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Optimization of location of thermo-compressor suction in MED-TVC desalination plants

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ABSTRACT

Multi-effect desalination with thermal vapor compression (MED-TVC) is particularly more attractive than other thermal desalination systems due to its low energy consumption. One of the major component of MED-TVC desalination system is thermo-compressor. The overall efficiency of the system is directly influenced by the performance of thermo-compressor. It enhances system's efficiency by reducing the energy consumption. The location of the steam extraction has a great effect on the performance of the MED-TVC plants. Higher gained output ratio of the desalination plant can be obtained at the optimum position of vapor extraction in the MED-TVC system. The optimization of location of suction position of thermo-compressor in MED-TVC desalination plants could result in maximization of gain output ratio (GOR) and consequently reduction in energy consumption. Furthermore, increasing the suction pressure also results in decreasing the energy consumption of the system. Therefore, this work will analyze the impact of suction position of thermo-compressor on the amount of energy consumption, specific heat transfer area, and GOR values of the plant. The effect of thermo-compressor's suction pressure on the energy consumption of a plant in different configurations of MED-TVC and MED was also analyzed in this work. A detailed mathematical model will be developed for the process in order to find the optimum location of thermo-compressor suction. The effect of changing the suction position of thermo-compressor on the entrainment ratio and the amount of energy consumption of the plant was analyzed.

Keywords: Multi-effect desalination (MED) process; Thermal vapor compression

1. Introduction

The multi-effect desalination (MED) process is the oldest process in water desalination [1]. There were several problems with this technology in the past, such as scaling problem and low production capacity. To make this technology competitive with the multi-stage flash (MSF) desalination process, rapid developments have been done recently in the MED systems [2–4]. As compared to the multi-stage flash (MSF) desalination, MED systems are more energy efficient because it minimizes the energy consumption which is needed to heat water [5–9]. MED-TVC system is more competitive and energy efficient as compared to the

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stand-alone MED system due to the addition of thermo-compressor [10]. So, the development of MED-TVC system is the major accomplishment into the conventional multi-effect unit [11]. The system can operate at lower top brine temperature and the unit capacity of the plant can be increased due to the combination of MED system and thermo-compressor [12].

Due to the developments in this technology, it enables MED-TVC system in gaining more market share. Some of the large MED-TVC desalination projects are listed in Table 1 [13].

Since the last two decades, a lot of research has been done regarding MED-TVC systems [14–18]. The studies include different conceptual designs and field research. Simulation codes and modeling programs have also been developed for MED-TVC plants.

El-Dessouky et al. developed mathematical models for the investigation of the single effect thermal vapor compression (TVC) process and the MED systems [5,14]. The results, model, and analysis for the single-effect TVC and the stand-alone MED form the basis for the development of the more complex MED-TVC model. To study the performance of MED-TVC system, a model was developed by El-Dessouky and Ettouney. The developed MED-TVC model is based on the two models conducted by El-Dessouky for the single-effect TVC and the multiple effect MED model developed by El-Dessouky et al. [15].

Kouhikamali et al. studied the influence of changing the suction position of thermal vapor compressor on the energy consumption [16]. Their study showed that the variation in suction position of thermo compressor has considerable influence on the entrainment ratio. But they did not present any mathematical modeling and simulation in their work.

Ha et al. proposed a method to improve the performance of thermal vapor compressor in MED-TVC systems by preheating TVC-entrained vapor [18]. The experimental verification has been done to confirm the effectiveness of the proposed method. Their work showed that the entrainment ratio of TVC increases by preheating the entrained vapor and eventually energy consumption of the plant reduces.

The horizontal falling film evaporators are the most commonly used evaporators in the MED plants owing to their distinct advantages [5,19]. As compared to MSF desalination systems, they provide low specific heat transfer surface area and higher overall heat transfer coefficients. They have ability to handle seawater scaling and have low requirements for pumping energy. In MED horizontal falling film evaporator, seawater is sprayed over the evaporator tube and forms a falling film over the successive tube rows. The heating steam condenses onto the surface in two distinct modes, known as “dropwise” and “filmwise.” A laminar film of vapor is formed over a surface in filmwise condensation. This film flows downwards, increasing in thickness as additional vapor is picked up along the way. While vapor forms at an acute angle to a surface in dropwise condensation. In filmwise condensation, the thickness of film depends upon several factors including; the viscosity of condensate, the rate of condensation, and whether the surface is vertical or horizontal [20]. Vapor condenses on the outer surface of the film and heat is transferred by the condensation through the film to the surface beneath. Several models have been developed to solve the boundary layer equation of the filmwise condensation. For instance, Nusselt solved a laminar filmwise condensation on a horizontal cylinder placed in quiescent vapor [21]. The same problem was solved by Chen for the two-phase boundary layer equation [22].

Indeed thermo-compressor plays a major role in multi-effect evaporation systems. It increases system’s efficiency by reducing the energy consumption. Energy consumption can be significantly influenced

Table 1
Example of large desalination projects of MED-TVC

Year	Country	Location	Unit capacity	Total output (m^3/d)	No. of units	GOR
1991	UAE	Mirfa	1.0 MIGD	9,100	2	8
1995	Italy	Trapani	2.0 MIGD	18,000	4	16
1997	Netherland	Curaçao island	2.6 MIGD	12,000	1	13.4
2000	UAE	Umm Al-Nar	3.5 MIGD	32,000	2	8.0
2001	UAE	Layyah	5.0 MIGD	45,696	2	8.4
2005	UAE	Sharjah	8.0 MIGD	36,368	1	8.4
2008	Bahrain	Al-Hidd	6.0 MIGD	272,760	10	8.9
2009	Saudi Arabia	Al-jubail	6.5 MIGD	809,109	27	9.8
2010	UAE	Fujairah	8.5 MIGD	454,600	12	10
2011	Qatar	Ras Laffan	6.3 MIGD	294,490	10	11.1
2012	Saudi Arabia	Yanbu 2	15 MIGD	146,160	2	9.7

by the geometry and operating conditions of thermo-compressor. The influence of different suction positions of thermo compressor on energy consumption of the plant is studied in this work.

2. Med-TVC components

Fig. 1 shows a schematic diagram of a MED–TVC system having five effects. The major components of MED-TVC system include number of effects, a condenser and a thermal vapor compressor. Feed seawater (F) from the condenser is distributed equally between the effects. Feed seawater enters into each effect at temperature T_f. The major part of seawater enters into the condenser is returned back to the sea as cooling water. The purpose of cooling water is to remove the extra heat added by the hot steam into the system. Feed seawater (F) is showered over the tube bundles in each effect and produces vapor streams from left to right in the direction of reducing pressure.

Thermal vapor compressor is used to compress and entrain the part of vapor produced. For this purpose, steam from the external source such as boiler enters into the thermal vapor compressor. The compressed stream ($D_m + D_{ev}$) is directed into the tube side in the first effect. This stream is used to rise the temperature of feed seawater (F) to the boiling temperature of the first effect which is also known as top brine temperature (T_1). Due to this heat transfer, a portion of feed seawater of the first effect evaporates and produces vapors. The produced vapor enters into the next effect at a lower pressure and temperature than the previous effect. This vapor serves as the heating medium in the second effect. The evaporation of the feed seawater takes place in the second effect due to the vapor generated in the first effect. This iterative process continues to the end of middle effect.

The brine (B_1) from the first effect enters into the second effect in order to utilize its energy and this process continues to the end of last effect at a lower pressure than the previous effect. Some amount of the produced vapor in the middle effect is entrained by the thermal vapor compressor as shown in Fig. 1. The vapor inside the effects two to five is generated by boiling and flashing. Flashing also occurs inside the flash boxes due to the distillate condensation.

3. Optimization of TVC suction location in MED-TVC

This research work focuses on the modeling of MED-TVC system from the steady-state conditions. Also, all aspects of the design procedure for an MED-TVC system were considered. MATLAB code was also

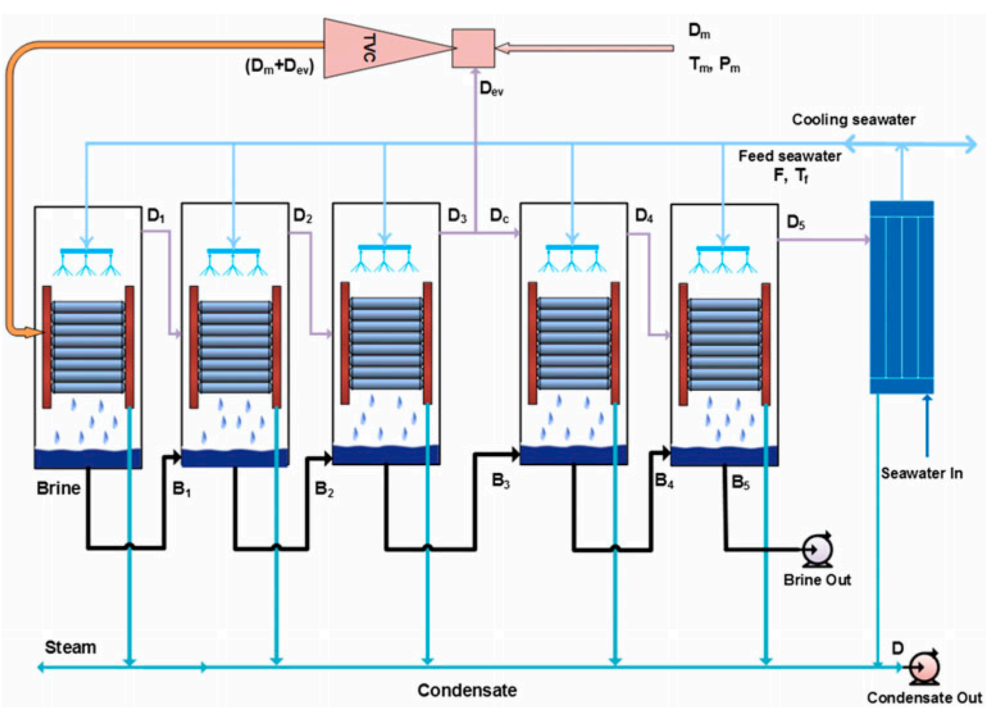

Fig. 1. Schematic diagram of a MED-TVC system having five effects with thermo-compressor placed between the middle effects.

developed to optimize the location of thermo-compressor suction in MED-TVC desalination plants. Suction pressure of thermo compressor has considerable influence on the energy consumption of the system. The effect of thermo compressor's suction pressure on the energy consumption of a plant in different configurations of MED-TVC and MED was analyzed in this work. The main assumptions used to develop the mathematical model are listed below:

(1) It is assumed that the process is steady state [18].
(2) The distillate is free of salt [23].
(3) Temperature difference is constant across each effect [8].
(4) Thermodynamic losses are negligible [18].
(5) Flow rate of feed seawater is equal in each effect [8].

The following section consists of the mathematical modeling of MED-TVC system (Fig. 1) to perform the parametric analysis. The model includes mass and energy balances, heat transfer equations and correlations for the physical properties of water.

Temperature difference between the effects i:

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

Temperature of compressed steam (T_s) can be calculated as follows:

$$T_s = T_1 + \Delta T \tag{2}$$

Temperature of vapor in the last effect can be obtained using the following equation:

$$T_{v_n} = T_n - \text{BPE} \tag{3}$$

The boiling point elevation (BPE) is obtained using the following empirical formula [5]:

$$\text{BPE} = X_b \cdot [B + (C \cdot X_b)] \cdot (10)^{-3} \tag{4}$$

With

$$B = [6.71 + (6.34 \cdot (10)^{-2} \cdot T_n) + (9.74 \cdot (10)^{-5} \cdot (T_n)^2)] \cdot (10)^{-3}$$

$$C = [22.238 + (9.59 \cdot (10)^{-3} \cdot T_n) + (9.42 \cdot (10)^{-5} \cdot (T_n)^2)] \cdot (10)^{-8}$$

where X is the salt concentration in ppm and T is the temperature in ℃. The BPE equation is valid over the following ranges: 20℃ < T < 180℃, 20,000 < X < 160,000 ppm.

Pressure of compressed vapors (P_s) and entrained vapors (P_{ev}) is calculated from the correlation developed by EI-Dessouky et al. [24]:

$$P_s = 1000 \cdot \exp\left(\frac{-3892.7}{T_s + 273.15 - 42.6776} + 9.5\right) \tag{5}$$

$$P_{ev} = 1000 \cdot \exp\left(\frac{-3892.7}{T_{v_n} + 273.15 - 42.6776} + 9.5\right) \tag{6}$$

where P is in kPa and T is in ℃.

Entrainment ratio of thermal vapor compressor can be obtained using several approaches but most of them involves very lengthy mathematical method [24,25]. Hassan and Darwish published a paper on the performance of TVC [26]. They developed new correlations to calculate the entrainment ratio which are very accurate one. These correlations are given below:

$$\begin{aligned} R_a = {} & -1.93422581403321 + 2.152523807931 \cdot \text{CR} \\ & + \frac{113.490932154749}{\text{ER}} - 0.52222106115497 \\ & - \frac{14735.9653361836}{\text{ER}^2} - \frac{31.8519701023059 \cdot \text{CR}}{\text{ER}} \\ & + 00.047506773195604 \cdot \text{CR}^3 + \frac{900786.04455}{\text{ER}^3} \\ & - \frac{495.581541338594 \cdot \text{CR}}{\text{ER}^2} \\ & + \frac{10.0251265889018 \cdot \text{CR}^2}{\text{ER}}, \\ & \text{If ER} \geq 100 \end{aligned} \tag{7a}$$

$$\begin{aligned} R_a = {} & -3.20842210618164 + 3.93335312452389 \cdot \text{CR} \\ & + \frac{27.2360043794853}{\text{ER}} - 1.19206948677452 \cdot \text{CR}^2 \\ & - \frac{141.423288255019}{\text{ER}^2} - \frac{22.5455184193569 \cdot \text{CR}}{\text{ER}} \\ & + 0.125812687624122 \cdot \text{CR}^3 + \frac{348.506574704109}{\text{ER}^3} \\ & - \frac{41.7960967174647 \cdot \text{CR}}{\text{ER}^2} \\ & + \frac{6.43992939366982 \cdot \text{CR}^2}{\text{ER}}, \\ & \text{If } 100 \geq \text{ER} \geq 10 \end{aligned} \tag{7b}$$

$$\begin{aligned} R_a = {} & -1.61061763080868 + 11.0331387899116 \\ & \cdot \mathrm{LN(CR)} + \frac{13.5281254171601}{\mathrm{ER}} \\ & - 14.9338191429307 \cdot \mathrm{LN(CR)}^2 \\ & - \frac{34.4397376531113}{\mathrm{ER}^2} \\ & - \frac{48.4767172051364 \cdot \mathrm{LN(CR)}}{\mathrm{ER}} \\ & + 6.46223679313751 \cdot \mathrm{LN(CR)}^3 \\ & + \frac{29.9699902855834}{\mathrm{ER}^3} \\ & + \frac{70.8113406477665 \cdot \mathrm{LN(CR)}}{\mathrm{ER}^2} \\ & + \frac{46.9590107717394 \cdot \mathrm{LN(CR)}^2}{\mathrm{ER}}, \\ & \text{If } 10 \geq ER \geq 2 \end{aligned} \tag{7c}$$

The entrained vapor (D_{ev}) can be calculated as follows:

$$D_{ev} = \frac{D_m}{R_a} \tag{8}$$

The brine temperature in an effect i is T_i, the brine temperature in the next effect $i + 1$ can be calculated using the following formula:

$$T_{i+1} = T_i - \Delta T, \quad i = 1, 2, 3, \ldots, n \tag{9}$$

Vapor temperature in an effect i:

$$T_{v_i} = T_i - \mathrm{BPE} \tag{10}$$

The feed water flow rate F is distributed equally to all effects at a rate equal to F_i:

$$F_i = \frac{F}{n}, \quad i = 1, 2, 3, \ldots, n \tag{11}$$

Latent heat is estimated from [24]:

$$\lambda_i = 2589.583 + 0.9156 \cdot T_i - 4.834 \cdot 10^{-2} \cdot T_i^2 \tag{12}$$

In the above equation, temperature is in ℃ and latent heat is in kJ/kg.

The amount of vapor produced in the first effect by the boiling only:

$$D_1 = \frac{(D_m + D_{ev}) \cdot \lambda_s - F_1 \cdot C_p \cdot (T_1 - T_f)}{\lambda_1} \tag{13}$$

where D_m = motive steam flow rate; D_{ev} = entrained vapors flow rate; λ_s = latent heat of evaporation at temperature T_s; λ_1 = latent heat of evaporation at temperature T_1.

Brine leaving the first effect and its salinity can be calculated by applying material balance and salt balance as follows:

$$B_1 = F_1 - D_1 \tag{14}$$

$$X_{b_1} = \frac{F_1}{(F_1 - D_1)} \cdot X_f \tag{15}$$

Vapor generated in the second effect is obtained by applying the energy balance:

$$D_2 = \frac{D_1 \cdot \lambda_1 - F_2 \cdot C_p \cdot (T_2 - T_f) + B_1 \cdot C_p \cdot (T_1 - T_2)}{\lambda_2} \tag{16}$$

Brine leaving the second effect and its salinity can be calculated using the following two material balance equations:

$$B_2 = F_2 + B_1 - D_2 \tag{17}$$

$$X_{b_2} = \frac{X_f \cdot F_2 + X_{b_1} \cdot B_1}{B_2} \tag{18}$$

Non equilibrium allowance ($\mathrm{NEA_i}$) for the effects $2 - n$ can be expressed as follows [5]:

$$\mathrm{NEA}_i = \frac{33 \cdot (T_{i-i} - T_i)^{0.55}}{T_{v_i}}, \quad i = 2, 3, 4, \ldots, n \tag{19}$$

The cooling temperature of brine is achieved using the following formula:

$$T_i' = T_i + \mathrm{NEA}_i, \quad i = 2, 3, 4, \ldots, n \tag{20}$$

Vapor generated due to the brine flashing in the effects $2 - n$ is given by:

$$d_i = \frac{B_{i-1} \cdot C_p \cdot (T_{i-1} - T_i')}{\lambda_i}, \quad i = 2, 3, 4, \ldots, n \tag{21}$$

The cool down temperature of condensing vapors when it enters to flash boxes:

$$T_i'' = T_{v_i} + \mathrm{NEA}_i', \quad i = 2, 3, 4, \ldots, n \tag{22}$$

Vapor generated due to the flashing inside the flash boxes can be calculated using the following formula:

$$d_i' = D_{i-1} \cdot C_p \cdot \left(\frac{T_{c_{i-1}} - T_i''}{\lambda_i'}\right), \quad i = 2, 3, 4, \ldots, n \tag{23}$$

Vapor generated from the effects other than 1 and 2 can be calculated using the following energy balance equation:

The energy balance equation for the effect after the thermo compressor (Fig. 1) is shown in the following equation:

$$D_i = \frac{(D_{i-1} \cdot \lambda_{i-1} + d_{i-1} \cdot \lambda_{i-1} + d_{i-1}' \cdot \lambda_{i-1}') - F_i \cdot C_p \cdot (T_i - T_f) + B_{i-1} \cdot C_p \cdot (T_{i-1} - T_i)}{\lambda_i} \tag{24}$$

Vapors generated in the third effect is divided into two parts, one is directed to the next effect (D_c) while other part is entrained by thermal vapor compressor

$$D_4 = \frac{(D_c \cdot \lambda_3 + d_3 \cdot \lambda_3 + d_3' \cdot \lambda_3') - F_4 \cdot C_p \cdot (T_4 - T_f) + B_3 \cdot C_p \cdot (T_3 - T_4)}{\lambda_4} \tag{25}$$

(D_{ev}). The amount of vapor goes to the next effect can be calculated as follows:

$$D_c = D_3 - D_{ev} \tag{26}$$

Total amount of distillate (D_t) is given by:

$$D_t = D_1 + D_2 + D_3 + \ldots + D_n = \sum_{i=1}^{n} D_i, \quad i = 1, 2, 3, \ldots, n \tag{27}$$

Amount of brine leaving the effects and brine salinity for the effects $3 - n$ is calculated from the following two equations:

$$B_i = F_i + B_{i-1} - D_i, \quad i = 3, 4, \ldots, n \tag{28}$$

$$X_{b_i} = \frac{X_f \cdot F_i + X_{b_{i-1}} \cdot B_{i-1}}{B_i}, \quad i = 3, 4, \ldots, n \tag{29}$$

$$U_i = \frac{\left(1939.4 + 1.40562 \cdot T_i - 0.0207525 \cdot (T_i)^2 + 0.0023186 \cdot (T_i)^3\right)}{1000} \tag{30}$$

Heat transfer area for the first effect is computed using the following equation:

$$A_1 = \frac{(D_s + D_{ev}) \cdot \lambda_s}{U_1 \cdot (T_s - T_1)} \tag{31}$$

Heat transfer area for the effects $2 - n$:

$$A_i = \frac{D_i \cdot \lambda_i}{U_i \cdot (T_{c_i} - T_i)}, \quad i = 2, 3, 4, \ldots, n \tag{32}$$

Total heat transfer area of the effects (A_e) is obtained as follows:

$$A_e = A_1 + A_2 + A_3 + \ldots + A_n = \sum_{i=1}^{n} A_i, \quad i = 1, 2, 3, \ldots, n \tag{33}$$

Overall heat transfer coefficient and logarithmic mean temperature difference of the condenser can be calculated using the following two expressions [27]:

$$(\mathrm{LMTD})_c = \frac{(T_f - T_{cw})}{\ln\left[\frac{T_{v_n} - T_{cw}}{T_{c_n} - T_f}\right]} \tag{34}$$

$$U_c = 1.7194 + 3.2063 \cdot 10^{-2} \cdot T_{v_n} - 1.5971 \cdot 10^{-5} \cdot (T_{v_n})^2 + 1.9918 \cdot 10^{-7} (T_{v_n})^3 \tag{35}$$

Condenser heat transfer area can be obtained from the following equation:

$$A_c = \frac{D_c \cdot \lambda_n}{U_c \cdot (\mathrm{LMTD})_c} \tag{36}$$

Cooling water flow rate (M_{cw}) can be obtained by applying the energy balance around the condenser:

$$M_{cw} = \frac{D_c \cdot \lambda_n}{C_p \cdot (T_f - T_{cw})} \tag{37}$$

Specific heat transfer area (A_d) is calculated from the following equation:

$$A_d = \frac{A_e + A_c}{D_t} \tag{38}$$

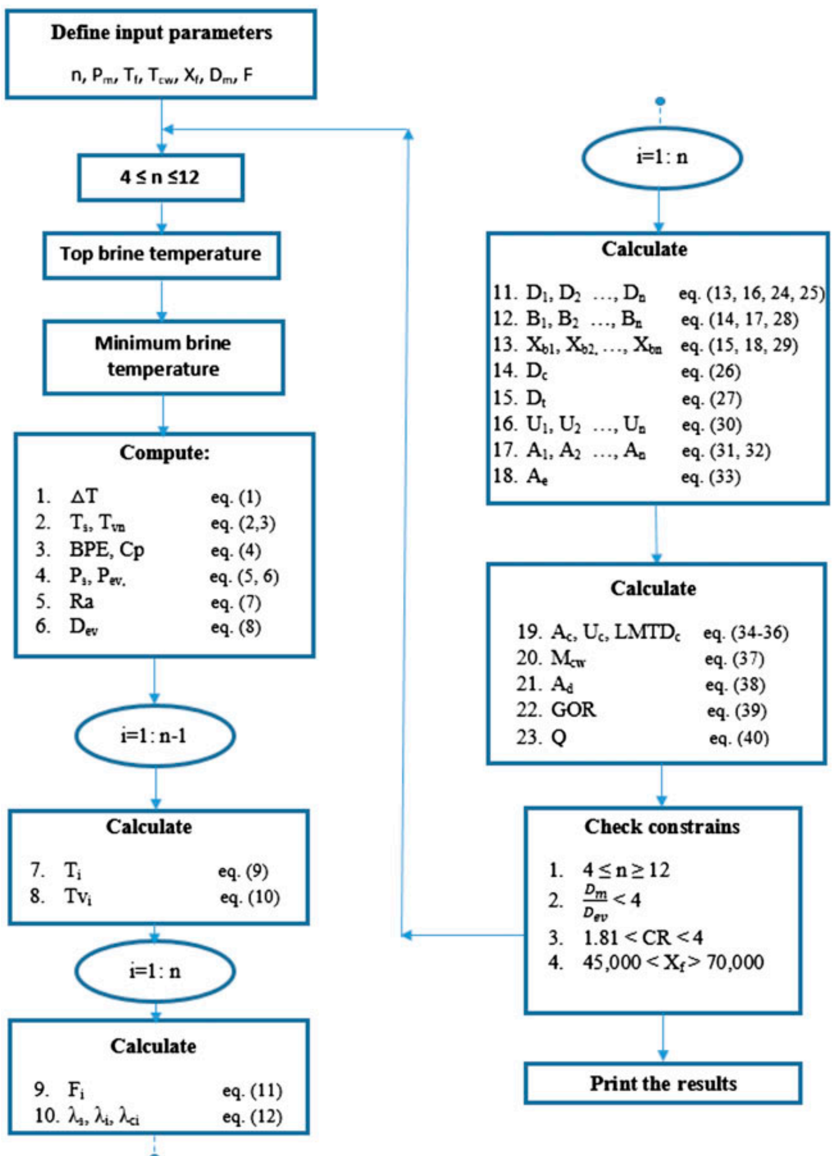

Fig. 2. Solution algorithm of the MED-TVC system.

Gain output ratio (GOR) is used to measure the system performance of MED-TVC model and is calculated using the following expression:

$$\mathrm{GOR} = \frac{D_t}{D_m} \tag{39}$$

Specific heat consumption (Q) is defined as the thermal energy used to generate 1 kg of distilled water and it is given by:

$$Q = \frac{D_m \cdot \lambda_m}{D_t} \tag{40}$$

The developed model consists of a set of highly non-linear equations. A MATLAB program was used to solve the above Eqs. (1)–(37) and the performance of system (Eqs. (38)–(40)) was evaluated. The aim of this work is to develop the optimization system which can give higher efficiency in term of GOR, specific heat transfer area, distillate production and specific heat consumption. The iterative procedure for direct substitution is considered to solve the highly non-linear equations. Design parameters and constrains and parameters should be defined properly in order to perform the optimization of any system. A standard design optimization algorithm is presented in Fig. 2. The model was solved for the MED-TVC units varying from 4 to 12. The constraints of compression and ratios are $4 \le \mathrm{CR} \ge 1.81$ and $R_a = 4$, respectively [6]. To avoid scaling and corrosion problem, most of the MED-TVC systems operate with low brine temperature, not more than 75˚C. Therefore, 67˚C is set here as the upper limit of top brine temperature. The lower limit of top brine temperature is assumed to be 56˚C. The salinity of feed seawater ranges from 45,000 to 70,000 ppm.

4. Results and conclusions

A MATLAB program was used to perform the parametric analysis. The developed model was tested against some commercial MED-TVC plants; Tripoli, Yanbu II, Rabigh, and Trapani plants. Good results are obtained as shown in Table 2.

The parametric analysis is based on the GOR, entrainment ratio, compression ratio (CR), and specific heat transfer area. The analysis was performed for MED-TVC system with different number of effects. To study the effect of suction pressure of thermo compressor, suction position of thermo compressor is moved from last effect to the preceding ones. A schematic of parametric simulation in MATLAB for MED-TVC plant is shown in Fig. 3.

The performance of TVC is measured by its entrainment ratio that is defined as the ratio of the mass flow rate of the entrained vapor to the mass flow

Table 2
Mathematical model comparison against four commercial plants with different number of effects

Desalination Plants	Tripoli [28]		Yanbu II [29]		Rabigh [29]		Trapani [30]	
	Model	Actual	Model	Actual	Model	Actual	Model	Actual
Operating and design conditions								
Number of effects n	4	4	5	5	6	6	12	12
Motive pressure P_m (kpa)	2,300	2,300	1,500	1,500	1,770	1,770	4,500	4,500
Top brine temperature T_1 (˚C)	60.1	60.1	63	63	70	70	62.2	62.2
Minimum brine temperature T_n (˚C)	46	46	45	45	49.4	49.4	37	37
Temperature drop per effect (˚C)	4.9	4.9	4.5	4.5	4.1	4.1	2.3	2.3
Feed temperature T_f (˚C)	41.5	41.5	43	43	32	32	35	35
Cooling seawater temperature T_{cw} (˚C)	31.5	31.5	30	30	23	NA	25	NA
Motive steam flow rate D_m (kg/s)	8.8	8.8	101.7	101.7	7.06	7.06	6.25	6.25
TVC design								
Entrainment ratio Ra	1.19	1.14	0.84	0.82	1.47	NA	1.94	NA
Expansion ratio ER	240.9	NA	104.4	100.4	151.4	NA	736.1	730
Compression ratio CR	2.66	NA	1.97	1.91	3.22	NA	4.3	4
System performance								
Distillate production D (kg/s)	59.66	57.8	792.5	793.1	56.6	57.9	107	104
Gain output ratio GOR	6.78	6.51	7.7	7.84	8.01	8.2	16.8	16.7
Specific heat consumption Q (kJ/kg)	360.6	NA	312.03	NA	298.5	NA	148.6	NA
Specific heat transfer area A_d (m^2/kg/s)	283.7	NA	373.7	NA	312.5	NA	2,066.2	NA

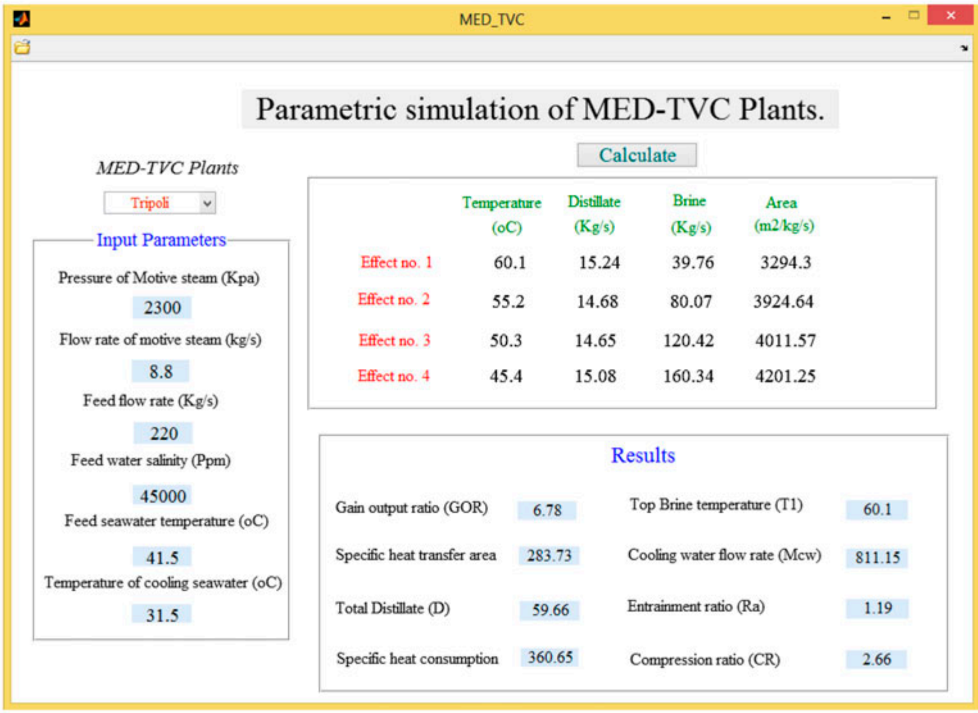

Fig. 3. Input and output panels of MED-TVC MATLAB simulation code.

rate of the motive steam. The entrainment ratio depends on the CR of the thermo-compressor. The entrainment ratio of thermo-compressor increases by moving the suction position of thermo-compressor toward the middle effects. Eventually, energy consumption of the plant reduces. But on the other hand, number of effects in MED-TVC system will be reduced by changing the suction position of thermo-compressor to the middle effects. As a result of this, various combinations of MED-TVC system and conventional MED system will be obtained.

It is also obvious that MED system with a thermo-compressor has a lower amount of energy consumption as compared to the MED units without a thermo-compressor. In MED-TVC system, part of vapor is reused in the system. So, it is necessary to optimize the system to find the best location of the thermo-compressor suction position which will give the best integration of MED-TVC and MED. For this purpose, optimization has been done in this research for different number of effects.

Since GOR is one of the important performance parameter of MED-TVC system, Fig. 4 illustrates the effect of suction pressure of thermo-compressor on the GOR of MED-TVC system. The major parameter for the optimization of suction position of thermo-compressor is suction pressure. Effect of suction pressure of the thermo-compressor was investigated for different number of effects.

It can be seen from Fig. 4 that the maximum GOR can be achieved when thermo compressor is placed between middle effects and the optimum suction pressure is always a medium pressure. Numbers on the curve indicate the effect number. Fig. 4(a) shows that the maximum GOR can be achieved when suction port of thermo compressor is the third effect. Fig. 4(b) shows that the maximum GOR can be obtained when thermo-compressor is placed between third and fourth effect. While for MED-TVC system with six effects as shown in Fig. 4(c), optimum position is the fourth effect and in case of Fig. 4(d), maximum efficiency can be achieved when thermo-compressor is placed after the seventh effect. Results showed that the MED-TVC + MED combination has fewer irreversibilities and higher GOR than the MED-TVC.

Fig. 5 shows the effect of suction pressure on specific heat transfer area of MED-TVC system with different number of effects. It can be seen that the specific heat transfer area of MED-TVC effects decreases by increasing the suction pressure of thermo-compressor. It can also be observed that this trend is almost same for all four MED-TVC systems.

Fig. 6 demonstrates the variations in specific heat consumption (Q) as a function of suction pressure of

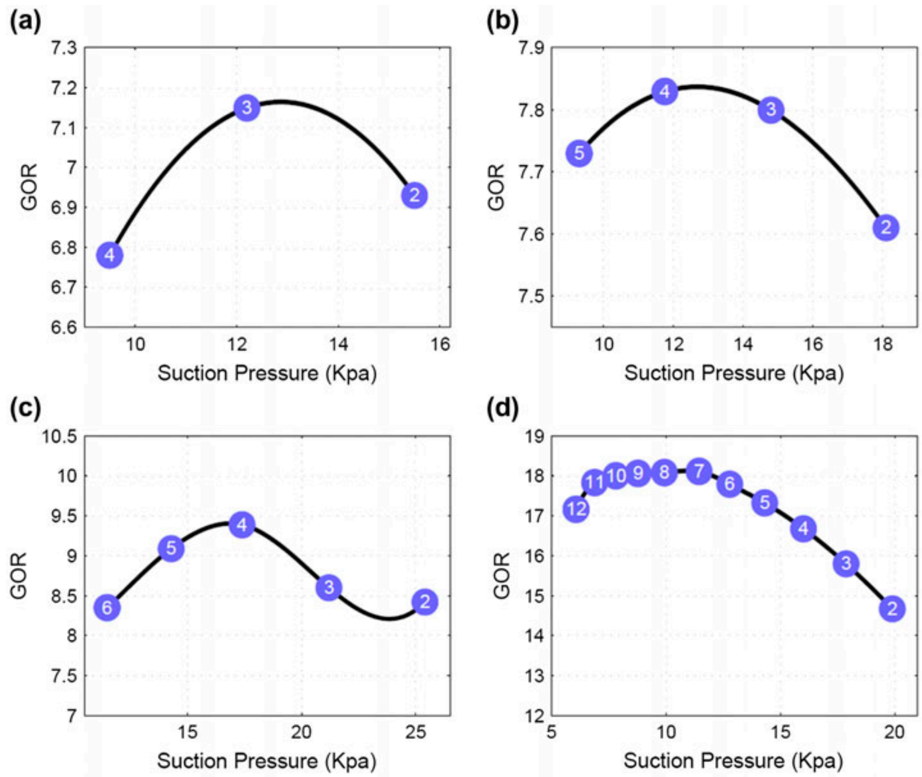

Fig. 4. The effect of variation in suction pressure on GOR of MED-TVC system with different number of effects, i.e. (a) 4 effects, (b) 5 effects, (c) 6 effects, and (d) 12 effects.

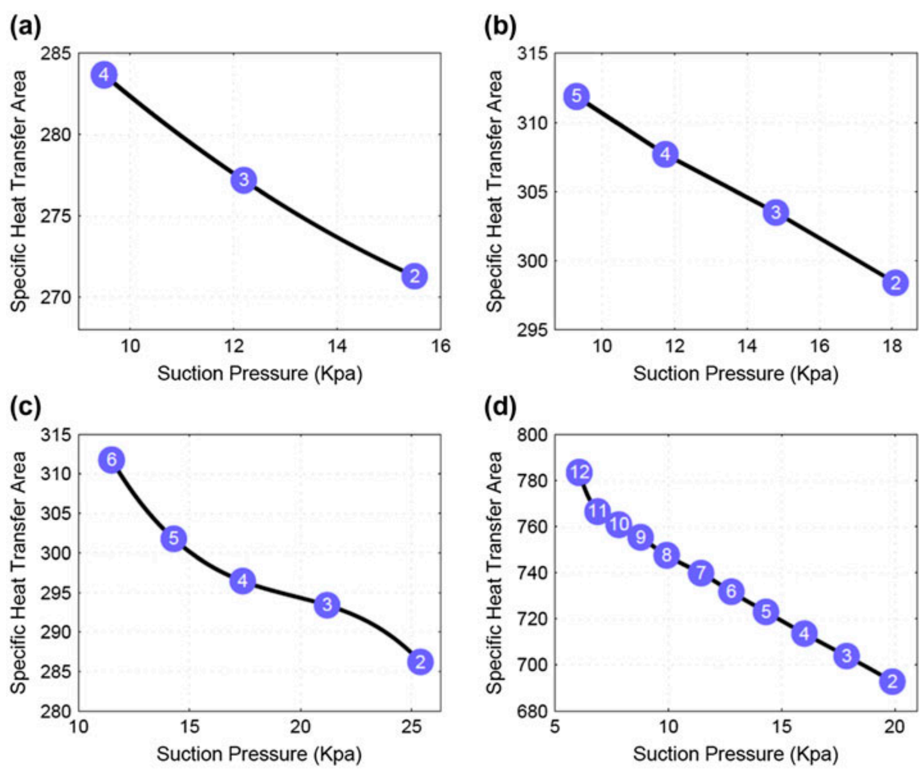

Fig. 5. The effect of variation in suction pressure on the specific heat transfer area ($m^2/kg/s$) of MED-TVC system with different number of effects, i.e. (a) 4 effects, (b) 5 effects, (c) 6 effects, and (d) 12 effects.

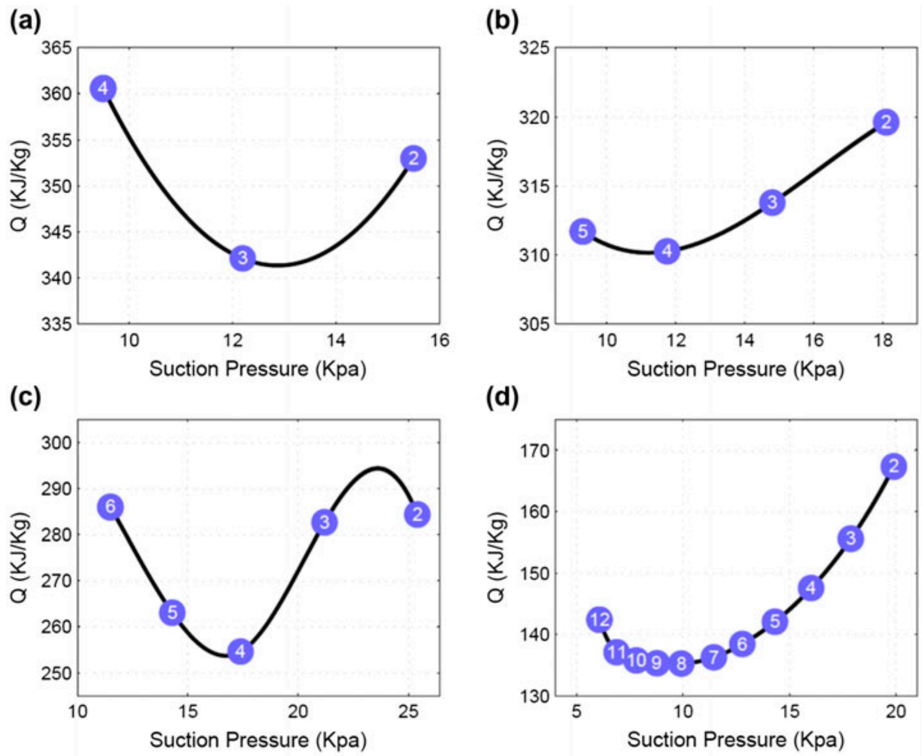

Fig. 6. The effect of variation in suction pressure on the specific heat consumption, Q (kJ/kg) of MED-TVC system with different number of effects, i.e. (a) 4 effects, (b) 5 effects, (c) 6 effects, and (d) 12 effects.

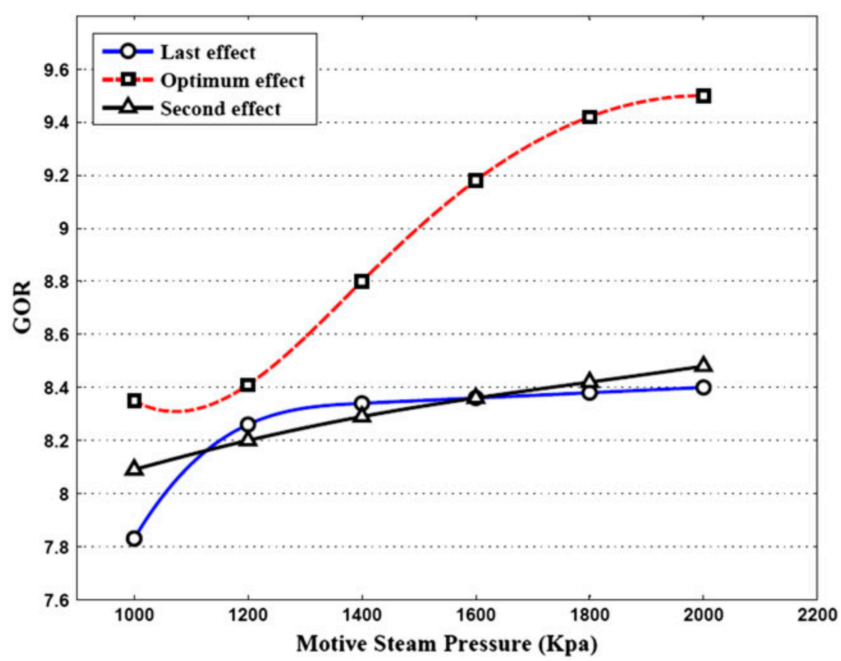

Fig. 7. Effect of motive steam pressure on the GOR.

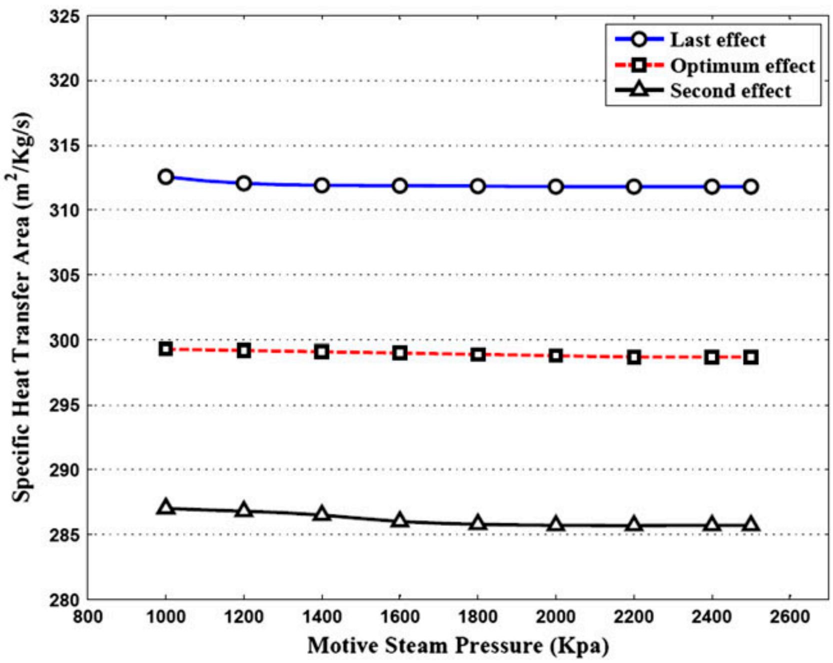

Fig. 8. Effect of motive steam pressure on the specific heat transfer area.

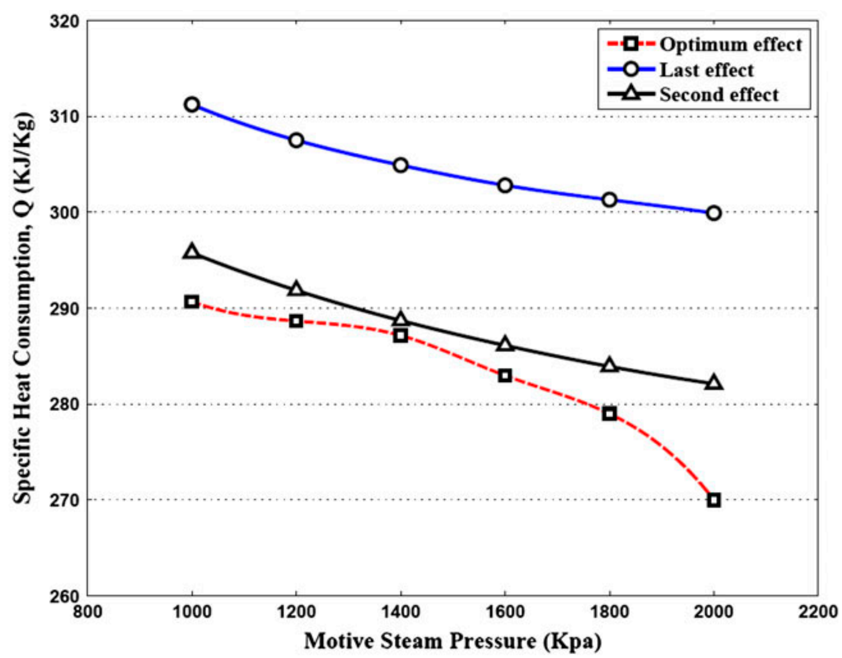

Fig. 9. Effect of motive steam pressure on the specific heat consumption.

thermo compressor. Specific heat consumption is dependent on the total distillate produced. It is clearly obvious in Fig. 6 that the specific heat consumption is minimum when thermo compressor is placed at the optimum position where GOR is maximum. So, it can also be concluded from here that the minimum specific heat consumption can be obtained when thermo-compressor is placed between middle and last effects.

For further parametric analysis, we have selected Rabigh MED-TVC plant with six effects in which

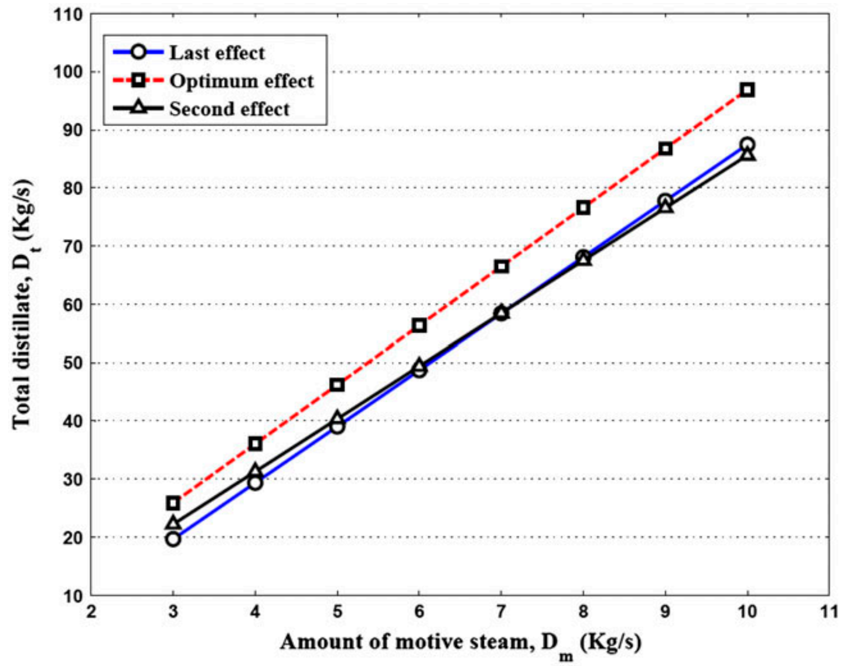

Fig. 10. The effect of steam flow rate on the produced water.

fourth effect (middle effect) is the optimum effect for the suction port of thermo-compressor.

Another important parameter of MED-TVC system is motive steam pressure. It reflects the quality of steam used. The effect of motive steam pressure on GOR of MED-TVC system is illustrated in Fig. 7. For low motive steam pressures, first effects have high GOR as compared to the last effects. Though it is clearly visible from Fig. 7 that for any amount of motive steam pressure, middle effects or optimum effects have higher GOR compared to the initial effects and last effects. The increase in motive pressure from 1,000 to 2,000 kPa gives an increase of 12.1, 6.8, and 4.6% in the GOR for the middle (optimum), last, and initial effects, respectively. Motive steam with high pressure possess enough energy to entrain large amount of entrained vapor. As a result, amount of used motive steam reduces and GOR of the system increases [14]. Motive steam with high pressure improves the performance of MED-TVC plants.

Fig. 8 shows the effect of variation in motive pressure on the specific heat transfer area. Result showed that the motive steam pressure has no influence on the specific heat transfer area of MED-TVC systems.

Fig. 9 shows that the specific heat consumption decreases by increasing the motive steam pressure. It can also be seen from the Fig. 9 that the middle effects have low specific heat consumption compared to the last and initial effects.

The steam flow rate can be varied to maintain the amount of total distillate water produced. The distillate output increases with the increase in the steam flow rate as depicted in Fig. 10 and consequently GOR increases. The increase in the total amount of distillate is almost same when thermo compressor is placed after first and last effects. Middle effects or the optimum effects have higher GOR than the first and last effects arrangements.

5. Conclusion

This work presents an efficient and accurate mathematical model describing the MED-TVC desalination system. MATLAB algorithm is developed and used to solve the mathematical model and optimize the suction port of thermo compressor in the MED-TVC system. This study shows that the simulation model is an effective tool to design MED-TVC system for different number of effects with any desired capacity. Also, it provides an effective tool to evaluate the system performance of any MED-TVC unit. Good agreement is achieved between model data and real plant data. Results showed that the maximum GOR can be achieved when thermo compressor is positioned near the middle effects.

Parametric analysis of MED-TVC system was performed to find the optimum configuration of MED-TVC and MED combination in point of view of the suction position of the thermo-compressor. Effects of different parameters including motive steam pressure, suction pressure, and amount of motive steam were studied. It was also found that the middle effects have several advantages over the other two combinations. They have highest GOR, lowest specific heat consumption, and fewest irreversibilities. Specific heat transfer area of MED-TVC effects decreases by increasing the suction pressure of thermo-compressor. Calculations also showed that the distillate output increases with the increase in the amount of motive steam and consequently GOR increases in all arrangements.

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Nomenclature

A	—	Heat transfer area (m^2)
A_c	—	Condenser heat transfer area (m^2)
A_d	—	Specific heat transfer area (m^2/kg)
A_e	—	Total heat transfer of the effects (m^2)
B	—	Brine flow rate (kg/s)
BPE	—	Boiling point elevation (°C)
C_p	—	Specific heat capacity of water (kJ/kg K)
CR	—	Compression ratio
D	—	Distillate (kg/s)
D_c	—	Non-entrained vapor (kg/s)
D_{ev}	—	Entrained vapor to the ejector (kg/s)
D_m	—	Motive steam flow rate (kg/s)
D_t	—	Total amount of distillate (kg/s)
ER	—	Expansion ratio
F	—	Feed flow rate (kg/s)
GOR	—	Gain output ratio
LMTD	—	Logarithmic mean temperature difference
M_{cw}	—	Cooling seawater flow rate (kg/s)
MED	—	Multi-effect desalination
NEA	—	Non-equilibrium allowance (°C)
n	—	Number of effects
P_{ev}	—	Entrained vapor pressure (kPa)
P_m	—	Motive steam pressure (kPa)
P_s	—	Compressed vapor pressure (kPa)
R_a	—	Entrainment ratio
Q	—	Specific heat consumption (kJ/kg)
T	—	Brine temperature (°C)
T_1	—	Top brine temperature (°C)
T_{cw}	—	Cooling seawater temperature (°C)
T_f	—	Feed seawater temperature (°C)
T_m	—	Motive steam temperature (°C)
T_n	—	Last effect temperature (°C)
T_v	—	Saturated vapor temperature (°C)
TVC	—	Thermal vapor compression
ΔT	—	Temperature diff. per effect (°C)
U_i	—	Heat transfer coefficient of effect i (kW/m^2 K)
U_c	—	Condenser heat transfer coefficient (kW/m^2 K)
X_b	—	Salt concentration of brine (ppm)
X_f	—	Salt concentration of feed (ppm)
λ	—	Latent heat of evaporation (kJ/kg)

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