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Exergy analysis of a closed mechanical vapour compression desalination system by the entropy method

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ABSTRACT

Corrosion is a common problem for desalination systems. To protect the compressor in a desalination system from being corroded and damaged, a novel mechanical vapour compression desalination system, denoted as a closed mechanical vapour compression desalination system, is proposed, in which the compressor does not contact the vapour produced by seawater directly. Mathematical models corresponding to the proposed system were established, and then an exergy analysis based on entropy method was achieved to investigate the performance of the system with a flow rate of 1,000 kg/h. The results showed that the total exergy loss was 29.4 kW, for which the circulating water tank accounts for 41% due to a superimposition of flashing and mixing, followed by the heat exchanger (23%), evaporator (16%), compressor (13%), preheater (5%) and pumps (1%). The exergy loss of the pumps is much smaller due to their lower power consumption.

Keywords: Closed mechanical vapour compression; MVC; Desalination; Exergy loss; Entropy method

1. Introduction

Fresh water, an indispensable resource for human beings, is limited on the earth, and the scarcity of fresh water is a serious problem. Seawater desalination seems to be one of the feasible approaches to cope with this issue. Many seawater desalination plants have been built worldwide [1], mainly based on two technologies, namely, the separation membrane and thermal methods. The separation membrane includes reverse osmosis [2,3] and electrodialysis (ED) [4–6], whereas vapour and electrical energy are employed in the thermal method as the heat source. For example, the thermal energy of multi-effect desalination [7,8] and multi-stage flash (MSF) [9–11] is from vapour at high temperature, and for the mechanical vapour compression (MVC), the energy is obtained from a compressor driven by electricity. MVC is reported as an attractive method for seawater desalination because of its higher energy efficiency [12]. Numerous studies have performed research on MVC systems. Jamil and Zubair [13] provided an analysis of a single-effect MVC desalination system operating with and without brine recirculation based on thermo-economics. Furthermore, Jamil and Zubair [14] designed and analysed a forward-feed multi-effect MVC desalination system based on the exergy-economic method. Jamil and Zubair [15] also compared the energy consumption, exergy destruction, heat transfer area and product cost of a multi-effect MVC desalination system with those of three different feed flow arrangements. Han et al. [16] proposed a zero-emission desalination system (ZEDS) based on MVC.

Various combined systems have also been presented. A hybrid desalination system with MVC and adsorption techniques was proposed by Askalany [17], and when compared with an adsorption desalination system, the products

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increased by 10%–45%. Ettouney [18] worked out a new design for a multistage flash mechanical vapour compression desalination process. The analysis of the proposed system was performed based on energy, exergy and thermo-economic methodologies. Alasfour and Abdulrahim [19] proposed a steady-state mathematical model for a hybrid MSF–MVC desalination system and summarized the relationship between the temperature and the specific power consumption and distillate water production.

Compressors are the key components in MVC desalination, and methods for optimizing compressor performance have also been reported. An MVC desalination system is suggested, in which the compressor is driven by a transcritical carbon dioxide (CO_2) Rankine cycle (CRC) [20] and by an organic Rankine cycle (ORC) [21]. Shen et al. [22,23] reported on MVC desalination systems with water-injected twin-screw compressors. Yang et al. [24] studied MVC desalination with a wet compression single screw compressor. Corrosion is a common problem for seawater desalination [25]. In a traditional MVC system, as shown in Figs. 1a and b, vapour produced by seawater evaporation is compressed through a compressor with increases in pressure and temperature and then reused to heat the incoming seawater; therefore, the mechanical compressor is the key component and accounts for most of the manufacturing cost. The vapour always carries seawater droplets and other volatile materials corrosive to the compressor. Measures should be taken to prevent the compressor from corrosion and damage. In the conventional method, the vapour flows through a separator or gas washing tower before entering the compressor; thus, the droplets can be separated from the vapour with the assistance of centrifugal force or resistance. In practice, the separator and gas washing tower are usually combined, and multiple filters are employed to improve the vapour purity.

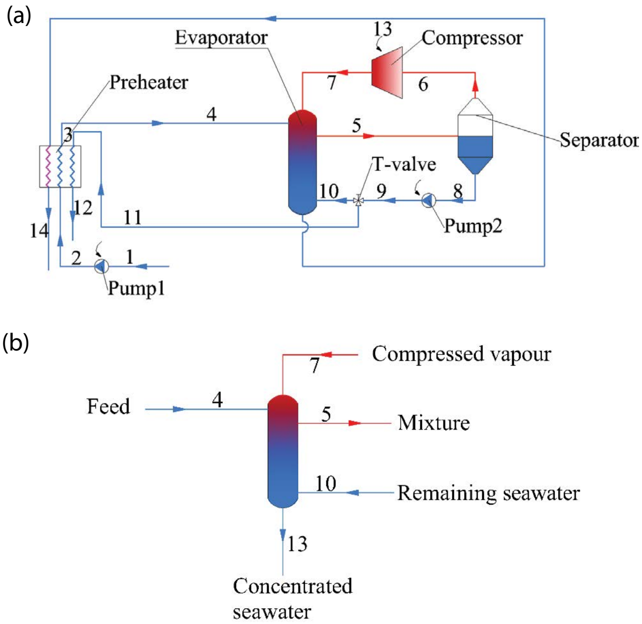

Fig. 1. (a) Schematic diagram of a traditional MVC system and (b) details of the evaporator inlet and outlet in a traditional MVC system.

However, droplets cannot be completely removed, and the corrosion problem still exists.

In this paper, an innovative MVC desalination system, denoted as a closed mechanical vapour compression (CMVC) seawater desalination system, was proposed. As shown in Figs. 2a and b, the CMVC seawater desalination system consists of an evaporator, a preheater, a compressor, a heat exchanger and a circulating tank. There is no separator or gas washing tower in the CMVC seawater desalination system, unlike in a traditional MVC desalination system. The advantage of the CMVC desalination system is that the contact between the compressor and the vapour carried with the seawater droplets is thoroughly avoided.

2. Scheme of the system

The scheme of the CMVC desalination system is presented in Figs. 2a and b. Seawater at ambient temperature is pumped by pump 3 from the feed tank to the pre-heater, where the sensible heat from the concentrated solution and treated water is transferred to this initial seawater; the seawater is further heated in the evaporator, which is a shell and tube heat exchanger. Part of the seawater evaporates in the evaporator, and the vapour is generated; the remaining seawater returns to the evaporator and mixes with the incoming seawater at point J until the predetermined concentration is attained. In the evaporator, seawater passes through a tube side, and vapour from the compressor goes through the shell side to serve as the heat source.

The vapour from the top of the evaporator releases its latent heat to the circulating water in the heat exchanger; the treated water is extracted from the seawater after the vapour condensation. The distilled water from the evaporator and the circulating water are mixed in the circulating water tank, reaching heat equilibrium. The mixture flashes on the top of the circulating water tank because of the pressure difference;

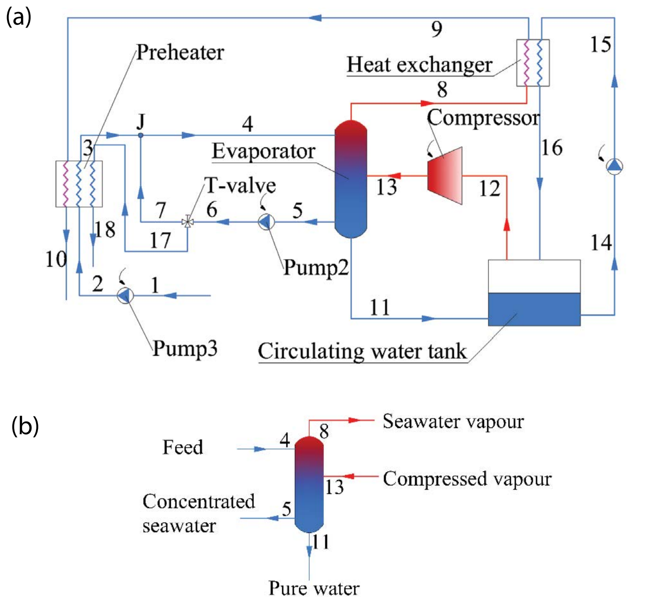

Fig. 2. (a) Schematic diagram of CMVC system and (b) details of the evaporator inlet and outlet in a CMVC system.

the flashing vapour is induced into the compressor, the temperature of the vapour as well as the pressure is raised in the compressor, and the vapour at high pressure and temperature is reused as the heat source.

The system can be divided into three loops: a pure water loop, a circulating water loop and a seawater loop. The pure water flashes in the circulating tank, the flashed vapour is compressed in the compressor, supplies the seawater with heat in the evaporator and condenses after releasing latent heat, and the condensed distilled water returns to the circulating tank again. The circulating water from the circulating tank receives the latent heat of the seawater vapour in the heat exchanger, is heated to high temperature, flows back into the circulating tank and mixes with the pure water. The seawater is heated in the evaporator by the vapour from the compressor, turns into vapour with droplets and concentrated solution, the vapour generated by seawater releases latent heat to the circulating water in the heat exchanger and condenses to treated water, and the concentrated solution and treated water heat the new seawater in the preheater. The pure water does not contact the seawater directly in the loop; therefore, the pure water is not polluted by the seawater droplets and volatile matter from the evaporating seawater. The vapour induced into the compressor is clean from salt composition.

3. Exergy analysis of the desalination system

Entropy is a state function; it was originally introduced to explain why part of a thermodynamic system's total energy is unavailable to do useful work. It represents the irreversibility of a process. To evaluate the entropy distribution of the system, components are abstracted from the system. Each component can be regarded as a control volume and forms an isolated system with the heat source and mass source. The entropy generation of the isolated system δs_g is equal to the entropy change, which includes the entropy change of the control volume ds_{cv}, the heat source $\frac{\delta Q_0}{T_0}$ and the mass flow $s_o\delta m_o - s_i\delta m_i$; the formulation is given by Bejan [26].

$$\delta s_g = ds_{cv} + \frac{\delta Q_0}{T_0} + s_o\delta m_o - s_i\delta m_i \tag{1}$$

The thermodynamic models are developed based on the following assumptions for any single component entropy analysis.

- Heat loss of the components, including the evaporator, the preheater, the compressor and the heat exchanger, is neglected.
- All the processes are regarded to take place under thermal equilibrium.
- The environmental dead states of the system are selected as an environmental temperature of 20°C and one atmospheric pressure.
- The mass flow is steady, and the differences in the kinetic and potential energies of the inflow and outflow are negligible.
- The Gibbs free energy is not considered because no chemical reactions occur within the desalination.
- In addition to the main components, several valves are neglected in this study because of their insignificant entropy compared with the main components.

3.1. Entropy generation in the evaporator

The system contains an evaporator with seawater flowing inside the tubes and vapour condensing on the shell side.

As shown in Fig. 3, the evaporator is an open system with five streams of mass flow: outflow of the vapour 8; outflow of the pure water 11; outflow of the remaining seawater 5; inflow of the compressed vapour 13; and inflow of the feed and remaining seawater 4. The mixture of the feed seawater and the remaining seawater flows inside the tube side and absorbs the latent heat of the vapour 13 flowing in the shell side. The mixture is heated up to the vaporization temperature T_b from the initial temperature $T_{sw,i}$ and evaporates at the temperature of T_b; meanwhile, the vapour condenses at the temperature of T_c. According to formulation (1), the entropy generation of the evaporator from irreversible heat transfer between the vapour and the mixture is given by:

$$\delta s_{evp,g} = ds_{evp,cv} + \frac{\delta Q_0}{T_0} + \Sigma s_{evp,o}\delta m_{evp,o} - \Sigma s_{evp,i}\delta m_{evp,i} \tag{2}$$

According to the assumptions above:

$$ds_{evp,cv} = 0 \tag{3}$$

and

$$\delta Q_0 = 0 \tag{4}$$

Therefore,

$$\begin{aligned}\delta s_{evp,g} &= \Sigma s_{evp,o}\delta m_{evp,o} - \Sigma s_{evp,i}\delta m_{evp,i} \\ &= \int_{T_{sw,i}}^{T_b} \frac{m_{sw,i}c_{p,sw}dT}{T} + \frac{m_{evp}\gamma_b}{T_b} + \frac{m_{cond}\gamma_c}{T_c}\end{aligned} \tag{5}$$

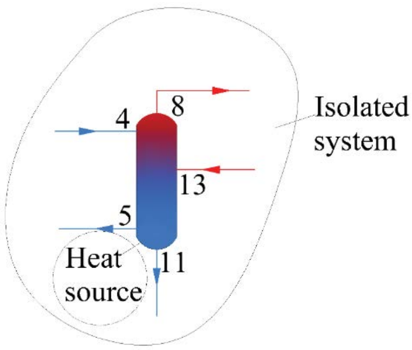

Fig. 3. Control volume of the evaporator.

in which $c_{p,\mathrm{sw}}$ is the seawater specific heat; see Appendix A. T_b is the vaporization temperature, γ_b is the water specific latent heat of vaporization, γ_c is the vapor specific latent of condensation, $m_{\mathrm{sw},i}$ is the mass flow of seawater supplied to the evaporator, m_{evp} is the mass flow of vapor evaporates from seawater and m_{con} is the mass flow of compressed vapour.

3.2. Entropy generation in the circulating water tank

As shown in Fig. 4, the circulating water is heated in the heat exchanger and then flows back into the circulating water tank again at a higher temperature. In the heat exchanger, the circulating water is warmed from $T_{c,o}$ to $T_{c,i}$, the corresponding pressure increases from $P_{c,o}$ to $P_{c,i}$, and flashing of the circulating water takes place as the water is introduced into the circulating water tank at lower pressure and temperature. Flashing is an irreversible process and is accompanied by entropy generation. The entropy generation associated with the flashing evaporation can be estimated from [26] the following equation:

$$\delta s_{\mathrm{flash}} = \int \frac{\delta Q_{\mathrm{flash}}}{T} = m_{\mathrm{flash}} \int_{T_{c,o}}^{T_{c,i}} \frac{c_{p,w} dT}{T} - \mathrm{Rg} \ln \frac{P_{c,o}}{P_{c,i}} \tag{6}$$

where m_{flash} is the flash vapour mass flow rate, and $c_{p,w}$ is the specific heat of pure water, which is assumed to be constant because of the minor temperature difference in the process.

The pure water produced from the compressed vapour in the evaporator is mixed with the circulating water in the circulating water tank. During this process, the pure water experiences a drop in temperature and a pressure with consequent entropy generation. The entropy generation in the process can be expressed by the equation [26] as follows:

$$\delta s_{\mathrm{mix}} = \int \frac{\delta Q_{\mathrm{mix}}}{T} = \int_{T_d}^{T_{\mathrm{mix}}} \frac{m_p c_{p,w} dT}{T} + \int_{T_{\mathrm{mix}}}^{T_c} \frac{m_c c_{p,w} dT}{T} \tag{7}$$

where T_d, T_c and T_{mix} are the temperatures of the pure water, the circulating water and the water mixture, respectively. m_p and m_c are the mass flows of the pure water and the circulating water, respectively. The entropy generation in the circulating water tank is as follows:

$$\delta s_{\mathrm{ct},g} = \delta s_{\mathrm{flash}} + \delta s_{\mathrm{mix}} \tag{8}$$

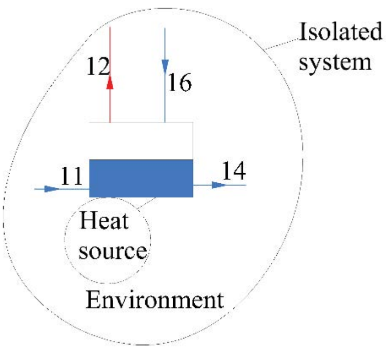

Fig. 4. Control volume of the circulating tank.

3.3. Entropy analysis for the pumps and compressors

One compressor and three pumps are used in the system: the feed pump, the circulating water pump and the circulating solution pump. The entropy generation comes from three sources in any motor-driven pump or compressor: (1) entropy generation in the motor due to heat generated by its electrical resistance, (2) entropy generation due to frictional effects, which is completely converted into heat and dissipated into the surroundings and (3) entropy generation due to frictional effects, which is converted into heat supplied to the fluid. The entropy for pumps and compressors is given by El-Nashar and Al-Baghdadi [27]. For pumps, this amount of heat is transferred to the fluid at an essential constant temperature, T_p, since the temperature rise of the fluid through the pump is negligibly small. The entropy for pumps is given by the equation as follows:

$$\delta s_{\mathrm{pump},g} = m_{p,o} s_{p,o} - m_{p,i} s_{p,i} = \frac{(1-\eta_{\mathrm{in}})\eta_{\mathrm{mech}} W_p}{T_0} + \frac{(1-\eta_{\mathrm{mech}}) W_p}{T_p} \tag{9}$$

$$W_p = V \rho g H \tag{10}$$

where $m_{p,o}$ and $m_{p,i}$ are the outflow and inflow of the pumps, respectively, and $m_o = m_i \cdot s_{p,o}$ and $s_{p,i}$ are the entropies of outflow and inflow, respectively.

For the compressor, the temperature increases as the heat is transferred to the fluid. The entropy is expressed as follows:

$$\delta s_{\mathrm{com},g} = m_{c,o} s_{c,o} - m_{c,i} s_{c,i} = \frac{(1-\eta_{\mathrm{in}})\eta_{\mathrm{mech}} W_c}{T_0} + \frac{(1-\eta_{\mathrm{mech}}) W_c}{T_i} \tag{11}$$

$$W_c = m_i \frac{\kappa}{\kappa - 1} \mathrm{Rg}\, T_i \left[1 - \left(\frac{p_o}{p_i} \right)^{\frac{\kappa-1}{\kappa}} \right] \tag{12}$$

W_p and W_c are the electrical energy supplied to the motor. η_{mech} is the mechanical efficiency, and η_{in} is the internal efficiency. V is the volume flow, ρ is the density, g is the acceleration due to gravity, and H is the delivery head.

3.4. Entropy generation in the preheater

The preheater has three channels including the initial seawater stream, the treated water stream and the concentrated seawater stream. The stream of treated water and initial seawater is continuous, and the concentrated seawater stream is discontinuous. A density detector is arranged at 6, and when the determined density is obtained, the passage of 6 to 17 is opened. The initial seawater enters the cold channel at $T_{\mathrm{sw},i}$ and leaves at $T_{\mathrm{sw},o}$, while treated water and concentrated water at $T_{\mathrm{trw},i}$ and $T_{\mathrm{conc},i}$ are cooled to $T_{\mathrm{trw},o}$ and $T_{\mathrm{conc},o}$, respectively. Otherwise, the passage of 6 to 7 is opened, and the initial seawater is heated by the treated water. The entropy generation due to irreversible heat transfer in the two cases is expressed as follows [26]:

Case 1:

$$\delta s_{\mathrm{pre},g} = \Sigma s_{\mathrm{pre},o}\delta m_{\mathrm{pre},o} - \Sigma s_{\mathrm{pre},i}\delta m_{\mathrm{pre},i} = \int_{T_{\mathrm{sw},i}}^{T_{\mathrm{sw},o}} \frac{m_{\mathrm{sw}} c_{p,\mathrm{sw}} dT}{T} + \int_{T_{\mathrm{trw},i}}^{T_{\mathrm{trw},o}} \frac{m_{\mathrm{trw}} c_{p,w} dT}{T} + \int_{T_{\mathrm{conc},i}}^{T_{\mathrm{conc},o}} \frac{m_{\mathrm{conc}} c_{p,\mathrm{sw}} dT}{T} \tag{13}$$

Case 2:

$$\delta s_{\mathrm{pre},g} = s_{\mathrm{pre},o}\delta m_{\mathrm{pre},o} - s_{\mathrm{pre},i}\delta m_{\mathrm{pre},i} = \int_{T_{\mathrm{sw},i}}^{T_{\mathrm{sw},o}} \frac{m_{\mathrm{sw}} c_{p,\mathrm{sw}} dT}{T} + \int_{T_{\mathrm{trw},i}}^{T_{\mathrm{trw},o}} \frac{m_{\mathrm{trw}} c_{p,w} dT}{T} \tag{14}$$

3.5. Entropy in the heat exchanger

Vapour produced by the seawater is reused by indirect heat exchange. An amount of latent heat of vapour is transferred to the circulating water and condenses at temperature T_v, the circulating water is warmed to $T_{\mathrm{cw},o}$ from $T_{\mathrm{cw},i}$. The entropy can be estimated from the following equation:

$$\delta s_{\mathrm{hx},g} = s_{\mathrm{hx},o}\delta m_{\mathrm{hx},o} - s_{\mathrm{hx},i}\delta m_{\mathrm{hx},i} = \int_{T_{c,i}}^{T_{c,o}} \frac{m_{\mathrm{cw}} c_{p,w} dT}{T} + \frac{m_v \gamma}{T_v} \tag{15}$$

3.6. Exergy loss of the system

Exergy is the maximum amount of work obtainable when a system is brought into equilibrium from its initial state to the environmental state. The irreversibility occurs in the evaporator, preheater, compressor, circulating water tank, heat exchanger and the pumps in this system. Exergy loss, the result of irreversibility in the energy conversion processes such as heat transfer and pressure drop, is defined as [26] follows:

$$\mathrm{Ex}_{\mathrm{loss}} = T_0 \delta s_g \tag{16}$$

where

$$\delta s_g = \delta s_{\mathrm{evp},g} + \delta s_{\mathrm{ct},g} + \delta s_{\mathrm{pump},g} + \delta s_{\mathrm{com},g} + \delta s_{\mathrm{pre},g} + \delta s_{\mathrm{hx},g} \tag{17}$$

T_0 is the environmental temperature.

4. Results and discussion

As demonstrated above, the entropy generation of the system has a close relationship with the concentration of the seawater, evaporative temperature, heat transfer temperature difference in the evaporator, compressor efficiency and flashing pressure difference. As shown in Table 1, the original concentration of seawater is 3%, the concentration of the concentrated seawater is 18%, and the evaporative temperature varies from 323 to 343 K.

4.1. Exergy balance of the system

The operating parameters such as flow rate, temperature, enthalpy and entropy of CMVC desalination system are shown in Table 2. The saturated vapour generated in the evaporator flows into the heat exchanger, and it releases the latent heat and changes into treated water. The circulating water is heated from 43°C to 48°C. The circulating water with high temperature flashes in the circulating tank, and then the temperature and pressure of the flashing vapour increase after the vapour is compressed by the vapour compressor. The pressure is raised to 0.18 bar, and the compression ratio of the vapour compressor is 2.46. The saturated vapour is compressed to over-heated vapour during the compression due to irreversible loss. The compressed vapour with high temperature and pressure heats the seawater in the evaporator, which serves as a heat source and is collected as pure water in the circulating tank after condensing. The circulating water circulates repeatedly in this way. Therefore, the heat exchanger and the circulating tank are the devices that recover the waste heat, and the vapour compressor produces high pressure vapour to force the separation of the salt and water. The evaporator uses the latent heat of condensation. The exergy input of the system is the power of the vapour compressor, the pumps and the feed seawater. The output exergy is in the product water and concentrated seawater. Table 2 also shows the entropy distribution of the system.

The exergy balance of the desalination system is shown in Fig. 5 and demonstrates that 77.4 kW of exergy enters the system by the feed seawater, compressor and pumps, 24.2 kW of exergy is carried out of the system by the concentrated seawater and the product water, 23.8 kW of exergy is recycled in the system, and 29.4 kW exergy is lost in the system by virtue of the irreversibility taking place in the operation.

Table 1
Thermal parameters of the desalination system

Thermal parameter	Value
Seawater flow rate (m_{sw}), kg/h	1,000
Concentration of seawater (S), %	3.0–18.0
Temperature of original seawater and environment (T_0), K	298
Compressor internal efficiency (η_{in}), %	74
Compressor mechanical efficiency (η_{mech}), %	85
Inlet pressure of the compressor (Pi), bar	0.18
Outlet pressure of the compressor (Po), bar	0.07
Polytropic index (n)	1.13
Evaporative temperature (T_b), K	323–343
Heat transfer temperature difference (ΔT), K	2–6
Specific heat (C_{pw}), kJ/kg K	4.18

4.2. Exergy loss analysis

Based on Tables 1 and 2, the entropy generation of the CMVC seawater desalination system is analysed. The proportion of exergy loss of each component is shown in Table 3. The circulating water tank accounts for the largest proportion of entropy generation, followed by the heat exchanger. To decrease the exergy loss, first, the areas of the heat exchanger

Table 2
Operating parameters of the CMVC desalination system

Working medium	Flow rate (kg/h)	Temperature (K)	Enthalpy (kJ/kg)	Entropy (J/kg K)
Feed seawater	1,000	20	80.34	281.15
Preheated seawater	1,000	25	100.37	346.87
Concentrated seawater	167	53	167.14	374.32
Seawater vapour	833	50	2,592.17	8,063.12
Product water	833	50	209.41	703.79
Condensed pure water	895	58	242.72	806.02
Circulating water	94,457	43	179.99	611.97
Heated circulating water	94,457	48	200.89	677.56
Drainage concentrated seawater	167	53	167.14	374.32

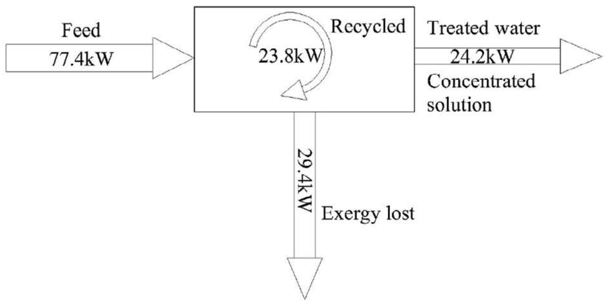

Fig. 5. Exergy balance of the system.

Table 3
Exergy losses of the main components

Component	Exergy losses (%)
Circulating water tank	41
Heat exchanger	23
Evaporator	16
Compressor	14
Preheater	5
Pumps	1

should increase, or material with higher thermal conductivity should be adopted. Second, the heat transfer temperature difference in the evaporator should be reduced. Finally, a pump with high efficiency should be used. Finally, a vapour compressor with a low compression ratio and high internal efficiency should be selected.

The heat exchanger, evaporator, circulating water pump and vapour compressor, the main determiners of the irreversible loss of the closed vapour compression seawater desalination system, are correlated among each other. First, the flashing pressure determines the suction pressure of the vapour compressor as well as the circulating water temperature difference between the inlet and outlet of the heat exchanger. The exergy loss is smaller for a smaller temperature difference. However, the amount of vapour generated by flashing will also be lower. Therefore, the flashing pressure must be reasonable. Second, the evaporative temperature, heat transfer temperature difference in the evaporator and the boiling point elevation determined the discharge temperature of the vapour compressor as well as the discharge pressure, and a suitable suction temperature should be selected to lower the pressure ratio and the compressor consumption. Finally, the seawater vapour condenses on one side of the heat exchanger, and a large amount of latent heat is released; meanwhile, the circulating water is heated to a higher temperature on the other side. To make full use of the latent heat, plenty of circulating water is required because of the lower sensible heat of the water. A circulating water pump with suitable capacity is important for this system.

5. Conclusions

To prevent the compressor from being corroded and damaged, a novel MVC desalination system, denoted as a closed vapour compression desalination system, was proposed. In the system, the vapour produced by the seawater released the latent heat to the circulating water; thus, the temperature increased. The pure vapour from the circulating water flashing was compressed by the compressor and used as the heat source. Therefore, the major feature of the system is that the vapour produced by the seawater does not contact the compressor directly, but it still recycles the waste heat rather than discharging into the environment.

The corresponding mathematical models for an exergy analysis based on the entropy method are established. The exergy loss in an operating CMVC desalination system has been estimated for a typical flow rate of 1,000 kg/h. The following conclusions have been drawn.

- The input exergy comes from two sources, the exergy carried by the feed seawater and the exergy provided by the compressor and pumps, in which 29.4 kW is lost by virtue of the irreversibility taking place in the operation.
- The CMVC desalination system includes an evaporator, a compressor, a pre-heater, a heat exchanger, a circulating tank and three pumps. It has been shown that the major exergy loss takes place in the circulating water tank, which accounts for 41%, since this is a superimposition of flashing and mixing. Additionally, the heat exchanger and evaporator were found to be responsible for a large amount of exergy loss due to the high temperature

difference during heat transfer. It was found that an excessive amount of exergy was lost by the compressor due to the high pressure ratio.

- By optimizing the flashing pressure, the exergy loss in the circulating tank should be decreased. Higher efficiency heat exchangers and lower heat transfer temperature differences can contribute to less exergy loss in the heat exchanger and the evaporator. A suitable compressor and pumps should be selected and operated under the design condition to maximize the efficiency and decrease the exergy loss.

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Symbols

c_p	—	Specific heat
m	—	Mass flow
Q	—	Heat
s	—	Entropy
V	—	Volume flow
η	—	Efficiency
κ	—	Adiabatic exponent
h	—	Enthalpy
P	—	Pressure
Rg	—	Gas constant
T	—	Temperature
W	—	Working
ρ	—	Density

Subscripts

c	—	Circulating water
ct	—	Circulate tank
cv	—	Control volume
d	—	Distilled water
g	—	Generation
i	—	Inlet
mix	—	Mixture
p	—	Pump
sw	—	Seawater
v	—	Vapour
0	—	Environment
con	—	Condensation
conc	—	Concentrated water
com	—	Compressor
evp	—	Evaporator
hx	—	Heat exchanger
mech	—	Mechanical
o	—	Outlet
pre	—	Preheater
trw	—	Treated water
w	—	Water

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Appendix

The relevant parameters can be calculated as follows [28]:
Seawater entropy:

$$s_{\mathrm{sw}}(t,s,p)=c_{p,\mathrm{sw}}(t,s,p_0)+(p-p_0)\times (a_1+a_2t+a_3t^2+a_4t^3+S\times(a_5+a_6t+a_7t^2+a_8t^3)$$

where $c_{p,\mathrm{sw}}(t,s,p_0)$ is given by

$$c_{p,\mathrm{sw}}(t,s,p_0)=A+B(t+273.15)+C(t+273.15)^2+D(t+273.15)^3$$

$$a_1=-3.1118, a_2=0.0157, a_3=5.1014\times10^{-5}, a_4=-1.0302\times10^{-6}$$

$$a_5=0.0107, a_6=-3.9716\times10^{-5}, a_3=3.2088\times10^{-8}, a_4=1.0119\times10^{-9}$$

$$A=5328-9.76\times10^{1}S+4.04\times10^{-1}S^2$$

$$B=-6.913+7.351\times10^{-1}S+3.15\times10^{-3}S^2$$

$$C=9.6\times10^{-3}-1.927\times10^{-3}S+8.23\times10^{-6}S^2$$

$$D=2.5\times10^{-6}+1.666\times10^{-6}S-7.125\times10^{-9}S^2$$

Seawater density:

$$\rho_{\mathrm{sw}}\left(t,S,P\right)=\rho_{\mathrm{sw}}\left(t,S,P_0\right)\times F_P$$

where

$$\rho_{\mathrm{sw}}(t,S,P_0)=(a_1+a_2t+a_3t^2+a_4t^3+a_5t^4)+ (b_1S_{\mathrm{kg/kg}}+b_2S_{\mathrm{kg/kg}}t+b_3S_{\mathrm{kg/kg}}t^2+b_4S_{\mathrm{kg/kg}}t^3+b_5S_{\mathrm{kg/kg}}t^4$$

$$a_1=9.999\times10^{2}, a_2=2.034\times10^{-2}, a_3=-6.162\times10^{-3}, a_4=2.261\times10^{-5}, a_5=-4.657\times10^{-8}$$

$$b_1=8.020\times10^{2}, b_2=-2.001, b_3=1.677\times10^{-2}, b_4=-3.060\times10^{-5}, b_5=-1.613\times10^{-5}$$

$$S_{\mathrm{kg/kg}}=S/1{,}000$$

$$F_P=\exp\left(\int_{P_0}^{P}\kappa_{T,\mathrm{sw}}dP\right) =\exp\left[\begin{array}{l}(P-P_0)\times(c_1+c_2t+c_3t^2+c_4t^3+c_5t^4+c_6t^5)+\\ S\times(d_1+d_2t+d_3t^2)+\dfrac{(P^2-P_0^2)}{2}\times(c_7+c_8t+c_9t^3+d_4S)\end{array}\right]$$

$$c_1=5.0792\times10^{-4}, c_2=-3.4168\times10^{-6}, c_3=5.6931\times10^{-8}$$

$$c_4=-3.7263\times10^{-10}, c_5=1.4465\times10^{-12}, c_6=-1.7058\times10^{-15}$$

$$c_7=-1.3389\times10^{-6}, c_8=4.8603\times10^{-9}, c_9=-6.8039\times10^{-13}$$

$$d_1=-1.1077\times10^{-6}, d_2=5.5584\times10^{-9}, d_3=-4.2539\times10^{-11}, d_4=8.3702\times10^{-9}$$

Seawater isothermal compressibility correlation:

$$\kappa_{T,\mathrm{sw}}=\kappa_{T,w}+S\times(B_1+B_2t+B_3t^2+B_4P)$$

where

$$\kappa_{T,w}=A_1+A_2t+A_3t^2+A_4t^3+A_5t^4+A_6t^5+P\times\left(A_7+A_8t+A_9t^3\right)$$

$$A_1=5.0792\times10^{-4}, A_2=-3.4168\times10^{-6}, A_3=5.6931\times10^{-8}$$

$$A_4=-3.7263\times10^{-10}, A_5=1.4465\times10^{-12}, A_6=-1.7058\times10^{-15}$$

$$A_7=-1.3389\times10^{-6}, A_8=4.8603\times10^{-9}, A_9=-6.8039\times10^{-13}$$

$$B_1=-1.1077\times10^{-6}, B_2=5.5584\times10^{-9}, B_3=-4.2539\times10^{-11}, B_4=8.3702\times10^{-9}$$

Seawater enthalpy:

$$h_{\mathrm{sw}}(t,S,P_0)=h_{\mathrm{sw}}(25°\mathrm{C},S,0.101\mathrm{MPa})+\int_{25}^{t}c_{p,\mathrm{sw}}(t,S,P_0)dt+ \int_{0.101}^{P_0}\left(\frac{1}{\rho_{\mathrm{sw}}}-\frac{(t+273.15)\beta_{P,\mathrm{sw}}}{\rho_{\mathrm{sw}}}\right)dP$$