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# The treatment of chemical high-salt wastewater by ED-MVR coupling technics and its energy consumption analysis

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## ABSTRACT

In this study, electrodialysis mechanical vapor recompression (ED-MVR) coupling technics that could recycle the salt and the freshwater from the wastewater was put forward to treat the chemical wastewater with high salt. In order to make sure the economic feasibility of the ED-MVR coupling technics, the energy consumption was calculated by the theoretical model. Three parameters (the concentration of the feed, the concentration of the concentrated solution by ED, and the pressure of the evaporator) were researched to provide scientific guidance for the process optimization. In this work, the foremost factor found out during the analysis of energy consumption is the feed concentration which decides the scope of the ED-MVR process. When the concentration is lower than 12%, the technology reveals its advantages comparing with the stand-alone MVR process. At the same time, the energy consumption of the ED-MVR process decreases with the increase of the enrichment concentration. Also, the energy consumption of the MVR stage is influenced by the pressure of the evaporator. From the analysis, new thinking to deal with the chemical high-salt wastewater is provided by the ED-MVR coupling technics.

*Keywords:* ED-MVR coupling technics; Chemical high-salt wastewater; Energy consumption

## 1. Introduction

With the rapid development of the chemical industry, a large amount of water is required, and a large amount of chemical wastewater is discharged at the same time. High-salt wastewater is one of the most difficult to treat industrial wastewater. It has the characteristics of high salt content, complex salt content, easy scale and corrosion, high concentration of organic matter, and difficult degradation. How to treat it and achieve "zero emissions" requirements for low energy consumption and high processing efficiency have become a major problem in the domestic environmental

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protection field [1]. Therefore, it is necessary to explore a cost-effective treatment technology for high-salinity wastewater with nearly zero discharge.

According to domestic and foreign research reports, the technologies for treating high-salt wastewater include biological methods, membrane methods, evaporation methods, and ion-exchange methods [2]. At present, the main ways to achieve desalination treatment of high-salt wastewater include membrane treatment technology, electrochemical technology, heating evaporation technology, and so on.

Heating evaporation technology refers to using heating to vaporize and remove part of the solvent in the solution, thereby increasing the solution concentration, reducing the volume of wastewater, or creating conditions for solute precipitation.

The currently widely used heating evaporation technologies include single effect evaporation (SEE), multi-stage flash (MSF), multiple-effect evaporation (MEE), thermal vapor compression (TVC), and mechanical vapor recompression (MVR). Among them, MVR technology is the most energy-efficient evaporation treatment technology with organic matter removal among the existing evaporation treatment technologies. The treated solution is circulated and evaporated in the heat exchanger through the material circulation pump in the falling film or rising film evaporator of the MVR. Faisal et al. [3] studied four different steam recompression desalination systems, built models for these four systems, and compared and analyzed the parameters of heat exchange area, cooling water flow, and energy consumption ratio of each system. The results show that the MVR evaporation system has the simplest structure and does not require the use of condensed water, and the energy-saving effect is obvious. Tleimat [4] built a mechanical steam recompression process system for wastewater treatment. The compressor used a cam compressor, the evaporator uses a wiped film evaporator, and the evaporation temperature is only 50°C. The unit production capacity of the evaporator was 11.6 kg/h and the energy consumption was 20 kW/t. The results show that the recovery rate of wastewater can reach 98.6%. Wang et al. [5] studied the application of MVR technology in the concentrated brine process, and the results showed that MVR technology can optimize the traditional caustic soda brine process, using more than 90% of the brine, and nearly double the brine production capacity of salt wells. MVR is rapidly developing with the maturity of technologies such as pressure steam and heat transfer and worldwide energy-saving and emission reduction. And due to the reuse of the energy of vapor produced in the evaporator and only requiring electrical energy rather than a steam generator, MVR becomes an alternative method for the treatment of chemical high-salinity wastewater.

Although MVR has the advantage of using the waste heat fully, both the energy consumption of disposing of the chemical high-salinity wastewater and the equipment investment are still huge because of the enormous handling capacity. Therefore, it is helpful to reduce the energy consumption and equipment investment by decreasing the handing capacity depending on other technologies.

Electrodialysis (ED) is an electrochemical process for the desalination and concentrating of electrolyte solution under the influence of an electrical potential difference [6]. In the ED stack, only anions can pass through the anion exchange membranes, and only cations can pass through the cation exchange membranes, which gives ED the ability to desalt and concentrate. Under the action of a direct-current electric field, three streams flow across the stack of anion and cation ion-exchange membranes, the electrolyte water, the desalted stream, and the concentrated stream, thereby achieving separation of the electrolyte from the solution. It has been proved that electrodialysis is an effective method to dispose of the solutions containing salts, has been utilized for treating various industrial wastewater.

Wei et al. [7] obtained outstanding ED performances in desalination applications. Masigol et al. [8] studied on sodium sulfate removal from magnesium stearate (MgSt) aqueous slurry by using batch electrodialysis (ED) process. Eberhard and Hamawand [9] used selective electrodialysis for copper removal from brackish water and coal seam gas water, with a removal rate of around 98% for copper in both experiments and 100% for sulfate over 3 h at a starting temperature of 23°C. To evaluate the feasibility of electrodialysis for cadmium removal from wastewater containing cadmium in high concentration, Lee [10] studied the effects of operating parameters on the removal performance of electrodialysis.

It's an environment-friendly and economic-feasible technology that is suitable to deal with the chemical high-salt wastewater. ED has been wide application prospects in the fields of brackish water and seawater desalination, chemical separation, industrial wastewater treatment, food, medicine, and other fields due to its advantages such as simple operation, high fresh room recovery rate, and no environmental pollution [11].

Kazemimoghadam [12] used electrodialysis to re-concentrate RO seawater to achieve a higher concentration as a raw material for the Chlor-alkali industry. Zhang et al. [13] conducted a study on the simultaneous production of coarse salt and pure water by electrodialysis in the treatment of concentrated seawater. Zhang et al. [14] considered the technical-economical analysis to reduce the operating cost of the process in the process of increasing the water recovery rate of electrodialysis to treat thick seawater, and confirmed the feasibility and stability of the technology.

These studies provide an important basis for the wider application of electrodialysis to industrial wastewater treatment [15,16]. At the same time, this article proposes to introduce ED into the MVR process to help reduce the handing capacity in the field of disposing of the chemical high-salinity water.

Synthesizing the advantages of the ED and the MVR, a coupling technology is proposed to treat high-salinity chemical wastewater. Process schematic drawing of the ED-MVR coupling technology is shown in Fig. 1.

In this process, the raw wastewater goes into the ED stage after some simple pretreatments such as flocculation, the granulated substance filters, ultrafiltration, and the like. Then the wastewater is divided into two parts, the desalted solution, and the concentrated solution. By virtue of the function of ED (desalination), the handling capacity of the MVR (the concentrated) is reduced. Meanwhile, the concentration of the solution in the electrodialysis increased. Diminishing capacity and increasing concentration of the

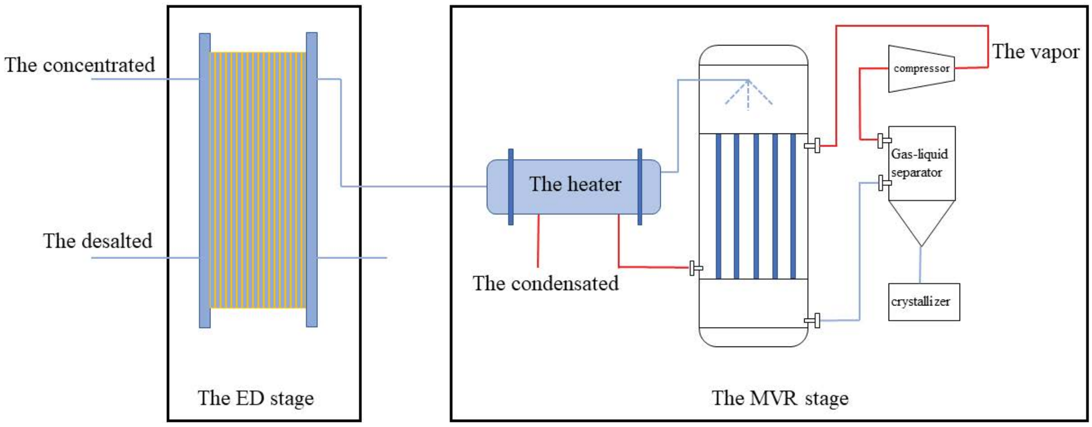

Fig. 1. Process schematic of the ED-MVR coupling technology.

solution entering the MVR are both possible reasons for reducing the energy consumption of the MVR. Similarly, the energy consumption of electrodialysis increases with the increase of desalination capacity [17]. Consequently, energy consumption may be reduced independently compared to MVR processes.

In this study, the energy consumption of the ED-MVR under different conditions was analyzed. Firstly, by the comparison of the energy consumption of the ED-MVR and the s-MVR, the advantages of the ED-MVR are expressed. The suitable initial concentration is researched to make sure the range of application for the ED-MVR dealing with the chemical high-salinity wastewater [18,19]. Simultaneously, by researching the energy consumption of the ED-MVR and its sub-processes under different conditions, the reasons for the energy consumption variation and the optimal technological parameters of the ED-MVR are investigated. Therefore, suitable highly saline wastewater handled with the ED-MVR coupling technics can be found out and proper operating conditions of the ED-MVR can be made up.

## 2. Materials and methods

### 2.1. Energy consumption of the ED process

The total energy consumption in electrodialysis for the actual desalination process is given by the electricity passing through the electrodialysis stack multiplied with the total voltage drop between the electrodes [20]:

$$E = UIt \tag{1}$$

where $E$ is the energy consumption of the ED for the transfer of ions from the feed to the concentrate solution; $U$ is the total voltage drop between the electrodes; $I$ is current passing through the electrodialysis.

In electrodialysis, there is a positive correlation between the voltage of the stack and membrane pair. The relation is shown by [21]:

$$U = NU_p \tag{2}$$

where $U_p$ is the voltage of membrane pair and $N$ is the number of membrane pairs.

As for the electricity, it can be calculated by Faraday's laws (of electrolysis).

Before entering the ED stack, the wastewater will be divisible into the desalted solution and the concentrate solution [22]. By the desalination of the ED, the salt of the desalted solution transfer to the concentration solution [23]. Therefore, the desalted solution becomes diluent while the concentrate solution becomes concentrated. It is shown in Fig. 2.

The blocks with capital letters $S$ and $W$ represent the salt, residual wastewater without salt, respectively. The lowercase letters $n$, $x$, and $a$ in the block with $S$ mean the amount of salt. The lowercase letters $m$ and $y$ in the block with $W$ mean the amount of water.

The hydraulic equilibrium can be calculated by the law of conservation of mass. It can be calculated by [24,25]:

$$Q = Q_1 + Q_2 \tag{3}$$

$$Qc = Q_1c_1 + Q_2c_2 \tag{4}$$

where $Q$ is the handling capacity (L/h) of the feed; $c$ is the concentration (mol/L) of the feed; $Q_1$ and $Q_2$ are the flow (L/h)

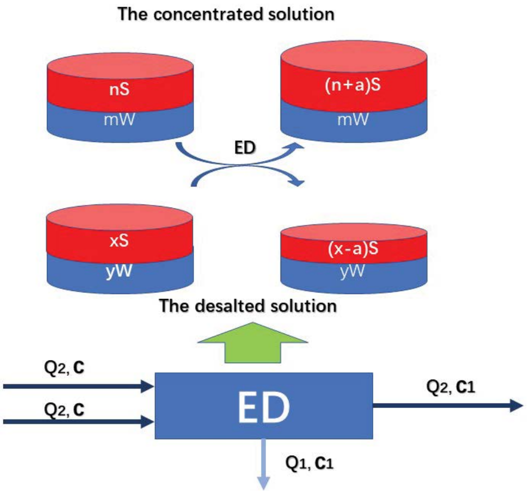

Fig. 2. Schematic of the ED and its hydraulic equilibrium.

of the concentrate solution and the desalted solution, respectively; $c_1$ and $c_2$ are the concentration (mol/L) of the concentrated and the desalted, respectively.

The aim of the ED set is desalting, so the amount of desalination reflects the ability of the ED process dealing with the feed. It can be acquired by [26]:

$$Q_N = Q_2\left(c - c_2\right) \tag{5}$$

where $Q_N$ is the amount of desalination per hour (mol/h).

Also, as we can know in Faraday's laws (of electrolysis), the amount of desalination is relevant to the electricity and the time. The amount of desalination can be calculated as follows [27]:

$$Q_N = \frac{I \times 3{,}600 \times N \times \eta_e}{F} \tag{6}$$

where $F$ is the Faraday constant (96,485 C/mol) and $\eta_e$ is the efficiency of the electricity; $I$ is the average current (A) in the ED set.

So, the average current can be acquired by:

$$I = \frac{Q_2\left(c - c_2\right)F}{3{,}600 N \eta_e} \tag{7}$$

Therefore, the total energy consumption in electrodialysis can be calculated by:

$$E = \frac{Q_2\left(c - c_2\right)F}{3{,}600 \eta_e} U_p t \tag{8}$$

### 2.2. Energy consumption of compressor

In the vapor cycle process, energy consumption comes from the compressor. The energy consumption can be figured up by the $P$–$V$ curve of the vapor in the roots blower [28].

From the $P$–$V$ curve, the shaded area represents the work of the compressor. It can be calculated by [29]:

$$\begin{aligned} W_s &= H_s - H_V \\ H_s &= H_s\left(S_v, P_s\right) \\ w_s &= \left(P_2 - P_1\right) \times V_s \end{aligned} \tag{9}$$

where $w_s$ is the compression work (J); $P_1$ is the pressure (Pa) of the vapor before compressed; $P_2$ is the pressure (Pa) of the vapor after compressed. $V_s$ is the volume (m$^3$/kg) compressed.

Compression ratio is one of the important parameters for the compressor to work, which decides the change of the pressure. Also, the effectiveness should be considered when calculating the energy consumption of the compressor. Then the energy consumption can be got by [30]:

$$W_f = \frac{\left(\phi - 1\right)P_1 V_s}{\eta_c} \tag{10}$$

where $W_f$ is the actual input energy (J); $\phi$ is the compression factor; and $\eta_c$ is the efficiency of the compressor.

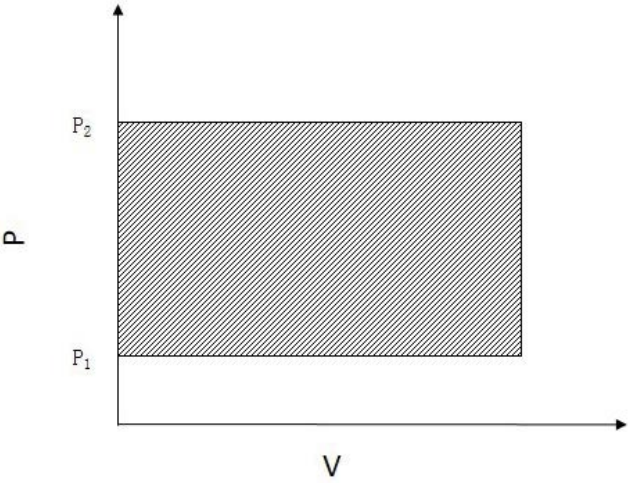

Fig. 3. $P$–$V$ curve of the roots blower.

### 2.3. Energy consumption of the preheater

The concentrated water from the ED stage should be preheated before entering the evaporator [31]. In this process, the heat of condensate water from the evaporator can be used effectively. But the heat can't offer enough energy for the water to raise its temperature to the boiling point [32]. Hence another heat should be supplied to heat the water.

According to the law of conservation of energy, the maximum heat transfer of the condensate water can be calculated by [33]:

$$q = \frac{\bar{\rho} Q_1}{1{,}000} \bar{c}_p \left(T' - T_1\right) = \frac{\rho \Delta Q}{1{,}000} c_p \left(T_2 - T'\right) \tag{11}$$

where $q$ is the theoretical quantity of heat (kJ/h) of the condensate water; $\bar{\rho}$ is the density (kg/m$^3$) of the solution; and $\bar{c}_p$ is the specific heat capacity (kJ kg$^{-1}$ °C$^{-1}$) of the solution. $T_1$, $T'$, and $T_2$ are the temperature of solution entering the preheater, the maximum temperature of solution after heat exchanging and the temperature of the solution entering the evaporator, respectively; and $\rho$ is the density (kg/m$^3$) of water; $\Delta Q$ is the vapor flow (L/h); $c_p$ is the specific heat capacity (kJ kg$^{-1}$ °C$^{-1}$) of the solution.

In the heat transfer process, the temperature gradient is a prerequisite to promote heat transfer. Meanwhile, the heat transfer accompanies energy loss. Then the actual provided heat is less than the theoretical heat [15].

$$\bar{q} = \theta q \tag{12}$$

where $\bar{q}$ is the actual provided quantity of heat (kJ/h); $\theta$ is the effective coefficient.

The total amount of heat required for the solution heating can be calculated by [34]:

$$q_s = \frac{\bar{\rho} Q_1}{1{,}000} \bar{c}_p \left(T_2 - T_1\right) \tag{13}$$

where $q_s$ is the heat (kJ/h) for the solution heating.

The additional quantity of heat can be calculated by [35]:

$$q_c = q_s - \bar{q} \tag{14}$$

$$q_c = \frac{\bar{\rho} Q_1}{1,000} \bar{c}_p \left( T_2 + (\theta - 1) T_1 - \theta T' \right) \tag{15}$$

where $q_c$ is the additional quantity of heat.

### 2.4. Relative parameters for theoretical calculation of the energy consumption

In this study, the theoretical energy consumption for the desalination of NaCl is calculated according to the theoretical model above-mentioned.

Some parameters are fixed as constant in order to simplify the calculation and make the date more comparative is shown in Table 1.

The physical parameters of the saturated steam are shown in Table 2.

The physical parameters of the NaCl solution necessary are shown in Fig. 4.

Table 1
Relative parameters used in the calculation

| Parameter | Unit | Quantitative value |
|---|---|---|
| $U_p$ | v | 0.8 |
| $c_1$ | g/L | 0.5 |
| $T_1$ | °C | 35 |
| $\eta_e$ | | 0.8 |
| $\varphi$ | | 1.5 |
| $\eta_c$ | | 0.65 |
| $\theta$ | | 0.7 |

$U_p$: voltage of membrane pair, whose value is usually from 0.5 to 1.5 v.
$c_1$: the desalted concentration.
$T_1$: the temperature out of the electrodialysis set.
$\eta_e$: the current efficiency of the ion exchange membrane.

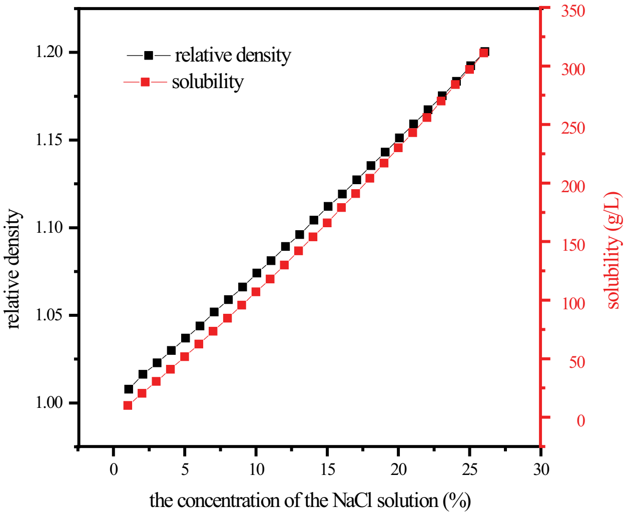

Fig. 4. Relationship between the solubility and relative density of NaCl.

## 3. Results and discussion

### 3.1. Factors reducing the energy consumption of ED-MVR comparing with s-MVR

The initial concentration is an important parameter influencing the energy consumption of the stand-alone MVR (s-MVR) and ED-MVR. The energy consumption of ED-MVR and s-MVR under different initial concentrations at 26% of the concentrated concentration of the ED and 30.00 KPa of the pressure of the evaporation is shown in Fig. 5. The energy consumption in the ED-MVR process increases rapidly with the increase of initial concentration before the concentration achieving 18%, after that, the energy consumption decreases. The energy consumption of the ED-MVR is lower than the energy consumption of the s-MVR at the light concentration (<12%). Conclusions can be drawn from Fig. 5. Firstly, the energy consumption of the ED-MVR is restricted by the initial concentration seriously. Under the light concentration (<12%), the energy consumption of the ED-MVR can be significantly reduced due to the adoption of the ED process. Next, the initial concentration will have an impact on the energy consumption of the MVR process, which can provide evidence that

Table 2
Physical parameters of saturated steam used in the calculation

| Absolute pressure (kPa) | Temperature (°C) | Specific volume of the vapor (m³/kg) | Density of water vapor (kg/m³) |
|---|---|---|---|
| 30 | 66.5 | 5.24 | 0.19093 |
| 40 | 75.0 | 4.00 | 0.24975 |
| 50 | 81.2 | 3.25 | 0.30799 |
| 60 | 85.6 | 2.74 | 0.36514 |
| 70 | 89.9 | 2.37 | 0.42229 |
| 80 | 93.2 | 2.09 | 0.47807 |
| 90 | 96.4 | 1.87 | 0.53384 |
| 100 | 99.6 | 1.70 | 0.58961 |

Physical parameters of the NaCl solution necessary are shown in Fig.4.

the increasing concentration of the solution entering the MVR stage due to ED concentration is one of the reasons reducing the energy consumption of the ED-MVR.

In this process, the concentrated concentration and pressure of the evaporator were 26% and 30.00 KPa, respectively.

The relationship between the energy consumption and the reducing quantity of water is shown in Fig. 6. With the increase of the initial concentration, the reduction amount of water is superimposed, and the MVR stage increases. This reflects that the decreasing handing capacity is another reason reducing the energy consumption of the ED-MVR. Due to the natural osmosis of the salt solution and the concentration limit of the ion exchange membrane, when the osmotic strength is greater than the electric field strength, the increase in the salt concentration will reduce the water reduction in the ED process. Correspondingly, the reduced mass of water in the MVR process increases as the salt concentration increases. The energy consumption of the process firstly increases due to the increase of the salt concentration. When the salt concentration reaches an appropriate range, both the ED process and the MVR process are in an energy-saving state, which also leads to a decrease in the total energy consumption.

In this chapter, the concentrated concentration and the pressure of the evaporator are 26% and 30.00 KPa, respectively. The concentrated concentration is 26% because the equilibrium concentration of the NaCl solution is around 26%. However, due to the limitation of ion-exchange membrane properties, it is difficult to concentrate the solution to 26% by electrodialysis in the presence of water infiltration, alt dialysis, and other processes. Therefore, the concentrated concentration is replaced by 20% in the following passage.

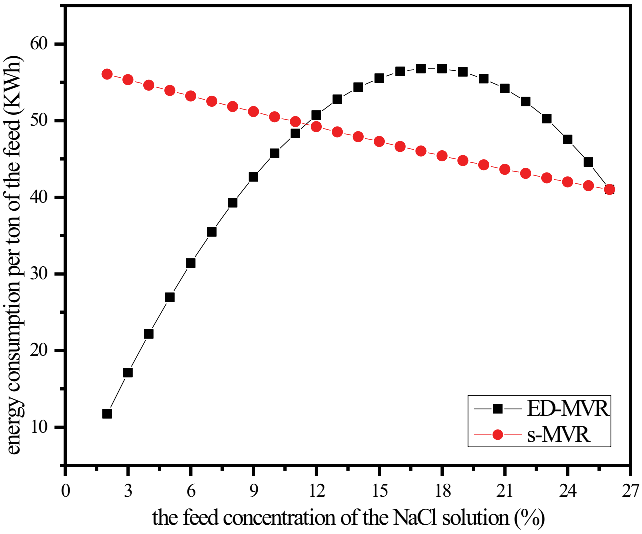

Fig. 5. Comparison of energy consumption between ED-MVR and s-MVR under different initial concentrations.

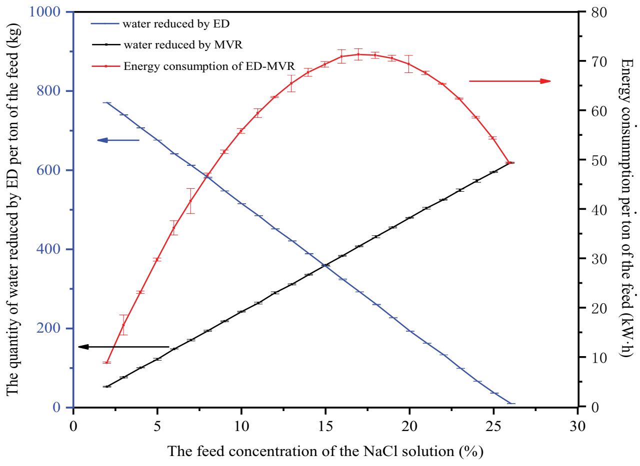

Fig. 6. Relationship between energy consumption and the reducing quantity of water under different initial concentrations.

### 3.2. Effect of initial concentration on energy consumption by the ED-MVR

The energy consumption of the ED-MVR and its ED, MVR stage at different initial concentrations are 20% of the concentrated concentration of the ED and 31.16 KPa of the pressure of the evaporation, as shown in Fig. 7. It can be seen from Fig. 7, when the initial concentration is less than 10%, the energy consumption of the ED stage rises with the increasing of the initial concentration. When the initial concentration is higher than 10%, the energy consumption of the ED stage decreases, meanwhile the energy consumption of the MVR stage goes up with the increasing of the initial concentration.

The energy consumption change of ED-MVR is caused by the interaction between energy consumption in the ED stage and the MVR stage. With the increasing of the initial concentration, the energy consumption of ED-MVR rises below 10% due to the increase of the ED stage and MVR stage. When the concentration between 10% and 14%, the energy consumption of the ED-MVR stage is still increasing

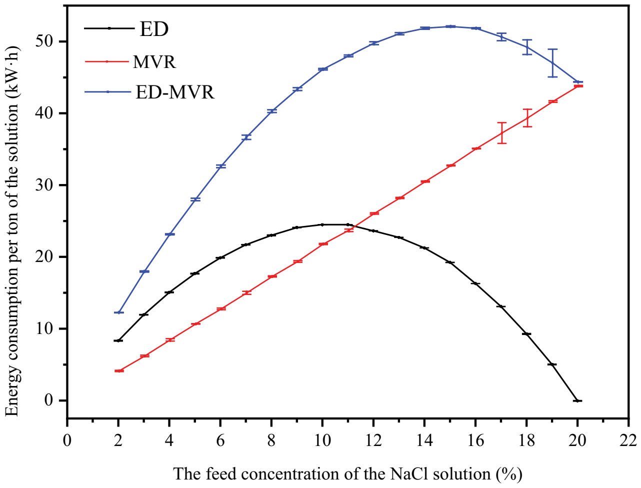

Fig. 7. Energy consumption of the ED-MVR coupling technic and its sub-processes (the ED stage and the MVR stage) under different initial concentrations.

because the energy consumption increase of the MVR stage is greater than the energy consumption reduction of the ED stage. On the contrary, when the initial concentration is higher than 14% the energy consumption of ED-MVR is reduced.

In this progress, the concentrated concentration and the pressure of the evaporator are 20% and 30.00 KPa, respectively.

The energy consumption of the MVR stage is related to the workload, and there is a positive correlation between the energy consumption of the ED stage and the amount of desalination. Therefore, the reason for the change in energy consumption at different initial concentrations can be obtained from the change in the amount of desalination. When the total processing amount, the diluted concentration, and the concentrated concentration remain invariant, the distribution of the concentrated water increases, and the distribution of the diluted water decreases due to the increase of the initial concentration. When the initial concentration is higher than 10%, the change of the diluted water flow will dominate. However, when the initial concentration is less than 10%, the diluted water flow is large. This leads to when the initial concentration is less than 10%, the amount of desalination increases, and when the initial concentration is greater than 10%, the amount of desalination decreases. Therefore, the energy consumption of the ED level first increases and then decreases with the increase of the initial concentration, while the energy consumption of the MVR level increases with the increase of the initial concentration.

The curves about the energy consumption of the NaCl solutions with initial concentrations of 2%, 3%, 4%, and 5% are concentrated to different concentrations, as shown in Fig. 8.

It can be clearly acquired that when the initial concentration is concentrated from different concentrations to the same concentration, the higher the initial concentration, the greater the energy consumption.

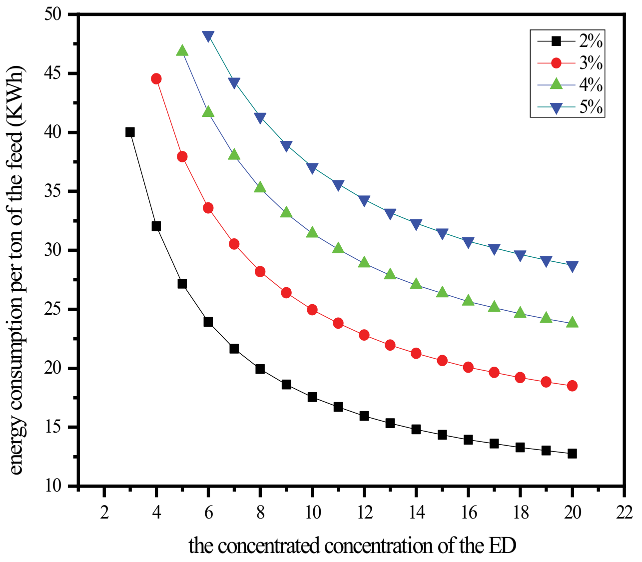

Fig. 8. Energy consumption of the ED-MVR coupling technic concentrated from the initial concentration (2%, 3%, 4%, and 5%) to different concentrated concentration.

In this progress, the concentrated concentration and the pressure of the evaporator are 20% and 30.00 KPa, respectively.

In conclusion, the initial concentration plays a significant role in ED-MVR. A suitable solution disposed of by the ED-MVR can reduce the energy consumption effectively.

In the low concentration region (<8%), the introduction of ED concentrated can visibly help reduce the handling capacity of the MVR stage without consuming a lot of energy during the ED stage.

In the high-concentration region, the handling capacity of the MVR stage can't be decreased effectively by the ED pre-concentrated, and the total energy consumption of the ED-MVR process will be increased because of the huge energy consumption of the ED stage, the total energy consumption of the ED-MVR process will also increase. However, in the low-concentration region, the energy consumption per ton of the feed of the ED-MVR process is lower than the stand-alone MVR process. With the decreasing of the initial concentration, the superiority is more manifest.

### 3.3. Effect of concentrated concentration on energy consumption by the ED-MVR

The energy consumption of the ED stage and the energy consumption of the MVR stage is affected by the ED concentrated concentration. Fig. 9a shows the energy consumption of the ED-MVR process during the ED stage of a NaCl solution with a concentration from 2% to 20%. The energy consumption of the ED-MVR process is affected signally by the change of the ED concentrated concentration. With the increase of ED concentrated concentration, the energy consumption of the treatment undergoes two stages: the rapid decline first, and then the slow decline. When the concentrated concentration of ED is higher, the reduction of MVR caused by concentrating the same concentration gradient is less.

As a result, the reduction rate of energy consumption is gradually reduced. The energy consumption of the ED-MVR process and its sub-processes when the ED concentrated concentration is gradually increased from 2% to 20% are shown in Fig. 9b. At the same ED concentrated concentration, the increasing amount of the ED stage in energy consumption is less than the decreasing amount of the MVR stage in energy consumption. Therefore, the energy consumption of the ED-MVR process decreases with the increasing of the ED concentrated concentration. Similarly, the energy consumption of the coupling process decreases faster when the ED concentrated concentration is lower.

In this process, the initial concentration of the ED stage and the pressure of the evaporator are 2% and 30.00 KPa, respectively.

In summary, when the initial concentration of the coupling process is determined, the higher the ED concentrated concentration, the lower the energy consumption. Performance requirements of ion exchange membranes will become more trenchant with the increasing of the ED concentrated concentration. Therefore, the curves of energy consumption under different ED enrichment concentrations can guide us to find out a suitable concentration factor to achieve the purpose of optimizing the process.

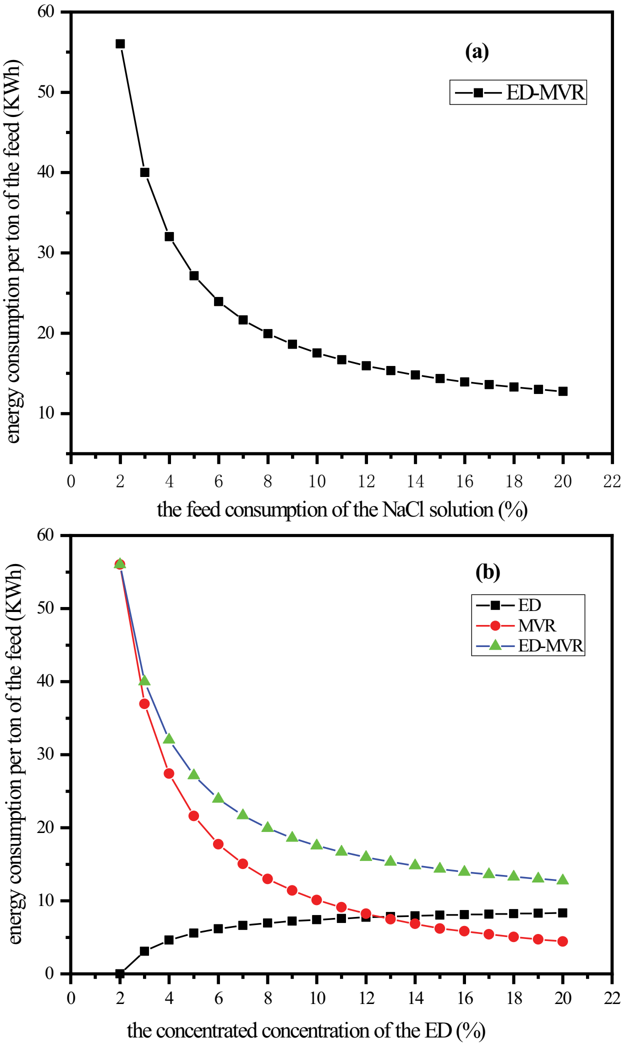

Fig. 9. (a) Energy consumption of the ED-MVR coupling technic under the different concentrated concentration of the ED stage and (b) energy consumption of the ED-MVR coupling technic and its sub-processes (the ED stage and the MVR stage) under the different concentrated concentration of the ED stage.

### 3.4. Effect of the evaporator pressure on energy consumption by the ED-MVR

In this process, the initial concentration and concentrated concentrations are 2% and 20%, respectively.

In the ED-MVR process, the energy consumption of the preheater and compressor is affected by the pressure of the evaporator. Energy consumption of the ED-MVR process varies with the operating pressure of the evaporator during the ED process of the NaCl solution concentrated gradually increased from 2% to 20% is shown in Fig. 10a. As the operating pressure decreases, the energy consumption of the ED-MVR coupling process decreases, that is, the energy consumption of the MVR during the coupling process is reduced. Therefore, the energy consumption can be reduced by reducing the operating pressure.

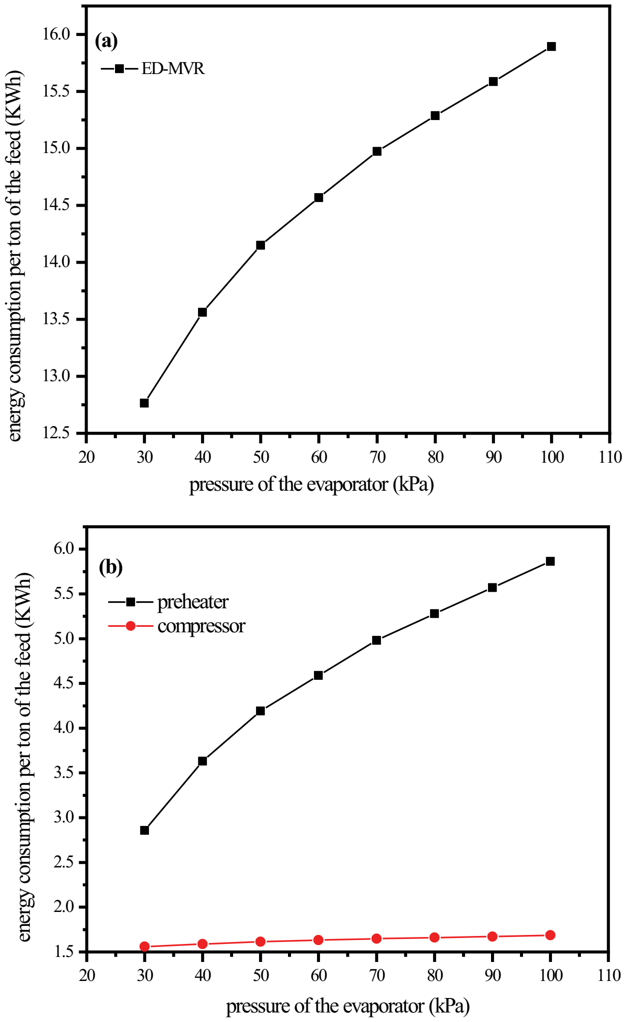

Fig. 10. (a) Energy consumption of the ED-MVR coupling technic under different pressures of the evaporator and (b) energy consumption of the preheater and the compressor under different pressures of the evaporator.

In the MVR stage, total energy consumption includes the preheater's energy consumption and the compressor's energy consumption. The energy consumption of the preheater and compressor varies with the operating pressure of the evaporator, as shown in Fig. 10b. As the operating pressure of the evaporator rises, both the energy consumption of the preheater and the energy consumption of the compressor increase. However, the increase in energy consumption of the preheater is greater than that of the compressor. Simultaneously, under the same operating pressure, the energy consumption of the preheater is much larger than that of the compressor. Therefore, the main reason for reducing the energy consumption of the MVR stage caused by the pressure in the evaporator is the reduced boiling point temperature affected by the pressure.

## 4. Conclusions

In this work, the energy consumption of the ED-MVR process for treating the NaCl solution under different conditions was calculated theoretically. The three values of the initial concentration, the enrichment conduction, and the pressure of the evaporator were investigated. The initial concentration is a crucial factor affecting the energy consumption of the ED-MVR process. Compared with the stand-alone MVR process, the energy consumption of the ED-MVR process is lower when its initial concentration is at the light concentration (<8%). In addition, it can be found that the ED-MVR process gradually highlights the advantages of low energy consumption with the decreasing of the initial concentration. Therefore, the initial concentration can determine whether a solution is suitable for the ED-MVR process. As for the enrichment concentration, at a certain initial concentration, the energy consumption decreases as the concentration increases. This is one of the important effects on energy consumption. The pressure of the evaporator is the factor affecting the energy consumption of the MVR stage only. By analyzing the energy consumption of the NaCl solution, applicable wastewater and the suitable operating conditions can be found out. Meanwhile, the superiorities of the ED-MVR process revealed during the analysis of energy consumption demonstrate its feasibility. Through energy consumption analysis, the law of energy consumption in the ED-MVR process is revealed, and a new idea for the treatment of saline wastewater with low energy consumption, high efficiency, and high-water recovery is provided.

## Author contributions

Conceptualization: DW; methodology: WM; software: GW; validation: SL, DC; formal analysis: MZ; investigation: SL; data curation: WQ; writing – original draft preparation: WM; writing – review and editing: CL; funding acquisition: GW. All authors have read and agreed to the published version of the manuscript.

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