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Energy and exergy analyses of a novel multi-effect distillation system with thermal vapor compression for seawater desalination

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ABSTRACT

In this work, the first and second laws of thermodynamics were applied to conduct energy and exergy evaluations of a novel integrated multi-effect distillation with thermal vapor compression (MED-TVC) system for seawater desalination. In addition, the behavior of the MED-TVC system was analyzed for various operating conditions such as the top brine temperature, the number of effects, and the motive steam flow rate. The obtained results confirmed that the major causes of irreversibilities in the MED-TVC system are the ejector and effects, which account for 45% and 37% of the total exergetic destruction, respectively. Moreover, the results of the energetic analysis showed that maximum energy losses of about 42% occur in the condenser primarily due to heat transfer over large temperature differences. Finally, the parametric study revealed that operating the MED-TVC desalination system with reduced top brine temperature and motive steam flow is highly recommended to improve the overall efficiency while increasing the number of effects is particularly suitable for high system performance and productivity.

Keywords: Seawater desalination; Multi-effect distillation; Thermal vapor compression; Energetic analysis; Exergy efficiency; Performance

1. Introduction

Seawater and brackish water desalination are among the most interesting technologies for drinking-water supply in water-scarce and semi-arid regions. Currently, more than 18.000 desalination plants operate in 150 countries producing approximately 38 billion m^3/y. By the year 2030, this number is projected to increase to 54 billion m^3/y, 40% more compared to 2016. Although seawater desalination accounts for about 59% of installed capacity worldwide, followed by brackish water desalination accounting for 23% of global desalination capacity, but the use of other water sources, such as river water, and both domestic and industrial wastewater has been steadily increasing. However, desalination is a highly energy-intensive water treatment process that consumes at least 75.2 TWh/y, which is equivalent to around 0.4% of global electricity consumption. Most of the energy required for desalination presently comes from fossil fuels which are the major source of CO_2 emission. Presently, globally installed desalination capacities are contributing 76 million tons of CO_2 annually and it is expected to grow to 218 million tons of CO_2 per year by 2040. Therefore, there is a need for new methods which limit environmental burdens associated with the more conventional types of seawater desalination techniques, and they must fulfill the growing demand for potable water, simultaneously [1].

The commercial desalination technologies can be divided into two main categories: thermally-driven methods such as multi-effect desalination (MED), multistage flash

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desalination (MSF) and adsorption cycles methods (AD), and membrane separation processes such as reverse osmosis (RO), and ultra/nano/ionic (UF/NF/IF) filtration. In addition, there are different emerging technologies which are that are under research or in commercialization stages including forward osmosis (FO), membrane distillation (MD), capacitance deionization (CDI), gas hydrates (GH), freezing and humidification dehumidification (HDH). Recently, hybridization trends of desalination technologies such as MED-AD, MSF-MED and RO-MSF are evolving to improve processes performance by overcoming conventional methods limitations but also to maximize operational reliability and recovery [2–4]. Among the available desalination techniques, multi-effect distillation with thermal vapor compression (MED-TVC) represents a promising alternative compared to other well-established desalination systems because of its improved efficiency, simplicity of operation and maintenance, and economic viability [5,6].

The performance of thermal systems could be thermodynamically analyzed by applying energy and exergy methodologies. The thermodynamic inefficiencies are evaluated using the energetic analysis method. However, this methodology lacks significant information on losses and the sites where they take place. The exergetic analysis approach is widely regarded as a powerful tool for determining the causes, locations, kinds, and importance of the thermodynamic inefficiencies of a given system [7,8].

Hamed et al. [9] applied the exergetic analysis approach to a four-stage MED-TVC desalination system situated in the United Arab Emirates, based on real operating data. The exergy losses have been assessed and compared with those of other traditional desalination systems. The findings revealed that the first effect and the ejector account for the majority of exergetic destructions with about 39% and 17%, respectively.

Al-Najem et al. [10] performed energetic and exergetic analysis for two commercially available thermal desalination systems (single and multi-effect TVC) installed by SIDEM Company (France). The results showed that the thermo-compressor and evaporators are the major sources of exergetic destruction rate in the TVC system.

Alasfour et al. [11] carried out an energetic and exergetic analysis of three distinct multi-effect TVC configurations. In all configurations, the irreversibilities in the thermo-compressor and evaporators were found to be the most important causes of exergetic destruction. The thermal analysis also revealed that the first effect accounts for up to 50% of the total effect's exergetic destruction.

Choi et al. [12] analyzed the thermal performance of four MED-TVC desalination systems with various capacities provided by Hyundai Heavy Industries (HHI) Company (Korea). The exergy losses in subsystems of every MED-TVC system have been evaluated. According to their findings, above 70% of the total exergetic destruction is attributed to the TVC and the effects.

Sayyadi et al. [6] carried out thermodynamic and thermoeconomic optimization based on the exergy and economic analysis of a typical MED-TVC system in order to minimize the water production cost and maximizing the exergetic efficiency. The results revealed that maximum exergetic efficiency and minimum cost of water production are obtained at a much higher value of the number of effects. This was later confirmed by Esfahani et al. [13].

Benimar [14] evaluated and improved the performance of three commercial MED-TVC systems with different capacities based on energy and exergy analyses. The findings indicated that the major part of the exergetic destruction rate results in the steam ejector and the effects. Moreover, the results indicated that the first effect is responsible for around 46% of the total effects' exergetic destruction, which decreases with an increasing number of effects.

Sadri et al. [15] analyzed and optimized a MED-TVC system in the Tripoli plant (Libya) using the energy and exergy approach. The results displayed that evaporators are the major causes of exergetic destruction, whereas the first effect is accounting for around 73% of the exergetic destruction rate of all the effects.

Eshoul et al. [16] performed exergy and economic analyses of a MED-TVC system for various operating parameters and configurations. According to the results, the ejector and effects are the primary causes of exergetic destruction, accounting for around 40% and 35% of the total exergetic destruction, respectively.

Elsayed et al. [17] developed an exergo-economic model to simulate the performance of a MED-TVC system having a variety of feed options. Their findings confirmed that 58% of exergy destruction takes place in the TVC section and could be much lower by decreasing the supplied pressure of motive steam.

Khorshidi et al [18] presented exergetic analysis and optimization of a MED-TVC system situated in the south of Iran, based on a genetic algorithm. The exergetic analysis of the system indicated that more the 80% of the exergetic destruction takes place in the ejector and effects. The optimization results showed that the distilled water production could be improved by 16.62%, while the total exergetic destruction rate was reduced to 3.58%.

Tontu et al. [19] analyzed a four-stage MED-TVC system coupled with a thermal power plant situated in the eastern part of Turkey by applying energy, exergy, and thermoeconomic approaches and by considering different operating conditions. Their results revealed that approximately 45% of the total exergetic destruction rate belonged to the thermo-compressor.

Recently, Cao et al. [20] performed energy and exergy analyses of MED and MED-TVC desalination systems using different group division techniques. The findings indicated that the performance of the MED-TVC system could be improved if the effects are distributed more uniformly across effect groups. It is also found that exergetic efficiency could be significantly enhanced by raising the suction effect number.

In this paper, a novel scheme in which feedwater preheater is integrated with the MED-TVC desalination system is presented. This MED-TVC based scheme could reduce the waste exergy from the production line, in the global capacity of the desalination system. In addition, energetic and exergetic analyses are accomplished for all components within the MED-TVC system. Based on the obtained thermal and exergy losses, an attempt is made to minimize the losses and enhance the overall system efficiency.

Table 1
Mass and energy balance model equations [21,22]

Parameter	Equation	No
Temperature difference across the effects	$\Delta T = \frac{T_1 - T_n}{n-1}$	(1)
Temperature of compressed steam	$T_s = T_1 - \Delta T$	(2)
Vapor temperature in the last effect	$T_{vn} = T_n - \text{BPE}$	(3)
	$\text{BPE} = X_b\left[B + CX_b\right]\times 10^{-3}$	(4)
Boiling point elevation (BPE)	$B = \left[6.71 + \left(6.34\times 10^{-2}\times T_n\right) + \left(9.74\times 10^{-5}\times T_n^2\right)\right]\times 10^{-3}$	(5)
	$C = \left[22.238 + \left(\left(9.59\times 10^{-3}\times T_n\right) + \left(9.42\times 10^{-5}\times T_n^2\right)\right]\times 10^{-8}$	(6)
	$C_p = \left[a + b\times T_1 + c\times T_1^2 + d\times T_1^3\right]\times 10^{-3}$	(7)
	$a = 4206.8 - \left(6.6197\times S\right) + \left(1.2288\times 10^{-2}\times S^2\right)$	(8)
Heat capacity of water	$b = -1.1262 + \left(5.4178\times 10^{-2}\times S\right) - \left(2.2719\times 10^{-4}\times S^2\right)$	(9)
	$c = \left(1.2026\times 10^{-2}\right) - \left(5.3566\times 10^{-4}\times S\right) + \left(1.8906\times 10^{-6}\times S^2\right)$	(10)
	$d = \left(6.8777\times 10^{-7}\right) + \left(1.517\times 10^{-6}\times S\right) - \left(4.4268\times 10^{-9}\times S^2\right)$	(11)
Pressure of compressed vapors	$P_s = 1000\times\exp\left(\frac{-3892.7}{T_s + 273.15 - 42.6776} + 9.5\right)$	(12)
Pressure of entrained vapors	$P_{ev} = 1000\times\exp\left(\frac{-3892.7}{T_{vn} + 273.15 - 42.6776} + 9.5\right)$	(13)
Expansion ratio (ER)	$\text{ER} = \frac{P_m}{P_{ev}}$	(14)
Compression ratio (CR)	$\text{CR} = \frac{P_s}{P_{ev}}$	(15)
Entrainment ratio (Ra)	$\text{Ra} = 0.235\frac{P_s^{1.19}}{P_{ev}^{1.04}}ER^{0.015}$	(16)
Entrained vapors flow rate	$D_{ev} = \frac{D_m}{\text{Ra}}$	(17)
Brine temperature in each effect	$T_{i+1} = T_{i+1} - \Delta T,\quad i = 1,2,\ldots,n$	(18)
Vapor temperature in each effect	$T_{vi} = T_i - \text{BPE}$	(19)
Feed seawater flow rate in each effect	$F_i = \frac{F}{n},\ i = 1,2,\ldots,n$	(20)
Vapor condensation temperature	$T_{ci} = T_i - \text{BPE} - \Delta T_p + \Delta T_t - \Delta T_c$	(21)
Latent heat of vaporization at steam temperature	$\lambda_s = 2501.897149 - 2.407064037\times T_s + 1.192217\times 10^{-3}\times T_s^2 - 1.5863\times 10^{-5}\times T_s^3$	(22)

(Continued)

Table 1 Continued

Parameter	Equation	No
Latent heat of distillate vapor	$\lambda_i = 2501.897149 - 2.407064037 \times T_i + 1.192217 \times 10^{-3} \times T_i^2 - 1.5863 \times 10^{-5} \times T_i^3$	(23)
Latent heat of motive steam	$\lambda_m = 2501.897149 - 2.407064037 \times T_m + 1.192217 \times 10^{-3} \times T_m^2 - 1.5863 \times 10^{-5} \times T_m^3$	(24)
Mass balance in each effect	$B_1 = F_1 - D_1$	(25)
	$B_i = F_i + B_{i-1} + D_i,\ i = 2,3...,n$	(26)
Brine salinity at the outlet of the effect	$X_1 = \frac{F_i}{B_i} \times X_f$	(27)
	$X_i = \frac{F_i}{B_i} \times X_f + \frac{B_{i-1}}{B_i} \times X_{i-1},\ i = 2,3,.....,n$	(28)
	$D_1 = \frac{1}{\lambda_1}\left[\left(D_m + D_{\text{ev}}\right)\lambda_s - F_1 \times C_p\left(T_1 - T_f\right)\right]$	(29)
	$D_i = \frac{1}{\lambda_i}\left[\left(D_{i-1} + D'_{i-1}\right)\lambda_{i-1} - F_i \times C_p\left(T_i - T_f\right) - B_{i-1} \times C_p\left(T_{i-1} - T_i\right)\right]$	(30)
Vapor produced in the last effect	$D'_i = D_{i-1} C_p \frac{T_{v,i-1} - T'_i}{\lambda_i}$	(31)
	$T'_i = T_{v,i-1} - NEA_i$	(32)
	$\text{NEA}_i = 33\frac{\left(T_{i-1} - T_i\right)^{0.55}}{T_{v,i}}$	(33)
Distillate water flow rate	$D_t = \sum_{i=1}^{n} D_i$	(34)
Overall heat transfer coefficient	$U_i = \frac{1939.4 + 1.40562T_i - 0.020752T_i^2 + 0.0023186T_i^3}{1000}$	(35)
Heat transfer area in each effect	$A_1 = \frac{\left(D_m + D_{\text{ev}}\right)\lambda_s}{U_1\left(T_s - T_1\right)}$	(36)
	$A_i = \frac{D_i \lambda_i}{U_i\left(T_{c,i} - T_i\right)},\ i = 2,3,..........,n$	(37)
Total heat transfer area	$A_e = A_1 + A_2 + \ldots + A_n = \sum_{i=1}^{n} A_i$	(38)
Cooling seawater flow rate	$M_{cw} = \frac{D_c \lambda_n}{C_p\left(T_f - T_{cw}\right)}$	(39)
Condenser heat transfer area	$A_c = \frac{D_c \lambda_n}{U_c\left(\text{LMTD}\right)_c}$	(40)
	$\left(\text{LMTD}\right)_c = \frac{(T_f - T_{\text{cw}})}{\ln\left[\frac{T_{v,n} - T_{\text{cw}}}{T_{c,n} - T_f}\right]}$	(41)
	$U_c = 1.7194 + 3.2063 \times 10^{-2} T_{v,n} - 1.5971 \times 10^{-5} T_{v,n}^2 + 1.9918 \times 10^{-7} T_{v,n}^3$	(42)

2. System description

A schematic of the proposed MED-TVC system is represented in Fig. 1. The most important components of the desalination unit are the thermo-compressor (ejector), the condenser, and the evaporators (effects). The motive steam (D_m) is introducted into the thermo-compressor at moderate pressure and employed to compress a part of the steam formed in the last effect. With the mass flow rate ($D_m + D_{ev}$), the compressed vapor and expanded motive steam exit the ejector and enter the first effect (heat source), thus condensing and releasing their latent heat within the tubes. Each evaporation effect is sprayed with pre-heated feed saltwater, which flows down as a liquid layer. As a result of motive steam condensation, the film is heated to the boiling point, and a part of it is evaporated. A portion of the condensate is returned to its source, while the remainder is added to the desalinated water product.

The first effect's produced vapor (D_1) is fed to the second effect, where it serves as a heat source. Then, the heated brine from the first effect is transferred to the second effect, which has a lower temperature and pressure. In the second effect, the vapor (D_2) is produced by flashing brine (B_1) and evaporated feed seawater (F_2). After then, the process is repeated for each effect. A fraction of the produced vapor in the last effect is sucked by the thermo-compressor, whereas the remaining part is condensed in the condenser, warming the seawater to a higher temperature. The system excess heat introduced by the hot motive steam into the first effect is extracted using cooling seawater.

3. Modeling and system analysis

A mathematical model of the proposed MED-TVC desalination system was developed using the first and second laws of thermodynamics. In addition, the equations for calculating the physical properties of seawater and heat transfer coefficients are included.

The following assumptions and hypotheses have been considered for simplifying the developed model:

- A steady-state process is assumed.
- The effects have the same temperature difference.
- In both effects, the feed-flow rate is constant.
- The distillate is salt-free.
- Thermodynamic losses have been studied.
- An average pump efficiency of 75% is estimated.

3.1. Mass and energy balance model

For the evaluation of mass and energy conservation, several unknown variables must be calculated. The details of these variables and the thermodynamic losses of the MED-TVC system, that is, boiling point elevation (BPE) of brine, non-equilibrium allowances (NEA) in the flashing boxes, temperature difference between the effects, and condensation process, are described by the equations listed in Table 1.

3.2. Exergy analysis

The total exergy rate can be divided into four major parts: physical ($\dot{E}_{ph}$), chemical ($\dot{E}_{ch}$), kinetic ($\dot{E}_{ke}$), and potential ($\dot{E}_{pe}$) exergies [23]. The general exergy balance is given by the following equation:

$$\dot{E}x = \dot{E}_{ph} + \dot{E}_{ch} + \dot{E}_{ke} + \dot{E}_{pe} \tag{43}$$

Kinetic and potential exergy terms may be excluded based on the selected reference value. The general exergy rate balance for open systems in steady-state is expressed as [24]:

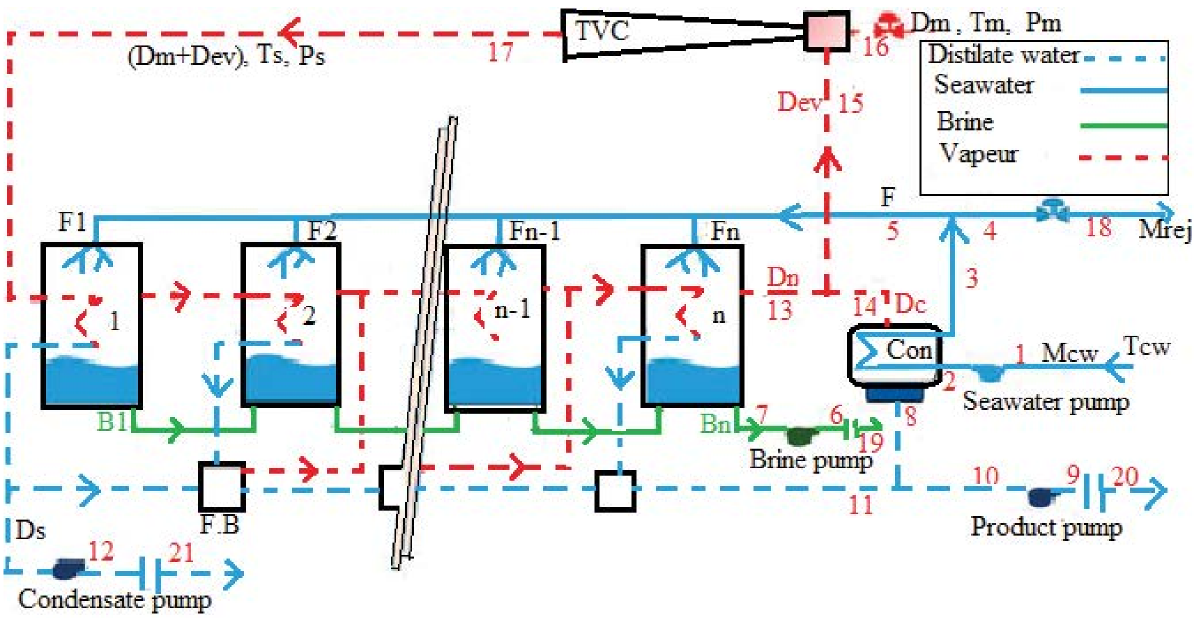

Fig. 1. Schematic diagram of the proposed MED-TVC system.

$$\sum_j \dot{Q}_j \left(1 - \frac{T_0}{T_j}\right) - \dot{W}_{cv} + \sum_i \dot{m}_i e_i - \sum_e \dot{m}_e e_e - \dot{E}_d = 0 \quad (44)$$

The Gouy–Stodola equation is used to determine the exergy destroyed (irreversibility) caused by entropy generation as follows:

$$\dot{E}_d = T_0 \dot{S}_g \quad (45)$$

The second law can be written as [25]:

$$\dot{S}_g = \sum_e \dot{m}_e e_e - \sum_i \dot{m}_i e_i + \frac{\dot{Q}_j}{T_0} \quad (46)$$

where $\dot{S}_g$ is the rate of entropy generation during the process associated with the irreversibilities; $\dot{Q}_g$ represents the heat transfer rate at reference temperature T_0; $\frac{\dot{Q}_j}{T_0}$ denotes the entropy transfer rate.

If the above heat transfer is neglected along with kinetic and potential energies of the stream, the result is:

$$\dot{W}_{cv} = \dot{W}_u = \sum_i \dot{m}_i e_i - \sum_e \dot{m}_e e_e - T_0 \dot{S}_g \quad (47)$$

The steady-flow components do not contribute to the work performed during the process since their boundaries are constant. By changing the entropy generation term $\dot{S}_g = 0$, the useful (reversible) work can be obtained. As a result, Eq. (47) is expressed as follows:

$$\dot{W}_{rev} = \dot{W}_{u,max} = \dot{m}\left(e_i - e_e\right) \quad (48)$$

The physical and chemical exergy values are determined as:

$$\dot{E}_{ph} = \dot{m}e_{ph} = \dot{m}\left[\left(h_s - h_0\right) - T_0\left(s_s - s_0\right)\right] \quad (49)$$

$$\dot{E}_{ch,w} = \dot{m}e_{ch} = \dot{m}\sum \omega_k \left(\mu_k^s - \mu_{ok}^o\right) \quad (50)$$

In these equations, the subscript (s) designed the initial state, and the reference state is denoted by the subscript (0). The chemical potential and mass fraction are denoted by (μ) and (ω). The terms (e_{ph}) and (e_{ch}) stand for specific physical and chemical exergy, respectively.

By the aid of Eqs. (49) and (50), Eq. (51) is obtained as an exergy formulation. The following equation may be used to calculate the reversible work:

$$\dot{W}_{u,max} = \sum_i \dot{E}x_i - \sum_e \dot{E}x_e \quad (51)$$

The rate of irreversibility is equivalent to the loss of exergy as follows:

$$\dot{I} = \dot{W}_{u,max} - \dot{W}_u = T_0 \dot{S}_g \quad (52)$$

The pump's internal power input may be written as:

$$\dot{W}_p = \dot{m}_i h_i - \dot{m}_e h_e \quad (53)$$

The rate of irreversibility is:

$$\dot{I}_p = \sum_i \dot{E}x_i - \sum_e \dot{E}x_e - \dot{W}_p \quad (54)$$

The reversible work related to heat transfer is equivalent to the irreversibilities rate in effects, condenser, and thermo-compressor. The expression is:

$$\dot{I} = \dot{W}_{rev} - \dot{W}_u = \dot{W}_{rev} = \sum_i \dot{E}x_i - \sum_e \dot{E}x_e \quad (55)$$

There are three streams in the MED-TVC desalination unit: seawater, pure water, and steam. Thermodynamic properties of the considered fluids are calculated using empirical models described in [26–31].

3.3. System performance

The performance of MED-TVC desalination systems is usually evaluated using the following parameters:

3.3.1. Gain output ratio

The gain output ratio (GOR) is calculated by dividing the total production of distilled water (D_t) by the motive steam supply flow rate (D_m).

$$\text{GOR} = \frac{D_t}{D_m} \quad (56)$$

3.3.2. Specific heat consumption

The specific heat consumption is evaluated in terms of the amount of thermal energy used by the system for producing 1 kg of distilled water.

$$Q_{th} = \frac{D_m \lambda_m}{D_t} \quad (57)$$

3.3.3. Specific heat transfer area

The specific heat transfer area is defined as the sum of the total effects area (A_e) and the condenser's heat transfer area (A_c) divided by the overall distillate production:

$$A_d = \frac{A_e + A_c}{D_t} \quad (58)$$

3.3.4. Exergy efficiency

The exergy efficiency of a system is the ratio between the minimum work of separation and the fuel exergy:

$$\eta_{ex} = \frac{\dot{W}_{min}}{\dot{E}_f} \quad (59)$$

The minimum work of separation ($\dot{W}_{min}$) represents the product exergy in the desalination process, while the fuel exergy ($\dot{E}_f$) is the thermal energy provided to the system.

3.3.5. Universal performance ratio

The universal performance ratio (UPR) is a common platform to evaluate the desalination processes based on primary energy consumption [32,33]:

$$\text{UPR} = \frac{\text{evaporative energy}}{\text{primary energy input}} = \frac{\lambda_m}{3.6 \times Q_{\text{PSE}}} \tag{60}$$

where Q_{PSE} is the standard primary energy calculated as:

$$Q_{\text{PSE}} = \left[\left(\left(\frac{\text{kWh}_{\text{elec}}}{\text{m}^3}\right) \times \left(\text{CF}_{\text{elec}}\right)\right) + \left(\left(\frac{\text{kWh}_{\text{th}}}{\text{m}^3}\right) \times \left(\text{CF}_{\text{th}}\right)\right)\right] \tag{61}$$

where CF_{elec} and CF_{th} are, respectively, the conversion factors for electricity and thermal input primary energy. The kilo-watt hour per cubic meter (kWh/m^3) is the specific energy consumption in terms of electrical and thermal.

3.3.6. Thermodymanic limit

The thermodynamic limit (TL) is an ideal concept of desalination with no entropy generation, and hence, the system is independent as there is zero recovery. Depending on the source of seawater, where the salinity may vary from 3.0% to 4.5% by weight, the specific energy consumption is calculated to be in the range of 0.7 to 0.85 kWh/m^3. The TL that has a minimum work of typical seawater at ambient temperature and 3.5% concentration by weight of dissolved salts is about 0.78 kWh/m^3 or 2.8 kJ/kg as given by the Gibbs equations As a result, the UPR theoretical limit based on minimum separation work theory is 828 [34,35].

4. Results and discussion

4.1. Model validation

MATLAB software was employed for modeling the MED-TVC desalination system. Accordingly, a series of mathematical calculations have been performed based on the design parameters previously described to order to analyze the performance of the MED-TVC system under different operating conditions. The thermodynamic characteristics of saline water were calculated using the most recent data available in the literature [36,37]. Model input parameters and the output results are given in Table 2. The validity of the developed model was tested by comparing the obtained results with some available data from three commercial desalination plants in literature, and a good agreement is demonstrated (Table 3).

The overall exergy efficiency calculated for the MED-TVC desalination system is very low (3.46%) as indicated in Table 1. However, the obtained value is in the same order of magnitude as those reported in the literature for other MED-TVC units, ranging between 2.24% and 7% [39–42]. It should be noted that the main cause of the low exergy efficiency of the MED-TVC process is associated with the application of high-pressure motive steam in the TVC unit to compress a portion of the last effect generated vapor to the first effect [43]. Further studies demonstrated this can be also attributed to other factors such as the efficiency of the thermal separation process, the larger number of components, and the higher latent heat of vaporization because of the low operating pressure within the effects [16]. However, the performance of the MED-TVC system could be further enhanced by adding more heaters between the desalination effects.

Table 2
MED-TVC modeling input parameters and results

Parameter	Value
Motive steam flow rate, kg/s	8.8
Motive steam pressure, kPa	230
Feed seawater temperature, K	314.5
Cooling water temperature, K	304.5
Feedwater salinity, ppm	46,000
Top brine temperature, K	333.1
Bottom brine temperature, K	318.4
Temperature difference, K	5.23
Entrainment ratio (Ra)	1.166
Expansion ratio (ER)	23.69
Compression ratio (CR)	2.77
Distillate production, kg/s	55.59
Gained output ratio (GOR)	6.31
Cooling water flow rate, kg/s	423.24
Specific heat consumption, kJ/kg	308.75
Specific heat transfer area, m^2/kg/s	224.36
Exergetic efficiency, %	3.46
Standard primary energy, kWh/m^3	5.3
Universal performance ratio (UPR)	102.2
UPR % of thermodynamic limit (TL)	12.34%

The UPR value of the MED-TVC desalination system is found to be 102.2 which is much better compared to conventional desalination processes such as MED (UPR = 88) and RO (UPR = 86). This is mainly due to the use of TVC process that enhances the heat transfer of film evaporation on tube surfaces of MED and the low grade steam utilization that has very small proportion in primary energy. It should be noted that MSF processes performance is the lowest (UPR = 60) because they consume high temperature steam and high electricity that makes more share in primary energy. Moreover, the obtained results show that the MED-TVC system is operating of only at 12.34% of ideal or thermodynamic limit whereas the sustainable desalination can be achieved by approaching 25%–30% of TL. This will be only possible either by hybridization of different processes or by innovative membrane materials such as aquaporins, graphanes, etc. [32–35].

4.2. Energy and exergy analyses

Table 4 shows the characteristics and flow rates of exergy in all streams. The ratio of exergetic destruction for every component using a Grossman diagram is shown in Fig. 2. As expected, the major exergy destruction occurs both in MED-TVC effects and thermo-compressor accounting for 81.58% of the total exergetic destruction. Such high

Table 3
Mathematical model comparison against three commercial plants with different sizes

Desalination plants	Tripoli [38]		Trapani [11]		Umm Al-NAR [39]	
	Actual	Model	Actual	Model	Actual	Model
Operating and design conditions						
Number of effects	4	4	12	12	6	6
Motive pressure, kPa	2,300	2,300	4,500	4,500	2,500	2,500
Top brine temperature, K	333.1	333.1	335.2	335.2	334.8	334.8
Minimum brine temperature, K	318.4	318.4	310	310	315.8	315.8
Temperature drop per effect, K	4.9	4.9	2.3	2.3	3.74	3.74
Feed seawater temperature, K	314.5	314.5	308	308	313	313
Cooling seawater temperature, K	304.5	304.5	298	298	303	303
Motive steam flow rate, kg/s	8.8	8.8	6.25	6.25	10.6 × 2	10.6 × 2
TVC design						
Entrainment ratio (Ra)	1.14	1.148	NA	1.86	1.36	1.29
Expansion ratio (ER)	NA	240	730	703.83	NA	321.16
Compression ratio (CR)	NA	2.73	4	4.3	NA	3.06
System performance						
Distillate production, kg/s	57.8	55.7	105.2	111.93	184.4	205.75
Gain output ratio (GOR)	6.51	6.31	16.7	17.91	8.6	9.07
Specific heat consumption, kJ/kg	NA	299.54	NA	150.61	NA	294.9
Specific heat transfer area, m^2/kg/s	NA	237.7	NA	272.85	NA	398.25

Table 4
Exergetic flow rates and properties at different states in the MED-TVC system

Stream No	Mass flow rate (kg/s)	Temp. (K)	Salinity (ppm)	Enthalpy (kJ/kg)	Entropy (kJ/kg K)	Exergy rate (MW)
1	425.50	334.50	46,000	125.4	0.4343	0.000
2	425.50	304.60	46,000	125.8	0.4356	0.002
3	425.50	314.50	46,000	165.4	0.5633	0.290
4	205.50	314.50	46,000	165.4	0.5633	0.140
5	220.00	314.50	46,000	165.4	0.5633	0.150
6	161.81	318.44	46,000	177.4	0.5947	0.283
7	161.81	318.43	70,000	177.2	0.5945	0.253
8	06.66	318.40	0	190.1	0.6435	0.020
9	58.18	323.94	0	213.3	0.7158	0.242
10	58.18	323.74	0	212.4	0.7133	0.240
11	51.52	324.24	0	214.5	0.7197	0.218
12	08.80	338.00	0	272.1	0.8939	0.076
13	14.75	318.40	0	2583.7	8.1686	1.597
14	06.66	318.40	0	2583.7	8.1685	0.713
15	08.09	318.40	0	2583.7	8.1685	0.866
16	08.80	397.82	0	2713.3	7.1051	4.933
17	16.00	338.00	0	2618.2	7.8425	4.069
18	205.50	304.50	46,000	125.4	0.4343	0.000
19	161.81	304.50	70,000	122.6	0.4190	0.056
20	58.18	304.50	0	132.0	0.4565	0.112
21	08.80	304.50	0	132.0	0.4565	0.017

irreversibilities are mainly induced by the significant pressure of motive steam and the temperature gradient through the MED-TVC system, additionally to the heat transmission process in the effects associated with phase change [17]. The condenser represents the third contributor of exergetic destruction because of heat transfer loss during the condensation process. Exergy destruction rates are the lowest in output streams and pumps, respectively.

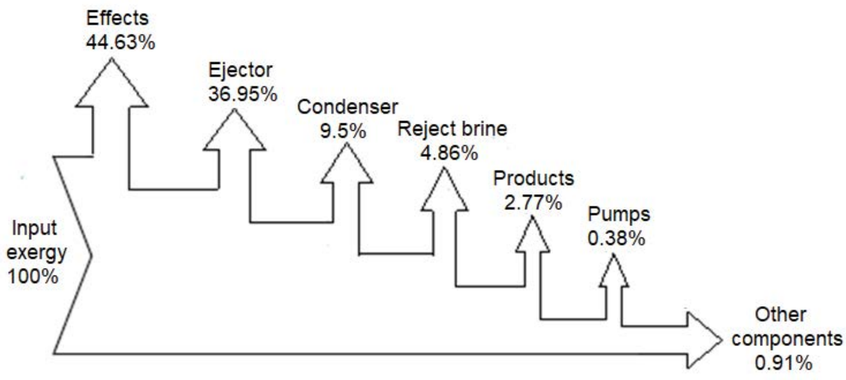

Fig. 2. Exergy loss and flow (Grassmann) diagram for the MED-TVC system.

Exergy destruction and energy losses in the major components of the MED-TVC system are presented in Fig. 3. The results from energy analysis show that the energy loss rate is much higher at the condensation section (878 kW). These losses are associated with emissions at a very close temperature to that of the environment. The thermo-compressor is the second-highest source of energetic losses, which is equivalent to 558 kW, due to heat loss and friction. The water production section (effects) account for an energy loss of 372 kW owing to the larger temperature difference through the effects, and the heat transfer between steam and feedwater. The pumps have a low energy loss, which represents 230 kW of the total energy of the system.

According to the exergy analysis, the largest irreversible losses in the MED-TVC desalination system take place in the steam generation section (1,600 kW). This can be explained by the irreversible heat transmission to feed water for steam generation, water vapor condensation, and seawater vaporization. The condensation section (condenser) is another significant source of irreversibilities with 1,270 kW of exergetic destruction. The high-energy loss throughout the process of condensation is related to the higher heat transfer to cooling water. The third source of the exergetic destruction is the thermo-compressor (1,170 kW), resulting from energy losses by heat transmission added to mixing and expansion processes. The lowest exergetic destruction rate occurred in the pumps, which equals 220 kW.

4.3. Parametric study

4.3.1. Top brine temperature (TBT)

The top brine temperature (TBT) is a key factor for thermal desalination systems because it determines the quantity of thermal energy required to operate the MED-TVC process [44]. The effect of TBT on exergy efficiency is shown in Fig. 4. As seen in this figure, the exergy efficiency and the minimum work of separation decrease with higher TBT values because of the increased flow rate of heating steam. Hence, low-temperature vapor could be employed to improve exergy efficiency.

Fig. 5 represents the energetic losses of the components of the MED-TVC system as a function of TBT. It can be seen that energy losses in effects rise with increasing TBT, due to the increased temperature difference which increases sensible heat of the feed stream rising heat transfer. However, the energy losses of the condenser and the thermo-compressor decrease with the increase of TBT. This is mainly due to the rise in the amount of steam produced in the last effect and the increase in entrainment ratio, which decreases the

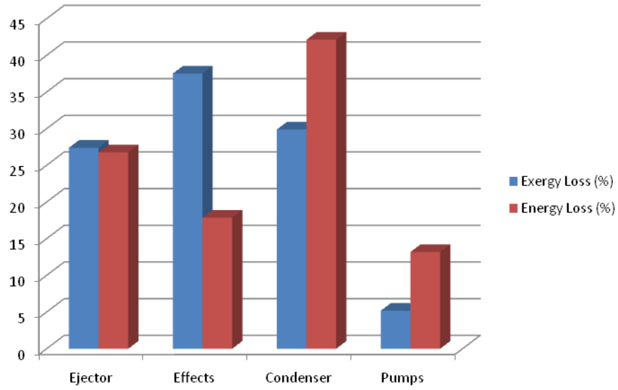

Fig. 3. Comparison of sectional energy and exergy losses within the MED-TVC system.

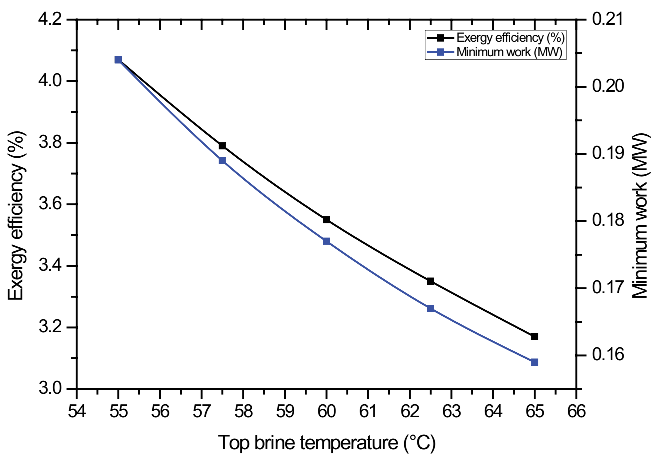

Fig. 4. Influence of the top brine temperature on exergetic efficiency and minimum work of separation.

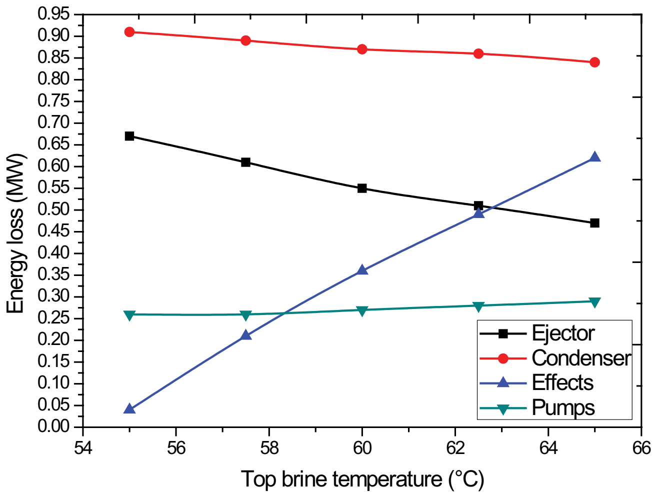

Fig. 5. Influence of the top brine temperature on energetic losses of the components.

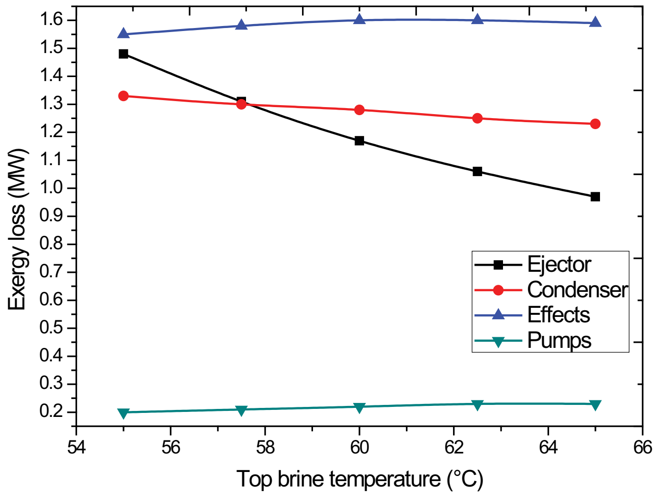

Fig. 6. Influence of the top brine temperature on exergetic losses of the components.

entrained vapor and the amount of steam being generated to the condenser, resulting in a reduction in the heat transfer rate.

Fig. 6 shows component exergetic losses as a function of top brine temperature. This figure reveals that exergy losses in the effects rise with the increase in TBT because of the use of low waste exergy. Exergetic losses in the condenser and the thermo-compressor decrease with increasing TBT due to the decrease in exergy produced in the last effect, which reduces the amount of exergy generated in these components.

Fig. 7 represents the impact of top brine temperature on total energetic and exergetic losses of the MED-TVC system. As shown in the figure, the total energy loss increases by 12.27% while the total exergy loss decreases by 12.82% for TBT ranging from 55°C to 65°C. This is mainly due to the increase in thermodynamic losses in the effects and the decrease in the thermo-compressor exergy destruction.

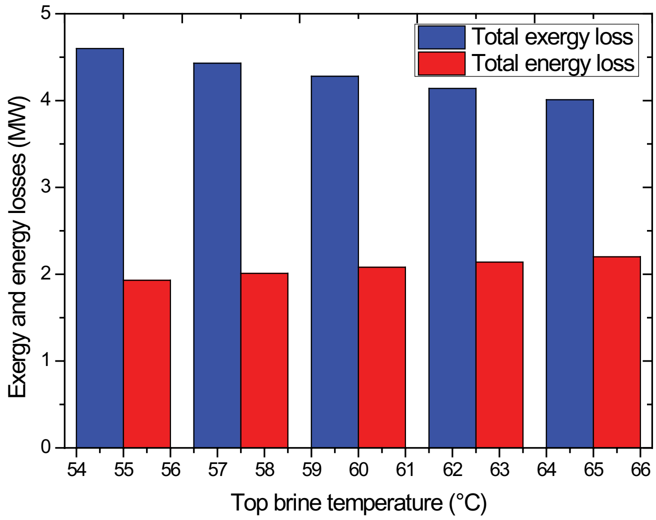

Fig. 7. Influence of the top brine temperature on total energetic and exergetic losses.

4.3.2. Number of effects

The number of effects is often regarded as one of the most relevant variables influencing the performance of MED-TVC processes [45]. The effect of the number of effects is shown in Fig. 8. It can be seen that the exergetic efficiency of the MED-TVC desalination system is greater with a larger number of effects because of the increased use of waste exergy, as indicated by the rise in the minimum work of separation in the same figure. The exergy efficiency increased by about 54.49% as the number of effects varies from 4 to 10. In other words, despite the reducing irreversibility of the effects, the overall exergy destruction decreases as the number of effects gets higher.

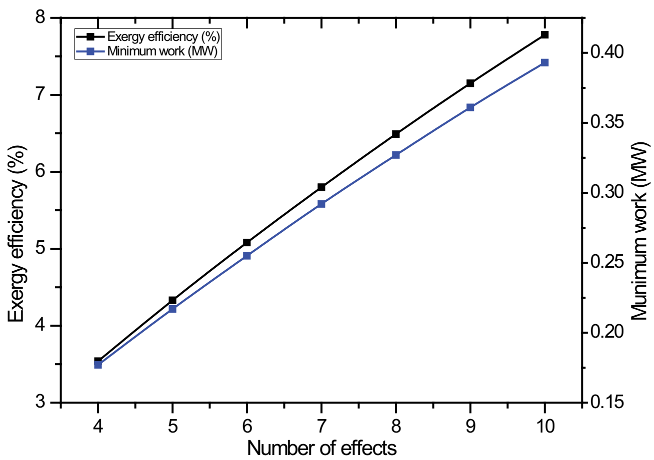

Fig. 8. Influence of the number of effects on exergetic efficiency and minimum work of separation.

Fig. 9 shows the evolution of energy losses of the components with the number of effects. As observed, the energy losses of the steam ejector rise as the number of effects grow because of the reduction in the entrainment ratio which increases the entrainment flow rate generated to the thermo-compressor. There is also a decrease in the condenser losses as the heat load transferred to the condenser is decreased. By expanding the number of effects,

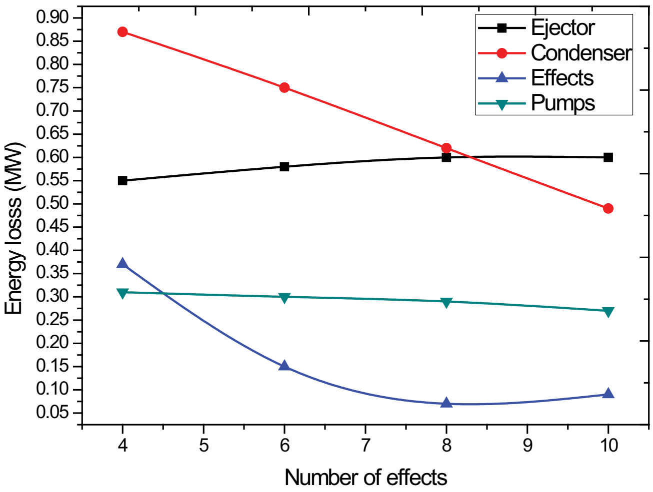

Fig. 9. Influence of the number of effects on energetic losses of the components.

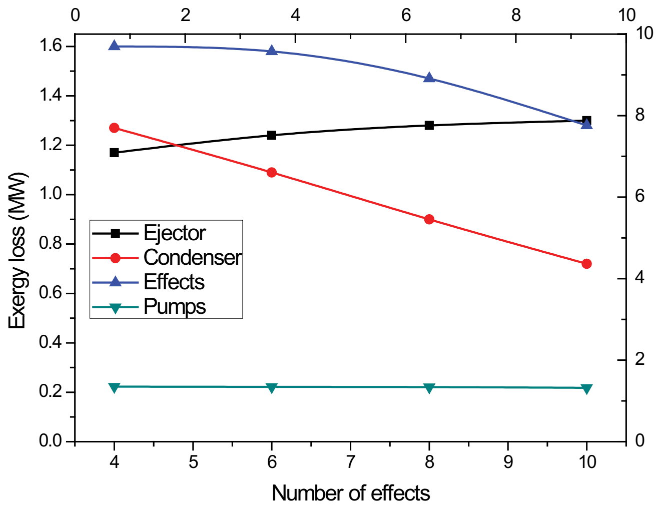

Fig. 10. Influence of the number of effects on exergetic losses of the components.

energy losses in effects are reduced owing to a drop in the heat transmission rate induced by a rise in the temperature gradient.

The dependence of exergetic losses of the MED-TVC components on the number of effects is depicted in Fig. 10. It is found that, for a large number of effects, the exergetic losses in the effects decrease due to the high level of waste exergy. In addition, the exergetic losses in the condenser decrease as the amount of exergy transferred to the condenser decreases. However, the thermo-compressor exergy losses increase when the number of effects gets higher owing to the largest exergy destruction generated in the thermo-compressor.

Fig. 11 represents the impact of the number of effects on total exergetic and energetic losses of the MED-TVC system. As described in this figure, when the number of effects upgraded from 4 to 10, the rates of exergy and energy losses dropped down to values of about 17.52% and 27.4% respectively.

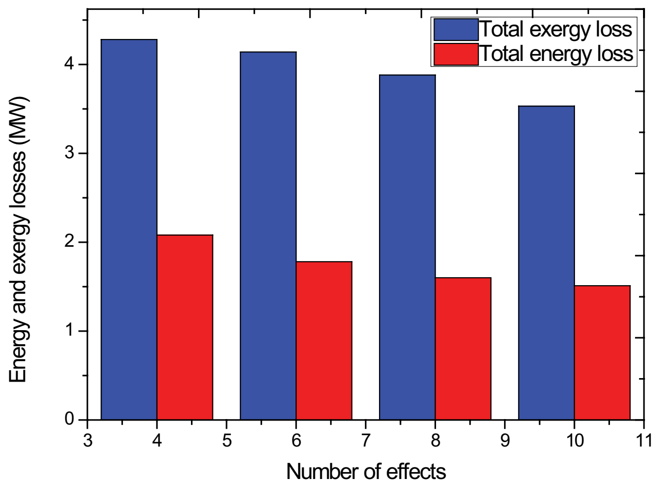

Fig. 11. Influence of the number of effects on total energetic and exergetic losse.

4.3.3. Motive steam flow rate

Motive steam flow rate has a major impact on the capacity and performance of thermal desalination units. The effect of flow rate variation on exergetic efficiency is shown in Fig. 12. It can be observed that a larger flow rate of motive steam results in a decrease of the exergetic efficiency. This is induced by the increase in the heating stream's flow exergy and the use of low-exergy waste, leading to a slight increase in the minimum work of separation.

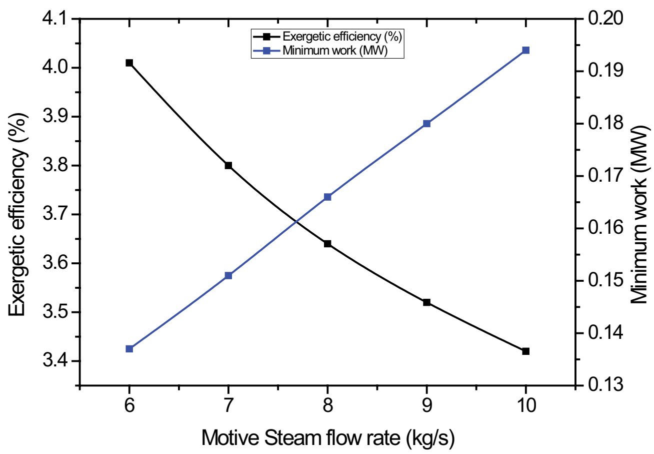

Fig. 12. Influence of the motive steam flow rate on exergetic efficiency and minimum work of separation.

Fig. 13 illustrates the change in energy losses of the MED-TVC system components with the motive steam flow rate. The findings show that the energy losses in the effects decrease with increased flow rate prior to the rise in the amount of water evaporated from feedwater which increases the water production in the effects and decreases the output stream. Energy losses in the thermo-compressor and condenser increase with increasing motive steam flow rate resulting from the increase in vapor production at the last effect for a constant entrainment ratio. This consequently increases the amount of steam generated to the condenser

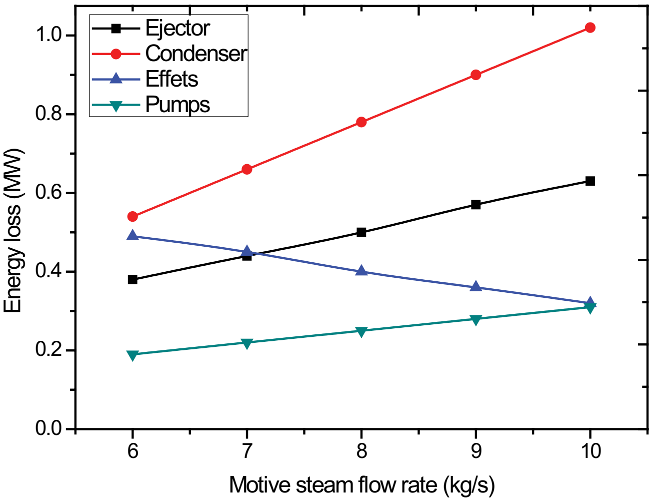

Fig. 13. Influence of the motive steam flow rate on energetic losses of the components.

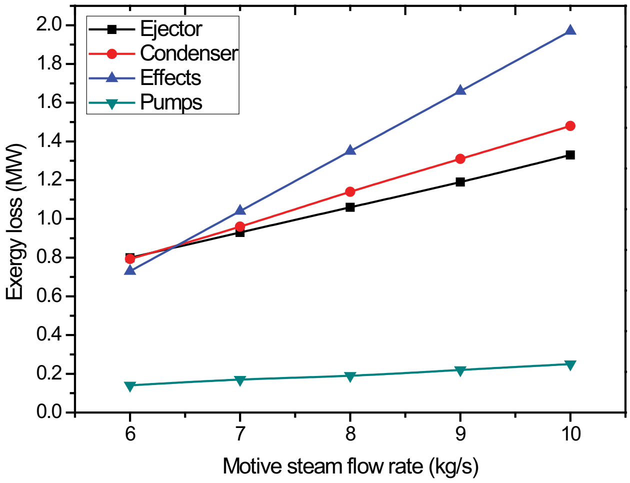

Fig. 14. Influence of the motive steam flow rate on exergetic losses of the components.

and the thermo-compressor leading to an improved rate of heat transmission.

The exergetic losses of the components in terms of motive steam flow rate are illustrated in Fig. 14. It is found that for a high flow of motive steam, the exergy losses within the effects increase due to low use of the exergy waste associated with the increase in heating exergy of the MED-TVC system.

Fig. 15 represents the influence of motive steam flow rate on the MED-TVC desalination system's total exergy and energy losses. As shown in this figure, the values of energy and exergy losses increased by 11.68% and 12.47%, respectively, as the flow rate increased from 6 to 10 kg/s.

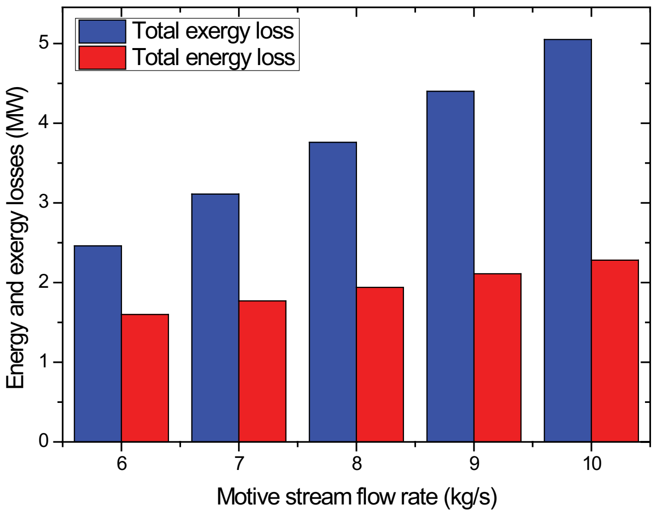

Fig. 15. Influence of the motive steam flow rate on total exergetic and energetic losses.

5. Conclusion

In this paper, energy and exergy analyses of a novel MED-TVC desalination system have been performed. The obtained results showed that the MED-TVC system has a very low exergy efficiency value (3.46%) because high-pressure motive steam is employed to drive a portion of the last effect vapor back to the first effect. However, the MED-TVC system performance could be further enhanced by adding more heaters between the effects. The results also confirmed that the MED-TVC process is operating at only 12.34% of thermodynamic limit of UPR which is unsustainable for future desalinated water supplies, and hence there is much opportunity to improve the desalination system performance to achieve UPR 25%–30% by hybridizing the existing processes and the development of better materials.

The results from the energetic analysis revealed that the main source of energy losses is the condenser, which is followed by the ejector and effects. While from an exergetic viewpoint, the thermo-compressor has the highest level of irreversibilities, which represents over 82% of the total exergetic destruction. Therefore, it is necessary to pay close attention to these components for improving the MED-TVC system performance.

Besides, the effect of different operating parameters has been investigated and the following points can be concluded:

- Increasing the top brine temperature will decrease both the exergy efficiency and the minimum work of separation because of the increase in vapor pressure. Therefore, larger amount of motive steam is needed to compress the vapor at the higher pressure.
- The minimum work of separation increase as the number of effects increased owing to a larger production of distilled water, whereas the performance of the MED-TVC desalination system is improved.
- An increase in the flow rate of motive steam results in a reduction in the exergy efficiency and a slight increase in the minimum work of separation. This is due to the increase in the quantity of entrained vapor for a constant

entrainment ratio, resulting in the generation of more vapor and, hence, a higher exergy flow rate for heat production.

Based on these conclusions, the design and performance of the MED-TVC desalination system could be enhanced by considering different options to optimize the operating parameters of current designs. However, any increase in thermodynamic efficiency has, in general, an economic and environmental impact. It will be the purpose of the second part of the present research, including exergoeconomic and exergo-environmental optimization.

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