Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2023.29814

304 (2023) 25–35
August

Study on multi-effect mechanical vapor recompression systems used for the concentration of industrial high salt wastewater

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Received 28 December 2022; Accepted 25 July 2023

ABSTRACT

Multi-effect mechanical vapor recompression (MVR) system is an effective technology for concentrating industrial high-salt wastewater that has high boiling point elevation (BPE). To minimize the technical requirements of steam compressor, a superheat eliminator is incorporated in the multi-effect MVR system. By employing the Aspen Plus software, simulations are conducted to evaluate the performance of the modified single-effect to five-effect MVR systems in concentrating calcium chloride solute from 5% to 30%. With the simulation results, impact of the number of evaporators and heat transfer temperature difference, along with the benefit of superheat eliminator are analyzed. This analysis aims to guide the optimal design of a multi-effect MVR device. It is concluded that the heat transfer temperature difference should not be higher than 9°C for systems with more than three evaporators. The addition of evaporators leads to higher pressure ratio of the compressor and increased consumption of fresh steam. The operation costs of two-effect system and three-effect system are similar. Furthermore, the benefit derived from the superheat eliminator, in terms of power and suction volume reduction, become more pronounced as the BPE increases. Incorporating energy-efficient devices for fresh steam generation can further facilitate the utilization of multi-effect MVR systems for high-salt wastewater concentration.

Keywords: Multi-effect; Mechanical vapor recompression; Boiling point elevation; Exergy analysis; Gained output ratio

1. Introduction

Currently, the world is grappling with significant challenges regarding energy and freshwater scarcity. These issues are particularly acute in developing countries, such as China, where rapid development exacerbates the situation [1]. Additionally, industrial regions in these countries face severe pressures of high-salt wastewater treatment. Resents reports indicate a concerning rise in the discharge volume of high-salt wastewater in the Yangtze River Delta of China, increasing from 9,670 million·m^3 in 2016 to 10,594 million·m^3 in 2018 [2]. Notably, the salt mass fraction of the high-salt wastewater is greater than 1% and its composition is complex, including Cu^{2+}, K^+, Ca^{2+}, Na^+, Mg^{2+}, CO_3^{2-}, NO_3^{2-}, Cl^-, SO_4^{2-} and other ions [3]. Discharging such high-salt wastewater poses a severe threat to water resources, necessitating the development of advanced industrial wastewater treatment technologies that can adhere to stringent emission standards.

The emerging technology of zero liquid discharge (ZLD) has garnered significant attention and is considered to be a key pathway to achieve industrial sustainable development [4]. The ZLD process comprises four steps [5]: physical/chemical pretreatment, concentration, crystal and solid–liquid separation. Although the ZLD technology is capable of minimizing contamination of water sources, its widespread implementation is constrained by the substantial costs and

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intensive energy consumption [6]. A viable approach to promote the application of ZLD is to minimize the investment and operating cost associated with concentration process [5].

In comparison to membrane-based reverse osmosis (RO) and electro dialysis (ED), the thermal-based concentration technologies are more adaptable and relatively mature in terms of treating high-salt and organic wastewater [7]. Among various thermal-based technologies, multi-effect evaporation systems have emerged as the prevailing choice for industrial wastewater treatment [8]. However, traditional thermal wastewater concentration processes consume a substantial amount of energy due to the significant latent heat of water. Besides, part of the steam condensing heat is wasted. Consequently, many scholars have proposed various self-heat recovery (SHRT) methods to recycle the waste heat [9,10]. Mechanical vapor recompression (MVR) technology is one of the most effective way, which enables the complete recovery of condensing heat from low-temperature steam by compressing it to a higher temperature level. The compressed steam is then utilized as the heat source for the wastewater evaporation. The integration of MVR with multi-effect evaporation systems has been proven to exhibit high energy efficiency for different industrial wastewater treatment [11,12].

In recent years, numerous studies have been carried out on the application of multi-effect MVR systems for treating the industrial high-salt wastewater. He et al. [9] conducted an energy consumption comparison between a single-effect MVR system and a conventional three-effect evaporation system for the concentration of calcium chloride solution ($CaCl_2$). It was concluded that the single-effect MVR system consumed less energy until the inlet mass fraction of $CaCl_2$ was over 38%. Liang et al. [13] proposed a double-effect MVR system for the treatment of high-salt wastewater. The system was simulated by Engineering Equation Solver selecting ammonium sulfate wastewater as the treated solution. Results showed that the power consumption of double-effect MVR system was lower. Yue et al. [10] proposed a cogeneration system integrating thermal-based concentration and power generation. $CaCl_2$ solution was selected as the treatment solution and the system was simulated by Aspen Plus software. Results showed that the cogeneration system was more energy-saving. Yang et al. [14] compared the performances of single-effect MVR, double-effect thermal vapor recompression (TVR) and double-effect MVR systems based on Aspen Plus simulation results. It was concluded that the double-effect MVR system was more energy efficient than single-effect MVR and double-effect TVR systems when the treated solution was brine. Liu et al. [15] proposed a kind of hierarchical compression MVR evaporation system, considering the pressure and temperature elevation capability of steam compressors. It was concluded that the proposed system was more suitable for solutions with boiling point elevation (BPE) over 15°C. Jiang et al. [16] designed a parallel-connected double-effect MVR evaporation crystallization system, which combined the falling film evaporator with the forced circulation evaporator. By using 5% sodium sulfate solution as the treated solution, they found that the new system outperformed the multi-effect evaporation (MEE) system.

It is widely recognized that each solution has a corresponding BPE, which raises the solution's boiling temperature [17]. Moreover, the evaporated steam is in superheat state. Fig. 1 illustrates the relationship between the BPE of some solutions and their solute concentration. It is evident that higher solute mass fractions lead to greater BPE. The BPE has direct influence on the required technical parameters of the steam compressor including the achievable pressure ratio, suction volume and compression power. As the steam compressor is the critical component, its technical parameters not only affect the energy efficiency but also the investment and operating cost of different MVR concentration plants [18,19]. At present, few studies were reported on the optimal design of multi-effect MVR systems dealing with industrial high-salt wastewater. Therefore, there is a need to investigate how to strike a balance between the achievable technical parameters of an actual steam compressor, the number of evaporators, and the associated system investment and operating costs.

This paper introduces a modification to the multi-effect mechanical vapor recompression (MVR) system by incorporating a superheat eliminator at the steam compressor inlet. Fresh steam is necessary to maintain the heat balance. Taking the often-studied $CaCl_2$ solution as the representative of industrial high-salt wastewater, performances of five multi-effect MVR systems are simulated, ranging from a single-effect MVR system to five-effect MVR system. The simulations are carried out using Aspen Plus software, which is widely used for theoretical research in this field. According to the simulation results, the influence of the heat transfer temperature difference and number of evaporators on the system performance are investigated. Additionally, the economics and exergy aspects of each MVR system are analyzed. To assess the energy-saving benefits, the gained output ratio (GOR) index is employed. Notably, this study incorporates the influence of fresh steam consumption into all analyzed performance parameters, which was often overlooked in previous studies. It is aimed to provide theoretical support and reference for the optimal design of a multi-effect MVR device to treat industrial high-salt wastewater.

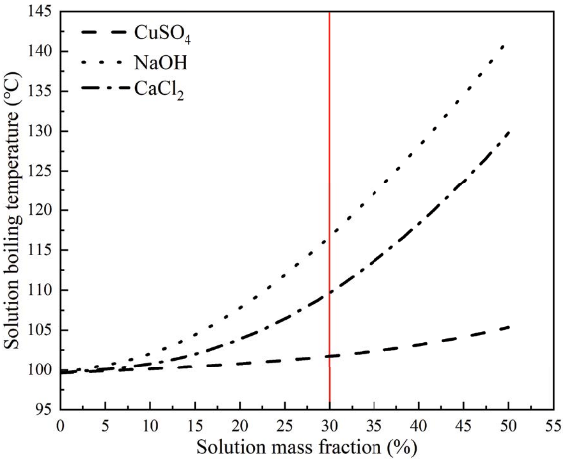

Fig. 1. Relationship between BPE and concentration of saline solutions.

2. System description

Fig. 2 shows the *p-h* diagram of a typical MVR process used for high-salt industrial wastewater. Points 1 and 2 represents the low-pressure wastewater evaporation stage, where the steam generated is in a superheated state due to the effect of BPE. Subsequently, the low-pressure steam is compressed from state 2 to state 3 by a steam compressor. The high pressure compressed steam undergoes condensation from state 3 to state 4, with the released heat serving as the heat source for the low-pressure water evaporation.

If the superheat of the low-pressure steam is eliminated, the compression process changes from state 2′ to 3′. It is noteworthy that eliminating the superheat reduces both the compression power and the discharge temperature of the steam compressor. Typically, higher pressure ratio results in higher superheat value or higher temperature of compressed steam. In reality, the discharge temperature sets a limit on the achievable pressure ratio of a steam compressor. Besides, the specific volume of the steam at state 2′ is smaller than that at state 2. Consequently, not only the compression power but also the volume flow rate of the steam compressor can be decreased once the steam superheat is eliminated. Although part heat is wasted, this modification proves more advantageous for the steam compressor. Therefore, incorporating a superheat eliminator is considered when modifying a multi-effect MVR system for high-salt industrial wastewater concentration.

From Fig. 2, it can also be observed that the condensation latent heat released by the high-pressure steam is smaller than the evaporation latent heat of low pressure water. Besides, the feed solution in the first effect evaporator should be pre-heated to saturation. As a result, a small amount of fresh steam is still required for a multi-effect MVR system since the compression power may not adequately compensate for the heat difference. The fresh steam with the same pressure as the compressed steam is mixed with the compressed steam at the steam inlet of the first effect evaporator. Both the superheat eliminator and fresh steam are crucial for a multi-effect MVR system capable of handling high-salt wastewater with significant BPE. Consequently, five modified multi-effect MVR systems are introduced and studied, ranging from single-effect MVR system to five-effect MVR system. In order to void crystallization of the concentrated solution, the preheater to recycle the heat of concentrated solution is eliminated in each modified system.

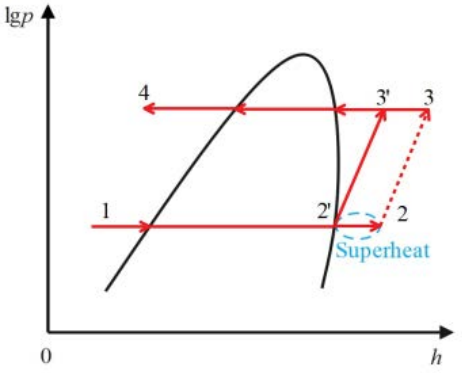

Fig. 2. Temperature entropy diagram of steam compressor.

2.1. Single-effect MVR system

Fig. 3 presents the schematic diagram of a single-effect MVR system, which operates as follows: initially, the feed solution is pumped into the preheater, where it is preheated by the condensed water from the evaporator. Subsequently, the preheated solution enters the evaporator and is heated by the high temperature steam. Therefore, the secondary steam is generated by water evaporation, while the solution is concentrated. Due to the effect of BPE, the secondary steam is in a superheated state (a′). Before entering the steam compressor, the secondary steam is cooled to saturate state (a) by the superheat eliminator. The compressed high-pressure steam (b) and the fresh steam are then directed back into the evaporator, where they release their condensation heat to the solution. Before discharging into a water tank, the condensed water (c) will be cooled to state (d) by the feed solution in the preheater. The concentrated solution out of the evaporator will flow into the subsequent crystallization equipment.

2.2. Multi-effect MVR systems

Taking the three-effect MVR system as an example, its system diagram is depicted in Fig. 4. On the base of a single-effect MVR system, the addition of one effect means adding one evaporator with a lower pressure. Both the secondary steam and the concentrated solution from the preceding evaporator flow into the subsequent evaporator for further concentration. The steam compressor draws its suction steam from the final effect evaporator. The feed solution undergoes continuous preheating through the condensed water from the final evaporator to the first evaporator. The compressed steam, in conjunction with the supplied fresh steam, is solely directed to the first effect evaporator. The main difference between the single-effect system and the multi-effect MVR system is that additional flash steam

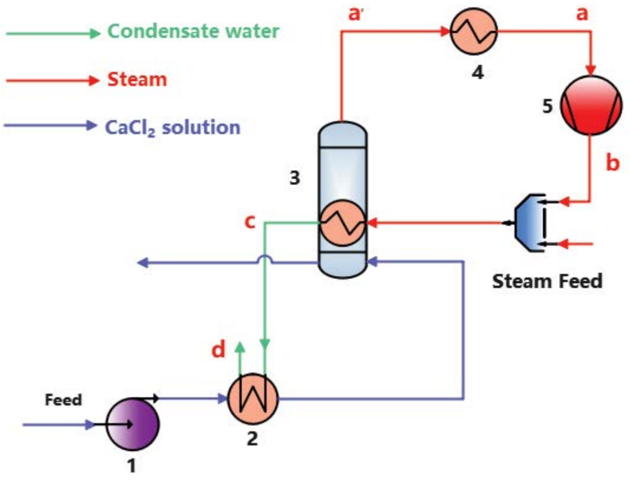

Fig. 3. Schematic diagram of a one-effect MVR system. (1) Centrifugal pump; (2) preheater; (3) evaporator; (4) superheat eliminator; (5) steam compressor.

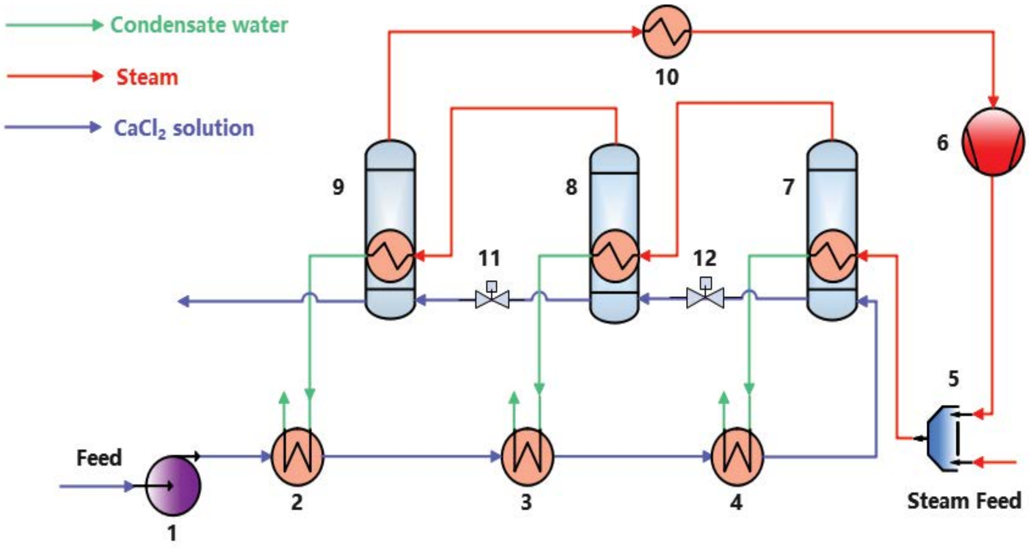

Fig. 4. Schematic diagram of the three-effect MVR system. (1) Centrifugal pump; (2–4) preheaters; (5) mixer; (6) steam compressor; (7) first evaporator; (8) second evaporator; (9) third evaporator; (10) superheat eliminator; (11–12) pressure reducing valve.

can be generated once solution with a relatively high temperature enters the evaporator with lower pressure. As a consequence, the solution experiences progressive concentration. Moreover, with a constant solution concentration, an increase in the number of evaporators leads to a decrease in the size of each individual evaporator. However, the pressure ratio or saturate temperature rise of the steam compressor will increase.

3. Methods

Method of theoretical research on the performance of five multi-effect systems are adopted in this paper. The simulation process and performance definition are included in this section. The assumptions, models, model validation and parameter definitions are all referred to [20].

3.1. Basic assumptions

The following basic assumptions are made for the process simulation:

- Steady-state operation;
- No heat losses to surroundings;
- Pressure drop of the pipeline and power consumption of the pump are ignored.

3.2. Models

3.2.1. Mass balance

Mass balance equations of the multi-effect MVR system are expressed according to the relevant schemes:

$$m_f + m_{\text{st}} = \sum_{i=1}^{n} m_i + m_{\text{con}} \tag{1}$$

where m_f is the mass of feed solution, kg/h; m_{st} is the mass of fresh steam, kg/h; m_i is the mass of condensed water, kg/h; m_{con} is the mass of the concentrated solution.

3.2.2. Energy balance

Overall energy balance of the multi-effect MVR system can be figured by:

$$H_f + P_c + H_{\text{st}} = \sum_{i=1}^{n} H_i + H_{\text{con}} \tag{2}$$

where H_f is enthalpy of feed solution, kJ; P_C is the power consumption of the compressor, kJ; H_{con} is the enthalpy of concentrated solution, kJ; H_{st} is the enthalpy of fresh steam, kJ; H_i is the enthalpy of condensed water in each evaporator, kJ.

3.2.3. Compressor model

The compression power of the steam compressor is given as:

$$P_c = m_i \frac{p_{c,s}}{\eta_c \eta_m} = m_i \frac{kR_g T_i}{\eta_c \eta_m (k-1)} \left[\left(\frac{P_o}{P_i} \right)^{\frac{k-1}{k}} - 1 \right] \tag{3}$$

where η_c is the thermal efficiency of the compressor; η_m the mechanical efficiency of the compressor; k is the adiabatic exponent during the compression process; $p_{c,s}$ is the compressor power in isentropic process, kW; p_o is the compressor outlet pressure, kPa; p_i is the compressor inlet pressure, kPa; m_i is the mass flow rate of secondary steam in compressor, kg/h; R_g and T_i is the gas constant and compressor inlet temperature, respectively.

3.2.4. Simulation model

Based on the schematic diagrams of single-effect MVR system to five-effect MVR system, simulation models are established using Aspen Plus v11 software. As an example, the simulation model of the three-effect MVR system is presented in Fig. 5. The compressor utilizes the COMPR module, while the evaporator consists of a FLASH module and a HEATER module. It is important to note that the gas fraction at the outlet of the hot flow unit in the HEATER module is set to zero. The preheater is composed of two HEATER modules and the mixer is represented by a MIXER module.

3.3. Model validation

In order to assess the validity and precision of the developed simulation models, the performance of a single-effect MVR system in the Eunice et al. [21] is firstly simulated. Table 1 shows the comparison between the simulation results, the reported experimental findings, and the design parameters. It can be found that the deviation between the simulation results and experimental results is minimal. From the error of different parameters, it can be concluded that the established simulation model has a certain accuracy for the simulation of the single-effect MVR system and can be confidently employed for simulating multi-effect MVR systems within an acceptable range of error.

3.4. Parameters setting

Aspen Plus has a complete physical property system and the physical property data are the key to obtain accurate and reliable simulation results. Based on the BPE variation of $CaCl_2$ solution illustrated in Fig. 1, it is observed that the BPE of the solution experiences a rapid increase when the solute mass fraction exceeds 30%. To maintain a specific heat transfer temperature difference, the compressor power exhibits a sharp rise with the BPE increment. Hence, the final concentration of the $CaCl_2$ solution is set at 30% for the simulation of each MVR system in this paper with the aim of determining an optimal number of evaporators.

To satisfy the heat transfer temperature difference requirement of each evaporator, it is crucial to ensure a sufficiently large pressure difference between each effect of the multi-effect MVR system. The pressure adjustment

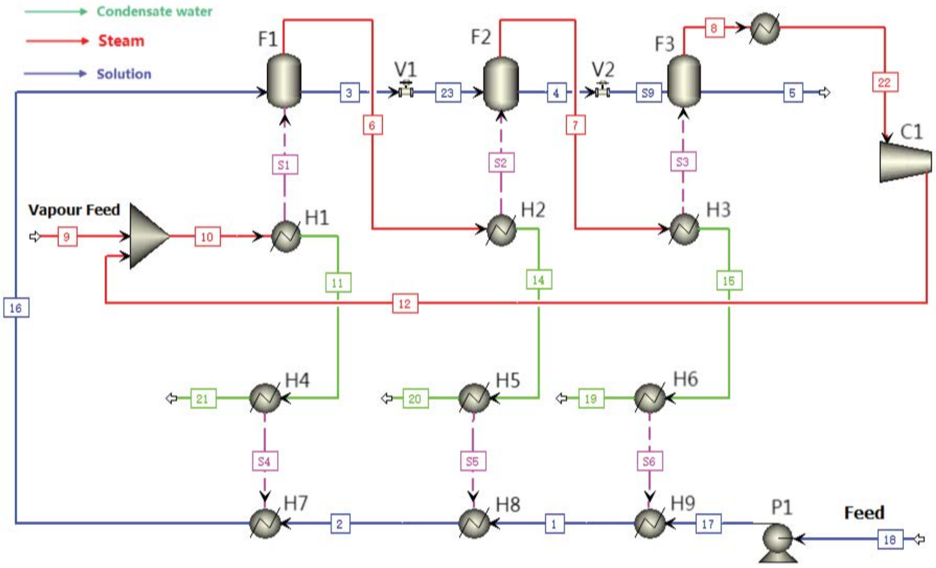

Fig. 5. Simulation diagram of three-effect MVR system. P1 centrifugal pump; H1–H9 heat exchanger; H10 superheat eliminator; M1 mixer; F1 first evaporator; F2 second evaporator; F3 third evaporator; C1 steam compressor; V1–V2 pressure reducing valve.

Table 1
Simulation results and experimental results vs. design parameters

Process parameters	Design parameters	Experimental results	Simulation results	Error (%)
Mass flow rate of feed (kg/h)	25.0	24.0	25.0	4.2
Concentration of feed (%)	2.0	2.0	2.0	0
Temperature of feed (%)	78.0	78.0	78.0	0
Condensing temperature (°C)	86.0	86.3	86.0	–0.4
Concentration (%)	10.0	10.0	10.0	0
Evaporation rate (kg/h)	20.0	20.0	19.7	–0.1
Evaporation pressure (kPa)	47.4	48.6	47.4	–2.4
Condensation pressure (kPa)	60.1	61.8	60.1	–2.7
Temperature difference (°C)	5.0	5.2	5.1	–0.6

step is set at 5 kPa. The heat transfer temperature difference between the steam and wastewater is set to be no less than 5°C. Another objective of this research is to assess the impact of the heat transfer temperature difference. The mass flow rate of the feed is fixed at 1,000 kg/h, while the temperature and concentration of the feed solution are set at 25°C and 3%, respectively. Before entering the evaporator, the feed solution is preheated by the condensed water to a degree of 65°C. Since the primary focus of this paper is to investigate the influence of evaporator numbers, the steam compressor efficiency is maintained at a constant value of 0.72 [16]. Details of other main setup parameters for the simulation are listed in Table 2.

3.5. Performance definition

One characteristic of the five multi-effect MVR systems is the requirement for fresh steam during system operation. While the inclusion of fresh steam supply has been mentioned in some previous studies, its impact on system performance has received limited attention. In order to provide a more comprehensive understanding for the optimal design of multi-effect MVR devices, this paper takes the consumption of fresh steam into consideration when discussing system performances.

3.5.1. Operating cost

The operating cost of a multi-effect MVR system is applied to evaluate the economy, which is given by:

$$C = c_{\mathrm{st}} \times q_{\mathrm{st}} + c_{\mathrm{el}} \times P_c \tag{4}$$

where C is the operating cost of the system, yuan/h; c_{st} is the unit price of fresh steam, yuan/t; q_{st} is the flow rate of fresh steam, t/h; c_{el} is the unit price of electricity, yuan/(kW·h).

3.5.2. Exergy efficiency and destruction

Exergy efficiency is used to assess the thermodynamic perfection of the system. The exergy destruction can indicate the direction of the optimization way to further improve the system energy efficiency [22]. Taking the state of feed solution as the ambient reference state, the exergy efficiency of the system is defined as follows:

$$\eta_{\mathrm{ex}} = \frac{E_{o1} + E_{o2}}{P_c + E_{\mathrm{st}}} \tag{5}$$

where E_{o1} is the exergy of the condensed water out of the system, kJ; E_{o2} is the exergy of the concentrated solution out of the system, kJ; E_{st} is the exergy of the consumed fresh steam, kJ.

The total exergy destruction is represented as follows:

$$A_n = (P_c + E_{\mathrm{st}}) \times \left(1 - \eta_{\mathrm{ex}}\right) \tag{6}$$

The percentage of compressor exergy destruction to total exergy destruction is defined as:

$$\eta_c = \frac{P_c - \left(E_{X2} - E_{X1}\right)}{A_n} \tag{7}$$

where E_{x2} is the exergy of the outlet steam of the compressor, kJ; E_{x1} is the exergy of the suction steam of the compressor, kJ.

The percentage of evaporator exergy destruction is expressed as follows:

$$n_{\mathrm{e}} = \frac{\left(E_{x3} - E_{x4}\right) - \left(E_{x5} + E_{x6} - E_{x7}\right)}{A_n} \tag{8}$$

where E_{x3} is the exergy of steam at the inlet of the evaporator, kJ; E_{x4} is the exergy of condensed water at the outlet of the evaporator, kJ; E_{x5} is the exergy of the secondary steam out of the evaporator, kJ; E_{x6} is the exergy of the concentrated solution out of the evaporator, kJ; E_{x7} is the exergy of the solution at the evaporator inlet, kJ.

The percentage of pre-heater exergy destruction is calculated as follows:

$$n_{\mathrm{pre}} = \frac{\left(E_{x8} - E_{x9}\right) - \left(E_{x10} - E_{x11}\right)}{A_n} \tag{9}$$

where E_{x8} and E_{x9} is the exergy of condensed water at the preheater heat inlet and outlet, respectively, kJ; E_{x10} and E_{x11} is the exergy of feed at the preheater inlet and outlet, respectively, kJ.

3.5.3. Gained output ratio

The GOR index is used to evaluate the thermodynamic efficiency of multi-effect MVR systems which is defined as follows:

$$\mathrm{GOR} = \frac{m_d}{m_s + m_q} \tag{10}$$

Table 2
Main parameter setting values for the simulation process

Parameters	One-effect	Two-effect	Three-effect	Four-effect	Five-effect
First effect pressure (kPa)	50	85	105	130	150
Second effect pressure (kPa)	–	50	85	105	125
Third effect pressure (kPa)	–	–	50	85	100
Fourth effect pressure (kPa)	–	–	–	50	80
Fifth effect pressure (kPa)	–	–	–	–	50
Fresh steam pressure (kPa)	–	105	130	156.5	182.5

where m_d is the fresh water production rate of the multi-effect MVR system, kg/h; m_s is the amount of water converted from the fresh steam consumption, kg/h; m_q is the amount of water converted from the power of steam compressor, kg/h.

The pressure of fresh steam is the same as the compressed steam out of the compressor. The water vapor is condensed into saturated water in the evaporator, and the temperature of saturated water decreases by 40°C after entering the preheater to preheat the solution. The m_s and m_q are calculated as follows:

$$m_s = \frac{Q_{\mathrm{st}} + Q_{\mathrm{wa}}}{q_{s1} + q_{s2}} \tag{11}$$

$$m_q = \frac{P_c \times 3600}{q_{s1} + q_{s2}} \tag{12}$$

where Q_{st} is the latent heat released by the fresh steam, kJ; Q_{wa} is the consequent sensible heat released by the condensed water, kJ; P_c is the compression power of a steam compressor, kJ; q_{s1} is sensible heat absorbed per unit mass of solution in the evaporator of a single-effect system, kJ/kg; q_{s2} is the latent heat absorbed per unit mass of solution in the evaporator of a single-effect system, kJ/kg. The q_{s1} and q_{s2} are defined in this way to better analyze the impact of increasing the number of evaporators.

4. Results and discussion

In this section, a comprehensive analysis of the multi-effect MVR system is conducted based on the simulation results, including energy analysis, economic analysis, exergy analysis, and thermodynamic efficiency analysis. The objective is to investigate the effects of various factors, including the number of evaporators, heat transfer temperature difference, and superheat eliminator, on the system performance. The results are crucial for optimizing the design of multi-effect MVR devices employed in the concentration of industrial high-salt wastewater. The heat transfer temperature difference is defined as the difference between the steam condensing temperature and the solution evaporating temperature.

4.1. Energy analysis

The compression power and fresh steam are the two main energy form consumed by the multi-effect MVR system. The relationship between the number of evaporators, heat transfer temperature difference, and the consumption of compression power and fresh steam is depicted in Figs. 6 and 7, respectively. The variation of pressure ratio and suction volume flow of the steam compressor are also shown in Fig. 6. Generally, as the number of evaporators increases, the compression power decreases gradually. However, the rate of decline diminishes progressively. The compression power even starts to increase when the number of evaporators reaches four to five with a heat transfer temperature difference of 9°C. Conversely, the consumption of fresh steam increases as the number of evaporators rises. This is primarily due to that the multi-effect system utilizing the pressure difference between the evaporators to evaporate a portion of the water, known as the SHRT (Secondary Heat Recovery Technology). As a result, the mass of steam entering the compressor from the final evaporator decreases, as shown in Fig. 6. The compression power is determined by the mass of compressed steam and pressure ratio. Although the mass of compressed steam decreases with the increasing number of evaporators, the pressure ratio rises. The influence of pressure ratio gradually becomes more pronounced as its value increases. As the mass of compressed steam into the first effect evaporator decreases, more fresh steam is required to maintain the heat balance due to the latent heat difference increases with the number of evaporators.

The heat transfer temperature difference is a significant parameter for the design of evaporators. From Figs. 6 and 7, it can be concluded that both the compression power and fresh steam consumption increase with the rise of heat exchange temperature difference. This can be attributed to the larger pressure ratio of the compressor and higher temperature or pressure of the fresh steam associated with a higher temperature difference. Fig. 2 illustrates that the latent heat difference also escalates with the saturation temperature difference. Consequently, both the compression power and fresh steam consumption experience an increase. However, the

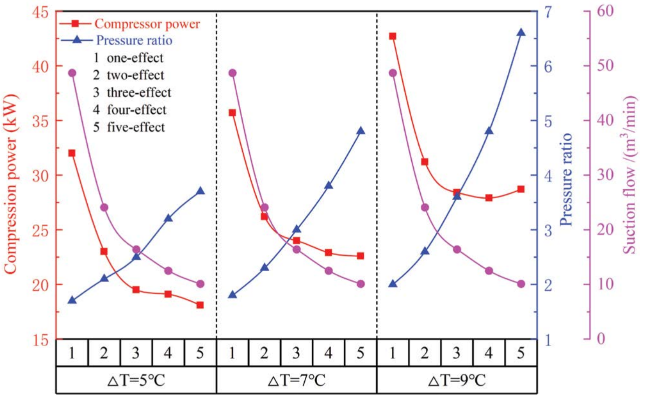

Fig. 6. Parameters of steam compressor in multi-effect MVR systems.

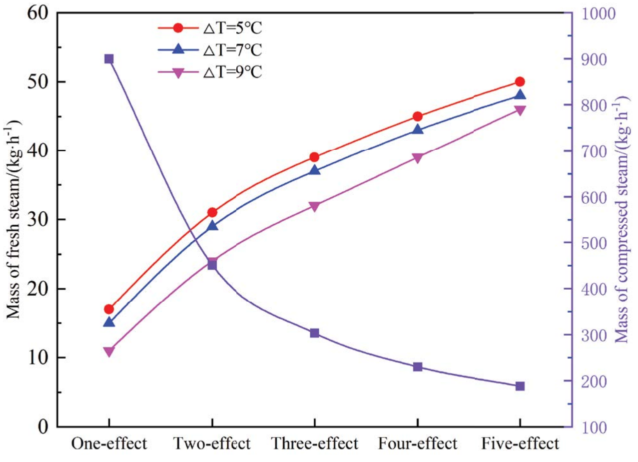

Fig. 7. Mass of fresh steam and compressed steam of multi-effect MVR systems.

mass of compressed steam is not affected by the heat transfer temperature difference. Although the fresh steam has the following functions: (1) preheating the feed solution; (2) compensating the latent heat difference between low pressure solution and high pressure steam; (3) compensating the heat dissipated by the superheat eliminator, its mass is still quite small compared to the compressed steam.

4.2. Economic analysis

Based on energy consumption, the operation costs of a multi-effect system can be calculated using Eq. (1). It should be noted that the electricity and steam prices vary across regions. In China, the price ranges for electricity and steam are 0.7–1.0 yuan/kW·h and 150 to 250 yuan/t, respectively. To accurately estimate the operational costs of multi-effect MVR systems, four different price combination plans from Shen et al. [20] are considered for the economic analysis, as presented in Table 3. Fig. 8 shows the operating cost of each MVR system with different heat transfer temperature difference. It can be observed that the operating costs of the four multi-effect MVR systems are all lower than that of the single-effect MVR system for the four price plans. When the heat transfer temperature difference is 5°C, the operation cost remains relatively stable with the number increase of evaporators when the number of evaporators is bigger than two. For larger heat transfer temperature difference, the operation cost initially decreases and then increases with the number increase of evaporators. The operation costs of two-effect system and tree-effect MVR system are comparable.

In addition to operation costs, the investment cost is another factor that has to be considered for the design of a multi-effect MVR system. The investment cost primarily depends on the evaporators and steam compressor. The manufacturing technology for the evaporator has been well established, given the widespread use of multi-effect concentration systems. For the fixed concentration demand, the total heat transfer area varies little. Consequently, the investment cost of the steam compressor becomes more significant, which is mainly determined by the technical parameters including pressure ratio, suction volume flow and the power.

As shown in Fig. 6, the pressure ratio increases while the suction volume flow and compressing power decrease with an increasing number of evaporators. With a higher heat transfer temperature difference, the pressure ratio and compression power increase, but the suction volume remains constant. For a five-effect MVR system with a heat transfer temperature difference of 9°C, the pressure ratio reaches 6.6. It is challenging for a practical machine. A pressure ratio round 2.0 is more preferred and frequently used in MVR desalination systems.

To assess the effectiveness of a superheat eliminator, Table 4 lists the technical parameters of the steam compressors for the five MVR systems with and without suction superheat eliminator, when the heat transfer temperature difference is 5°C. In the table, Y and N represents the system with and without suction superheat eliminator, respectively. As depicted in Table 4, the suction flow and power of the steam compressor is reduced by adding a superheat eliminator at the suction side. However, the benefits of the superheat eliminator diminish with a mass decrease of compressed steam. As the precise cost of steam compressor is difficult to estimate accurately, its investment cost is not discussed. Nevertheless, the variation of pressure ratio and suction volume flow of the steam compressor, as clearly shown in Fig. 6, can provide significant reference for the optimal design of a multi-effect MVR device.

In conclusion, a two-effect MVR system emerges as a preferable option for concentrating industrial high-salt wastewater considering the initial investment and operating cost of a multi-effect MVR system. While increasing the number of evaporators can decrease the compressor suction

Table 3
Four price combinations

Plan	1	2	3	4
Steam price (yuan/t)	150	250	150	250
Electricity price Yuan (kW·h)	0.7	0.7	1	1

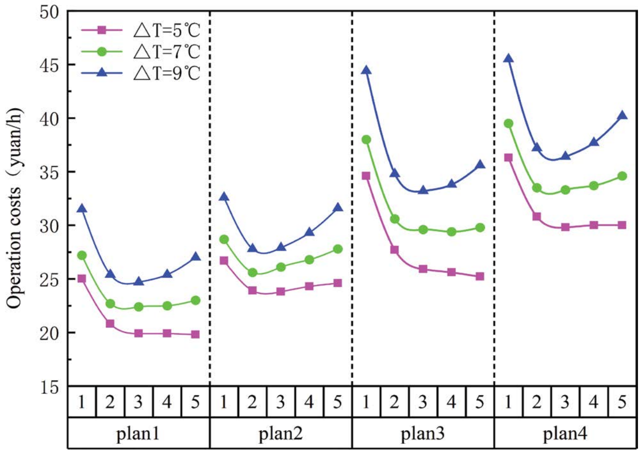

Fig. 8. Economic analysis results of multi-effect MVR systems.

Table 4
Selection parameters of the evaporators and compressor

Parameters	One-effect		Two-effect		Three-effect		Four-effect		Five-effect	
	Y	N	Y	N	Y	N	Y	N	Y	N
Pressure ratio	1.7	1.7	2.1	2.1	2.5	2.5	3.15	3.15	3.7	3.7
Suction flow (m^3/min)	48.9	50.1	24.5	25.1	16.4	16.9	12.5	12.8	10.1	10.4
Power (kW)	32.0	32.9	23.0	23.6	19.5	20.0	19.1	19.6	18.1	18.5

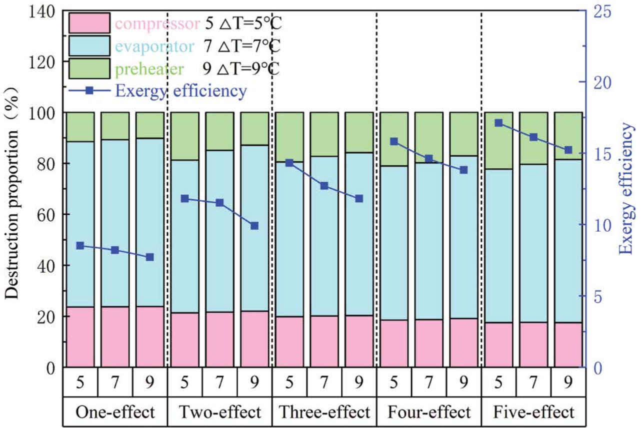

Fig. 9. Exergy analysis results of the multi-effect MVR systems.

volume flow, it is crucial to account for the achievable pressure ratio within a specific discharge temperature of a steam compressor, when determining the optimal number of evaporators.

4.3. Exergy analysis

Fig. 9 presents the calculated exergy efficiency and destruction results obtained by substituting the simulated data to the corresponding equations. It is evident that the exergy efficiency of an MVR system exhibits a gradual increase with an increasing number of evaporators, which aligns with the conclusion drawn from experimental data in Liang et al. [23]. Besides, the exergy efficiency decreases with the increase of heat transfer temperature difference. From the proportions of exergy destruction shown in Fig. 10, it can also be found that the evaporator in each effect MVR system accounts for the largest proportion of exergy destruction. As the number of evaporators rises, the exergy destruction proportion of the preheater shows a gradual increase, while the exergy destruction proportion of the compressor decreases. Meanwhile, with an increasing heat transfer temperature difference, the exergy destruction of the compressor in each MVR system remains relatively stable, whereas the exergy destruction of the evaporator increases and the exergy destruction of the preheater decreases.

4.4. Thermodynamic efficiency analysis

The solid lines in Fig. 10 illustrate the variation of GOR with the number of evaporators and heat transfer temperature difference. A decrease in GOR means a reduction in system thermal efficiency. As shown in Fig. 10, the GOR of one-effect MVR system is the highest. Under the same temperature difference, the GOR progressively decreases with an increasing number of evaporators. This outcome stems from the rise in fresh steam consumption as shown in Fig. 7. Despite the decrease in compression power in a multi-effect MVR system, the converted fresh steam flowrate is not negligible. The impact of fresh steam on the GOR is substantial.

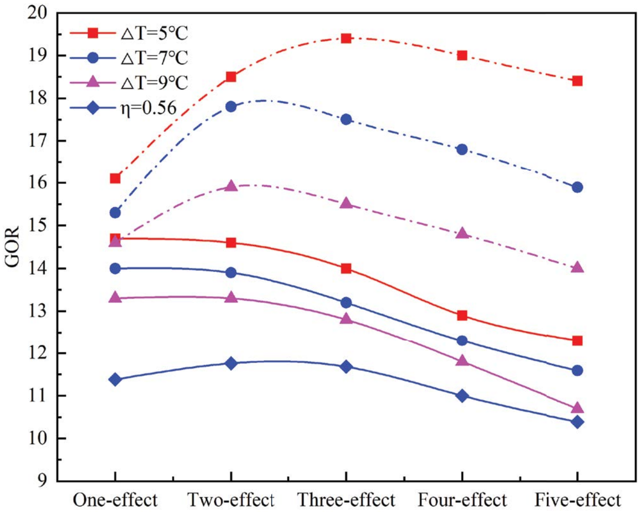

Fig. 10. GOR analysis results of multi-effect MVR systems.

Although the multi-effect MVR system has lower operating cost, their GOR is smaller due to the fresh steam consumption. A promising approach to enhance the GOR of multi-effect MVR system is to reduce the energy consumption associated with the fresh steam. Scholars both domestically and internationally have conducted numerous experiments on integrating novel energy steam generator devices into desalination and wastewater evaporation treatment systems, yielding remarkable experimental results [24–26].

If energy efficient devices are employed to provide fresh steam, the energy consumed by the fresh steam can be significantly reduced. For instance, utilizing an air source heat pump with a coefficient of performance (COP) of 2 to provide fresh steam, the GOR results of the multi-effect MVR system are depicted as the dotted line in Fig. 10. It can be found that the GOR of all the five system increases. Besides, an optimal number of evaporators exists to get the highest GOR. With the ongoing advancements in heat pump technology to achieve higher COP, the advantages of multi-effect MVR systems will become increasingly prominent. Another factor that affects the GOR a lot is the compression efficiency of a steam compressor. The GOR of each system with a compression efficiency of 0.56 and a constant heat transfer temperature difference of 7°C is also presented in Fig. 10. It can be concluded that lower compression efficiency results in smaller GOR. A further study is still necessary to consider the energy consumption of fresh steam and compression efficiency of steam compressor more precisely by referring the practical product parameters.

5. Conclusion

By incorporating a superheat eliminator at the suction side of a steam compressor, five multi-effect MVR systems, ranging from single-effect to five-effect, are proposed for the treatment of industrial high-salt wastewater. Since the compression power could not fully maintain heat balance, additional fresh steam is supplied to the first evaporator of each system. $CaCl_2$ solution is selected as the treated solution, and performances of the five systems are simulated using the Aspen Plus software. The analysis of energy consumption, operating cost, exergy and GOR are carried out to provide reference for the optimal design of a multi-effect MVR device. Based on the results, the following conclusions are drawn:

- Generally, the compression power decreases and the fresh steam consumption increases as the number of evaporators increases. The heat transfer temperature difference should not be higher than 9°C when the number of evaporators exceeds three.
- When considering the operating cost, the two-effect or three-effect MVR system should be given priority. The advantages of a larger number of evaporators diminish when the steam price is high. Considering the complexity and operating cost of a multi-effect MVR system, a two-effect MVR system proves to be a better choice for concentrating industrial high-salt wastewater.
- In view of the large BPE of industrial high-salt wastewater, the addition of a superheat eliminator can reduce the suction volume flow and compression power of the steam compressor. However, when determining the evaporator number and heat transfer temperature difference, the achievable pressure ratio of a steam compressor must be taken into account.
- The exergy efficiency of a multi-effect MVR system gradually increases with an increase in the number of evaporators and decreases with the rise of heat transfer temperature difference. Among all components in each MVR system, the evaporator exhibits the highest proportion of exergy destruction.
- Fresh steam consumption and compression efficiency of the steam compressor have obvious impact on the system GOR. Considering GOR and operating cost, integrating new energy-efficient steam generator with the multi-effect MVR system presents a promising option for further optimizing the design of multi-effect MVR systems treating industrial high salt wastewater.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (Grant No.52006092).

Symbols

A_n	—	Total exergy destruction, kJ/kg
C	—	Operation cost, yuan/h
c	—	Unit price, yuan
E	—	Exergy, kJ/kg
H	—	Enthalpy, kW
i	—	Number
m	—	Mass flow, kg/h
n	—	Percentage of exergy destruction
P	—	Pressure, kPa
P_c	—	Compressor power, kW
q	—	Heat absorbed by the solution, kJ/kg
Q	—	Total heat absorbed by the solution, kJ
r	—	Latent heat of vaporization, kJ/kg
R_g	—	Gas constant, J/(kg·K)
T	—	Temperature, °C

Greek symbols

κ	—	Adiabatic exponent
η	—	Efficiency

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