



# Exergy Analysis and Optimization of Multi-effect Distillation with Thermal Vapor Compression System of Bandar Abbas Thermal Power Plant Using Genetic Algorithm

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## Abstract

Multi-effect distillation desalination system with thermal vapor compression is one of the systems of producing fresh water based on distillation desalination. This type of desalination system is one of the most appropriate and economic types of desalination systems for low to high capacities of seawater and brackish water in which evaporation and distillation have occurred in a vacuum and in temperature below 70 °C. This research provides a mathematical model in the steady-state conditions for multi-effect distillation desalination system with thermal vapor compression in Bandar Abbas thermal power plant in south of Iran. The genetic algorithm is used for maximizing the produced fresh water and minimizing total exergy destruction rate. Exergy analysis shows that the thermo-compressor and effects are the main sources of exergy destruction in the system (more than 80%). The actual operating data in summer and winter were used for the exergy destruction study. The results show that the exergy destruction in winter is more than summer. Parametric analysis for studying the effects of key parameters shows that increasing the top brine temperature leads to increase in the total exergy destruction of the system. The optimization of the system with two-target genetic algorithm causes distillate production to increase by 16.62%, and the total exergy destruction rate decreases by 3.58%.

**Keywords** Desalination · Multi-effect distillation · Exergy · Irreversibility · Genetic algorithm

## List of symbols

$B$	Brine flow rate (kg/s)	$h_{ev}$	Enthalpy of the Entrained vapor (kJ/kg)
BPE	Boiling point elevation (°C)	$h_m$	Motive steam enthalpy (kJ/kg)
$C$	Specific heat capacity of water (kJ/kgK)	$h_s$	Input steam enthalpy to first effect (kJ/kg)
CR	Compression ratio	$h_w$	Enthalpy of Spray water (kJ/kg)
$D_i$	Distillate (kg/s)	$h_0$	Environment state enthalpy (kJ/kg)
$d_i$	Flash vapor flow rate (kg/s)	$L$	Latent heat (kJ/kg)
$E$	Exergy	$M_c$	Condenser vapor flow rate (kg/s)
$E_{D,c}$	Exergy destruction rate of component (kW)	$M_{cw}$	Cooling water flow rate (kg/s)
$E_{D,t}$	Total exergy destruction rate (kW)	$M_d$	Discharge steam flow rate (kg/s)
$E_{SD}$	Specific exergy destruction (kJ/kg)	$M_{ev}$	Entrained vapor flow rate (kg/s)
ER	Expansion ratio	$M_m$	Motive steam flow rate (kg/s)
$F_i$	Feed water flow rate (kg/s)	$M_s$	Input steam flow rate to first effect (kg/s)
GOR	Gain output ratio	$M_{sw}$	Seawater flow rate (kg/s)
$h_d$	Enthalpy of the discharge steam (kJ/kg)	NEA	Non-equilibrium allowance
$h_{fs}$	Saturated liquid enthalpy (kJ/kg)	$n$	Number of effects
		PCF	Pressure correction factor
		$P_d$	Discharged vapor pressure (kPa)
		$P_{ev}$	Entrained vapor pressure (kPa)
		$P_m$	Motive steam pressure (kPa)
		$P_s$	Input steam pressure to first effect (kPa)
		$Q_d$	Specific heat consumption (kJ/kg)
		Ra	Entertainment ratio

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$s_{ev}$	Entrained vapor entropy (kJ/kgK)
$s_{fs}$	Condensate vapor entropy (kJ/kgK)
$s_s$	Input steam entropy to first effect (kJ/kgK)
TBT	Top brine temperature
TCF	Temperature correction factor
$T_d$	Discharge steam temperature (°C)
$T_{ev}$	Entrained vapor temperature (°C)
$T_f$	Feed water temperature (°C)
$T_i$	Effect temperature (°C)
$T_m$	Motive steam temperature (°C)
$T_s$	Input steam temperature to first effect (°C)
$T_{sw}$	Seawater temperature (°C)
$T_{v,i}$	Output vapor temperature from effect (°C)
$T_0$	Dead state temperature (K)
$\Delta T$	Temperature difference per effect (°C)
$X_{b,i}$	Brine salinity (g/kg)
$X_f$	Seawater salinity (g/kg)

### Greek symbols

$\psi$	Exergy efficiency
$\delta$	Exergy destruction rate

### Subscripts

b	Brine
c	Condenser
D	Destruction
d	Discharge steam
de	Desuperheater
dis	Distillate
e	Effect
ej	Ejector
ev	Entrained vapor
f	Feed
in	Input
m	Motive steam
out	Output
rej	Rejection
s	Input vapor to first effect

## 1 Introduction

The surge in agriculture and industrial activity and increasing population has been responsible for the increase in the world water demands. Brackish or seawater desalination offers a promising choice for water security, especially for the coastal countries. Desalination technology can produce fresh water from salty water which is done based on the separation of water, salty and other insoluble solids in water. One of the desalination methods is thermal process which is associated with phase change (evaporation and distillation). These processes need remarkable energy due to high latent heat of water. The main desalination

systems based on distillation include: multiple effect distillation (MED), multistage flash (MSF), multi-effect distillation with thermal vapor compression (MED-TVC), Multi-effect distillation with mechanical vapor compression (MED-MVC).

Right now, the thermal process is used solely or in combination for desalination in large scale (Ettouney and El-Dessouky 1999). From among thermal desalination systems, MED is the most efficient thermal distillation process in terms of thermodynamic. One of the advantages of this type of desalination is its low operating temperature. Energy consumption of MED desalination technology is less than MSF (Ophir and Lokiec 2005; Darwish 1995; Michels 1993). Thermodynamic analysis of MED-TVC system is based on first and second law of thermodynamics. The first law is an important tool in assessing the total performance of the system while using thermodynamic analysis based on the second law which is known as exergy analysis can identify the destruction points and quality of energy.

Many researches have been done on thermodynamic modeling of thermal desalinations. El-Dessouky and Ettouney (1999) studied and compared all distillate thermal systems in terms of function and heat transfer areas upon providing an algorithm for simulating the process in the steady-state conditions. The results of their researches predict reducing function ration upon increasing input steam temperature.

Geankoplis (2003) presented a simple model of MED. The model is based on designing parameters including effect dimensions, heat transfer area, temperature profile and performance ratio.

Binamer (2013) computed and improved the performance of units of the system with 2.4, 3.8, and 6.5 MIGD<sup>1</sup> upon extending a mathematical model for MED system with thermal vapor compression by energy and exergy analysis. The results showed that the most exergy destruction occurs in the first effect and exergy destruction reduces upon increasing the number of effects.

Choi et al. (2005) presented exergy analysis for MED-TVC units which have been developed by Hyundai Heavy Industries Company. The units have the capacities of 1, 2.2, 3.5 and 4.4 MIGD. Exergy analysis showed that the main exergy destruction is in the thermo-compressor and effects.

Hamed et al. (1996) assessed the performance of MED-TVC desalination system. They analyzed exergy of this type of system and compared it with MEB and MVC desalination systems. The results showed that MED-TVC systems have more exergy output compared to other systems.

<sup>1</sup> Million imperial gallons per day.

Al-Najem et al. (1997) studied single-effect SED-TVC system based on the first and second law of thermodynamics. The studies showed that steam ejector and evaporator are the main sources of exergy destruction in MED-TVC desalination.

Zhao et al. (2011) studied backward multi-effect distillation for high-salinity wastewater desalination. The high-salinity wastewater desalination was from a typical refinery in the northwest of china. The results indicated that more distillate products could be produced with high effect numbers and high effect numbers led to higher capital costs and distilled product cost. The gain output ratio (GOR) value could increase by the rise of evaporator temperature in last effect.

Sharaf et al. (2011) presented exergy and thermo-economic analysis for different configurations of MED with capacity of 100 m<sup>3</sup>/day by using solar power technology. They used two techniques for analysis, in the first technique only potable water is produced and in the second technique power electricity and desalted water are produced. The results showed that the desalination technique is considered more attractive than desalination and power technique due to higher gain ratio.

Mazini et al. (2014) developed a mathematical dynamic model for multi-effect desalination (MED) with thermal vapor compressor plant. They developed a model based on coupling the dynamic equations of material, salt and energy balance of the system. They validated the model by actual data of an operating plant in Kish Island (in the south of Iran).

Franz and Seifert (2015) described the coupling of a multi-effect distillation (MED) plant with a Clausius–Rankine cycle powered by a solar central receiver system. They developed a steady-state model of MED plant and deduced a correlation for the gained output ratio (GOR) as function of heating steam temperature, specific seawater mass flow and specific heat transfer surface of the desalination plant.

Abed et al. (2017) studied water desalination system driven by solar energy. The experimental and theoretical approaches were carried out for the multistage sola still design. The experimental approaches were executed for 5 months in the city of Kirkuk. Results showed that the system produced about 5 kg of clean water per day.

Hong et al. presented thermodynamic analysis and the energy and exergy flow diagrams for an evaporator–condenser-separated mechanical vapor compression (MVC) system. Results showed the exergy efficiency is low and the largest exergy loss occurs within the evaporator–condenser and the compressor (Hong et al. 2013).

Sarhaddi et al. (2011) obtained non-sensitive solutions in the multi-objective optimization of a photovoltaic/thermal (PVT) air collector. The overall energy efficiency and

exergy efficiency have been selected as the objective functions.

Recently, new exergy and energy analysis for engineering systems has been proposed (Ameri et al. 2016; Naserian et al. 2016, 2017; Sharifishourabi et al. 2017).

In this research, a mathematical model has been presented for MED-TVC desalination system via EES software and the results of model have been validated with the actual operating data of a unit with 2400 m<sup>3</sup> day<sup>-1</sup> capacity in Bandar Abbas thermal power plant, and the destruction resulted from irreversibility in subsystem and leaving streams were studied via exergy analysis. Modeling and exergy analysis have been done for winter and summer, and the results have been compared together. Meanwhile, optimization has been done in EES software having used two-target genetic algorithm. The purposes of the study are maximizing distillate production and minimizing total exergy destruction rate.

## 2 Process Description

Figure 1 shows the schematic diagram of MED-TVC desalination system which is analyzed in this study. This system is composed of five evaporators (effects), one condenser, one steam-circulator thermo-compressor and a desuperheater.

The basis of fresh water production in this system is evaporation and distillation of seawater in a vacuum state which is occurred in the evaporators. The superheat steam enters to the system from the boiler and passes through thermo-compressor. It suctions some of the steam of the last effect which has the lowest pressure. Finally, it mixes with the steam of the desuperheater and changes its state to saturation. This steam enters the tubes of the first effect as energy supplier of the system.

Seawater is sprayed via special nozzles as falling film on horizontal tube in each effect. It is evaporated when it comes into contact with the surfaces of the hot tubes of each effect. The steam inside the tubes transfers its thermal energy to the seawater and distillates in the tubes. The seawater which sprays on the tubes is divided into the two streams. Some of them evaporate and go to the next effect, and others cannot be evaporated and collect at the bottom of the evaporator. This stream exits from the evaporator as brine or waste water. The produced vapor goes to the inside of the tube of the next effect. This stream inside the tubes condenses because it transfers its latent heat to the seawater sprayed on the tubes. This condensed water is gathered as fresh water in each effect. In other words, the condensation occurs inside the tubes and evaporation occurs outside the tubes. This process continues until the last effect. The produced vapor in the last effect is divided into two streams. Some of them are suctioned via thermo-compressor, and the rest of them are distilled via preheating

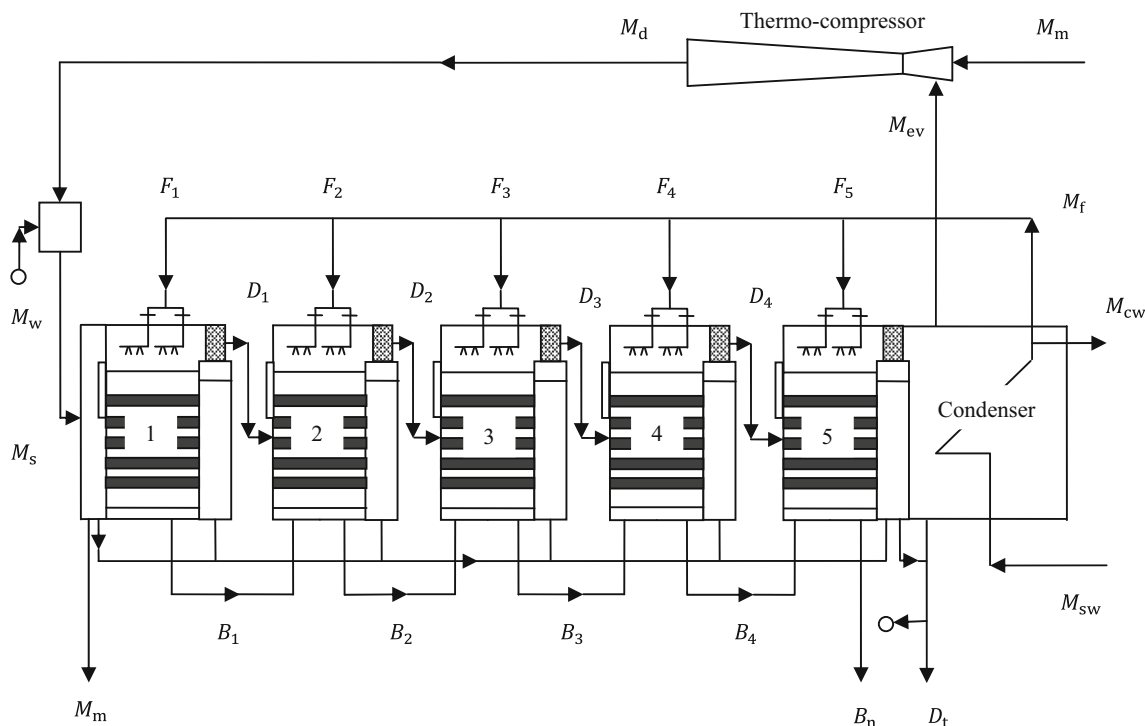


Fig. 1 A schematic diagram of MED-TVC system

the seawater in the condenser. The distilled water in the condenser is connected to the other distilled streams from the effects and is gathered as produced fresh water.

### 3 Modeling and System Analysis

A mathematical model has been used for MED-TVC desalination system for analyzing system based on first and second law of thermodynamics. This model has been presented by applying mass and energy conservation laws for thermo-compressor, effects, condenser and desuperheater (El-Dessouky and Ettouney 1999). For simplification of the system analysis, the following assumptions are considered:

1. The process is steady state.
2. Heat dissipation to environment is disregarded.
3. Produced water in each phase lacks salt.
4. Temperature difference among effects is similar, and it is considered as  $\Delta T$ .

$$T_{i-1} - T_i = \Delta T \tag{1}$$

$$\Delta T = \frac{T_s - T_f}{n + 1} \tag{2}$$

$$T_{v,i} = T_i - \text{BPE} \tag{3}$$

where  $T_s$  is input saturated steam temperature to the first effect tubes group,  $T_f$  is temperature of feed water, and  $n$  is number of effects.

According to Eq. (3), the temperature of produced vapor in each effect,  $T_{v,i}$ , is less than brine temperature (effect temperature)  $T_i$ . BPE is boiling point elevation which is computed as a function of temperature and salt concentration (salinity) of feed water.

5. According to the parallel feeding, feed water flow rate and salt concentration ( $X_f$ ) are considered similar for all effects. Feed water flow rate ( $F_i$ ) enters each effect with the Eq. (4).

$$F_i = \frac{M_f}{n} \quad i = 1, 2, \dots, n \tag{4}$$

According to the mass balance, output brine flow rate ( $B_i$ ) of effects is obtained from Eqs. 5, 8 and 11. Salt concentration ( $X_{b,i}$ ) in output brine of each effect is obtained via Eqs. 6, 9 and 12. Output vapor flow rate ( $D_i$ ) of effects is obtained from Eqs. 7, 10 and 13.

First effect

$$F_1 = B_1 + D_1 \tag{5}$$

$$F_1 \cdot X_f = B_1 \cdot X_{b1} + D_1 \cdot X_{d1} \quad X_{d1} = 0 \tag{6}$$

In which  $X_{d1}$  is salt concentration of distilled vapor.

$$M_s \cdot (h_s - h_{fs}) = F_1 \cdot C_1 \cdot (T_1 - T_f) + D_1 \cdot L_1 \tag{7}$$

In Eq. 7,  $C_1$  is specific heat capacity of the feed water with salt concentration of ( $X_f$ ) in the first effect. This parameter is computed as a function of the average feed water temperature ( $T_f$ ) and the top brine temperature

(TBT).  $L_1$ , is the latent heat of produced vapor in the first effect and a function of produced vapor temperature.

Second effect

$$F_2 + B_1 = B_2 + D_2 \quad (8)$$

$$F_2 \cdot X_f + B_1 \cdot X_{b1} = B_2 \cdot X_{b2} + D_2 \cdot X_{d2} \quad X_{d2} = 0 \quad (9)$$

$$D_1 \cdot L_1 = F_2 \cdot C_2 \cdot (T_2 - T_f) + D_2 \cdot L_2 \quad (10)$$

Effect (third to last)

$$F_i + B_{i-1} = B_i + D_i \quad (11)$$

$$F_i \cdot X_f + B_{i-1} \cdot X_{b(i-1)} = B_i \cdot X_{bi} + D_i \cdot X_{di} \quad X_{di} = 0 \quad (12)$$

$$D_{i-1} \cdot L_{i-1} + d'_{i-1} \cdot L_{i-1} = F_i \cdot C_i \cdot (T_i - T_f) + D_i \cdot L_i \quad (13)$$

Pressure in  $i$ -th effect is less than  $(i - 1)$ -th effect. Therefore, the flash evaporation occurred when the output brine from previous effect enters to the next effect. Produced flash from effect bottom ( $d'_i$ ) is computed via the equation presented by Miyatake et al. (1973).

$$d'_i = B_{i-1} \cdot C_{i-1} \cdot \frac{T_{i-1} - T'_i}{L_i} \quad (14)$$

$$T'_i = T_i + NEA_i \quad (15)$$

$$NEA_i = \frac{33.0(T_{i-1} - T_i)^{0.55}}{T_{v,i}} \quad (16)$$

where  $T'_i$  is brine temperature after entering next effect and  $NEA_i$  is non-equilibrium flash evaporation process term.

The produced vapor in the last effect in MED-TVC system is divided into two flows, one of them is suctioned via thermo-compressor ( $M_{ev}$ ) and the other enters condenser ( $M_c$ ).

$$D_n + d'_n = M_c + M_{ev} \quad (17)$$

By applying energy conservation law for condenser, input seawater ( $M_{sw}$ ) can be obtained.

$$M_c \cdot L_n = M_{sw} \cdot C_{sw} \cdot (T_f - T_{sw}) \quad (18)$$

Seawater temperature is increased by feed water temperature upon input vapor condensation to condenser, extra input seawater to condenser is returned to sea.

$$M_{cw} = M_{sw} - M_f \quad (19)$$

Total output produced water from effects is as follows:

$$D_t = \sum_{i=1}^n D_i + \sum_{i=2}^n d'_i \quad (20)$$

Energy balance equation is used for thermo-compressor for computing the output enthalpy from them. The assumed hypotheses for thermo-compressor are as follows:

- The processes with thermo-compressor (compression, mixing and expansion) are assumed as adiabatic.

Input steam to thermo-compressor ( $M_m$ ) is superheat, and suctioned steam ( $M_{ev}$ ) is as saturated.

$$M_d = M_m + M_{ev} \quad (21)$$

$$M_d \cdot h_d = M_m \cdot h_m + M_{ev} \cdot h_{ev} \quad (22)$$

For computing enthalpy of outflow from thermo-compressor, the ratio of motive flow rate to secondary flow rate (Ra) is used. It is an optimal ratio which improves the unit efficiency upon reducing motive steam (Utomo et al. 2008), this parameter has been presented by El-Dessouky and Ettouney (2002).

$$Ra = \frac{M_m}{M_{ev}} \quad (23a)$$

$$Ra = 0.296 \frac{P_d^{1.19}}{P_{ev}^{1.04}} \cdot \left[ \frac{P_m}{P_{ev}} \right] \cdot \left[ \frac{PCF}{TCF} \right] \quad (23b)$$

As seen, this ratio is a function of discharge pressure ( $P_d$ ), motive steam pressure ( $P_m$ ), suctioned steam pressure ( $P_{ev}$ ) in terms of compression ratio (CR) and expansion ratio (ER) which are as follows (El-Dessouky et al. 2000):

$$CR = \frac{P_d}{P_{ev}} \quad (24)$$

$$ER = \frac{P_m}{P_{ev}} \quad (25)$$

where PCF is motive steam pressure correction factor and TCF is suctioned vapor temperature correction factor.

$$PCF = 3 \times 10^{-7} (P_m)^2 - 0.0009 (P_m) + 1.6101 \quad (26)$$

$$TCF = 2 \times 10^{-8} (T_{ev})^2 - 0.0006 (T_{ev}) + 1.0047 \quad (27)$$

Output steam is from thermo-compressor of superheat steam which is transferred to saturated steam upon spraying water in desuperheater. The required water for spraying is obtained via mass and energy balance equations for desuperheater.

$$M_s = M_d + M_w \quad (28)$$

$$M_s \cdot h_s = M_d \cdot h_d + M_w \cdot h_w \quad (29)$$

### 3.1 Exergy Analysis

Exergy is maximum theoretical work which can be obtained from a system when the system changes a definite primary state to environmental dead state through a reversible process. This work shows the potential of system's useful work in a definite state. Exergy of a system in a definite state depends on environmental conditions (dead state) and system properties. Exergy is expressed in three flow stream  $E^f$ , heat transfer  $E^q$  and work transfer  $E^w$  in system (Tadeusz 1985).

$$E = E^f + E^q + E^w \tag{30}$$

In absence of nuclear, magnetic, electrical effects and surface tension, exergy components of material flow include: physical exergy  $E^{Ph}$ , kinetic exergy  $E^{kn}$ , potential exergy  $E^{Pt}$  and chemical exergy  $E^{ch}$ .

$$E^f = E^{Ph} + E^{Kn} + E^{Pt} + E^{ch} \tag{31}$$

In this research, kinetic, potential and chemical exergy were disregarded due to low speed of steam, regardless of height and lack of reaction.

$$E^{Ph} = m[(h - h_0) - T_0 \cdot (S - S_0)] \tag{32a}$$

$$E^q = Q \left( 1 - \frac{T_0}{T} \right) \tag{32b}$$

$$E^w = W \tag{32c}$$

In the steady conditions, total input exergy to system is equal to total output exergy from system together with exergy destruction within system. In the steady conditions, exergy balance is written as follows.

$$\sum E_{in} = \sum E_{out} + E_D \tag{33}$$

In which  $E_D$  is exergy destruction of system which is resulted from irreversibility within system.

$$\sum E_{in} = E_{steam} + E_{sw} \tag{34}$$

$$E_{steam} = M_m \cdot [(h_m - h_{fs}) - T_0 \cdot (s_m - s_{fs})] \tag{35}$$

$$E_{sw} = M_{sw} \cdot C_{sw} \cdot \left[ (T_{sw} - T_0) - T_0 \cdot \ln \left( \frac{T_{sw}}{T_0} \right) \right] \tag{36}$$

In which  $E_{steam}$  and  $E_{sw}$  are exergy of input steam to thermo-compressor and exergy of input seawater to system, respectively (Choi et al. 2005).

$$\sum E_{out} = E_{B_n} + E_{dis} + E_{rej} \tag{37}$$

$$E_{B_n} = B_n \cdot C_{B_n} \cdot \left[ (T_n - T_0) - T_0 \cdot \ln \left( \frac{T_n}{T_0} \right) \right] \tag{38}$$

$$E_{dis} = D_t \cdot C_{dis} \cdot \left[ (T_{dis} - T_0) - T_0 \cdot \ln \left( \frac{T_{dis}}{T_0} \right) \right] \tag{39}$$

$$E_{rej} = M_{cw} \cdot C_{rej} \cdot \left[ (T_{cw} - T_0) - T_0 \cdot \ln \left( \frac{T_{cw}}{T_0} \right) \right] \tag{40}$$

In which,  $E_{br}$ ,  $E_{dis}$  and  $E_{rej}$  are exergy of output brine, exergy of distillate production and exergy of seawater returned to sea, respectively (Choi et al. 2005).

Exergy destruction rate (kW) is given below for each of the components of MED-TVC desalination system (Binamer 2013).

Thermo-compressor

$$E_{D,ej} = M_m \cdot [(h_m - h_d) - T_0 \cdot (s_m - s_d)] - M_{ev} \cdot [(h_d - h_{ev}) - T_0 \cdot (s_d - s_{ev})] \tag{41}$$

Effects

$$E_{D,e1} = M_s \cdot [(h_s - h_{fs}) - T_0 \cdot (s_s - s_{fs})] - D_1 \cdot L_1 \cdot \left( 1 - \frac{T_0}{T_{v,1}} \right) - F_1 \cdot C_1 \cdot \left[ (T_1 - T_f) - T_0 \cdot \ln \left( \frac{T_1}{T_f} \right) \right] \tag{42}$$

$$E_{D,e2} = D_1 \cdot L_1 \cdot \left[ 1 - \frac{T_0}{T_{v,1}} \right] + B_1 \cdot C_1 \cdot \left[ \Delta T - T_0 \cdot \ln \left( \frac{T_1}{T_2} \right) \right] - D_2 \cdot L_2 \cdot \left[ 1 - \frac{T_0}{T_{v,2}} \right] - D_2 \cdot L_2 \cdot \left[ 1 - \frac{T_0}{T_{v,2}} \right] \tag{43}$$

$$E_{D,ei} = (D_{i-1} + d'_{i-1}) \cdot L_{i-1} \cdot \left[ 1 - \frac{T_0}{T_{v,i-1}} \right] + B_{i-1} \cdot C_{i-1} \cdot \left[ \Delta T - T_0 \cdot \ln \left( \frac{T_{i-1}}{T_i} \right) \right] - D_i \cdot L_i \cdot \left[ 1 - \frac{T_0}{T_{v,i}} \right] - F_i \cdot C_i \cdot \left[ (T_i - T_f) - T_0 \cdot \ln \left( \frac{T_i}{T_f} \right) \right] \quad i = 3, \dots, n \tag{44}$$

Condenser

$$E_{D,c} = D_n \cdot L_n \cdot \left( 1 - \frac{T_0}{T_{v,n}} \right) - M_{sw} \cdot C_{sw} \cdot \left[ (T_f - T_{sw}) - T_0 \cdot \ln \left( \frac{T_f}{T_{sw}} \right) \right] \tag{45}$$

Desuperheater

$$E_{D,de} = M_d \cdot [(h_d - h_s) - T_0 \cdot (s_d - s_s)] - M_w \cdot [(h_s - h_w) - T_0 \cdot (s_s - s_w)] \tag{46}$$

Leaving streams

$$E_{D,M_{ev}} = M_{ev} \cdot C_5 \cdot \left[ (T_{v,n} - T_{sw}) - T_0 \cdot \ln \left( \frac{T_{v,n}}{T_{sw}} \right) \right] \tag{47}$$

$$E_{D,M_c} = M_c \cdot C_5 \cdot \left[ (T_{v,n} - T_{sw}) - T_0 \cdot \ln \left( \frac{T_{v,n}}{T_{sw}} \right) \right] \tag{48}$$

$$E_{D,B_n} = B_n \cdot C_{B_n} \cdot \left[ (T_n - T_{sw}) - T_0 \cdot \ln \left( \frac{T_n}{T_{sw}} \right) \right] \tag{49}$$

### 3.2 System Performance

Performance of MED-TVC system can be studied considering the following components (Binamer 2013).



### 3.2.1 Gain Output Ratio

Gain output ratio is one of the used parameters for studying thermal performance of desalination processes. It is defined as the ratio of total distilled water produced to the motive steam (Zarei et al. 2017).

$$\text{GOR} = \frac{D_t}{M_m} \quad (50)$$

### 3.2.2 Specific Heat Consumption, $Q_d$

Specific heat consumption is one of the important thermal characteristics of desalination systems. Specific heat consumption is thermal energy consumption by system for producing 1 kg distilled water.

$$Q_d = \frac{M_m \cdot L_m}{D_t} \quad (51)$$

### 3.2.3 Specific Exergy Destruction

Specific exergy destruction is total exergy destruction resulted from irreversibility in thermo-compressor, effects, condenser, desuperheater and the leaving streams per unit distillate production.

$$E_{SD} = \sum \frac{E_{D,c}}{D_t} \quad (52)$$

$E_{D,c}$  is exergy destruction in each of the components of desalination (kW).

### 3.2.4 Exergy Efficiency and Exergy Destruction rate

For assessing the thermodynamic performance of system based on second law of thermodynamic, exergy efficiency is used as follows (Choi et al. 2005).

$$\psi = \frac{\sum E_{out}}{\sum E_{in}} \quad (53)$$

For thermodynamic assessment of an element in a system, exergy destruction rate is used apart from exergy destruction (Choi et al. 2005).

$$\delta = \frac{E_{D,c}}{\sum E_{in}} \quad (54)$$

## 4 Results

For modeling and assessing the performance of MED-TVC desalination system, EES software was used. Model validation was done by experimental data in two seasons of

summer and winter. In Table 1, design and operating parameters of MED-TVC unit of Bandar Abbas thermal power plant are given.

In Table 2, the calculated thermodynamic parameters are given.

In Table 3, the output results of system simulation with real units are compared in two seasons of summer and winter in terms of operating parameters.

In this research, exergy destruction of the components of desalination in two seasons of winter and summer was computed and compared regarding environmental conditions. Meanwhile, the effect of top brine temperature (TBT) on system performance was studied.

## 4.1 Results of Exergy Analysis

In this part, exergy destruction rate in MED-TVC desalination system is computed and assessed.

Table 3 shows the simulation results can predict the actual operating data with an acceptable error.

Table 4 indicates the exergy destruction rate and percentage for each of the components and the rate of total exergy destruction for summer and winter.

Table 4 and Figs. 2 and 3 show that thermo-compressor and effects are the main sources of exergy destruction in the system. Thermo-compressor consumes 1337 (kW) exergy in winter which is equal to 48.02% of the total exergy destruction of the system. It also consumes 1402 (kW) exergy in summer which is equal to 57.1% of the total exergy destruction of the system. Exergy destruction in thermo-compressor is due to irreversible processes of mixing and expansion.

Effects are the second factor of exergy destruction. Effects consume 1011 (kW) exergy in winter and 820.8 (kW) exergy in summer which is equal to 36.32 and

**Table 1** Thermodynamic parameters MED-TVC unit of Bandar Abbas thermal power plant

Thermodynamic parameters	Winter	Summer
Dead state temperature $T_0$ (°C)	20	34.3
Dead state pressure $P_0$ (kPa)	101	101
Motive steam temperature $T_m$ (°C)	195	195
Motive steam pressure $P_m$ (kPa)	910	910
Motive steam flow rate $M_m$ (kg/s)	3.47	3.44
Total feed water flow rate $M_f$ (kg/s)	76.39	76.39
Salinity of seawater $X_f$ (g/kg)	42.22	42.22
Feed water temperature $T_f$ (°C)	37.7	42.6
Seawater temperature $T_{sw}$ (°C)	23	35
Top brine temperature $T_1$ (°C)	63.42	63.44
Temperature difference per effect $\Delta T$	5	4.17

**Table 2** Mathematical model calculations

Temperature of effect $i$ ( $^{\circ}\text{C}$ )	Winter	Summer	Distillate production of effect $i$ (kg/s)	Winter	Summer
Temperature of effect 1, $T_1$	63.42	63.44	Distillate production of effect 1, $D_1$	4.665	5.295
Temperature of effect 2, $T_2$	58.19	59.27	Distillate production of effect 2, $D_2$	4.17	4.892
Temperature of effect 3, $T_3$	52.97	55.1	Distillate production of effect 3, $D_3$	3.918	4.648
Temperature of effect 4, $T_4$	47.75	50.93	Distillate production of effect 4, $D_4$	3.789	4.559
Temperature of effect 5, $T_5$	42.52	46.77	Distillate production of effect 5, $D_5$	4.1	4.61

**Table 3** Comparison between results of system simulation

Operating parameters	Winter			Summer		
	Model	Actual	Error (%)	Model	Actual	Error (%)
Motive steam to entrained vapor ratio Ra	2.05	–	–	1.58	–	–
Distillate production $D_i$ (kg/s)	20.65	20.55	0.48	24.01	20.84	15.12
Gain output ratio GOR	5.95	5.92	0.5	6.98	6.06	15.18
Compression ratio (CR)	3.562	–	–	2.735	–	–
Expansion ratio ER	110.3	–	–	88.64	–	–
Boiling point elevation BPE	0.42	–	–	0.44	–	–
Specific heat consumption $Q_d$ (kJ/kg)	329.2	–	–	280.7	–	–
Total exergy destruction rate $E_{D,t}$ (kW)	2796	–	–	2457	–	–
Specific exergy destruction $E_{SD}$ (kJ/kg)	135.2	–	–	102.3	–	–
Exergy efficiency $\psi$ (%)	9.65	–	–	4.72	–	–

**Table 4** Results of exergy analysis system components

Components	Winter			Summer		
	Exergy destruction $E_D$ (kW)	$E_{D,c}/E_{in}$ (%)	$E_{D,c}/E_{D,t}$ (%)	Exergy destruction $E_D$ (kW)	$E_{D,c}/E_{in}$ (%)	$E_{D,c}/E_{D,t}$ (%)
Thermo-compressor	1337	45.86	47.86	1402	53.87	57.04
Effect 1	220.5	7.56	7.89	190.5	7.32	7.75
Effect 2	199.9	6.85	7.16	165.5	6.36	6.73
Effect 3	196.7	6.75	7.04	158.9	6.11	6.46
Effect 4	197.1	6.76	7.06	154.9	5.95	6.63
Effect 5	200.9	6.89	7.19	153.9	5.89	6.24
Effects	1015	24.34	36.34	823.1	31.63	33.81
Condenser	200.1	6.86	7.16	135.9	5.22	5.53
Desuperheater	42.46	1.46	1.52	40.79	1.56	1.66
Leaving streams	198.62	6.81	7.11	55.72	2.14	2.23
Desalination system	2796	–	100	2457	–	100

33.43% of the total exergy destruction. Exergy destruction in the system is resulted from irreversibility of energy transfer processes like heat transfer.

According to Table 3, exergy destruction rate and specific exergy destruction in winter is 12.12 and 24.33% more than summer. According to Fig. 2 and Table 4, exergy destruction rate in effect, condenser, desuperheater and leaving streams in winter is more than in summer. In

winter, the required energy for evaporation increases due to reducing the feed water temperature. When the feed water temperature is decreased, irreversibility of the flash evaporation in the second effect is increased.

Meanwhile, increasing temperature difference between the feed water and motive steam leads to increase the temperature difference among the effects. Exergy efficiency is 9.65% in winter and 4.72% in summer (Table 3).



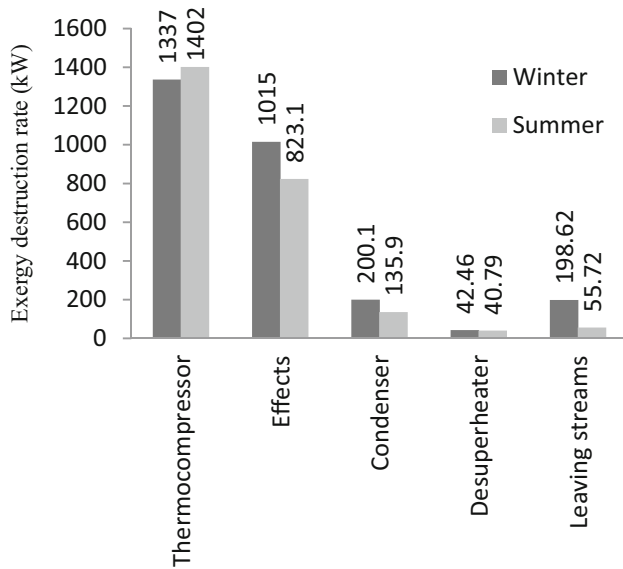


Fig. 2 Component exergy destruction rate for various operating condition

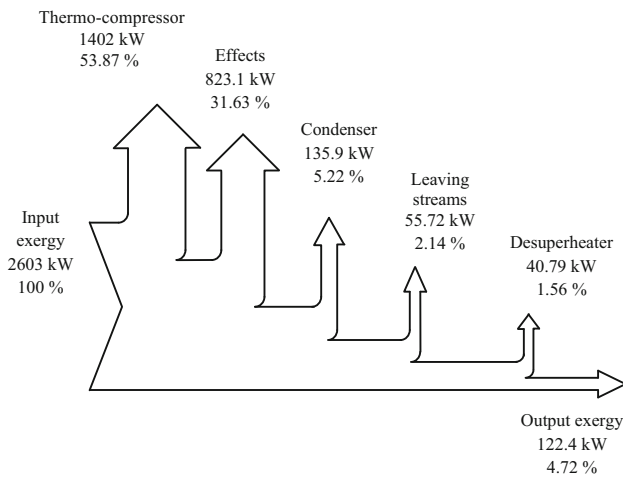


Fig. 3 Grassman diagram of components exergy destruction as a percentage of total input exergy

The reason for decreasing the exergy efficiency in summer is increasing the environmental temperature.

Figure 3 shows Grassman diagram for summer. Grassman diagram shows that output exergy from system is 4.7% of total input exergy to system. Meanwhile, thermo-compressor consumes 53.87% and effects consume 31.63% of input exergy.

### 4.2 Effect of Top Brine Temperature (tbt)

One of the most important effective parameters on distillate production and exergy destruction of the system is top brine temperature. This temperature range is 60–70 °C in most of the new MED-TVC systems. Figure 4 shows the

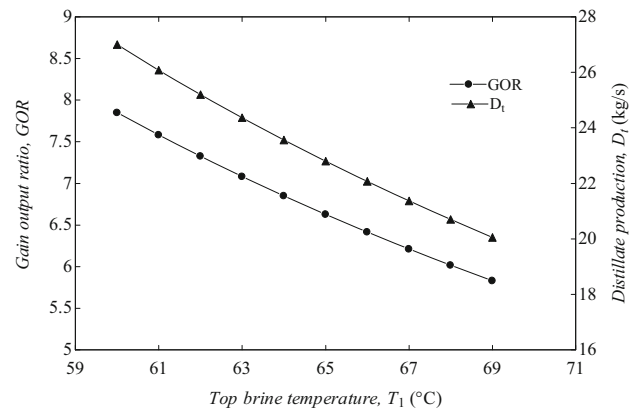


Fig. 4 Effect of top brine temperature on the distillate production and GOR

gain output ratio and distillate production as a function of top brine temperature. As can be seen, increasing the top brine temperature leads to reducing the distillate production by 25.74% and subsequently the gain output ratio is reduced by 25.72%. Whereas increasing the top brine temperature leads to reduction in vapor latent heat and feed sensible heating increases, according to Eqs. 10 and 13, the distillate production decreases. Figure 5 shows the effect of top brine temperature on the specific heat consumption. The results show that the specific heat consumption can be increased until 34.65% when the top brine temperature is increased. This is because the higher top brine temperature leads to the higher vapor pressure. So, the larger amount of motive steam is needed to compress the vapor at the higher pressure (Fig. 5).

Figures 6 and 7 show the effect of the top brine temperature on specific exergy destruction and total exergy destruction rate and various components of desalination system.

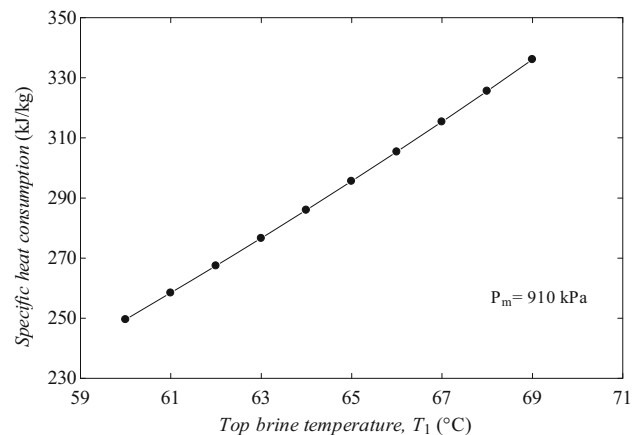
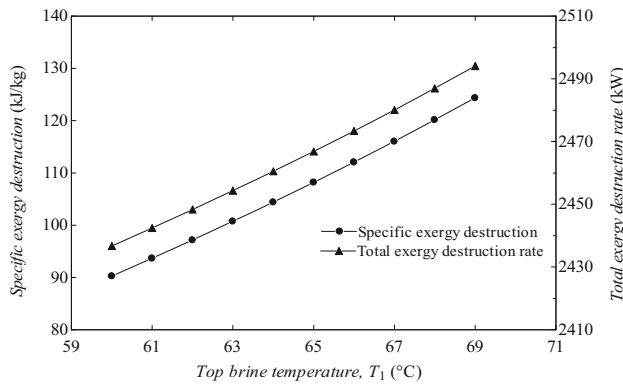
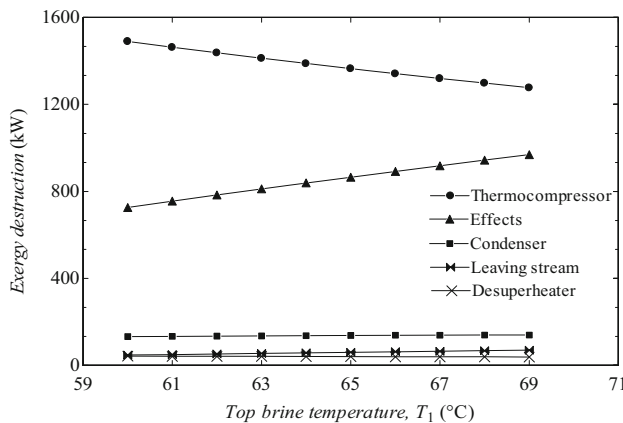


Fig. 5 Effect of top brine temperature on the specific heat consumption



**Fig. 6** Effect of top brine temperature on the specific exergy destruction and total exergy destruction rate



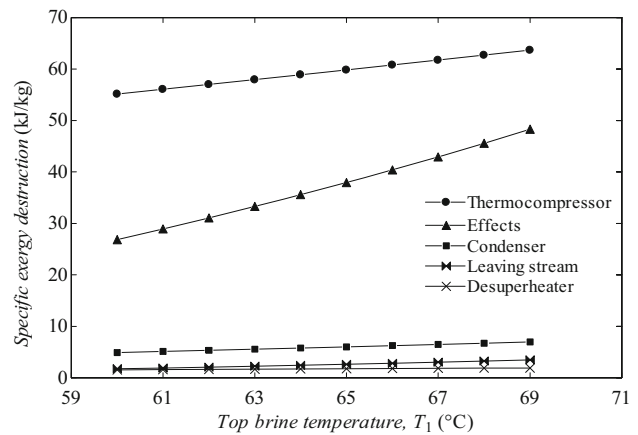
**Fig. 7** Effect of top brine temperature on components exergy destruction rates

Specific exergy destruction and total exergy destruction rate of the system is increased 37.84 and 2.34%, respectively, upon increasing the top brine temperature (Fig. 6).

Figure 7 shows that exergy destruction rate in thermo-compressor reduces 14.3% by increasing the top brine temperature. This is because of increasing the compression in the thermo-compressor and increasing the output exergy rate in the thermo-compressor.

Exergy destruction rate in effects increases remarkably by 33.6% by increasing the top brine temperature since the energy transferred to the feed water increases by increasing the top brine temperature. According to Fig. 7, exergy destruction rate of leaving streams from the effects increases since the temperature difference among the effects increases by increasing the top brine temperature. Pressure drop increases over effects and leads to increase the exergy destruction rate. Exergy destruction rate reduces in the desuperheater since output exergy rate from the desuperheater is increased.

According to Fig. 8, the specific exergy destruction increases for 15.39% in the thermo-compressor.



**Fig. 8** Effect of top brine temperature on components specific exergy destruction

Meanwhile, exergy destruction in the effects increases 79.83% with increasing the top brine temperature.

### 5 Optimization via Genetic Algorithm

Genetic algorithm is an optimization method based on the biological evolution. It was introduced by John Holland in 1970. Genetic algorithm seeks an optimal point, and in this regard, it searches in different points in work setting to meet the final condition. Genetic algorithm obtains an answer in shorter time compared to common algorithms. The structure of the algorithm used in the present work is illustrated in Fig. 9.

In this research, two-target optimization is used in which the distillate production amount and the total exergy destruction rate are considered as the target functions and optimization aims at maximizing the distillate production and minimizing total exergy destruction rate. The objective functions for this problem are given by

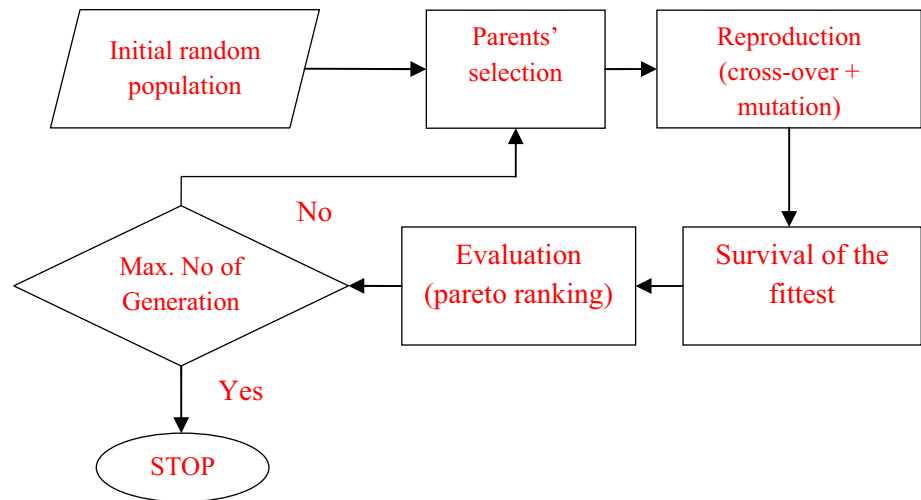
$$\text{Maximize : } D_t = \text{Eq. (20)}$$

$$\begin{aligned} \text{Minimize : } E_{D,t} = & E_{D,ej} + E_{D,e1} + E_{D,e2} + \dots + E_{D,e5} \\ & + E_{D,c} + E_{D,de} + E_{D,M_{ev}} + E_{D,M_c} + E_{D,B_n} \end{aligned} \tag{55}$$

The amounts of parameters related to genetic algorithm and ranges of design variable changes are brought in Table 5.

Optimal amount of design variables and target functions are shown in Table 6. Table 6 shows that in optimal state, distillate production increases 16.62% compared to distillate production in summer and total exergy destruction rate reduces 3.58% compared to total exergy destruction rate, in summer. According to used parameters in Table 6, the results from mathematical mode, governing the output, verify genetic algorithm.

**Fig. 9** Scheme for the evolutionary algorithm used in the present work



**Table 5** Parameters of optimization in genetic algorithm

Parameters	Value
Population size	250
Maximum no. of generations	300
Probability of crossover $P_c$	0.85
Probability of Mutation $P_m$	0.005
No. of crossover point	2
The range of motive steam pressure $P_m$ (kPa)	900–1200
The range of motive steam temperature $T_m$ (°C)	190–250
The range of seawater temperature $T_{sw}$ (°C)	30–38
The range of feed water temperature $T_f$ (°C)	35–49
The range of top brine temperature $T_1$ (°C)	60–70

**Table 6** Optimization results of MED-TVC system

Design variables/objective function	Optimal value
Motive steam pressure $P_m$ (kPa)	920.1
Motive steam temperature $T_m$ (°C)	192.4
Seawater temperature $T_{sw}$ (°C)	37.87
Feed water temperature $T_f$ (°C)	49
Top brine temperature $T_1$ (°C)	65.22
Distillate production $D_t$ (kg/s)	28
Total exergy destruction rate $E_{D,t}$ (kW)	2369

## 6 Conclusion

In this study, a proper model based on the first and second law of thermodynamics has been presented for MED-TVC desalination system with  $2400 \text{ m}^3 \text{ day}^{-1}$  in Bandar Abbas thermal power plant. The amount of distillate production, gain output ratio, total exergy destruction rate, exergy

destruction resulted from irreversibility in the various components of desalination, and the specific exergy destruction in winter and summer were calculated. Performance of the system in the various top brine temperature in the range of 60–70 °C was studied. Meanwhile, the desalination system was optimized by genetic algorithm. The obtained results are as follows:

- Exergy efficiency is 9.65% in winter and 4.72% in summer.
- Thermo-compressor and effects are the main sources of exergy destruction in the system. In winter, exergy destruction in the thermo-compressor and effects are 47.86 and 36.34% of the total exergy destruction, respectively. In summer, exergy destruction in the thermo-compressor and effects are 57.04 and 33.81% of the total exergy destruction.
- The specific exergy destruction in winter is 24.33% more than summer.
- Gain output ratio is reduced to 25.72% with increasing the top brine temperature, and the specific heat consumption is increased to 34.65%.
- Specific exergy destruction of various components of desalination increases with increasing the top brine temperature.
- Total exergy destruction rate and specific exergy destruction is increased by 2.34 and 37.84%, respectively, upon increasing the top brine temperature.
- Optimization results with genetic algorithm show that the distillate production in optimal state is 16.62% more than the distillate production in summer and total exergy destruction rate is 3.58% less than total exergy destruction rate in summer.

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