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A new approach for process optimization of a METVC desalination system

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ABSTRACT

Making potable water through desalination plants is a very important process in areas where clean water is highly required. One of the most common and acceptable desalination processes is multiple effect evaporation desalination (MED) process. The main objective of this paper is optimization of MED desalination with thermal vapor compression (METVC) from economical and thermodynamic point of view. Hence, first, a comprehensive thermodynamic model for METVC is developed and then the effect of operating parameters on thermal performance of the system is analyzed. Since the values of operating parameters have a great effect on both thermal performance and cost of the plant, the optimization of these parameters is very important. In this regard, some researchers have focused on improving the economical or thermodynamic aspect of the system. However, in practice it is reasonable to optimize both these criteria simultaneously. Based on this, in order to optimize the process of METVC and show influence of objective function on optimization results, four objective functions are chosen as four cases for optimization. These cases include 1) minimizing specific heat transfer area, 2) maximizing exergy efficiency, 3) maximizing performance ratio (*PR*) and 4) minimizing specific heat transfer area and maximizing *PR*. In fact, cases 1 to 3 are single objective problem while case 4 is a multi objective problem. All of the optimization problems are solved by a heuristic optimization problem, namely, Genetic Algorithm (GA). From optimization study, it can be seen that the results of multi objective problem are perfect and more reasonable than other cases. In other words, the results of cases 1 to 3 demonstrate some improvement in either thermodynamic or economical aspects of the system although multi objective optimization satisfy both thermodynamic and economical aspects of METVC and exhibit a rational system that could be applied for a real design approach.

Keywords: Multi effect thermal vapor compression desalination; Thermodynamic model; Exergy analysis; Genetic algorithm; Sequential quadratic programming; Optimization

1. Introduction

There is a huge amount of water in the Earth, but much of it is too salty for human use and only about 2.5 percent of the water on Earth exists as potable water. From the past, many technologies have been developed for making drinkable water from brackish and sea water. Using each of these technologies depend on quantity and quality of potable water, energy consumption, process efficiency and cost of product.

Today, distillation and membrane methods are the two main seawater desalination processes. Among these methods, multi-stage flash (MSF), multi-effect evaporation desalination (MED), vapor compression (VC) and

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reverse Osmosis (RO) are the more commonly used and suitable for large and medium capacity of potable water production [1,2]. However, some novel technologies such as adsorption desalination (AD) have been developed recently. Based on an experimental prototype AD plant, it was concluded that the specific energy consumption of the AD cycle is 1.38 kWh/m^3 which is the lowest ever reported [3]. Besides being cost-effective, the AD cycle is also environment-friendly.

The MSF and MED seawater desalination systems are suitable for cogeneration power plants because they could utilize the waste heat from power cycle to improve the fuel efficiency of the whole plants [4,5]. In other words, they usually use waste energy of flue gas exited from gas turbine cycles, extracted steam of steam turbines or heat recovery steam generator (HRSG) as dual purpose plants. Compared with the most widely used MSF desalination, MED and METVC has the advantages of lower corrosion and scaling rates, lower capital cost, longer operation life and less pumping power consumption [6].

Recently, many researchers have studied thermal desalination from thermodynamic and economic point of view. In 1999 and 2000, El-Dessouky and Ettouney present some comprehensive models for designing and simulating MSF, MED, MED with mechanical (MEMVC) and thermal vapor compression (METVC) [7–10]. They developed several models for different systems and configurations of thermal desalination plant. Alasfour et al., Mahbub et al., Baig et al., Kahraman and Cengel, Karl et al., Shih, Ji et al., Kamali et al., Ameri et al., Trostmann studied different aspect of thermal desalination and developed thermodynamic model to investigate effect of various parameters on systems performance [11–21]. In all of these researches, energy or exergy analysis or heat and mass transfer simulation of thermal system without economic consideration are presented.

On the other hand, some authors have considered economical aspects in design of thermal desalination plant. Nafey et al. presents a methodology of exergy and thermoeconomic analysis for performance of the multi-stage flash (MSF), multi-effect evaporation mechanical vapor compression (MEMVC) process using the developed package [22–24]. In another paper, they studied the effect of the oil prices on the cost of low pressure heating steam for thermal desalination systems, electricity and desalinated water [25]. Fiorini and Sciubba developed a simulation code to perform a thermoeconomic analysis of a MSF desalination plant and determine cost of the plant [26].

Although the previous mentioned works, developed several nice models for simulating different desalination processes, however none of them consider optimizing the process parameters to improve both thermal and economical aspects of the system. In fact, one of the most important challenges in designing thermal desalination plant is the interaction between cost and product that demonstrates the necessity of optimization approach. Optimization of operating variables in desalination plant is useful as it leads to an increase in distillate production rates and lower operating costs [27]. In this regard, some researchers have focused on minimizing the cost of produced potable water or maximizing thermal efficiency as a single or multi objective optimization problem.

Mussati et al. presented an optimal design for MSF desalination [28]. The MSF mathematical model included the physical constraints for the evaporation process, nonlinear equations in terms of thermo-physical properties and design equations. Kumar et al. conducted an optimization study on an MSF plant with an objective to increase the performance ratio (*PR*) and minimize the start-up time [29]. Abduljawad and Ezzeghni [27] presented an optimization study of a once through multistage flash (MSF) desalination. Their objective function was to maximize the performance ratio at different plant capacities by varying the top brine temperature. Bin Amer developed a steady state mathematical model of the METVC desalination system to determine the optimum operating and design conditions of the METVC desalination system through optimization study to maximize performance ratio [30]. A thermoeconomic optimization of multi effect distillation (MED) desalination system was performed by Sayyaadi and safari [31]. They considered a typical MED desalination system and developed thermodynamic modeling based on the energy and exergy analysis and then obtained the objective functions based on the thermoeconomic.

The object of this paper is to develop a complete and comprehensive thermodynamic model including all details for a METVC system. The METVC is combined with a gas turbine power plants, an Alstom GE13E plant, that has stood at the south of Iran, near seashore, and has a nominal output power of 165 Mw. Table 1 is shown the operating parameters of the plant. Fig. 1 describes the cogeneration cycle of selective METVC and power plant.

Table 1
Operating parameters of gas turbine plant

Parameter	Value
Air temperature (°C)	7–48
Air humidity (%)	10–85
Isentropic efficiency of compressor	.85
Isentropic efficiency of gas turbine	.89
TIT (°C)	1100
Mean compression ratio	13
Flue gas temperature (°C)	540

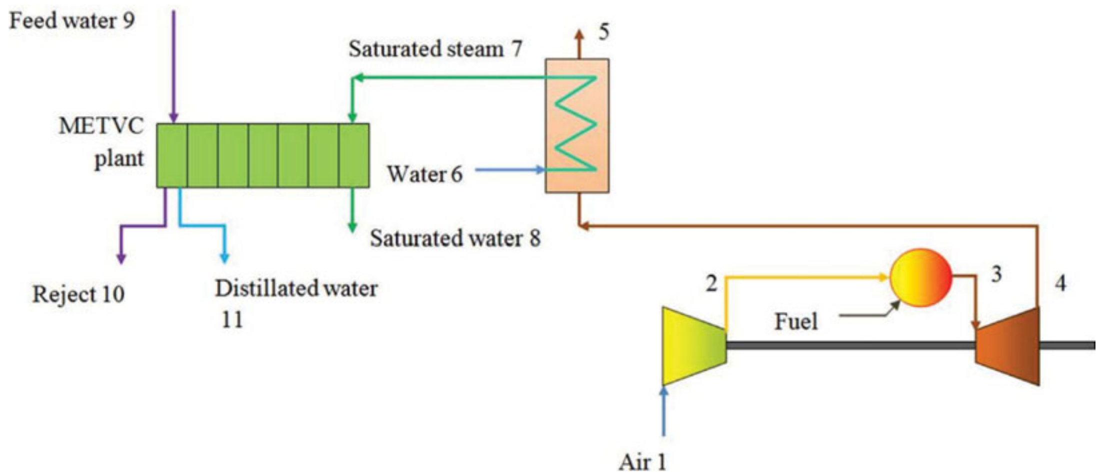

Fig. 1. Combined gas turbine cycle and desalination.

After governing energy and exergy equations, the effect of operating parameters on thermal performance of the chosen system is analyzed and the results as several figures are presented. After simulation stage, an optimization study with a new approach is performed by choosing several objective functions. The Four various objective functions, i.e. three single objective function and one multi-objective function, are examined and their effect on both thermal performance and cost of process are analyzed.

To optimize the thermal behavior of the plant, performance ratio (PR), the ratio of produced potable water rate to consumed motive steam rate and total exergy efficiency of the plant are considered as two objective functions. But as it was discussed, in order to carry out a complete study, the economical aspect of the plant must also be included in optimization process. As it is described in below equations, One of the main parameters that directly effects on the capital cost of evaporators, condensers, heat exchanger and consequently distillation desalination system is required heat transfer area [32,33]. These equations which were applied by several authors, show the relation between required heat transfer area and capital cost of distillation desalination units [22,23,25].

$$Z_{\mathrm{cc,eva/cond}} = 430 \times .582 \times U \times A \times \ddot{A}P_t^{-0.01} \times \ddot{A}P_s^{-0.1} \quad (1)$$

$$Z_{\mathrm{cc,hex}} = 1000 \times (12.86 + A^{0.8}) \quad (2)$$

However, it is necessary to note that in the first equation, overall heat transfer coefficient, U, and pressure loss have fairly constant values, because of specified temperature difference of first and last effect. So, heat transfer area is the most important parameter that has a very strong effect on the capital cost. In fact, it could be introduced as an economical characteristic without it needs to perform a complete economical analysis. So, selecting specific heat transfer area, ratio of required heat transfer area to produced potable water rate, is an innovative and appropriate approach as an economical objective function and thus is considered as third objective function. It is necessary to mention that none of the authors has noticed specific heat transfer area as an objective function in their optimization approaches, previously. Hence, three single optimization problem including specific heat transfer area, exergy efficiency and performance ratio (PR) as objective function were solved separately and after that a multi objective optimization is considered too. In multi objective problem, specific heat transfer area and PR were chosen to improve both thermodynamic performance and cost of the plant. In this approach, optimization problem results an optimal solution that leads to a high efficient and low capital cost plant which has very reasonable results in comparison with single objective results.

2. System description

Fig. 2 shows the desalination plant. The plant is parallel-cross feed and includes several effects that each effect has an evaporator and a flash box. There is a condenser after the last effect that its duty is preheating feed water and also condensing the vapor formed in the last effect. At the first, sea water flows into the condenser and absorbs the latent heat of vapors formed in the last effect and flash box where is heated from T_{cw} to T_f. After that, a specific part of heated sea water is rejected from the system as cooling

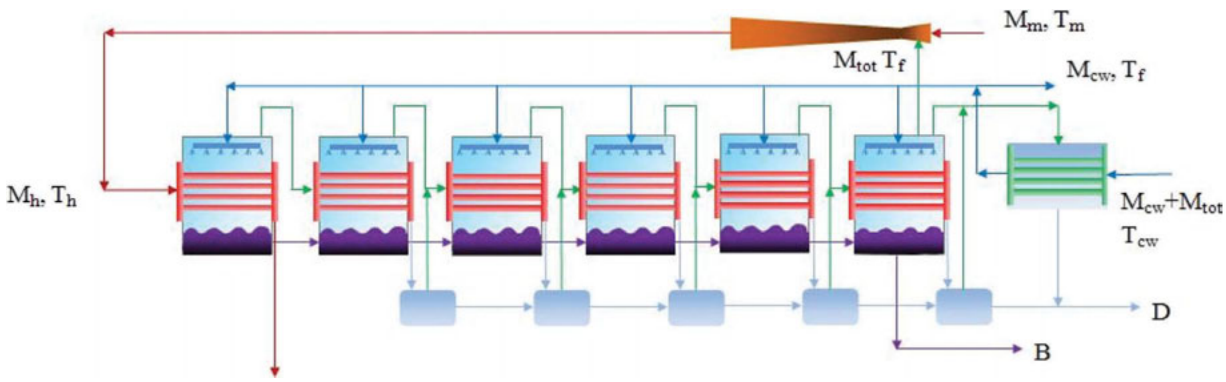

Fig. 2. A six-effect evaporation thermal vapor compression plant.

water. In fact, the cooling water removes the excess heat from the system [7]. The feed water is sprayed on the first effect tubes that inside of the tubes, heating steam flows. Heating steam is the result of mixing high pressure motive steam produced by boiler and low pressure entrained steam sucked from last effect. As a result of heat transfer between sprayed sea water and steam, a small portion of vapor is formed by boiling in the effect and goes inside tubes of next effect as heating steam. This vapor after condensing enters to the flash box of the same effect and a small part of it is flashed because the flash box operates in lower temperature of the evaporator. The rest of condensed vapor is collected in flash box as potable water and this process is repeated effect by effect. Also, the rest of sea water in each effect that has higher salinity than feed water salinity, flow into next effect and finally in the last effect is rejected from system.

3. METVC modeling

For evaluation of thermal performance and needed heat transfer area of system, a mathematical model is developed by applying mass and energy conservation laws to the evaporators, steam ejector, flash boxes and condenser.

The following assumptions are considered for desalination system:

- The desalination system works in steady sate.
- Vapor formed in each effect is free of salt.
- Thermal loss from desalination to environmental is negligible.
- Final reject salinity is assumed 70000 ppm.
- Heat transfer area of evaporators 2 to N is the same.
- For initial model, temperature difference of all effects is the same which T_s and T_f are heating steam and last effect temperature, respectively:

$$\ddot{A}T = \frac{T_1 - T_N}{N-1} \tag{3}$$

$$\begin{aligned} T_1 &= T_s - \ddot{A}T \\ T_{i+1} &= T_i - \ddot{A}T \qquad i = 2\ldots N \end{aligned} \tag{4}$$

- The feed seawater flow rate is distributed equally to all effects:

$$F = \frac{M_f}{N} \tag{5}$$

Water and salt mass balance for the first effect and the effects 2 to N is as follow:

$$B_1 = F - D_1 \tag{6}$$

$$B_i = F + B_{i-1} - D_i \qquad i = 2,..,N \tag{7}$$

$$x_1 = \frac{F}{B_1} x_f \tag{8}$$

$$x_i = \frac{F}{B_i} x_f + \frac{B_{i-1}B_i}{B_i} x_{i-1} \qquad i = 2,..,N \tag{9}$$

The motive steam of first effect is supplied by heat recovery steam generator. So, energy balance equation of first effect can be written as:

$$D_1 = \frac{1}{L_1}\left[M_s L_s - FC_P(T_1 - T_f)\right] \tag{10}$$

$$T_f = T_N - \ddot{A}T_{\mathrm{cond}} \tag{11}$$

On the other hand, vapor is produced by two mechanisms in the effect 2 to N: boiling and flashing. In these effects, brine reject of each effect inter to next effect and because of decreasing pressure, a small amount of vapor is formed. Another small quantity of vapor is formed in the flash box due to the flashing of distillate condensed in previous effect. The mass flow rate of vapor formed in the flash box obtains by following equation [7].

$$D'_i = D_{i-1} C_P \frac{T_{v_{i-1}} - T'_i}{L_i} \tag{12}$$

$$T_{v_{i-l}} = T_i - BPE(T, x) \tag{13}$$

$$T'_i = T_{v_{i-l}} - NEA_i(T) \tag{14}$$

$$\begin{aligned} BPE &= Ax + Bx^2 + Cx^3 \\ A &= 8.32 \times 10^{-2} + 1.883 \times 10^{-4} T - 4.02 \times 10^{-6} T^2 \\ B &= -7.625 \times 10^{-4} + 9.02 \times 10^{-5} T - 5.2 \times 10^{-7} T^2 \\ C &= 1.522 \times 10^{-4} - 3 \times 10^{-6} T - 3 \times 10^{-8} T^2 \end{aligned} \tag{15}$$

$$NEA_i = 33 \frac{(T_{i-1} - T_i)^{0.55}}{T_{v_i}} \tag{16}$$

So, energy balance equation of the effects 2 to N can be written as:

$$D_i = \frac{1}{L_i} \left[\left(D_{i-1} + D'_{i-1} \right) L_{i-1} - FC_p \left(T_i - T_f \right) - B_{i-1} C_P \ddot{A} T \right] \tag{17}$$

The cooling water flow rate is obtained from following equation:

$$M_{cw} = \frac{\left(D_N + D'_N - M_{ev} \right) L_s}{C_P \left(T_f - T_{cw} \right)} - M_f \tag{18}$$

Heat load and heat transfer coefficients of evaporator and condenser can calculate by blew equations:

$$A_1 = \frac{M_s L_s}{U_{e_1} (T_s - T_1)} \tag{19}$$

$$A_i = \frac{\left(D_{i-1} + D'_{i-1} \right) L_{i-1}}{U_{e_i} \ \ddot{A} T} \tag{20}$$

$$A_c = \frac{\left(D_N + D'_N \right) L_N}{U_c LMTD_e} \tag{21}$$

$$\begin{aligned} U_e = {} & 1.9695 + 1.2057 \times 10^{-2} T - 8.5989 \times 10^{-5} T \\ & + 2.5651 \times 10^{-7} T^3 \end{aligned} \tag{22}$$

$$\begin{aligned} U_c = {} & 1.7194 + 3.2063 \times 10^{-3} T_v + 1.5971 \times 10^{-5} T_v^2 \\ & - 1.9918 \times 10^{-7} T_v^3 \end{aligned} \tag{23}$$

For thermo compressor, the model developed by reference is used to calculate entertainment ratio as a function of compression ratio (Cr) and expansion ratio (Er) [34]:

$$Cr = \frac{P_s}{P_{ev}} \tag{24}$$

$$Er = \frac{P_m}{P_{ev}} \tag{25}$$

When motive steam flow rate (M_m) and entertainment ratio (Ra) is given, the mass flow rate of entrained vapor (M_{ev}) could be obtained from Eq. (26). M_{ev} is the mass flow rate of steam sucked from the last effect and entered to thermo compressor.

$$M_s = M_m \left(1 + \frac{1}{Ra} \right) \tag{26}$$

$$M_{ev} = M_m - M_s \tag{27}$$

The specific heat transfer area is defined as:

$$a = \frac{\sum_{i=1}^{N} A_i + A_c}{D_{\text{tot}}} \tag{28}$$

$$D_{\text{tot}} = \sum_{i=1}^{N} D_i \tag{29}$$

One of the most important parameters that show the desalination performance is performance ratio, the ratio between the mass of produced potable water to that of the consumed motive steam:

$$PR = \frac{D_{\text{tot}}}{M_m} \tag{30}$$

The specific entropy and enthalpy of a component per unit mole in an ideal solution at a specified temperature T and pressure P is [14]:

$$s = mf_s s_s + mf_w s_s \tag{31}$$

$$h = mf_s h_s + mf_w h_s \tag{32}$$

For exergy analysis, saline water can be considered to be an "ideal solution" with negligible error [14]. So

$$s_i = s(P, T)_{i,\,\text{pure}} - R_u \ln x_i \tag{33}$$

With above equation, specific entropy of seawater is calculated by:

$$\begin{aligned} s &= x_s s_s + x_w s_w = x_s \left[s_{s,\,\text{pure}} - R_u \ln x_x \right] \\ &\quad + x_s \left[s_{w,\,\text{pure}} - R_u \ln x_w \right] \\ &= x_s s_{s,\,\text{pure}} + x_w s_{w,\,\text{pure}} - R_u (x_s \ln x_s + x_w R_u \ln s x_s) \end{aligned} \tag{34}$$

So, exergy efficiency of making potable water through METVC is:

$$\varsigma = \frac{E_{D_{\text{tot}}} + E_{B_{\text{tot}}} - E_f}{(M_m e_m - M_s e_s) + W_{\text{pump}}} \tag{35}$$

4. The optimization approach

In order to achieve the optimal parameters, an optimization algorithm tool can be used. Although gradient descent methods are the most elegant and precise numerical methods to solve optimization problems, however, they have the possibility of getting trapped at local optimum depending on the initial guess of solution. In order to achieve a good final result, these methods require very good initial guesses for parameters. Stochastic optimization methods such as genetic algorithm (GA) seem to be promising alternative for solving this problem. In general, they are robust search and optimization techniques, able to cope with ill-defined problem domain such as multimodality, discontinuity and time-variance. Based on this, GA is used to solve the optimization problem in hand. However, to compare the GA results with a gradient method, i.e., successive quadratic programming (SQP) is used. In the following, SQP algorithm, single objective GA and multi-objective GA algorithm are described.

4.1. Single objective GA

Among the huge number of optimization methods, GA is a good alternative for dealing with these types of problems with both discrete and continuous variables as well as linear or nonlinear constraints [35–37]. GA is a population based optimization technique that searches the best solution of a given problem based on the concepts of natural selection, genetics and evolution [35]. The search is made starting from an initial population of individuals, often randomly generated. An individual is considered to be a possible candidate solution for the optimization problem in hand. At each evolutionary step, individuals are evaluated using an objective function [38]. The evolution (i.e. the generation of a new population) is done by three types of operators: breeding, mutation and selection while selection includes killing a given proportion of the population based on probabilistic "survival of the fittest". Killed individuals are superseded by children, which are created by breeding the remaining individuals in the population. For each child produced, breeding first requires probabilistic selection of two parent individuals, getting a more chance to choose fitter individuals. Mutation allows new areas of the response surface to be explored by random alterations of optimization variables. GA iteratively improved the set of tentative solutions by applying the aforementioned stages to find a good solution.

4.2. SQP algorithm

Also, to carry out a comparison with results obtained from GA, the successive quadratic programming (SQP) is used for single objective optimization. SQP is a nonlinear programming method that needs an initial point to start optimization process and finds a solution by applying the gradient methods. This approach can be used both in line search and trust-region frameworks, and is appropriate for small or large problems [39]. Unlike linearly constrained Lagrangian methods, which are effective when most of the constraints are linear, SQP methods show their strength when solving problems with significant nonlinearities in the constraints [39]. The method is closely similar to Newton's method for constrained optimization just as is done for unconstrained optimization [38]. Although the main advantage of SQP algorithm is having faster convergent speed around global optimum and higher convergent accuracy, its optimal solution extremely depends on initial point [38]. In addition, when the objective function has a lot of local minimum, the SQP is unable to scan the whole objective function.

4.3. Multi-objective GA

Against single objective optimization, in a multi objective optimization problem, more than one object exists that all of them must be satisfied. When it is tried to optimize several objectives simultaneously, the search space also becomes partially ordered. To gain the optimal solution, there will be a set of optimal trade-offs between the objectives. Hence, the optimum solution for multi objective optimization is not necessarily unique. In a typical multi-objective optimization problem, the interaction of multiple objectives yields a set of efficient or non-dominated solutions, known as Pareto-optimal solutions, which give a decision maker more flexibility in the selection of a suitable alternative [40]. There are several ways to approach a multi objective optimization problem, that all of them focus on the approximation of the Pareto-optimal solutions. For multi objective optimization, Evolutionary algorithms have been widely used because of their natural properties suited for these types of problems. So, in this paper multi objective genetic algorithm (MOGA) was applied for finding optimal solution.

5. Results and discussion

5.1. Results of simulation

For simulation and exergy analysis of the system, a computational code was developed that could be predicted the exergy destruction of different parts, the production rate of potable water and required heat transfer area. In contrast to some METVC models which are developed for specified production of potable water, the model developed by authors could be used for cogeneration purpose [7–9,17,19]. In other words, for a given motive steam flow rate supplied by HRSG, the model could predict the production rate of potable water. The properties of seawater and brine, the heat transfer coefficients of evaporation and condensation, BPE, NEA of flashing evaporation in the flash boxes were taken from references [7,8]. Table 2 shows the values which are supposed for METVC system. These parameters are the main functional parameters of multi effect evaporation desalination and have been used for presenting the results. Also, Table 3 shows the detail result of simulation of the system. For confirming the developed model, a comparison between present model and Wang & Lior model carried out that could be observed in Fig. 3 [6]. The graph shows the effect of compression ratio of thermo compressor on performance ratio of METVC. The results are presented for a 4, 6 and 8 effects plant. It is clear the difference between two models is less than 6% for 6 and 8 effects. These differences could return to how to calculate the entrainment ration from Power's model because the thermo compressor model that has been presented by Power is a graphical model and it is too difficult to use. Nevertheless, the developed model generally has acceptable results.

The results of simulation for METVC and its Performance are shown in Figs. (4–10). For better explanation, some results are presented by three dimensional graphs.

The exergy destruction of different parts of METVC is shown in Fig. 4. As it could be observed, thermo compressor and condenser have the highest and lowest rate of exergy destruction, respectively. Thermo compressor naturally is a low efficiency device since it mixes two

Table 2
Initial values and the results for the METVC system

Parameter	Value
Heating steam temperature (°C)	70
Top brine temperature (TBT)(°C)	67
Sea water temperature (°C)	35
Temperature difference between last effect and feed water (°C)	5
Number of effect	6
Motive steam pressure (kPa)	500
Compression ratio of ejector	3
Results:	
Reject salinity of last effect (ppm)	69952
Feed seawater salinity (ppm)	40000
Specific heat transfer area (m^2/(°kg/s))	307.49
Performance ratio	7.58
Exergy efficiency (%)	4.69
Conversion ratio (%)	42.9
Evaporators heat transfer area (m^2)	2211.93
Condenser heat transfer area (m^2)	108.81
Specific heat transfer area (m^2/(kg/s))	307.90

Table 3
Detail results for the METVC system based on 1 kg/s of motive steam

Effect number	1	2	3	4	5	6
T (°C)	67	62.61	58.70	54.91	51.16	47.35
D_i (kg/s)	1.4922	1.4001	1.3418	1.313	1.3148	0.7170
D_i (kg/s)	0	0.0092	0.0079	0.0078	0.0080	0.0067
E_d (kw)	45.54	38.70	36.06	34.74	34.26	26.90

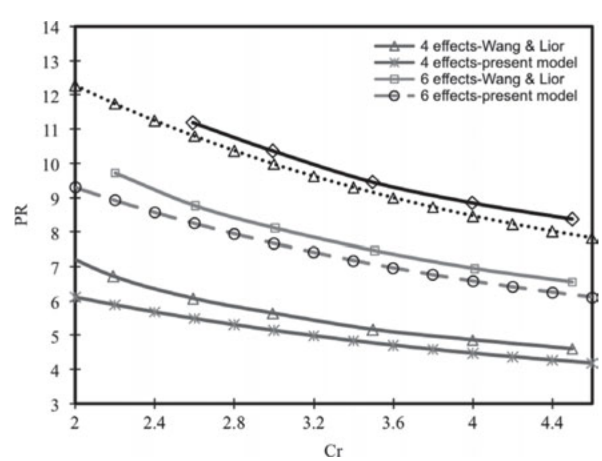

Fig. 3. Comparison of model predictions against available data for METVC units in reference [6].

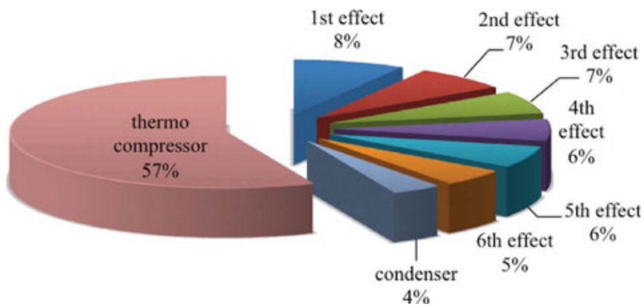

Fig. 4. Exergy destruction of different parts of METVC.

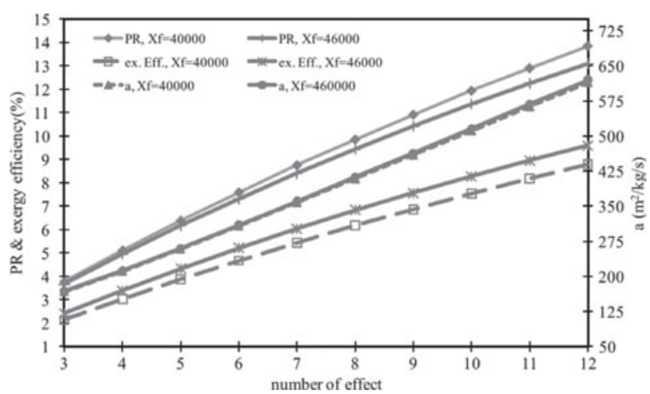

Fig. 5. Variation of PR, exergy efficiency and specific heat transfer area by number of effect.

streams in high and low pressure level. Then the outlet stream exits with an intermediate pressure level.

Fig. 5 shows the influence of number of effects on exergy efficiency, performance ratio and specific heat transfer area of METVC for different feed salinity. In fact, for a specified *Cr* and TBT, by increasing the number of effects, the temperature difference between consecutive effects reduces and therefore the needed heat transfer area must increase. On the other hand, because of increasing heat transfer area, higher number of effects results higher productivity and thus higher exergy efficiency. In addition, increasing feed salinity has a slight influence on specific heat transfer area while it results lower *PR* but higher η_{ex}. The reason of increasing η_{ex} returns to take the dead point for exergy analysis. For exergy analysis, the salinity and temperature of dead state are the same that is considered for seawater. So, when feed salinity changes, the specific exergy of each stream in the process changes. In other word by increasing feed salinity the numerator of exergy efficiency increases.

Fig. 6 and 7 illustrate influence of motive steam pressure and compression ratio on *PR* and η_{ex} of METVC. As it could be observed, both *PR* and η_{ex} reduces by increasing *Cr*. The reason of this behavior is that for a given T_s, the higher *Cr* results lower T_N and thus a lower T_N causes the increased temperature difference between

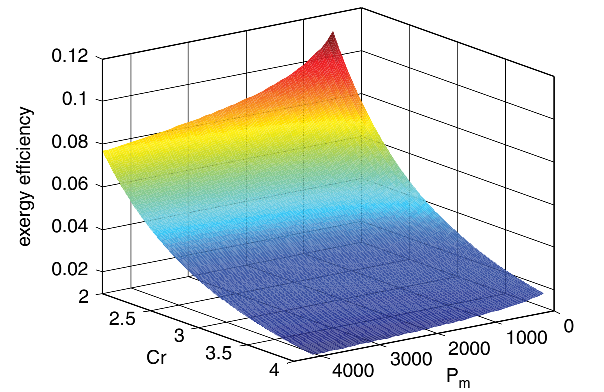

Fig. 6. The effect of motive steam pressure and compression ratio on exergy efficiency of desalination.

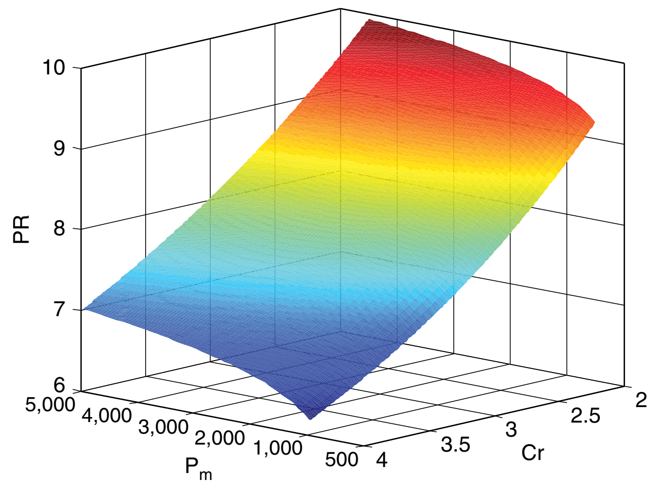

Fig. 7. The effect of motive steam pressure and compression ratio on desalination performance ratio.

first and last effect and consequently the needed heat transfer area goes down (Fig. 8). So, the production rate of *PR* and also η_{ex} in a specified motive steam decreases (Fig. 7). On the other hand, from Fig. 7 and Fig. 8 it could be realized that variation of motive pressure has different effects on *PR* and η_{ex} while higher motive pressure results higher *PR*, but lower η_{ex}. In fact, for a constant heating steam temperature, by rising motive pressure, the exergy destruction of thermo compressor increases and as a result, exergy efficiency reduces, but because of increasing the rate of entrained vapor that sucked from last effect, the mass flow rate of heating steam and thus *PR* goes up. Fig. 8 also describes the slight effect of motive pressure on specific heat transfer area.

Fig. 9 describes the variation of specific heat transfer by changing heating steam temperature and TBT. Based on Fig. 10, an increase or decrease in both T_s and TBT leads to change temperature difference in all effects. Hence, study of influence of T_s and TBT on thermal performance of METVC is very important. According to Fig. 9, when

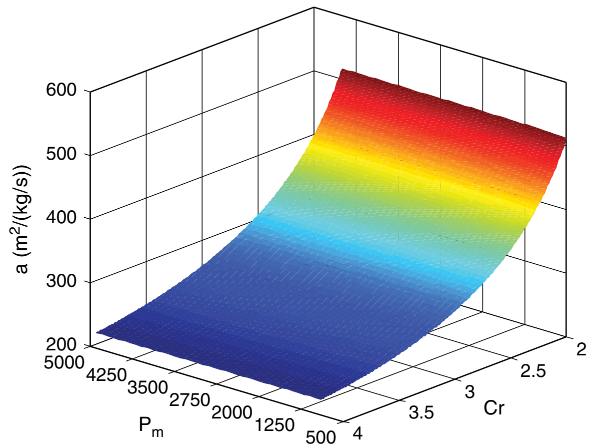

Fig. 8. The effect of motive steam pressure and compression ratio on specific heat transfer area.

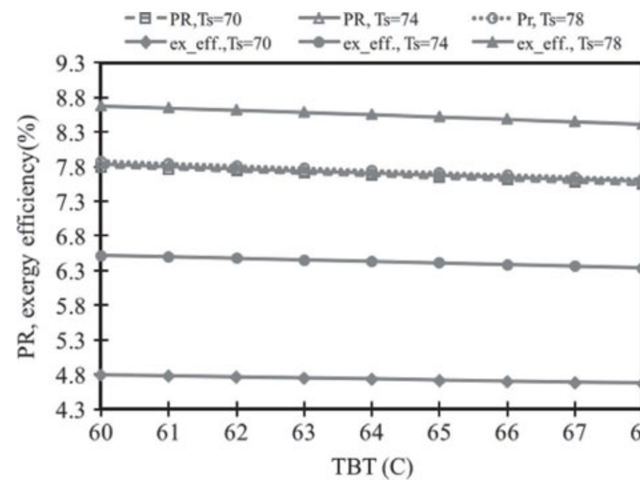

Fig. 10. Variation of *PR* and η_{ex} with TBT.

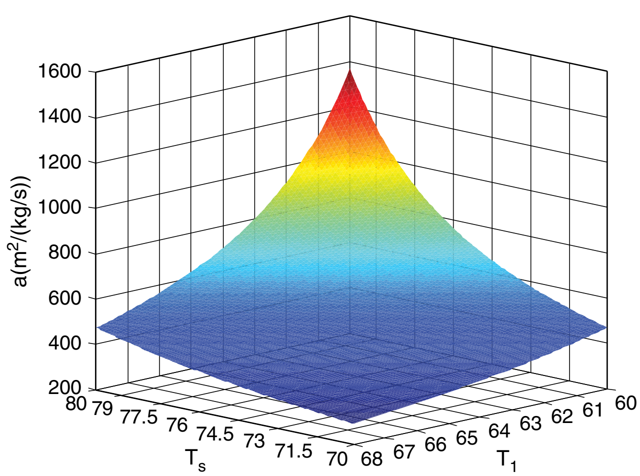

Fig. 9. Effect of heating steam temperature and TBT on specific heat transfer area.

the difference between T_s and TBT increases, specific heat transfer area increases too and eventually reaches to a maximum value. In fact, an increase in T_s causes the temperature of last effect (T_N) increases as for this case when T_s goes up from 70ºC to 80ºC; T_N rises from 41.53ºC to 50.03ºC. On the other hands, at the same time by increasing TBT, temperature difference between the effects rises and also specific heat transfer area dramatically goes down. Consequently higher difference between T_s and TBT implies higher specific heat transfer area.

From Fig. 10, it could also be concluded that *PR* has a slight change with variation of TBT and T_s. Higher TBT leads to lower formed vapor in the first effect and then the rate of heating steam of second effect and also other effect decreases. So, there is a decrease in productivity and thus in exergy efficiency. For a constant motive pressure, an increase in T_s causes the exergy destruction of thermo compressor steadily goes down and has an increasing impact in exergy efficiency.

5.2. Optimization

In this section, the results of optimization study are presented. To carry out a comprehensive study, several objective function were selected that they presented in Table 4. Also lower and upper bands of decision variables and constraints of optimization problem could be observed in Table 5. These constraints are related to operational limits of desalination plant including linear and non linear equations. The purpose of selecting different objective function was to demonstrate the effect of single objective and multi objective on optimal solutions. As it was mentioned, specific heat transfer area (a) is representative of economical point of view while *PR* and η_{ex} are related to thermodynamic aspect of system. In order to take both economic and thermodynamic aspects of the system into consideration, simultaneously, a multi objective problem for minimizing specific heat transfer area and maximizing *PR* was defined.

Table 4
Different objective function of optimization study

Case	Optimization type	Objective function
1	Single objective	Minimize *a*
2	Single objective	Maximize η_{ex}
3	Single objective	Maximize *PR*
4	Multi objective	Minimize *a* maximize *PR*

Table 5
Decision variables and constrains of the optimization problem

Parameters	Lower band	Upper band
T_s	60	90
TBT	60	80
P_m	500	4500
Cr	2	5
N	3	10
ΔT_{cond}	3	15

Linear constraint

$T_s - \mathrm{TBT}$ ¡Ý3

Nonlinear constraint

$T_1 - T_N$ ¡Ý3

$T_f - T_{\mathrm{cw}}$ ¡Ý3

$x_n -$ ¡Ü7000

Table 6
Results of optimal solution obtained by SQP method for objective function of case 1

Initial point	N	T_s (°C)	TBT (°C)	P_m (kPa)	Cr	ΔT (°C)	Value of objective function
1	7	72.40	69.14	1430.59	4.16	3.71	279.64
2	8	73.15	70.14	2632.81	3.09	10.64	395.05
3	8	73.15	70.14	2632.81	3.08	10.64	435.29
4	5	82.88	79.32	2385.30	5.00	8.58	163.70
5	5	76.18	73.18	1576.26	3.77	8.44	202.67
6	9	69.10	66.10	2636.26	3.16	4.54	444.24
7	8	69.03	66.03	1258.84	3.55	4.10	360.41
8	8	69.25	66.15	4213.25	3.42	5.35	372.71
9	10	72.86	69.75	3642.23	3.46	8.10	447.30
10	4	71.33	68.15	1006	3.42	7.09	188.69

Table 6 to Table 8 shows the optimum value of objective functions obtained by SQP method. As it was mentioned, SQP is a mathematical method which its result extremely depends on initial point. Here, for three objective functions, ten initial points were produced randomly and applied to run the optimization program. In comparison with results of GA shown in Table 9, not only SQP could not have obtained the optimum value of objective function but also the results heavily depend on the initial point. So, GA was chosen as the main optimization approach.

For all three cases the population size, crossover rate, mutation rate and number of iterations was 20, 0.8, 0.1 and 100, respectively. Table 9 shows the optimal values of decision parameters. As it could be observed, the minimum specific heat transfer area obtained by optimal solution is 109.74, but for this case the number of effects is the lowest value and consequently PR and η_{ex} is very low. Also, the values of T_s and TBT are near to upper band while amount of optimum P_m and ΔT_{cond} are between lower and upper band. From the definitions, we know specific heat transfer area is defined as a fraction that required heat transfer area and potable water mass flow rate are its numerator and denominator, respectively. Thus, it might be imagined that to achieve minimum value of specific heat transfer area, the optimization algorithm will probably minimize the numerator and maximize the denominator. The results show not only the denominator (i.e. PR) is not maximized but also PR has too low value. So, it could be concluded that selecting specific heat transfer area as an object, only leads to minimize required heat transfer area.

Table 7
Results of optimal solution obtained by SQP method for objective function of case 2

Initial point	N	T_s (°C)	TBT (°C)	P_m (kPa)	Cr	ΔT (°C)	Value of objective function
1	7	77.86	64.13	4096.02	2.70	6.67	8.55
2	5	77.87	66.52	2318.78	2.09	5.11	11.08
3	7	75.46	70.17	1747.76	2.45	6.57	9.92
4	4	82.44	69.97	1799.41	2.00	3.00	12.94
5	10	74.65	64.01	2100.32	3.09	3.97	8.32
6	9	78.36	68.14	4447.87	3.29	4.70	7.39
7	7	74.41	65.53	1217.20	2.29	8.59	11.07
8	5	76.64	65.56	4348.64	2.00	7.98	9.69
9	3	79.13	65.51	3554.69	2.14	11.44	5.73
10	10	70.89	62.13	2660.42	2.71	6.09	7.84

Table 8
Results of optimal solution obtained by SQP method for objective function of case 3

Initial point	N	T_s (°C)	TBT (°C)	P_m (kPa)	Cr	ΔT (°C)	Value of objective function
1	8	79.40	63.20	2625.30	2.80	13.30	10.29
2	8	68.68	64.10	863.30	2.13	6.52	11.90
3	5	68.10	64.30	2390.40	2.00	3.00	8.34
4	5	78.43	65.35	1576.25	2.09	6.91	7.84
5	9	66.39	63.32	2636.26	2.23	5.25	13.78
6	8	69.95	64.32	1258.84	2.32	3.64	12.17
7	10	77.17	65.30	3722.61	3.16	9.54	12.35
8	4	73.16	61.61	1006.01	2.00	3.00	6.48
9	6	79.67	64.57	2108.73	2.42	9.29	8.76
10	7	76.66	66.61	2890.09	2.60	7.93	9.98

For case 2, maximum exergy efficiency 20.30% obtained from GA. It is clear that when exergy destruction of whole system decreases, exergy efficiency goes up. So the results show that optimal motive pressure is exactly 500 kPa that it matches to the amount of lower band. Thus, exergy destruction of thermo compressor is kept in a low value because by rising P_m, the exergy destruction of thermo compressor increases. As it is shown in Table 9, optimum value of N and ΔT_{cond} obtained 4 and 11.32ºC, respectively. The optimum value of T_s is close to upper band but that has a significant difference with optimum TBT. Against case 1, in case 2, the obtained value for Cr is minimum, because according to Eq. (24), lower Cr results higher pressure and temperature in the last effect. Therefore, the temperature difference between first and last effect decreases and this implies higher exergy efficiency. Of course, transportation of high temperature potable water has many problems and thus it is not desirable. On the other hand, this case has a very larger amount of specific heat transfer area than ones obtained for case 1 which leads to increase capital cost of METVC.

For case 3, the maximum PR obtained 15.93. In this case, the optimum value obtained for T_s and TBT are lower than those obtained for case 1 and 2. When T_s, TBT and Cr has low values close to lower band, the temperature difference between feed water and effect is low and thus more vapors are formed in each effect. Also, number of effect obtains 10 and P_m is close to upper band. As it could be discussed by rising the number of effects, potable water production increases and consequently the maximum number of effect results high PR. In addition, in high motive pressure (P_m), the rate of entrained vapor that sucked from last effect increases and then the mass flow rate of heating steam and production go up. But similar to previous case, the specific heat transfer area has a high value.

Table 9
Optimal results given by optimization procedure for different objective function

Parameter	Case 1 GA	Case 2 GA	Case 3 GA	Case 4 MOGA
T_s(°C)	86.20	88.96	63.79	81.96
TBT(°C)	80.00	76.88	60.02	78.93
P_m(kPa)	2609.40	500.00	4368.73	3467.43
Cr	4.99	2.00	2.21	3.86
N	3	4	10	9
ΔT_{cond}(°C)	10.35	11.32	4.07	3.38
PR	3.02	5.63	15.93	10.31
η_{ex}	1.81	20.30	6.67	6.70
a(m^2/(kg/s))	109.74	893.43	834.51	334.39
T_N (°C)	50.45	72.74	47.92	52.29
T_f (°C)	39.28	60.51	43.04	48.08
Evaporators area (m^2)	255.93	5005.56	13209.90	3360.76
Condenser area (m^2)	75.83	28.11	86.76	85.81
Total exergy destruction (kW)	866.44	595.80	924.82	877.45

Comparison of these three cases show that single objective optimization is not a comprehensive approach since when thermodynamic characteristics such as PR and exergy efficiency were considered as the objects, optimization approach results a very high efficient system but with a large amount of heat transfer area. On the other hand, when it was taken economical aspect into consideration, although optimal solution results a system with low capital cost, amount of potable water production is the lowest. Hence, when both of thermodynamic and economical characteristics are important, multi objective optimization is inevitable. For these reasons, in addition to cases 1 to 3, a multi objective optimization problem was performed that included minimizing specific heat transfer area and maximizing PR, simultaneously.

For multi objective problem population size, crossover rate, mutation rate and number of iterations was considered 400, 0.8, 0.2 and 300, respectively. The Pareto-optimal solution of multi objective problem for case 4, was presented in Fig. 11 and the optimal amount of decision parameters could be observed in Table 9. From these results, it can be seen that T_s and TBT have lower values than ones obtained for case 1 and case 2 that results fewer scaling problems while Cr has an intermediate amount between lower and upper band of decision variables. Although, the number of effects obtained from optimal solution is 9, there is a reasonable amount of specific area of 334.39 and so, the heat transfer area of evaporators and condenser are not too large. It is so interesting that the amount of PR is 18.39 that is higher

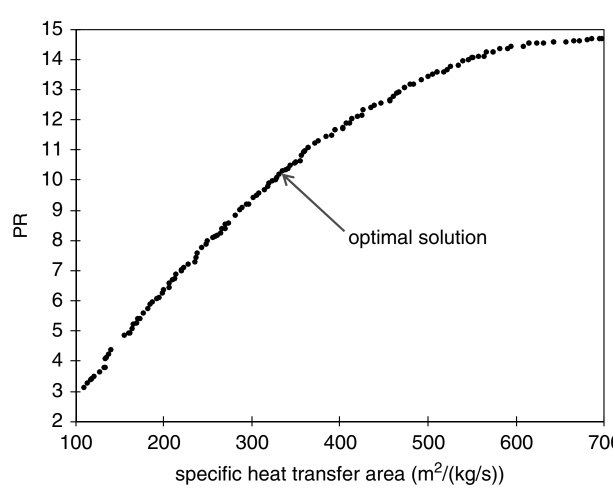

Fig. 11. Pareto-optimal solution for objective function of case 4.

than ones obtained in case 1 and case 2. Specific heat transfer area also has considerably lower value in comparison with case 2 and 3. So, it seems the results of case 4 are perfect and more reasonable than other cases. In fact, these results satisfy both thermodynamic and economical aspects of METVC. In other words, the results exhibit a rational system that could be applied for a real design approach.

6. Conclusions

In this paper, a METVC system were modeled and simulated. Energy and exergy equations for all part of system were developed. According to results obtained from modeling, following conclusion can be extracted:

- Thermo compressor and condenser have the highest and lowest rate of exergy destruction, respectively.
- For a specified *Cr* and TBT, rising N results the temperature difference between consecutive effects reduces and therefore the *PR*, exergy efficiency and needed heat transfer area go up.
- Rising *Cr* leads to reduce *PR*, η_{ex} and specific heat transfer area while variation of motive pressure has different effects on the METVC characteristics. Higher motive pressure results higher *PR* but lower η_{ex}.
- When the difference between T_s and TBT increases, specific heat transfer area increases. It could also be concluded that PR has a slight change with variation of TBT and T_s.

For optimization of METVC process, first SQP method was considered but because of its heavy dependence on initial point, GA was applied. Then, three single optimization problem including specific heat transfer area, exergy efficiency and performance ratio (*PR*) as objective function were solved separately and after that a multi objective optimization were considered too. The final purpose of multi objective problem was minimizing specific heat transfer area and maximizing *PR*. It seems the results of multi objective problem are perfect and more reasonable than other cases. In fact, these results satisfy both thermodynamic and economical aspects of METVC. In other words, the results exhibit a rational system that could be applied for a real design approach.

Symbols

a	—	specific heat transfer area (m^2/(kg/s))
A	—	area heat transfer (m^2)
B	—	rejected mass flow rate (kg/s)
BPE	—	boiling point elevation (ºC)
Cr	—	compression ratio
C_p	—	specific heat capacity (kJ/kg·ºK)
D	—	distillated mass flow rate (kg/s)
e	—	specific exergy (kW/kg)
E	—	exergy (kW)
Er	—	expansion ratio
F	—	feed mass flow rate of each effect (kg/s)
GA	—	genetic algorithm
h	—	specific enthalpy (kW/kg)
M	—	mass flow rate (kg/s)
N	—	number of effects
NEA	—	Non equilibrium allowance
L	—	latent heat of evaporation (kJ/kg)
LMTD	—	Logarithmic Mean Temperature Difference (ºC)
Ra	—	entrainment ratio
R_u	—	universal gas constant (J/mol·K)
P_m	—	motive steam pressure (kPa)
PR	—	performance ratio
s	—	specific entropy (kJ/kg·K)
SQP	—	successive quadratic programming
T	—	temperature (ºC)
TIT	—	turbine inlet temperature (ºC)
T_s	—	heating steam temperature (ºC)
T_v	—	vapor temperature (ºC)
TBT	—	Top brine temperature (ºC)
U	—	heat transfer coefficient(kw/m^2·ºC)
x	—	salinity (ppm), mole fraction

Subscripts

B	—	Brine
C	—	Condenser
Cond	—	Condenser
D	—	Distillate
E	—	Evaporator
Ev	—	entrained vapor
Ex	—	Exergy
F	—	feed water
I	—	effect number, component
M	—	motive steam
N	—	Last effect
S	—	heating steam
Sw	—	feed water
V	—	Vapor

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