output of TVC) and the last effect pressure were studied to find the minimum product cost of the desalination unit.

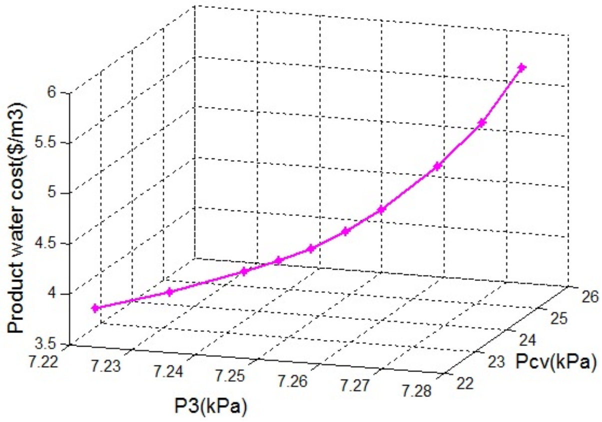

Fig. 9 Effect of the pressure of the last effect and the pressure of compressed vapor on the unit product water cost

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