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Analysis of a double-effect mechanical vapor recompression wastewater treatment system

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ABSTRACT

This paper presents an analysis of a double-effect mechanical vapor recompression (DEMVR) wastewater treatment system. Thermodynamic and economic characteristics are investigated using high salinity wastewater containing $(NH_4)_2SO_4$. Additionally, the effects of several important factors on the system are explored. The results indicate that compared with a single-effect mechanical vapor recompression system, the DEMVR system has an obvious advantage of improving thermodynamic performance. The DEMVR system saves 7.1% more energy compared with the single system. The energy saving rate of the system increases at a higher operating temperature and decreases with an increase in the temperature difference. The specific energy consumption is decreased slightly with an increase in operating temperature and decreased considerably with the reduction of temperature differences. Additionally, the specific heat transfer area tends to decrease with the rise of operating temperature and temperature difference. The minimum total power consumption and maximum coefficient of performance can be achieved at the intermediate concentration of approximately 32%. The results further reveal that the temperature difference has a considerable influence on the thermodynamic performance than does the operating temperature. The economic analysis shows that the specific evaporation cost of the system is low. Compared with the single system, the specific evaporation cost of the system could be lowered by 6.8%, to only 21 \$ ton^{-1}.

Keywords: Double-effect mechanical vapor recompression; High salinity wastewater; Energy saving

1. Introduction

Evaporation is the most widely used method in the field of high salinity wastewater treatment [1]. This approach consumes huge amounts of energy. Therefore, improving the energy utilization in this process is important. Many methods have been proposed to increase the efficiency of the evaporation such as multi-stage flash evaporation (MSFE), multi-effect evaporation (MEE), thermal vapor compression process and mechanical vapor recompression (MVR) process. Among these methods, MEE and MSFE are the ones most often used to treat wastewater [2,3]. However, both approaches have numerous drawbacks, such as complicated processes, troublesome operation and requiring large amount of external heating vapor. The MVR process is a promising methods due to such advantages as reusing vapor produced energy in the evaporator or flasher; compactness; efficient utilization of energy; easy integration with conventional desalination systems such as MSFE or MEE and other renewable systems such as solar; and low capital cost [4–6].

Most of the research thus far has been focused on single-effect MVR (SEMVR) in the desalination field. Ettouney [7,8] and Aybar [9] designed and analyzed SEMVR and its thermal performance by establishing a mathematical model. Jin [10], Jiao [11] analyzed the exergy of the SEMVR desalination system by applying the second thermodynamics law. The results provide a direc-

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tion for improving the performance of the MVR desalination system. Aly [12], Bahar [13], Yu [14], Jiao [15], Wu [16] and Li [17] conducted experimental work on the SEMVR desalination system. These experimental works demonstrated the MVC, which is the abbreviation of mechanical vapor compression and has the same process with MVR, is a promising energy-saving technology for desalination. Zejli [18] and Mussati [19] established a mathematical model for the optimization of the SEMVR desalination system and obtained some optimal results. Lukic [20] presented a thermoeconomic model for an SEMVR desalination system, which applied ion implantation on metallic surfaces for the adjustment of dropwise condensation. Mounir [21] developed a thermoeconomic model to optimize the cost of the SEMVR desalination system. Many researchers also investigated the MVC combined with other systems, such as the MSFE [22,23] and MEE [23,24] system. Additionally, the MVR desalination system can be driven by a renewable energy source, such as solar energy [18,25,26] or wind energy [18,27]. Some other researchers focused their research on the compressor of the MVR [28,29]. In addition to establishing a mathematical model for analyzing the MVR system, many researchers also investigated the MVC theoretically using software. Alasfour [5], Kishore [30] and Marcovecchio [31] adopted the software of IPSEpro, INFMED and GAMS, respectively, to analyze the MVR system. Using the MVR system to treat wastewater is also a potential method that has received attention by researchers. Han and Liang [32,33] researched a single MVR ammonia sulfate waste recovery system. The results show that the MVR system has obvious energy saving advantage as a wastewater treatment method. Mounir [21] presented a system to treat pollutant concentration with mechanical vapor compression and analyzed the effects of the temperature difference in the evaporator-condenser on the cost of the system. Zhou [34] investigated the thermal performance of a SEMVR system using salinity wastewater containing Na_2SO_4 with 2% concentration.

From the above reviews, it is obvious that researchers have put a lot of efforts into the SEMVC for desalination. The MVR technology has not, however, been widely applied in the wastewater process. One of the most important problems is that the saturation concentration of wastewater is usually high and will consume more energy using the SEMVR system because the water is evaporated under a high boiling point. Moreover, in the SEMVR system, the treatment capacity of compressor is large which leads to an increase in the size of compressor, and then the investment of compressor will be raised. Therefore, in this paper, a double-effect MVR (DEMVR) system to treat high concentration wastewater is developed and studied. The proposed system is simulated using the Aspen Plus simulator, and the results are validated by experimental data obtained from the literature. The thermodynamic performance of the DEMVR system compared with the SEMVR system is first investigated. Later, the effects of several important factors, including intermediate concentration, operating temperature and temperature difference on the performance of the DEMVR system, are investigated. Finally, an economic analysis is performed by comparing it with SEMVR system. The system was investigated using high salinity wastewater containing $(NH_4)_2SO_4$.

2. Process description

Wastewater has the feature that its boiling point increases as the concentration rising, such as wastewater containing ammonia sulfate. Evaporation, using the SEMVR system, will take place at higher concentration in the case of continuous operation. This causes the system working under higher boiling point, which leads to an increase in energy consumption of the compressor. The DEMVR system is a promising alternative for addressing this problem. With the DEMVR system, the first-effect MVR pre-evaporates a portion of the water under a lower concentration or boiling point, and the second-effect MVR evaporates remaining portion of water and crystallizes the inorganic crystal. This method avoids the problem of evaporating water under a high boiling point, which may reduce the total energy consumption of the system and improve the thermodynamic performance of the system. Also, the size of the every compressor is small in DEMVR system. Therefore, the investment cost of compressor may be lowered.

Based on the hypothesis described above, this paper proposes a double-effect MVR system which could treat high-concentration wastewater and recycle inorganic crystal. In this instance, the "double-effect" is different from the traditional double-effect. In this work, the double-effect system means a system which is coupled by the two SEMVR subsystems. The schematic of the DEMVR is shown in Fig. 1. The system is made up of two parts. Each part is a SEMVR subsystem, which mainly consists of a compressor, a flash evaporator, a heat exchanger and a circulation pump. The feed preheater is used to recover part of the sensible heat contained in the rejected condensate water to heat the intake wastewater. A vacuum pump is employed to maintain pressure and remove noncondensable gases.

The wastewater (feed stream) enters the preheater at a surrounding temperature in which most of the sensible thermal energy in the condensed water is recovered by the feed stream. Then the hot feed is sent to the first-effect, where it is mixed with recirculation-concentrated liquor

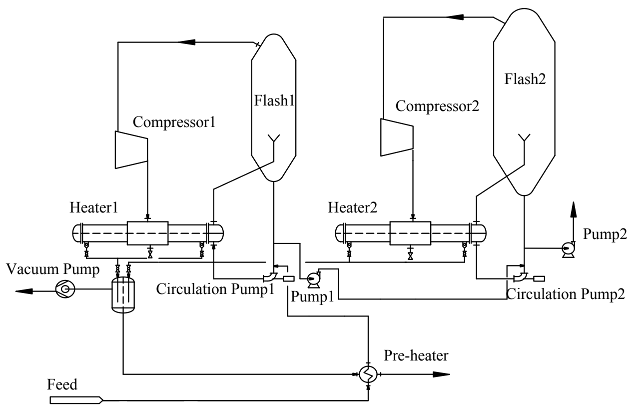


Fig. 1. Flow diagram of DEMVR system.

and is then pumped to the shell-and-tube heat exchanger (heater 1) by the circulation pump. The feed temperature is further increased to the boiling temperature of the wastewater. In the heater 1, the feed passes through the tube side. Because the tubes are flooded, the wastewater is under saturation pressure and will not be boiled. Subsequently, the feed enters first-effect flash (flash 1) and evaporation violently because of the abrupt decrease in pressure. The formed vapor is sucked by the compressor (compressor 1) through a wire mist eliminator which is used to separate the wastewater droplets. The compressor increases the pressure and temperature of the vapor. Next, the compressed vapor flows inside the shell side of the heater where it is condensed and releases its sensible and latent heat to the feeds in the tube side. The condensed water is collected into the bank and soon pumped through the preheater, where it exchanges heat with the intake stream. The concentrated liquor generated in the flash evaporator is divided into two streams. The first stream, most of the concentrated liquor, is recirculated back to the heater. Another stream, a few of concentrated liquor is sent to the second effect, where it joins the recirculating slurry and is pumped to the second-effect heater. In the second-effect, the process is similar to the first-effect one. The difference is that inorganic crystal will be crystallized in the flash evaporator (flash 2) when water is evaporated from the wastewater. That is to say, the solution from the flash evaporator is a mixture of crystal particles and liquid, which is known as the slurry. The slurry discharged by the DEMVR system is sent to a centrifuge (not shown) to separate the remaining water which flows back into the system. And the inorganic crystals can be recycled. It can be seen from the above process that the DEMVR system can recycled crystals from the wastewater and discharge clean water into the environment. This system is therefore environmental friendly. In order to analyze the advantages of the DEMVR system, it is compared with the SEMVR system. Flow diagram of SEMVR system is shown in Fig. 2. For the detailed description of the process, please refer to the literature [32].

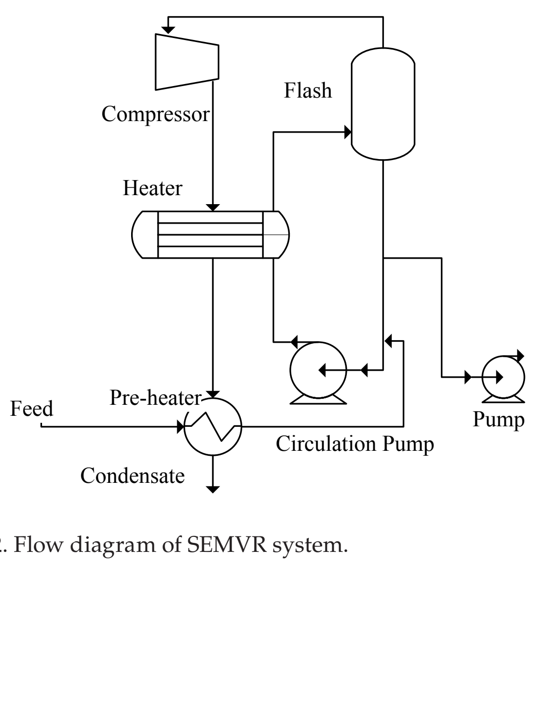


Fig. 2. Flow diagram of SEMVR system.

3. System process model

3.1. DEMVR and SEMVR process model

In this paper, the Aspen Plus simulator is used to analyze the features of the DEMVR system vs. the SEMVR system under different operation conditions. As process simulation software, Aspen Plus can simulate the steady state process in the chemical industry. It is widely used to investigate energy questions. Also, Aspen Plus can provide a favorable calculation method that ensures convergence of material and energy in the loop process. In Aspen Plus, there are many built-in model blocks such as heaters, separators, mixers, splitters, compressors and so on. Therefore, it is easy to create the model of researched system. Additionally, Aspen Plus has many databases including physical, chemical and thermodynamic properties for a wide variety of chemical compounds, as well as selectable thermodynamic models required for accurate simulation of any given chemical system.

The Aspen Plus model is shown in Fig. 3, in which Fig 3(a) is the SEMVR system and Fig 3(b) is the DEMVR system. The first-effect evaporator and the second-effect crystallizer are simulated by FLASH module and the CRY module, respectively. The preheater is simulated by three heaters as shown in model. heater 1 and heater 2 simulate the hot side, and heater 3 simulates the cold one. The condensed water from EXCH1 and EXCH2 flows into heater 1 and heater 2, respectively. They are cooled and release heat into heater 3, where the flow coming from the cold side absorbs the heat and makes the temperature rise. Considering that the simulation is the steady state process and the operating status can be set before computations, the vacuum system is not simulated.

3.2. Operating and performance parameters

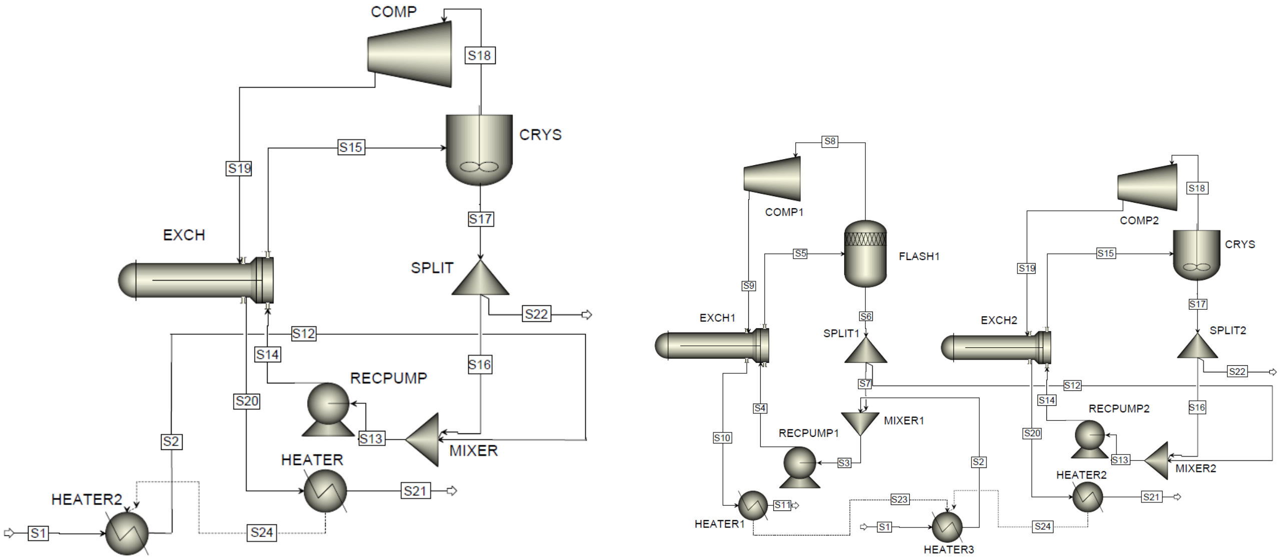
Operating parameters of MVR system such as evaporation (operating) temperature, temperature difference, intermediate concentration and so on have large effects on the system performance. Evaporation temperature means wastewater boiling point in evaporator. Temperature difference denotes the difference between condensation temperature of steam and boiling temperature of material. Intermediate concentration represents emission concentration of first-effect in DEMVR.

Specific energy consumption is defined as power consumption when the system evaporates 1 ton steam, which is given by:

$$U = \frac{\sum_{i=1}^{n} W_{c,i} + \sum_{i=1}^{n} W_{p,i}}{\sum_{i=1}^{n} V_i} \times 1000 \quad (1)$$

where U is specific energy consumption, kW.h t^{-1}. W_c and W_p are the work of compressor and circulating pump, respectively, kw. V is the vapor mass flow rate, kg h^{-1}.

Coefficient of performance is the ratio of heat to work, which indicates that the heat can be provided by unit power. The performance coefficient is as follows:



(a) (b)

Fig. 3. Model of the system builds by Aspen Plus: (a) Model of SEMVR, and (b) Model of DEMVR.

$$\varepsilon = \frac{\sum_{i=1}^{n} Q_i}{\sum_{i=1}^{n} W_{c,i} + \sum_{i=1}^{n} W_{p,i}} \tag{2}$$

where ε is coefficient of performance, and Q is the heat of heating material, kw.

Energy saving rate under the same circumstance, the improvement of energy consumption of DEMVR system compared with SEMVR system, can be calculated by:

$$\eta_t = \frac{W_S - \sum_{i=1}^{2} W_i}{W_S} \times 100\,\% \tag{3}$$

where η_t is energy saving rate, and W_s is power of SEMVR system, kw.

Specific heat transfer area is the ratio of the area of heater (heater 1 and heater 2) and the vapor mass flow rate, which can be expressed as:

$$k = \frac{\sum_{i=1}^{n} F_{H,i}}{\sum_{i=1}^{n} V_i} \tag{4}$$

where k is specific heat transfer area. F_H is heat transfer of heater.

3.3. Economic computation model

Fixed investment of system is composed of investment on compressor and ancillary equipment. Ancillary equipment includes heater, flash evaporator, pump and so on. Investment on ancillary equipment can be estimated as certain ratio of total system investment. Investment on compressor accounts for a large part of investment of MVR system, so investment on compressor could be estimated as follows [24]:

$$Z_c = 87560 \times a \times V \times \left(\frac{P_o}{P_i}\right) \times \left(\frac{\eta_c}{1-\eta_c}\right)^{0.7} \tag{5}$$

where Z_c is investment of compressor. a means rates of the US dollar against renminbi (RMB). V means steam flow, kg s^{-1}; P_i, P_o means import and export pressure of compressor, kPa; and η_c means compressor efficiency.

Total fixed investment of system can be expressed as [35]:

$$Z = \frac{Z_c}{1-C} \tag{6}$$

where C is proportion of investment of ancillary equipment in total investment.

Annual running costs is calculated by [36]:

$$A_C = f \times Z + C_m + C_e \tag{7}$$

where A_C is annual running costs. C_m is annual maintenance cost. C_e means electricity costs. f means recovery coefficient of investment, which can be given as [24]:

$$f = \frac{i \times (1+i)^n}{(1+i)^n - 1} \tag{8}$$

where i is interest rates. n means service life.

Annual maintenance cost mainly includes cost of labor, water, pollution, insurance, repair and others. It can be calculated as follows [36]:

$$C_m = b \times Z \quad (9)$$

where b means scale factor.

4. Results and discussion

The following basic assumptions were considered during simulation:

(1) The wastewater is the mixture of ammonia sulfate and water, no others;
(2) The heat loss of the equipment and pipeline are negligible;
(3) The power consumption of pump 1 and pump 2 in Fig. 1 is ignored and only considers the energy consumption of compressor and circulating pump; and
(4) The system works under steady-state conditions.

The main operating parameters of DEMVR and SEMVR system for the simulation are shown in the Table 1.

4.1. Thermodynamic performance

Reports on the use of the DEMVR system are limited. Table 2 provides a summary of the data extracted from the literature that relates to the MVR system, which is compared with the results in this paper. In Table 2, the second column details the DEMVR system used to treat ammonium sulfate wastewater, and the last column contains the results of the model used in this paper. The specific power consumption of the second column does not contain circulating-pump power. According to the data in Table 2, the specific power consumption in this paper, at an evaporation temperature of 70°C, is about 45 kWh t^{-1}, which is greater than the reported value of 41.5 kWh t^{-1}. However, if the circulating-pump power is taken into account, the values are similar. Therefore, these results indicate that the results of our model are consistent with the data published in the literature. And the model established by Aspen Plus can be used effectively to predict the behavior of the double-effect MVR system.

Table 3 shows the thermal performance results of the DEMVR and SEMVR systems. The results are obtained under certain conditions that the operating temperature is 60°C the temperature difference is 15°C, and the intermediate concentration of double MVR system is 32%. In Table 3, it can also be seen that the specific energy consumption for the SEMVR and DEMVR system is about 78.8 and 73.2 kWh t^{-1}, respectively. Correspondingly, compared with the SEMVR system, the saving rate of the DEMVR system is about 7.1%. That means the DEMVR system saves energy. Also, in Table 3, the coefficient of performance of the SEMVR and DEMVR system is about 7.8% and 8.3%, respectively. That is, the coefficient of performance of the DEMVR is 6.4% higher than that of the SEMVR. The reason is that the DEMVR system evaporates some portion of the water at the low boiling

Table 1
Main operating parameters

Parameters	Value
Feed flow rate, kg h^{-1}	2,500
Feed flow temperature, °C	30
Feed flow pressure, atm	1
Feed ammonium sulfate concentration, %	20
Range for concentration of the first effect, %	25~40
Discharging concentration, %	47
Range for the temperature difference, °C	8~20
Range for the evaporation temperature, °C	50~90
Service life, year	10
Interest rate, %	5.93
Scale factor, b, %	4
Price of electricity, \$ kW.h^{-1}	0.122
Annual operation time, h	7,200
Compressor efficiency	0.75
Proportion of ancillary equipment investment, %	20
Rates of the US dollar against RMB	6.56

Table 2
Comparison of experiment data and model results

	Literature [36]	This paper model
Feed rate, kg h^{-1}	2,500	2,500
Evaporation rate, kg h^{-1}	2,000	2,000
Specific power consumption, kWh t^{-1}	41.5	45
Heat-transfer area of heater, m^2	166.5	158.2
Evaporation temperature, °C	70	70
Temperature difference, °C	–	8

Table 3
Comparison of thermal performances of DEMVR and SEMVR system

Key performance	DEMVR system	SEMVR system
Power of the first-effect MVR, kw	60.4	–
Power of the second-effect MVR, kw	62.1	132.4
First circulation pump, kw	11.5	–
First circulation pump, kw	12.4	25.2
Total, kw	146.4	157.6
Heater of the first-effect heater, kw	641.1	–
Heat of the second-effect heater, kw	571.7	1,226.5
Total heat, kw	1,212.8	1,226.5
Specific energy consumption, kWh t^{-1}	73.2	78.8
Coefficient of performance	8.3	7.8
Saving rate, %	7.1	–

point in first-effect and then evaporates another remaining portion of water in the second-effect where ammonia sulfate crystallizes at the same time. Above process avoids the need for all of the water to be evaporated at a high boiling point, so energy consumption is reduced and the thermal performance of the system is increased. Therefore, compared with the single MVR system, the thermal performance of a double MVR system is better.

The intermediate concentration is an important factor for the DEMVR system. It is a key parameter that differs from the SEMVR system. It is necessary to analyze the influence of the intermediate concentration on system performance. Fig. 4 shows the effect of the intermediate concentration on the energy consumption and the performance coefficient. The figure is achieved under the condition that the operating temperature is 60°C, and the temperature difference is 15°C. It is shown that the total power decreases firstly and then increases with the increase of intermediate concentration. Conversely, the performance coefficient appears a maximum value with intermediate concentration increasing. This is due to the lower intermediate concentration, the higher vapor treatment capacity of the second effect and the total power of the system. On the contrary, the boiling point of the solution increases when the intermediate concentration of the first-effect is greater, which will lead to a larger compressive load and then to greater total power of the system. Therefore, the energy consumption of the system has a minimum value while the performance coefficient has a maximum value. Obviously, the minimum total power and the maximum coefficient of performance are obtained at an intermediate concentration of 32%, where the energy consumption of the system is about 146.4 kw, and the performance coefficient is about 8.3. Furthermore, when the intermediate concentration is 20%, that means that the first MVR system stops working and only the secondary system works. Namely, the DEMVR system transforms into a SEMVR system. It also can be seen in that the energy consumption of the DEMVR system is less than the SEMVR system energy consumption, while the performance coefficient is larger than the SEMVR system's performance coefficient.

Fig. 5 shows the influence of the evaporating temperature and the temperature difference on the total power and saving rate. The evaporating temperature is chosen from 50°C to 90°C, and the temperature difference is chosen as 10°C, 15°C and 20°C, respectively. As is shown in the Fig. 5, the total power of system decreases as the operation temperature increases. For example as the operation temperature is increased from 50°C to 90°C, the total power is reduced approximately 13.3% when the temperature difference is 15°C. It is determined by the decrease in the specific volume of the secondary steam and the compression ratio of the system at higher operation temperatures. In contrast, the saving rate increases with an increase in the evaporating temperature. For instance, when the temperature difference is 15°C, and the operating temperature is 50°C, the DEMVR system could save 6.5% in energy consumption. However, when operating temperature is 90°C, it could save 9.7% energy consumption. The reason is that the total power of the DEMVR system decreases as the operation temperature rises, and the higher operation temperature, the higher the saving rate.

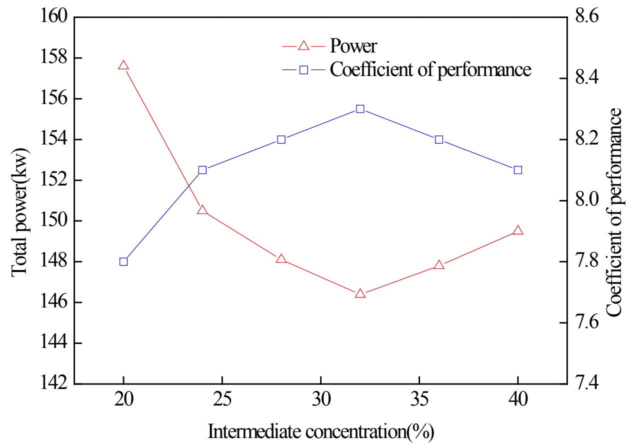


Fig. 4. Effect of the intermediate concentration on the total power and performance coefficient of system.

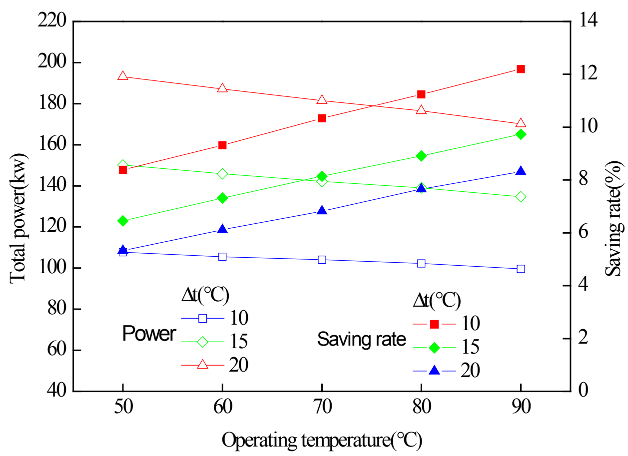


Fig. 5. Effect of operating temperature and temperature difference on the total power and saving rate.

It is also shown in Fig. 5 that the energy consumption of the system increases as the temperature difference increases. On the contrary, the saving rate decreases as the temperature difference increases. When operation temperature is 60°C, as the temperature difference grows from 10°C to 15°C and from 10°C to 20°C, the total power increases 38.26% and 77.3%, respectively, compared with the condition that temperature difference is 10°C. Similarly, the saving rate is reduced to 21.3% and 34.2%, respectively. Obviously, the temperature difference has a significant effect on the DEMVR's thermal performance.

Fig. 6 shows the results for the total area (heater 1 and heater 2) affected by the intermediate concentration when the operation temperature is 60°C. It indicates that the heat transfer area of heater 1 increases and that the transfer area of heater 2 decreases at higher intermediate concentrations. It is because the steam flow of the first effect increases when the intermediate concentration increases, which leads to an increase in the heat load also. Consequently, heater 1 requires a larger surface area. The change in the heater-2 area exhibits the opposite behavior, and the decrease in the heater-2 heat-transfer area is greater than the increase in the heater-1 heat-transfer area.

Fig. 7 shows variations in specific power consumption at different operating temperatures and temperature differences. It can be known that the specific energy (power) consumption is decreased slightly with the increase in the operating temperature and considerably with the reduction of temperature differences, which are similar with literature [35]. For example, at a temperature differences of 8°C, when the operating temperature increases from 40°C to 80°C, the specific power changes from 44 to 41.6 kWh t^{-1}, and the decrease of specific power is about 5.4%. However, the decrease is about 11.6% at a temperature difference of 20°C. It is also shown that the temperature difference has a much larger influence on the specific energy consumption than the operating temperature does. At an operating temperature of 80°C, an increase of approximately 42 kWh t^{-1} in the specific power is observed when the temperature difference is changed from 8°C to 20°C. This means that a high temperature difference is not recommended for the MVC system in practice. Otherwise, the specific power consumption is around 42.1 kWh t^{-1} at a temperature difference of 8°C and an operating temperature of 70°C.

Fig. 8 shows the variation of specific heat transfer area with an increase in operating temperature from 40°C to 80°C and temperature differences of Δt = 8°C, 10°C, 15°C, 20°C. It could be observed that the specific heat transfer area tended to decrease with the rise of operating temperature and temperature difference. This can be explained by higher operating temperature that leads to smaller viscosity of wastewater and increases the heat transmission coefficient, which then reduces the specific heat transfer area. Besides, the latent heat of vaporization decreases with the increasing operating temperature, which leads to the decrease in heat exchange loads and then reduces the specific heat transfer area as well. The heat transfer temperature difference of the heater decreases as the temperature difference decreases, leading to an increase in the specific heat transfer area. As shown in the figure, the variation range of the specific heat transfer area is less than 6% when the operating temperature changes from 40°C to 80°C. However, it is about 62% as temperature difference varying in the range of 8°C to 20°C. Accordingly, the temperature difference has a much larger influence on the specific heat transfer area than does the operating temperature.

4.2. Economy performance

Table 4 indicates a comparison of investment costs of DEMVR system with SEMVR system at the given operating condition: operating temperature of 60°C, temperature difference of 15°C and intermediate concentration of 32%. It can be seen in the Table 4 that the compressor investment of the DEMVR system is 6.6% lower than that of the SEMVR system. Moreover, compared with the SEMVR system, the maintenance and power costs of the DEMVR system are 6.7% and 7.1% less, respectively. It can also be found that the DEMVR system requires lesser unit cost, which is the cost to evaporate 1 ton of steam (water), than does the SEMVR system. The DEMVR system only needs 21 \$ ton^{-1} that is 6.8% lower than the SEMVR system. The results can be explained as follows: part of the water is pre-evaporated

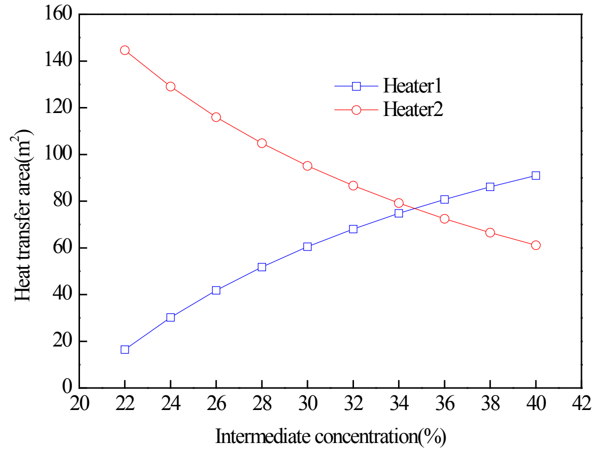


Fig. 6. Variation of the heat-transfer area as a function of the intermediate concentration.

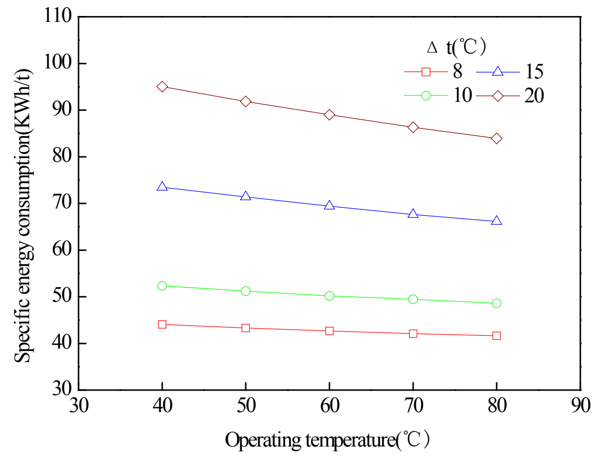


Fig. 7. Variation in specific energy consumption of the system as a function of the temperature difference and operating temperature.

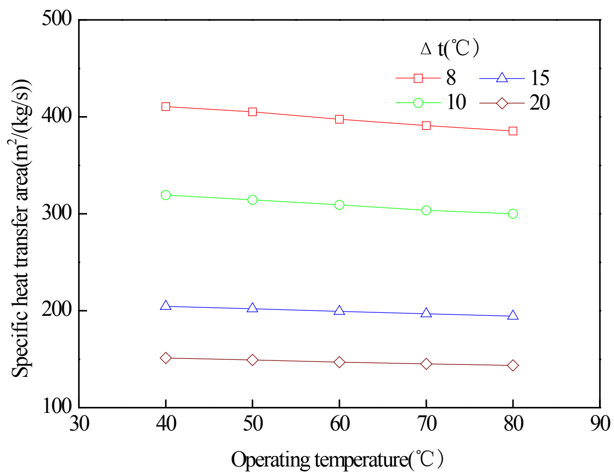


Fig. 8. Variation in specific heat transfer area of the system as a function of operating temperature and the temperature deference.

Table 4
Capital cost of DEMVR and SEMVR system

Investment	DEMVR system	SEMVR system
Investment of compressor (10^4 $)	20.75	22.21
Fixed investment (10^4 $)	25.93	27.77
Maintenance costs (10^4 $)	10.37	11.11
Electricity cost (10^4 $)	12.87	13.84
Annual running costs (10^4 $)	26.75	28.70
Unit cost ($ ton^{-1})	21	22.56

in the first-effect, which reduces the evaporation capacity of second-effect at a high boiling point, and then decreases the treating capacity of each compressor. On the other hand, steam is pre-evaporated at a low boiling point in the first-effect, which can reduce the compression ratios. Both above effects result in a lower investment cost for the DEMVR system.

5. Conclusions

In this study, an analytical investigation of the DEMVR system to treat wastewater was carried out. Aspen Plus was adopted to study the thermal performance of system and was verified by the experimental results obtained in the current literature. Economic models were built to analyze the economic performance of the system. The results of the thermal and economic performance of the DEMVR were compared with the SEMVR system. Furthermore, the three main parameters that have an influence on the system performance were investigated.

The main conclusions are summarized as follows:

(1) Improvements in the specific energy consumption and the coefficient of performance can be achieved by utilizing the DEMVR system. Under the calculating conditions, the specific energy consumption and coefficient of performance for the DEMVR system are about 73.2 kWh t^{-1} and 8.3, respectively, with a saving rate of about 7.1%.
(2) The maximum coefficient of performance and the minimum total power consumption were achieved at the intermediate concentration of 32%.
(3) The total power consumption decreases at higher intermediate concentrations and lower temperature difference. The saving rate becomes growth as the increase of operating temperature and the decrease of the temperature difference. The temperature difference has a much larger influence on total power consumption and saving rate than does the operating temperature.
(4) Increasing the operating temperature tends to decrease the specific power consumption. The same trend was attained by decreasing the temperature difference. The specific heat transfer area is inversely proportional to both the operating temperature and the temperature difference. Also, the temperature difference has a much larger influence on specific power consumption and temperature difference than does the operating temperature.
(5) The system has an advantage over the single MVR system in economic performance. Under the calculating conditions, unit cost of DEMVR system can decrease 6.8%, to only 21 $ ton^{-1}.

Acknowledgment

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Symbols

A_C	—	Annual running costs, $ year^{-1}
a	—	Rates of the US dollar against RMB
b	—	Scale factor
C	—	Proportion of investment of ancillary equipment in total investment
C_m	—	Annual maintenance cost, $ year^{-1}
C_e	—	Electricity costs, $ year^{-1}
F_H	—	Heat transfer of heater, m^2
f	—	Recovery coefficient of investment
i	—	Interest rates
k	—	Specific heat transfer area, m^2 (kg s^{-1})
n	—	Service life, year
P_o	—	Export pressure of compressor, kPa
P_i	—	Import pressure of compressor, kPa
Q	—	The heat of heating material, kw
Δt	—	Temperature difference, °C
U	—	Specific energy consumption, kWh t^{-1}
V	—	The vapor mass flow rate, kg h^{-1}
W	—	The work of compressor, kw
Z_c	—	Investment of compressor, $
Z	—	Total fixed investment of system, $
ε	—	Coefficient of performance
η_t	—	Energy saving rate
η_c	—	Means compressor efficiency

Subscripts

c	—	Compressor
i	—	Number of effect, i = 1, 2
p	—	Circulating pump
S	—	SEMVR

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