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Performance of MVR desalination system with variable operating conditions for wastewater treatment

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ABSTRACT

A complete mathematical model on the mechanical vapor recompression system considering the heat exchangers, pumps and compressor is developed and verified by experiment, by which the working process of the system is simulated and typical parameters are calculated. The treating capacity of system, distilled water temperature, power consumption influenced by feed temperature, feed concentration, discharge concentration, and circulation flow rate are analyzed. The results show that the increase of the feed temperature improves the treating capacity of system and reduces the distilled water temperature. Although more power is consumed by the system, the power consumption per ton of distilled water decreases. The mass flow rate of distilled water decreases with the feed concentration, but more feed solution flows into and discharge solution flows out of this system. The system consumes more power but only produces less distilled water for large feed concentration. The discharge concentration has little influence on the mass flow rate of distilled water despite the mass flow rates of the feed and discharge solutions decrease. The nearly constant power consumption for one ton of distilled water is obtained if the discharge concentration is larger than a certain value. The system performance is improved by increasing the circulation flow rate due to the better heat transfer effect.

Keywords: MVR; Desalination; Treat capacity; Power consumption

1. Introduction

Zero liquid discharge attracts extensive attentions recently in order to meet the increasingly strict environmental regulations [1]. Membrane technology provides wide selections for distillation or regeneration of solution with low concentration [2], but it is inapplicable for the highly concentrated solutions. A promising combination of pre-treatment by a membrane, concentration by evaporation, and crystallization by crystallizer is feasible [3,4], in which mechanical vapor recompression (MVR) system is a significant part due to its efficiency in high concentrated solution. Although multi-effect evaporator is still widely used for concentrating solutions and relevant research is continuing [5], a large amount of fresh steam consumption increases its operating cost. A new method named MVR system developed rapidly

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because it is remarkably energy saving. It is suitable for the evaporation and concentration processes of chemical solution, wastewater, and fruit juice to replace the traditional multiple-effect evaporation systems in the fields of seawater desalination, solution regeneration and other applications. Less steam is consumed in this system because the latent heat of the secondary steam is totally recovered. A steam compressor is used to increase the saturation pressure of the secondary steam from the evaporator, and the heat transfer temperature difference in evaporator is formed at the same time. Because the condensation heat is totally used to evaporate the feed solution, the system only consumes small electric power by compressor and pumps. Some steam is used to preheat the evaporator only during the startup process and a little steam is added to offset the heat loss of the whole system. Therefore, besides the compact structure and simple composition, the outstanding feature of this system is no fresh steam consumption and high efficiency.

In recent years, the MVR system is widely used in many application fields to recover wastewater and inorganic salt. Lots of studies focus on the feasibility and technique analysis in order to explore its application and evaluate its performance. The performance of the single and double-stage zero-emission desalination systems based mechanical vapor compression technology is compared with the conventional evaporation desalination system, and the energy-saving potential is analyzed using the energy and exergy methods by Han [6]. The system feasibility for landfill leachate is evaluated to reduce most of the pollutants and guarantee the effluent according to the discharge limits of the Chinese standard [7]. The techno-economic analysis of MVR for process integration of post-combustion CO_2 capture is finished by Jeong et al. [8]. The input parameters such as the cost index factor, electricity cost, compressor efficiency and the heat transfer areas have remarkable influences on the product cost for the mechanical vapor compression desalination system, and a forward feed multi-effect mechanical vapor compression desalination system is designed and analyzed by Jamil and Zubair [9,10]. An exergo-economic analysis is finished for a multi-effect desalination plant integrated into a mechanical vapor compressor unit with a water production capacity of 1,500 m^3/d by Elsayed et al. [11,12]. The stable operating performance of MVR regeneration system is analyzed by Ai et al. [13] and the performance influenced by some operation parameters is calculated. A comprehensive design model of a single-effect MVR system is presented by Zhou et al. [14], and their results are verified by a test system with high salinity wastewater containing Na_2SO_4. In order to reduce electric power consumption, clean energy is integrated into this system as an energy supplement to realize its application in a special place. The application of mechanical vapor compression desalination system driven by wind in Red Sea area is proposed by Karameldin et al. [15], and some operating parameters are recommended. The optimized design of a 120 m^3/d MVR desalination unit with a solar assisted-diesel powering system for remote areas in the UAE is presented by Helal and Al-Malek [16], and the compression ratio is considered as a significant parameter. An optimization model of MVR desalination plant driven by a wind/PV hybrid system with storage is developed by Zejli et al. [17], and three specific case studies in Morocco are analyzed. The results show that the domestic water demands are satisfied in each time interval at a reasonable economic cost compared with the current average cost of water in Morocco. A system consisting of MVR heat pump distillation and organic rankine cycle system to separate the benzene–toluene mixture is proposed and analyzed by Gao et al. [18], and its competitiveness is compared with the conventional distillation process.

MVR systems are similar to open-loop heat pump systems, and its working condition depends on equipment and operation parameters. Especially, the heat transfer temperature difference depends on the pressure ratio of compressor, but the pressure ratio is also related to the mass flow rate of centrifugal compressor. The steam parameters from compressor are always related to the performance curve of compressor if the operation condition is regulated. As a result, the heat balance in evaporator can be rebuilt if operation parameters are changed. It is unreasonable to analyze the performance of system if the coupling relationship between compressor and evaporator is ignored. And an improved simulation considering the couple of evaporating process in evaporator, preheating in preheater and performance curve of the compressor is necessary to evaluate the system performance with various operating conditions. In this paper, the performances influenced by the feed temperature, feed concentration, discharge concentration and circulation flow rate are analyzed, and the results are useful for the design and regulation of MVR system.

2. Theoretical analysis

An MVR system usually consists of an evaporator, separator, preheater, compressor, pump and other accessory equipment, which is shown in Fig. 1. The feed solution is first heated in the preheater by the distilled water from the evaporator and reaches higher temperature. It mixes with some high temperature concentrated solution from the separator and then flows into the tube side of evaporator. The temperature of mixed solution increases until it reaches the saturation point in evaporator and some steam is produced. After evaporation process, the mixture flows into separator and the steam is separated from the concentrated solution. The steam from separator is compressed by compressor and then flows into the shell side of evaporator to heat the solution. All the steam condenses in the shell side of evaporator and the solution evaporates in the tube side at the same time. Plenty of concentrated solution in the separator is circularly pumped into evaporator to increase the flow rate of solution in each tube, which is beneficial to avoid the dry-tube phenomenon. The non-condensable gas is unallowed in this system in order to ensure the phase change process, which is realized by a vacuum pump. The low-temperature solution needs to be heated to the evaporation temperature by external steam before system startup; then less extra steam is used to supplement the heat loss of system. The higher temperature extra steam is usually from pipeline or an individual boiler and it flows into system through an automatic vale. The working condition of compressor is not directly influenced by the extra steam because it is added from the discharge pipe of compressor.

The evaporator and compressor are the main parts of the MVR system. The falling film evaporator is an efficient heat

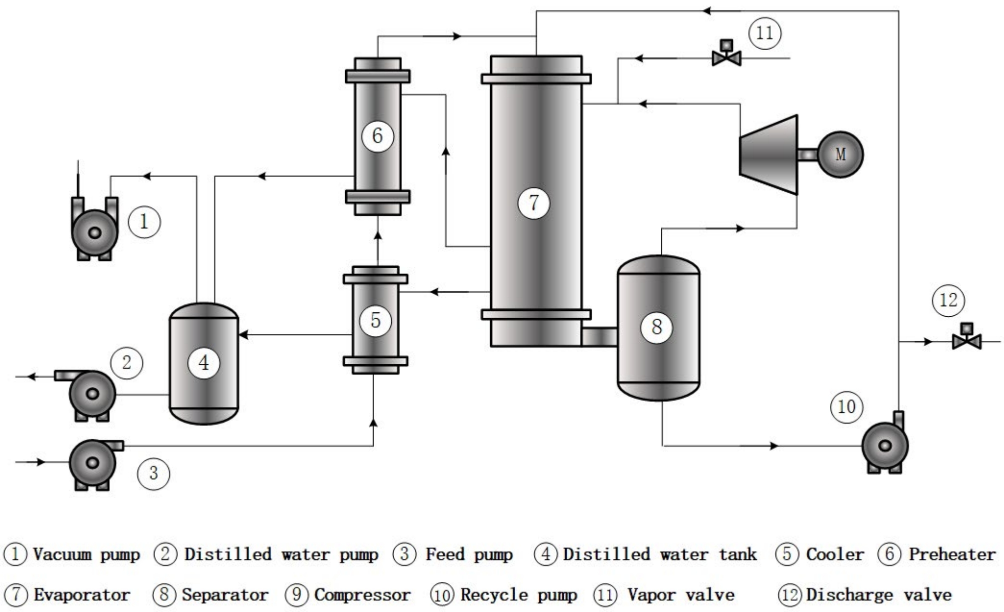

Fig. 1. Schematic diagram of MVR system.

exchanger and it is suitable for the low-temperature difference evaporation process. The roots blower and centrifugal compressor are suitable for this system, while centrifugal steam compressors have high efficiency, and it is fit for the large-scale systems. Hence, couple of falling film evaporator and centrifugal compressor is usually adopted for the actual large-scale MVR system.

The T-s diagram of evaporation is shown in Fig. 2. The temperature of the feed solution increases slightly after cooling the mixture of non-condensable gas and little steam (1–2). Then the solution flows into the preheater and absorbs the heat of distilled water from the evaporator (2–3). After preheating, the feed solution mixes with the circular concentrated solution and temperature increases (3–4), then they flow into evaporator together. The mixed solution is heated in the tube side of evaporator by steam (4–5–6) and some water is produced. The separated steam from separator is compressed by compressor (6–7) to reach higher pressure, and then the extra steam is added before it flows into the shell side of evaporator (7–8). The condensation process of steam (8–9–10) occurs in the shell side of evaporator and the generated distilled water flows into preheater (10–11). Because the concentrated solution in separator is pumped circularly to the evaporator in order to avoid the dry tube phenomenon and the circular flow rate is much larger than the value of feed solution, the concentration of solution in the evaporator is higher than the feed one.

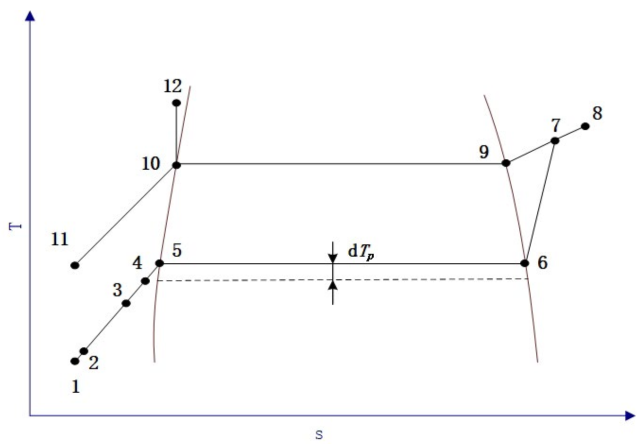

Fig. 2. T-s diagram of MVR system.

The treating capacity of this system relies on the law of mass conservation if no salt is carried by the steam. The mass flow rate of feed solution and steam from the compressor is decided by the feed and discharge concentration.

$$m_{\text{comp}} = m_{\text{fs}}\left(1 - \frac{c_{\text{fs}}}{c_{\text{ds}}}\right) \tag{1}$$

The non-condensable gas for the MVR system is nearly inevitable. First, air or some low boiling point gas is dissolved in the feed solution and it is given off gradually when it is heated. Second, some air leaks through the seal of compressor and pipe joints when the evaporation pressure is lower than the atmospheric one. The heat transfer process in cooler is shown as:

$$m_{\text{fs}} c_{p,\text{fs}} \left(t_2 - t_1\right) = m_{\text{ng}} c_{p,\text{ng}} \left(t_{10} - t_{\text{co}}\right) = K_{\text{cl}} A_{\text{cl}} \Delta t_{\text{cl}} \tag{2}$$

Because the non-condensable gas is discharged from the distilled tank and its flow rate is small, the inlet gas parameters of the vacuum pump are approximately equal to distilled water. The power of the vacuum pump can be calculated by the following equation.

$$W_{\text{vp}} = \eta_{\text{vp}} m_{\text{ng}} \Delta h_{\text{vp},s} \tag{3}$$

The feed solution is heated in the preheater by distilled water, and the heating process of liquid is described as the following equation [11].

$$m_{\mathrm{fs}}\left(h_3-h_2\right)=\left(m_{\mathrm{comp}}+m_{\mathrm{ex}}\right)\left(h_{10}-h_{11}\right) \tag{4}$$

$$K_{\mathrm{ph}}=0.023\frac{\lambda}{D}\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{5}$$

The temperature of feed solution increases after mixing with the circular concentrated solution, which is shown as:

$$m_{\mathrm{fs}}c_{p,\mathrm{fs}}\left(h_4-h_3\right)=m_{\mathrm{cf}}c_{p,\mathrm{ds}}\left(h_6-h_4\right) \tag{6}$$

After the feed solution flows into the evaporator, it is heated and gradually evaporates along the tube. The steam is produced until the solution flows out from the evaporator. The heat transfer process of the solution is described by the following equation [12].

$$K^{+}=h\left(\frac{V^2}{\lambda^3 g}\right)^{\frac{1}{3}} \tag{7}$$

$$\begin{cases} K^{+}_{\mathrm{La}}=1.428\,\mathrm{Re}^{\frac{-1}{3}}\left(\mathrm{Re}<400\right) \\ K^{+}_{\mathrm{Tur}}=0.00357\,\mathrm{Re}^{0.4}\,\mathrm{Pr}^{0.65}\left(\mathrm{Re}>3,200\right) \\ K^{+}=\left[\left(K^{+}_{\mathrm{La}}\right)^2+\left(K^{+}_{\mathrm{Tur}}\right)^2\right]^{\frac{1}{2}}\left(400\le\mathrm{Re}\le 3,200\right) \end{cases} \tag{8}$$

The mixture of superheated steam from the compressor and extra steam flows into the shell side of evaporator, where it changes as distilled water. The condensation process of steam in the shell side of the evaporator is described by the following equation [13].

$$\begin{cases} K^{+}=1.88\,\mathrm{Re}^{\frac{-1}{3}}\left(\mathrm{Re}<1,800\right) \\ K^{+}=0.0077\,\mathrm{Re}^{0.4}\left(\mathrm{Re}>1,800\right) \end{cases} \tag{9}$$

The evaporating process in the evaporator is related to the working condition of the compressor, and the actual evaporation and condensation pressure are influenced by the mass flow rate of steam from the evaporator.

$$\frac{P_{\mathrm{con}}}{P_{\mathrm{eva}}}=f\left(m_{\mathrm{comp}}\right) \tag{10}$$

Because the extra steam flows into the evaporator, the actual mass flow rate of distilled water is larger than the capacity of the compressor.

$$m_{\mathrm{dw}}=m_{\mathrm{ex}}+m_{\mathrm{comp}} \tag{11}$$

The extra steam flows into the outlet pipe of the compressor and mixes with the steam from the compressor. Because of its small mass flow rate compared with it of the compressor, the pressure loss is ignored. The energy conservation is shown as:

$$m_{\mathrm{comp}}\left(h_8-h_7\right)=m_{\mathrm{ex}}\left(h_{\mathrm{ex}}-h_8\right) \tag{12}$$

The circular pump is used to transport some of the concentrated solution return to the evaporator, and its shaft power is given as follows:

$$W_{\mathrm{cp}}=\eta_{\mathrm{cp}}m_{\mathrm{cf}}g\left(H_{\mathrm{cp}}+\Delta H_{\mathrm{cf}}\right) \tag{13}$$

When the evaporation pressure is lower than ambient pressure, the feed solution can flow into the system automatically unless the outlet pressure of the circular pump is high. The shaft power of the feed pump is given as:

$$W_{\mathrm{fp}}=\eta_{\mathrm{fp}}\left[m_{\mathrm{fs}}g\left(H_{\mathrm{fs}}+\Delta H_{\mathrm{fp}}\right)+m_{\mathrm{fs}}v_{\mathrm{fs}}\left(P_{\mathrm{eva}}-P_{\mathrm{at}}\right)\right] \tag{14}$$

The distilled water pump is used to maintain the water level of the tank. For a vacuum evaporation system, it is necessary and its shaft power is shown as:

$$W_{\mathrm{dp}}=\eta_{\mathrm{dp}}\left(m_{\mathrm{comp}}+m_{\mathrm{ex}}\right)v_{\mathrm{dw}}\left(P_{\mathrm{at}}-P_{\mathrm{con}}+\frac{g\Delta H_{\mathrm{dw}}}{v_{\mathrm{dw}}}\right) \tag{15}$$

3. Results and discussion

3.1. Experiment and typical results

A small-scale MVR system for wastewater treatment is designed and tested in a chemical plant to verify the mathematical model, in which a centrifugal compressor and a falling film evaporator are installed, as shown in Fig. 3. The feed solution flows into this system and the distilled water and concentrated solution are produced. Some operating parameters such as pressure, temperature, flow rate and power of compressor are tested. All the experimental data and control commands are connected to a control panel, which controls the startup, running and stop of the process. The system parameters are related to the wastewater, system efficiency, economic benefit and other factors. The larger temperature difference between evaporation and condensation can reduce the equipment size, but the larger compression ratio means larger power consumption and difficult design for the compressor; especially for a centrifugal compressor. The optimized design parameters of this experiment system are shown in Table 1.

For a centrifugal compressor, its capacity is different and its efficiency is sensitive with pressure ratio. It is hard to build an accurate model of the compressor to predict its performance, especially for the steam. A fitted performance curve by experiment is simple and accurate for a certain compressor, and it also simplifies the calculation process of the system, which is shown in Fig. 4.

In order to simulate the performance of the MVR system, some wastewater from a chemical plant is selected as feed solution to finish the evaporation and concentration process. Its performance is analyzed. The main components of the feed solution are shown in Table 2.

Fig. 3. Experimental MVR system.

Table 1
Design parameters of system

Parameters	Values
Feed concentration	0.02
Discharge concentration	0.10
Evaporation temperature/°C	70
Condensation temperature/°C	80
Area of evaporator/m^2	85
Area of preheater/m^2	12
Flow rate of compressor/m^3 min^{-1}	80

The regulation of the actual system is complex because the equipment and operation conditions influence each other. The system treating capability is mainly reflected as the mass flow rate of the feed solution, distilled water and discharge solution. The demand for extra steam is decided by the inevitable heat requirement for this system. The temperature of distilled water shows the state of heat recovery and the power consumption indicates the operating cost. The typical simulation results are shown in Table 3. For the simulation, the condensation temperature, feed temperature, feed concentration, discharge concentration and circulation flow rate are assigned and other parameters are calculated. Because the compressor and heat exchangers are fixed for a certain MVR system, the running conditions of the system need to match the heat balance in heat exchanger and performance curve of compressor. The results show that the compressor is the main power consumption equipment and consumes the most power comparing with other pumps. In addition, the total power directly reflects the running cost. The following discussions only focus on the total power consumption of system.

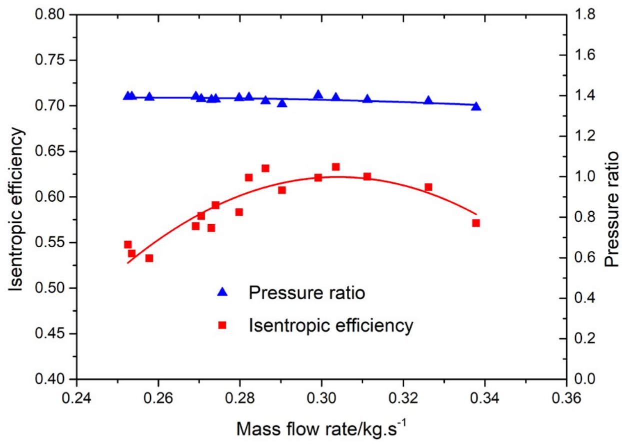

Fig. 4. Performance curve of compressor.

Table 2
Main components of feed solution

Calcium and magnesium, mg/L	14.24
Chloride, mg/L	14.4
Sulfate, mg/L	98.8
NH_3–N, mg/L	32

In order to reveal the evaporation process of the solution in the evaporator, the temperature and concentration of solution and the temperature of steam in evaporator are shown in Fig. 5. Because of the non-isentropic compression and extra steam, the high-temperature steam flows into the shell side of evaporator until it is condensated as water.

The temperature of feed solution increases along the tubes until it reaches the evaporation temperature. The simulation results show that the heat transfer process of superheated vapor and liquid (a), two-phase mixture and liquid (b), two-phase mixture and two-phase mixture (c) take up 41%, 13% and 46% of the whole area of evaporator. After mixed with the solution from circulation pump, the concentration and temperature of solution are only slightly lower than the discharge solution when it flows into the evaporator. If the temperature of solution reaches the boiling point, the vapor is separated from the solution and its concentration increases until it reaches the set value.

In order to verify the mathematical model, some tested data are adopted under different operating conditions, as given in Table 4. Although the working conditions in Table 4 are irregularly limited by the experiment conditions, it shows a wide range of application for this model.

The mass flow rate of discharge solution and distilled water, saturation temperature difference and shaft power of compressor under the tested conditions are shown in Tables 5 and 6. For different operating conditions, the simulation results have a good agreement with the tested ones. The maximum deviation for the mass flow rate of discharge solution, mass flow rate of distilled water, saturation temperature difference and shaft power of compressor are 6.67%, 7.84%, 4.82% and 9.09%, respectively. It provides a good verification for the mathematical model.

Table 3
Typical simulated results on MVR system

Parameters	Values	Data source
Condensation temperature/°C	80	Input
Feed temperature/°C	25	Input
Feed concentration	0.02	Input
Circulation flow rate/kg s^{-1}	5.56	Input
Discharge concentration	0.10	Input
Temperature of extra vapor/°C	120	Input
Evaporation temperature/°C	72.1	Result
Mass flow rate of feed solution/kg s^{-1}	0.342	
Mass flow rate of discharge solution/kg s^{-1}	0.068	Result
Mass flow rate of extra vapor/kg s^{-1}	0.011	Result
Distilled water temperature/°C	66.6	Result
Mass flow rate of distilled water/kg s^{-1}	0.274	Result
Shaft power of compressor/kW	25.1	Result
Shaft power of feed pump/kW	0.03	Result
Shaft power of circulation pump/kW	1.25	Result
Shaft power of vacuum pump/kW	0.37	Result

3.2. Influence by feed temperature

The treating capacity of system with feed temperature is shown in Fig. 6. The mass flow rate of the feed solution, distilled water and discharge solution increases with feed temperature, but the demand for extra steam decreases. For the preheater, the outlet temperature of the feed solution is higher when the temperature of the inflow solution is higher. It means the inlet temperature of solution is more approximate to the saturation point for the evaporator. More condensation heat is distributed to finish the evaporation process and more distilled water is produced. In view of the constant concentration ratio, the mass flow rates of feed solution, discharge solution and distilled water increase with the feed temperature. In addition, only a small amount of steam is needed when the temperature of feed solution is high. All the mass flow rates of feed solution, distilled water and discharge solution increase by 25.4% as the feed temperature increases from 20°C to 70°C. The mass flow rate of extra steam is 4.6% of the one of distilled water when the feed temperature is 20°C, but it is unnecessary if the feed temperature is 70°C .

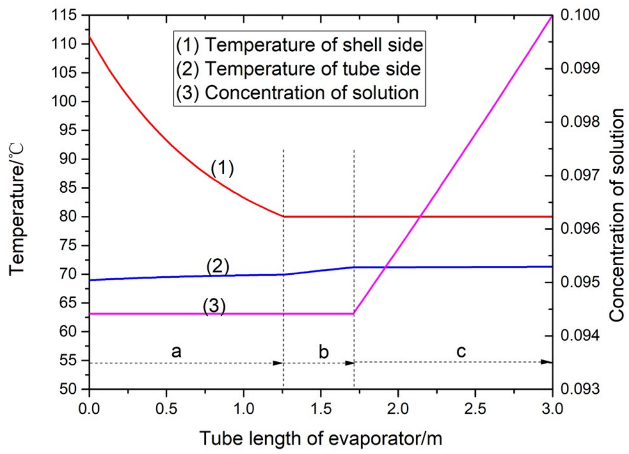

Fig. 5. Temperature and concentration in the evaporator.

Table 4
Working condition of experiment

Number	Feed temperature, °C	Concentration of feed solution, mg/L	Concentration of discharge solution, mg/L	Condensation temperature, °C
1	20.5	4,538	140,020	77.7
2	19.4	8,344	49,570	78.8
3	16.6	4,004	40,880	77.0
4	17.7	4,614	50,620	77.6
5	21.4	12,354	193,900	78.1
6	18.2	11,810	56,370	77.8

Table 5
Mass flow rate of discharge solution and distilled water

Number	Mass flow rate of discharge solution/kg s^{-1}			Mass flow rate of distilled water/kg s^{-1}		
	Experiment	Simulation	Deviation/%	Experiment	Simulation	Deviation/%
1	0.0093	0.0094	+1.08	0.2768	0.2701	–2.42
2	0.0513	0.0502	–2.14	0.2537	0.2465	–2.84
3	0.0269	0.0262	–2.60	0.2477	0.2452	–1.01
4	0.0269	0.0253	–5.95	0.2684	0.2560	–4.62
5	0.0171	0.0175	+2.34	0.2513	0.2657	+5.73
6	0.0710	0.0662	–6.67	0.2677	0.2467	–7.84

Table 6
Saturation temperature difference and shaft power of compressor

Number	Saturation temperature difference, °C			Shaft power of compressor, kW		
	Experiment	Simulation	Deviation/%	Experiment	Simulation	Deviation/%
1	7.7	7.8	+1.30	26.6	25.0	–6.02
2	8.2	7.9	–3.66	26.4	26.5	+0.38
3	7.9	7.8	–1.27	25.0	26.4	+5.60
4	7.8	7.8	0	25.4	25.5	+0.39
5	8.3	7.9	–4.82	26.9	25.1	–6.69
6	7.8	7.8	0	24.2	26.4	+9.09

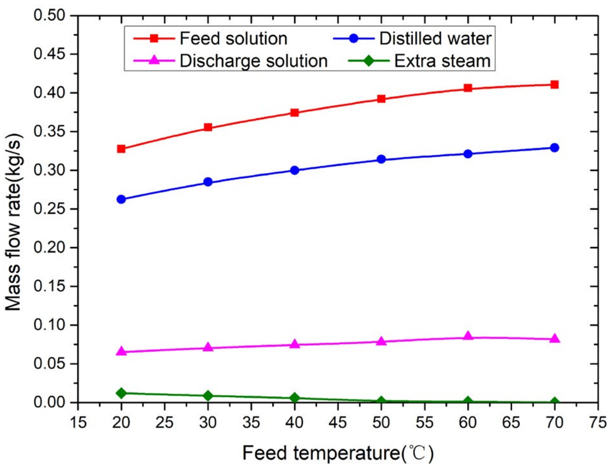

Fig. 6. Treat capacity with feed temperature.

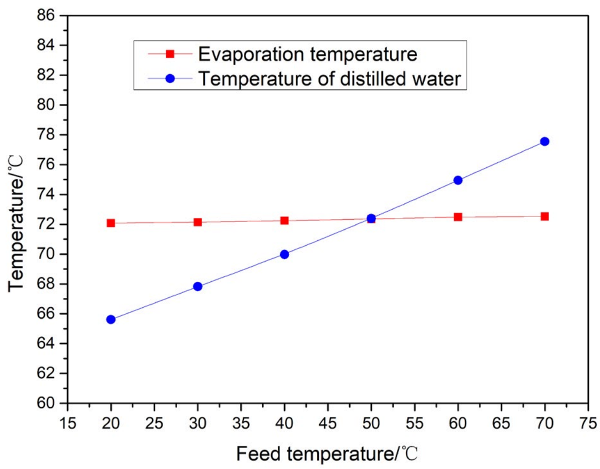

Fig. 7. Distilled water temperature with feed temperature.

The evaporation temperature and distilled water temperature are shown in Fig. 7. For the evaporator, a smaller pressure ratio of the compressor leads to a smaller saturated temperature difference. The higher feed temperature improves the treating capacity of system and produces more steam. The large mass flow rate of compressor also reduces its pressure ratio according to its performance curve, which means the small saturated temperature difference in evaporator. Because the pressure ratio of compressor changes slightly with its mass flow rate at this point, the variation of temperature difference between evaporation and condensation is small. The actual evaporation temperature only increases 0.4°C when the feed temperature increases from 20°C to 70°C. Usually, the high temperature of distilled water is not desirable because it shows that some heat has not been recycled. The proper parameters of preheater and evaporator are necessary to control this temperature for a certain operating condition, but the equipment cost also needs to be considered. The feed solution only needs less heat in preheater when the feed temperature is high, which leads to a higher temperature of distilled water, and the increment is 11.9°C under the same condition.

The steam compressor is the main power consumption equipment and it directly influences the power consumption of the system. The power consumption for one ton of distilled water is used to evaluate the operating cost of system. The power consumption is shown in Fig. 8. The power consumption of system increases with feed temperature because more steam is compressed by compressor. But the power consumption for one ton of distilled water decreases based on the high efficiency and small pressure ratio of the compressor. The total power consumption of system increases by 10%, but it decreases by 12.3% for one ton of distilled water when the feed temperature increases from 20°C to 70°C.

3.3. Influence by feed concentration

The system treating capacity influenced by the feed concentration is shown in Fig. 9. The concentration difference between feed and discharge solution directly influences the mass flow rate of distilled water. As feed concentration increases, only less water is needed to be separated from the feed solution. It means that the compressor has to reduce its capacity in order to maintain this set concentration, which also reduces the heat quantity of steam in the evaporator and distilled water in the preheater. Less steam is produced in evaporator but more concentrated solution is discharged. Ultimately, the mass flow rate of feed and discharge solution increases with the feed concentration, but the distilled water decreases. The extra steam is needed for the various feed concentrations but the mass flow rate changes slightly because of the large superheat degree deriving from the inefficient compressor with the low mass flow rate state. The mass flow rates of feed solution and discharge solution increase by 34.4% and 5.56 times, respectively, but the value of distilled water decreases by 24.9% when the feed concentration changes from 0.01 to 0.05. If the feed concentration is increased continually, the small mass flow rate of vapor may lead to the surge of compressors. Hence, the range of feed concentration is limited by compressor for the fixed discharge concentration.

The evaporation temperature and distilled water temperature influenced by feed concentration are shown in Fig. 10. Because of the increasing mass flow rate of feed solution and decreasing mass flow rate of distilled water with feed concentration, the thermal distribution in the preheater is changed. Less distilled water has to heat more feed solution, which leads to the larger decrement of distilled water temperature and small increment of feed solution temperature in the preheater. The temperature of distilled water decreases with the feed concentration and the value is 17.5°C. The low outlet temperature of feed solution from the preheater also influences the heat balance in the evaporator slightly, which leads to the increment of evaporation temperature.

The power consumption with feed concentration is shown in Fig. 11. Because the efficiency of the compressor is sensitive to its mass flow rate, the power of compressor increases with the feed concentration especially when its value is large. The total power consumption of the system is similar due to the large proportion of power consumption for the compressor. For the less distilled water with the high feed concentration, more power is consumed for one ton of distilled water. The value increases from 28.1 to 37.3 kWh/t as the feed concentration increases from 0.01 to 0.04, but it is 62.6 kWh/t if the feed concentration is 0.05.

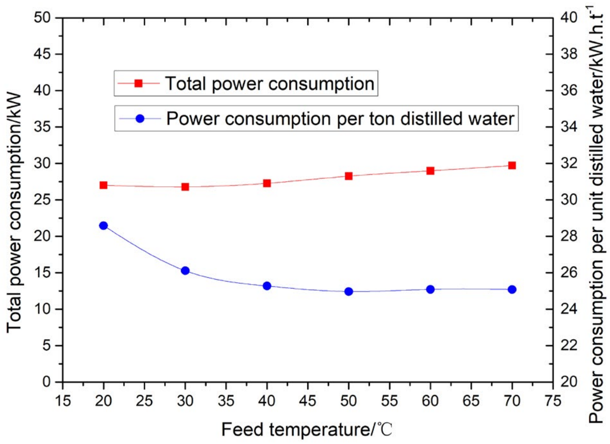

Fig. 8. Power consumption with feed temperature.

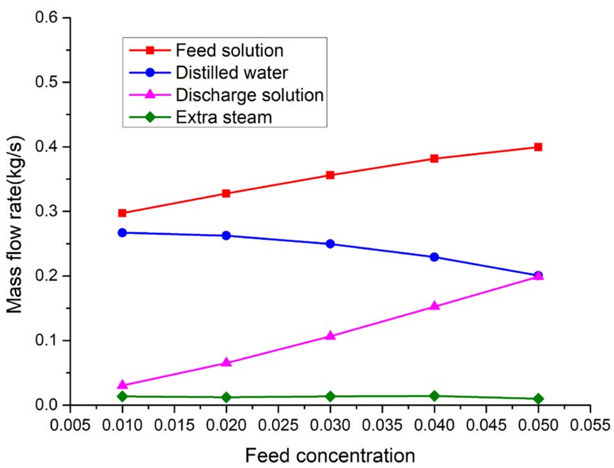

Fig. 9. Treating capacity with feed concentration.

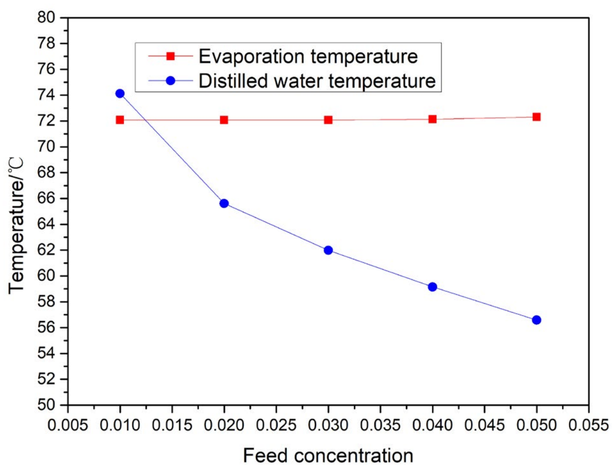

Fig. 10. Distilled water temperature with feed concentration.

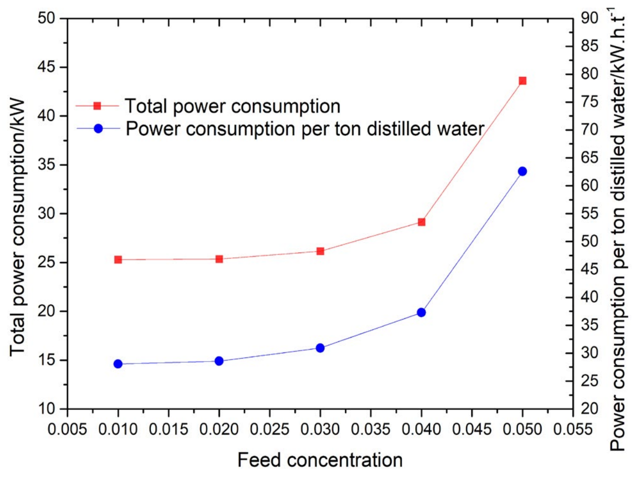

Fig. 11. Power consumption with feed concentration.

3.4. *Influence by discharge concentration*

The system treating capacity influenced by discharge concentration is shown in Fig. 12. For the larger discharge concentration, only a few concentrated solutions flow out from the system. Because the heat of the discharge solution is not recycled, the less discharge solution leads to less heat loss for the system. More heat is stored in the steam from the separator to finish the evaporation process, which slightly increases the mass flow rate of distilled water. The mass flow rate of feed solution also decreases depending on the decrement of discharge solution and slightly increment of distilled water. In addition, the mass flow rates of distilled water and feed solution are close to each other, and the heat from them is also more close. It only needs less extra steam to offset the heat loss of the system when the discharge concentration is high. The mass flow rates of feed solution, discharge solution and extra steam decrease by 14.3%, 63.1% and 39.8%, respectively, but the distilled water increases by 5.4% with the discharge concentration changes from 0.07 to 0.16.

The evaporation temperature and distilled water temperature are shown in Fig. 13. The distilled water temperature depends on the heat transfer process between the feed solution and distilled water in the preheater. Because more distilled water and less feed solution flow into preheater with the increasing discharge concentration, the small temperature difference of distilled water is needed to finish the preheating process of feed solution. The distilled water temperature increases with the discharge concentration and the increment is 1.63°C under the calculation condition. At the same time, the temperature of feed solution flowing into the evaporator also increases based on the heat balance. The thermal load of the evaporator is nearly constant because the higher inflow temperature of feed solution slightly decreases the heat transfer temperature difference in evaporator but the larger mass flow rate of distilled water slightly increases the heat transfer coefficient, which leads to the nearly constant evaporation temperature.

The power consumption with discharge concentration is shown in Fig. 14. Based on the mass flow rate of distilled water, the isentropic efficiency of the compressor

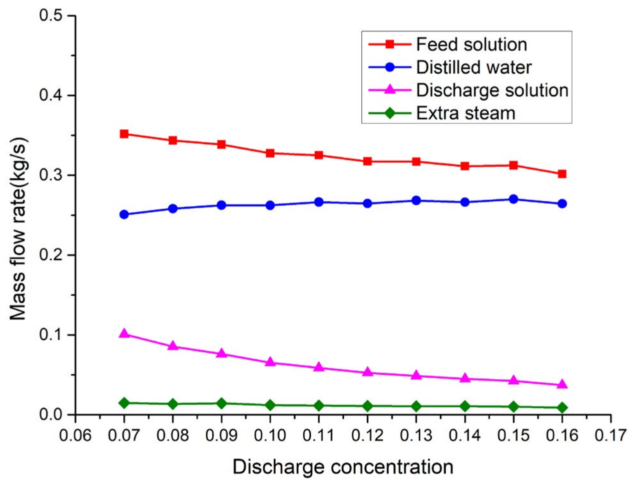

Fig. 12. Treating capacity with discharge concentration.

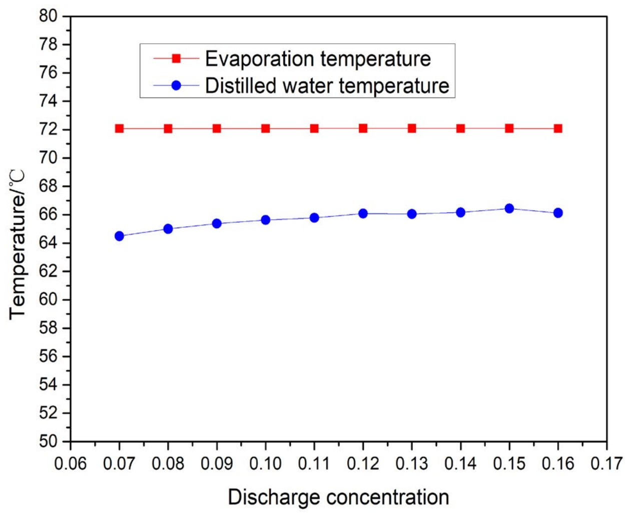

Fig. 13. Distilled water temperature with discharge concentration.

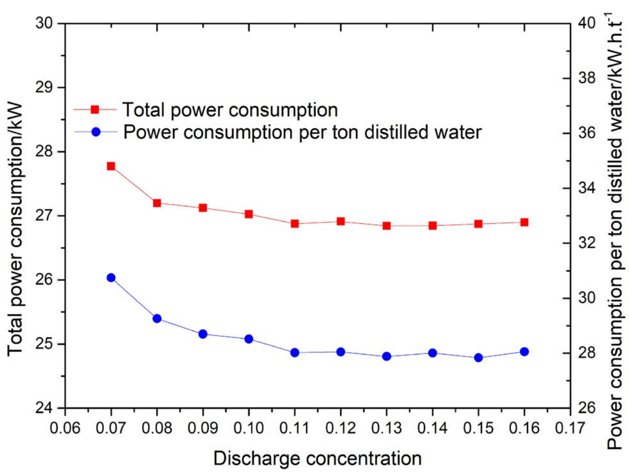

Fig. 14. Power consumption with discharge concentration.

increases first and then changes slightly. It results in the reverse variation for the power consumption of compressor and system. The nearly constant total power consumption and power consumption for one ton of distilled water are obtained when the feed concentration is larger than 0.11, and the values are 26.9 kW and 28 kW h/t.

3.5. Influence by circulation flow rate

The treating capacity influenced by the circulation flow rate is shown in Fig. 15. The dry-tube phenomenon influences the heat transfer effect and operation security for the falling film evaporator. A pump is installed between the separator and evaporator in order to increase the actual mass flow rate of solution for every tube, which can improve the heat transfer process and avoids the dry-tube phenomena. Because the circular solution only flows from separator to evaporator, the circulation flow rate is unrelated to the mass conservation of feed and discharge solution. The mass flow rate of the feed solution, distilled water, discharge solution and extra steam increases with the circulation flow rate, and the increment is 13.2%, 13.0%, 14.0%, 36.4% when circulation flow rate changes from 3.89 to 6.67 kg/s.

The evaporation temperature and distilled water temperature with the circulation flow rate are shown in Fig. 16. Because of the limited improvement of the heat transfer coefficient for the evaporator, the evaporation temperature is nearly constant. More distilled water also influences the distilled water temperature slightly, and it only increases 0.5°C when the circulation flow rate increases from 3.89 to 6.67 kg/s.

The power consumption with the circulation flow rate is shown in Fig. 17. Although the pump consumes more power with the large circulation flow rate, the power consumption of compressor decreases due to the improved isentropic efficiency. The total power consumption of system and the power for one ton of distilled water decrease with the circulation flow rate. The values decrease by 5.6% and 12.4%, respectively, when the circulation flow rate changes from 3.89 to 6.67 kg/s.

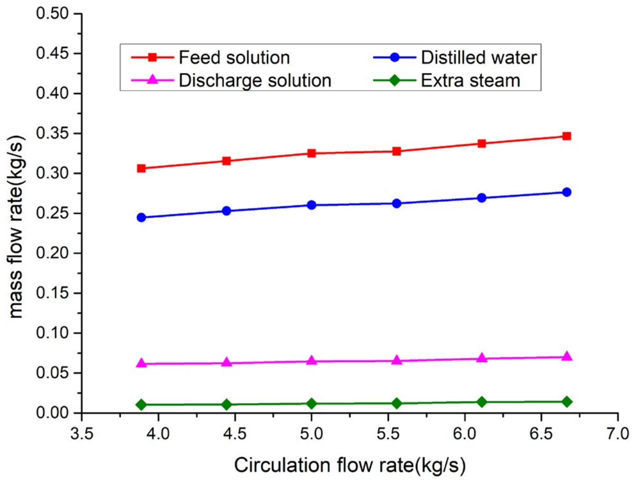

Fig. 15. Treating capacity with circulation flow rate.

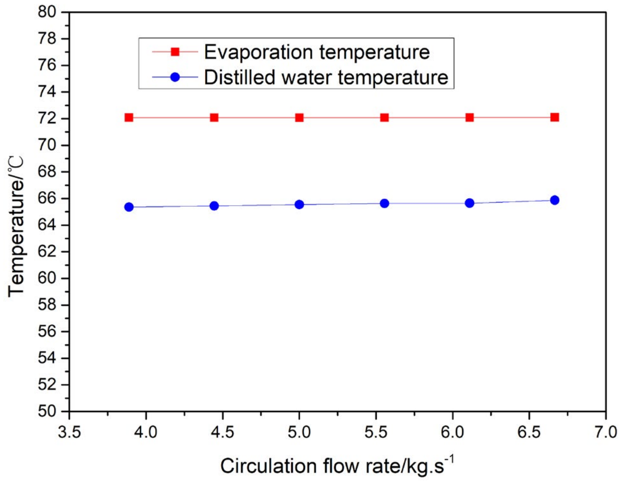

Fig. 16. Distilled water temperature with circulation flow rate.

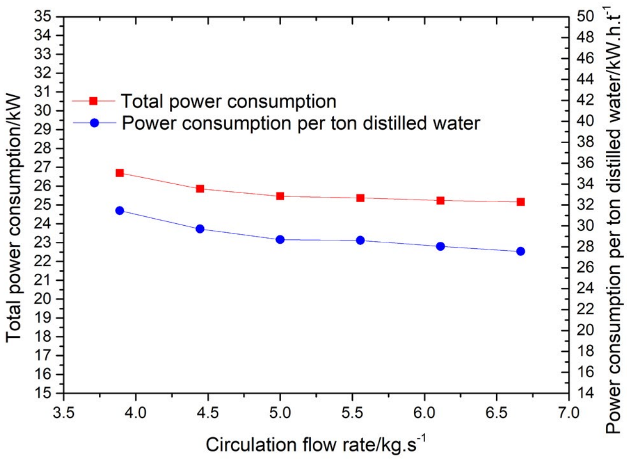

Fig. 17. Power consumption with circulation flow rate.

4. Conclusions

- The higher feed temperature improves the treating capacity of the system and reduces its power consumption. The mass flow rate increases by 25.4%, the distilled water temperature reduces 11.9°C, the power consumption increases by 10%, and the power consumption for one ton of distilled water decreases by 12.3% when the feed temperature goes from 20°C to 70°C.
- The higher feed concentration reduces the output of distilled water and its temperature but increases the mass flow rate of feed and discharge solution. The mass flow rate of distilled water decreases by 24.9% and its temperature reduces 17.5°C, the mass flow rate of feed and discharge solution increase by 34.4% and 5.56 times as the feed concentration changes from 0.01 to 0.05. The power consumption for one ton of distilled water increases rapidly especially when the feed concentration is larger than 0.04.
- The higher discharge concentration increases the output of distilled water and its temperature but reduces the mass flow rate of feed and discharge solution.

The increments are 5.4% and 1.63°C, and the decrement is 14.3% and 63.1%, respectively, with the discharge concentration changes from 0.07 to 0.16. The power consumption for one ton of distilled water decreases first and then changes slightly until the stable values of 28 kW h/t.

- Increasing the circulation flow rate in a certain range is helpful to improve the capacity of the system. The mass flow rate of the feed solution, distilled water, discharge solution increases by 13.2%, 13.0%, 14.0% with the circulation flow rate changes from 3.89 to 6.67 kg/s. The total power consumption and the power for one ton of distilled water decrease by 5.6% and 12.4%.

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Symbols

A	—	Area of heat transfer, m^2
c	—	Concentration
c_p	—	Specific heat, J (kg K)$^{-1}$
D	—	Equivalent diameter, m
g	—	Gravitational acceleration, m s^{-2}
h	—	Specific enthalpy, kJ kg^{-1}
H	—	Difference of liquor level, m
K	—	Coefficient of heat transfer, W m^{-2} K^{-1}
K^+	—	Dimensionless heat transfer coefficient
m	—	Mass flow rate, kg s^{-1}
p	—	Pressure, Pa
Pr	—	Prandtl number
Re	—	Reynolds number
v	—	Specific volume, m^3 kg^{-1}
W	—	Power, W
Δh	—	Enthalpy difference
ΔH	—	Pipe resistance, m
Δt	—	Heat transfer temperature, °C
η	—	Efficiency
λ	—	Thermal conductivity, W.(m K)$^{-1}$

Subscripts

at	—	Atmospheric
cf	—	Circulation flow
cl	—	Cooler
comp	—	Compressor
con	—	Condensation process
cp	—	Circulation pump
dp	—	Distilled water pump
ds	—	Discharge solution
dw	—	Distilled water
eva	—	Evaporation process
ex	—	Extra steam
fs	—	Feed solution
La	—	Laminar flow
ng	—	Non-condensation gas
ph	—	Preheater
s	—	Isentropic process
Tur	—	Turbulence flow
vp	—	Vacuum pump

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