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A lab-scale MED dealing with salinity wastewater: the study of optimal operation schemes and parameters

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ABSTRACT

Multi-effect distillation (MED) system with a top brine temperature lower than 70˚C, is one of the most successful desalination technologies. In this paper, a lab-scale vertical tube MED system was performed for salinity wastewater desalination of petrochemical enterprises, and five salinity wastewater treatment schemes including different combinations of evaporator types were investigated. As a result, the falling-falling-climbing (FFC) system was considered as the optimal scheme. Then, the operation parameters including the feedwater salinity, temperature, flow rate, and the fresh steam flow rate were further optimized. The results indicated that the CR and gained output ratio (GOR) would rise up by increasing effect numbers, fresh steam flow rate, and feedwater temperature. While CR and GOR would fall down with the increase of the feedwater salinity and flow rate. Therefore, the optimal operation parameters were experimentally determined as follows: the feedwater with salinity of 0.6%, flow rate of 75 kg/h, and temperature of 45˚C, and fresh steam flow rate of 17 m^3/h. The maximum CR and GOR were up to 5.08 and 4.13, respectively.

Keywords: Multi-effect distillation; Petrochemical enterprises; Salinity wastewater; Operation schemes; Operation parameters

1. Introduction

Petrochemical enterprise is one of the economy backbones in China. In the process of petrochemical enterprise, more and more water is consumed and a large amount of wastewater is discharged. In recent years, many methods have been used to prevent the hazard of wastewater which is discharged from petrochemical enterprises. Among various wastewaters, the treatment of salinity wastewater is the bottleneck problem to limit the "zero discharge" level of petrochemical enterprises [1]. So far, salinity wastewater has been mainly treated based on the traditional methods of the biological treatment systems, before being discharged into external environment [2–5]. In fact,

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several disadvantages restricted the application of biological method, including the trouble in salt-tolerant microbial cultivation, a large fluctuation of treatment performance caused due to high salinity etc. So, physicochemical separation techniques including reverse osmosis (RO), electrodialysis (ED), microfiltration (MF), and thermal methods such as multi-effect distillation (MED) and multi-stage flash (MSF) are widely used for desalination process [6–9].

MED is a traditional and representative desalination technology [10]. On the basis of energy consumption and heat transfer, it has been found that MED was more efficient than MSF [11]. The significant advantages, including low scale formation, easy operation, high performance ratio (PR), and operating with any available source of heat energy, have made MED to be widely used in seawater desalination [12–14]. For example, 14.5% of desalination plants adopt MED in China and the overall desalination capacity of MED is 232,000 m^3/d [15–17]. Although MED is one of the most important technologies in seawater desalination, yet the related reports about the application of MED process in refinery have not been found. Many researches have been made in MED desalination systems from different aspects and some progress has been obtained. For example, many reports have studied the general computer code and optimal model for thermo economic optimizations of MED desalination systems [18–22]. However, the related reports on operation parameters of lab-scale MED system were very less.

In this paper, a lab-scale vertical tube MED system for dealing with salinity wastewater of petrochemical enterprises had been established. In order to apply the MED system in the treatment of salinity wastewater from petrochemical enterprises, related parameters and performances of the MED system were investigated in detail. Many parameters of the MED system, such as evaporator types (climbing film and falling film), effect numbers, feedwater, and fresh steam, correlated closely with these performances including CR, gained output ratio (GOR), and distillated product, etc. For instance, different heat transfer efficiency produced different CR and GOR when climbing film and falling film were used separately. In addition, effect numbers also influenced GOR and heat utilization of the MED system. Through the experimental study, the optimal operation schemes and parameters could be confirmed, such as the feedwater salinity, temperature, and flow rate, and the fresh steam flow rate. Finally, the maximum CR and GOR could be obtained under these conditions. This paper would provide a very useful reference for the salinity wastewater reduction via MED process in petrochemical enterprises.

2. Experimental equipment and method

2.1. Experimental equipment

Traditionally, salinity wastewater from petrochemical enterprises often contained a large percentage of organic substances (including oil type matter) and suspended particles. The stability of MED process would be influenced if they were not removed. Consequently, it is very necessary to pretreat the salinity wastewater to remove the organic substances and suspended particles before salinity wastewater entered the MED system. In this paper, the fresh water mixed with NaCl used as simulated saline wastewater of petrochemical enterprises was selected as the feedwater. A simplified schematic diagram of the lab-scale MED system was shown in Fig. 1. The lab-scale vertical tube MED system included: (1) vertical tube evaporators (I and III were falling film evaporator and II and IV were climbing film evaporator), (2) four flashing chambers (A, B, C, and D), (3) distillated product, feedwater, condensate, and brine disposal pumps to circulate the streams, (4) steam-water separation (E), (5) condenser (F), and (6) the steam generator. There were two reasons why five schemes could be selected. First, the fresh steam from the steam generator could enter into the first effect evaporation and the second one via controlling the valves. Second, the feedwater could be pumped into the tuber of any evaporation. The principle of the MED system was as follows: the fresh steam entered into the first effect where it condensed. The latent heat of condensation was used to warm the feedwater to the boiling point, and then the heated feed entered the first flashing chamber where the secondary steam flashed off due to pressure drop. Subsequently, the steam formed in the first flashing chamber flowed to the second effect as heat source. The brine leaving the first effect was directed to the next effect which was at a lower pressure and would be heated by the steam formed in the first flashing chamber again, so the steam could be utilized repeatedly. This process was continued up to the last effect.

2.2. Experimental scheme

Based on the influence of structure characteristics and the pressure of each effect on the performances of the MED system, five schemes consist of different evaporator types could be designed, as presented in Table 1.

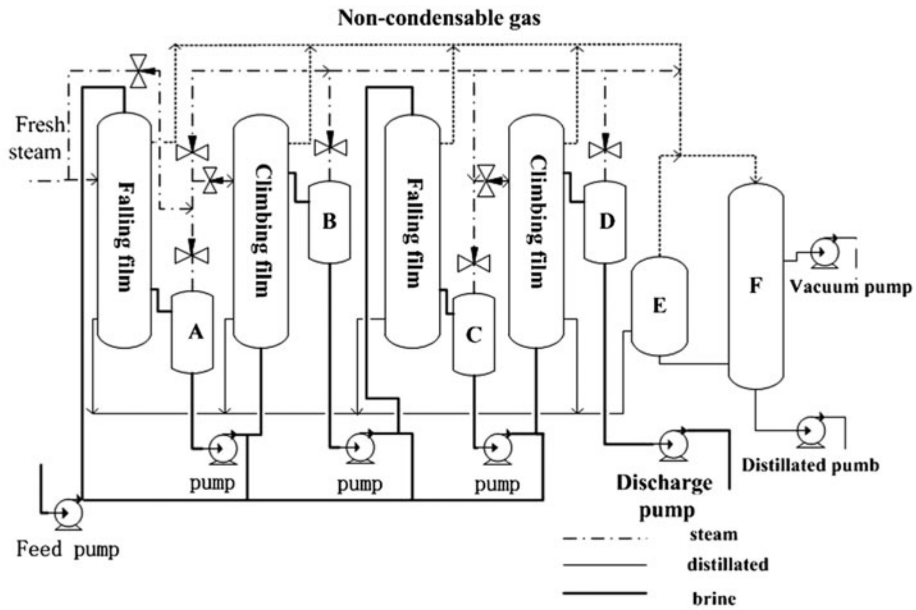

Fig. 1. The simplified schematic diagram of the lab-scale vertical tube MED system.

Table 1
Five experimental schemes with different combinations

Effect numbers	Scheme	Combinations	Pressure of each effect in due order (MPa)
2	A	Falling-falling (FF)	−0.060, −0.080
	B	Falling-climbing (FC)	−0.060, −0.080
	C	Climbing-climbing (CC)	−0.060, −0.080
3	D	Falling-falling-climbing (FFC)	−0.045, −0.065, −0.085
	E	Falling-climbing-climbing (FCC)	−0.045, −0.065, −0.085

2.3. Analysis method

Concentration ratio (CR) is the ratio between the discharging salinity and the feedwater salinity. CR serves as an important parameter because it is associated with the scaling rate, the total heat transfer areas reflect the concentration efficiency of the MED system. Besides that, the higher the CR, the less saline wastewater discharged to outside, and the more conducive to promote the "zero discharge" of petrochemical enterprises.

$$CR = W_1/W_2 \tag{1}$$

where W_1 is the discharging salinity (%), W_2 is the feedwater salinity (%).

GOR is the ratio of the quality of distillated products to the quality of the fresh steam. GOR is one of the major factors in thermal parameters. In addition, the higher the GOR will result in the better performance of MED system. This rating method does not account for the steam enthalpy difference across the desalting unit, the supply steam quality (temperature and pressure), or the pumping work [23].

$$GOR = M_d/M_s \tag{2}$$

where M_d is the quality of distillated products (kg), M_s is the quality of the fresh steam from steam generator (kg).

CR and GOR are both main parameters to assess the performance of MED system. Therefore, they are selected as the standard to determine the merits of five scheme performances in this paper.

3. Results and discussions

The optimal scheme was determined by taking CR and GOR as index. After determination of the optimal experimental scheme, several operation parameters involving the salinity, temperature, flow rate of the feedwater, and the flow rate of the fresh steam were tested, which influenced the performance of MED system.

3.1. Determination of the optimal experimental scheme

Five experiment schemes (Table 1) were investigated under the specific operating conditions. Operation parameters were controlled as follows: the feedwater salinity (0.6%), temperature (15℃), and flow rate (75 kg/h), the fresh steam pressure (0.5 MPa), density (2.679 kg/m^3), temperature (150℃), and flow rate (17 m^3/h), respectively. As shown in Fig. 2, the CR and GOR of scheme A, B, C, D, and E were compared and the conclusions were as below: the CR and GOR of the FF system were minimum, while the CC system were maximum among the two effects system. The reasons were as follows, in the climbing film, the feedwater went into the evaporator from the bottom. The residence time of the feeding process was longer and the heat exchanged more sufficiently than falling film. Hence, the CR and GOR of the CC system were the maximum owing to the longer residence time and more thermal power. The performance of the CC system was the best among the two effects system.

Meanwhile, it could be seen that the CR and GOR of the FCC system were both lower than the FFC system in Fig. 2. Although the FCC system had higher heat exchange efficiency, it had the shorter residence time in the second flashing chamber. Therefore, the CR and GOR of the FCC system were lower than the FFC system. However, neither the CR nor the GOR of these two effects systems was higher compared with the three effects systems, and the maximums of which were 2.83 and 2.15, respectively. The main reason was that effect numbers were too low, so that it was a vast waste of steam condensed directly which formed in flashing chamber. Meanwhile, the heated saline water was not concentrated sufficiently before it was discharged. The discharging concentration of each effect for the FFC and FCC system were shown in Fig. 3, it could be seen that the discharging concentration increased successively from the first effect to the third one. In addition, the increment of the concentration was also ascending. Heat exchange and evaporation happened in each effect, so secondary steam was produced and the brine was concentrated gradually.

From Fig. 2, the results indicated that higher CR and GOR were synchronized by increasing the effect numbers, the maximum could reach 4.50 and 2.99, respectively. Thus, rising of performance was obtained by increasing effect numbers appropriately, so that the steam could be utilized repeatedly and more distillated products could be obtained. However, effect numbers were closely related to the initial investment and distillated product cost, lower effect numbers could keep the balance between the more distillated product request and the less cost. So the choice of suitable effect numbers was very significant to design the MED system. Meanwhile, it was also observed that the discharging concentration of each effect from the FFC system was higher than the FCC system from Fig. 3. As a result, the FFC system was the optimal experimental scheme among these five schemes shown in the Table 1.

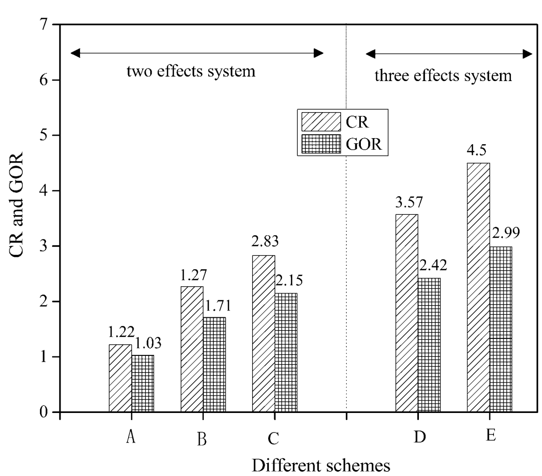

Fig. 2. The CR and GOR of five different schemes.

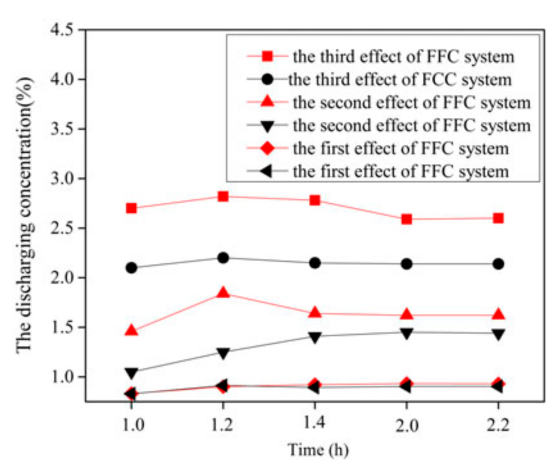

Fig. 3. The discharging concentration of each effect from the FFC and FCC system.

3.2. Optimization of the operation parameters

From the above discussion, the FFC system was the optimal experimental scheme, so it was taken as the research object. Operation parameters were controlled as follows: the vacuum from the first effect to the third one were −0.045, −0.065, −0.085 MPa in due order, the feedwater salinity (the mass fraction was 0.6, 0.8, 1, 2%), flow rate (75, 87.5, 100, 120 kg/h), fresh steam flow rate (6.5, 10.0, 13.5, 17.5 m^3/h) and feedwater temperature (15, 25, 35, 45℃). The optimum operation parameters would be defined based on the analysis of experimental data.

3.2.1. Influence of the feedwater salinity on the CR and GOR

The influence of feedwater salinity on CR and GOR were studied. The feed salinity used for the experiment was 0.6, 0.8, 1, and 2%, respectively. The feedwater flow rate was 75 kg/h, feedwater temperature was 15℃, and fresh steam flow rate was 17 m^3/h. As shown in Fig. 4, both CR and GOR gradually decreased with the increase of the feedwater salinity, which indicated that the treatment effect was reduced. The reasons were as follows. First, the viscosity increased with the increase of the feed salinity, and the diffusion coefficient and the thermal conductivity of NaCl in the feed solution were reduced. At the same time, the distillated product and the secondary steam formed in per effect were reduced. In addition, the influence of the boiling point elevation (BPE) rose with the increase of the salinity. As a result, the loss from heat transfer temperature difference of the system rose with the increase of the effect numbers, so that the heat transfer efficiency was decreased. Then the thermal efficiency of the system was reduced. From the analysis above, the optimal feedwater salinity was 0.6%.

3.2.2. Influence of the feedwater flow rate on CR and GOR

Various feed flow rates were used in the experiment (75, 87.5, 100, 120 kg/h) with employing the fresh steam flow rate (17 m^3/h), the feedwater temperature (15℃), and the optimum feedwater salinity (0.6%). In Figs. 5 and 6, CR, GOR, and discharging concentration of the MED system were all decreased with the increase of feed flow rate. The reason was that the residence time of the feeding in the evaporator decreased with the increase of feed flow rate. In addition, the increase of heat quantity was required to raise the temperature of the feedwater to the saturation temperature. The distillated product and GOR were decreased because more latent heat from the heat steam was taken away by the brine, and the secondary steam product was decreased. Meanwhile, the thermal power for heating the brine in the last two effects was inadequate because of the decrease of the secondary steam. Therefore, the CR and the discharging concentration were gradually decreased. It could be concluded that the optimal feed flow rate was 75 kg/h, as this amount of feedwater was appropriate for the feedwater to reach saturation temperature on the shell side, by pre-heating via the condensing steam in the tube side. The flow rate of 75 kg/h also ensured integral film formation on the shell walls of the vertical tube evaporator tubes to avoid hot spot formation [24].

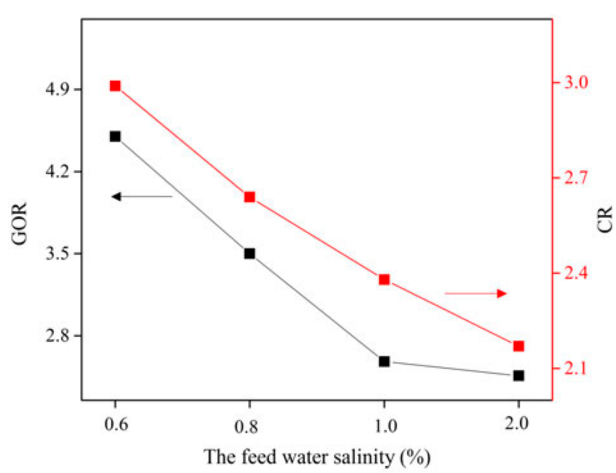

Fig. 4. Variations of CR and GOR with different feedwater salinity.

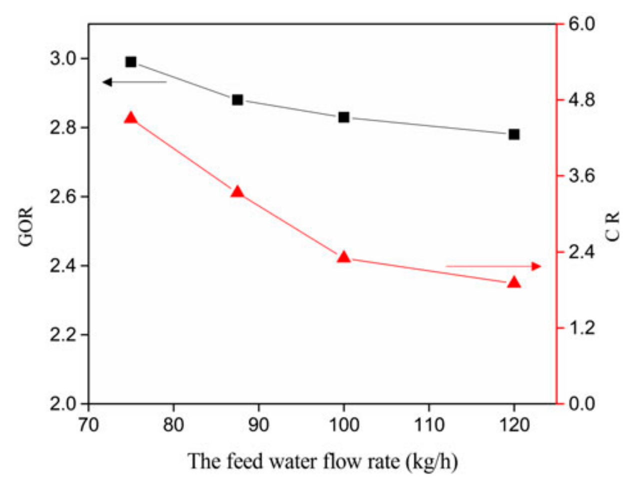

Fig. 5. Variations of CR and GOR with different feedwater flow rate.

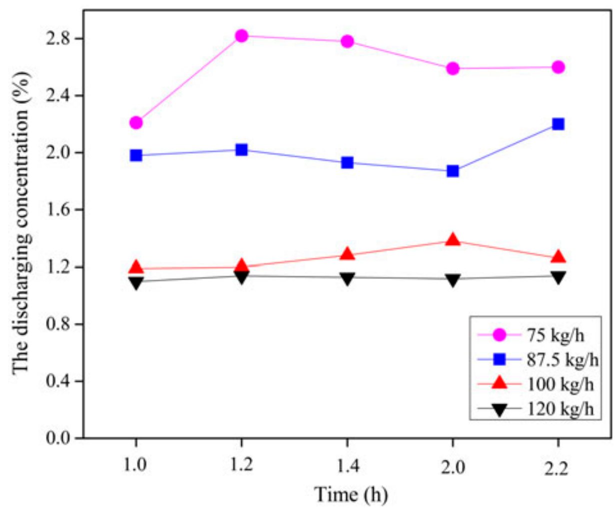

Fig. 6. The discharging concentration of the different feedwater flow rate.

3.2.3. Influence of the fresh steam flow rate on CR and GOR

The determined optimum feedwater salinity (0.6%) and flow rate (75 kg/h) were employed in this part. With the feedwater temperature at 15℃, the influence of the fresh steam flow rate on CR, GOR, and discharging concentration was studied by varying the steam flow (6.5, 10.0, 13.5, 17 m^3/h). In Figs. 7 and 8, the influence of different fresh steam flow rates on CR, GOR, and the influence of different fresh steam flow rates on different discharging concentration. It was evident that the CR, GOR, and the discharging concentration increased gradually with the increase of fresh steam flow rate. The main reason was that the feedwater could gain more thermal power to reach the saturation temperature when the fresh steam flow rate raised, and then the heated brine could generate more secondary steam in the flashing chamber, the brine concentration was increased and the brine was reduced simultaneously. As a consequence, both of CR and discharging concentration increased. Then GOR was raised. So the optimal fresh steam flow rate was 17 m^3/h.

3.2.4. Influence of the feedwater temperature on CR and GOR

The feedwater temperature to the first effect was important for optimizing the heat transfer rate for a given area of the tube surface. The difference in temperature ΔT between the tube and shell side should be kept small to have optimum recovery of distillation in subsequent effects. At the same time, ΔT should be sufficient for condensing the steam inside the tubes [25]. The influence of the feed temperature on CR and GOR was studied by varying the amount of the feed temperature used for the experiment (15, 25, 35, 45℃) with employing the feedwater salinity (0.6%) and flow rate (75 kg/h), the fresh steam flow rate (17 m^3/h) previously determined. The influence of different feedwater temperature on CR, GOR, and the discharging concentration were given in Figs. 9 and 10. It could be seen that the feedwater temperature exerted a strong influence on CR, GOR, and the discharging concentration. From the figures, it was indicated that

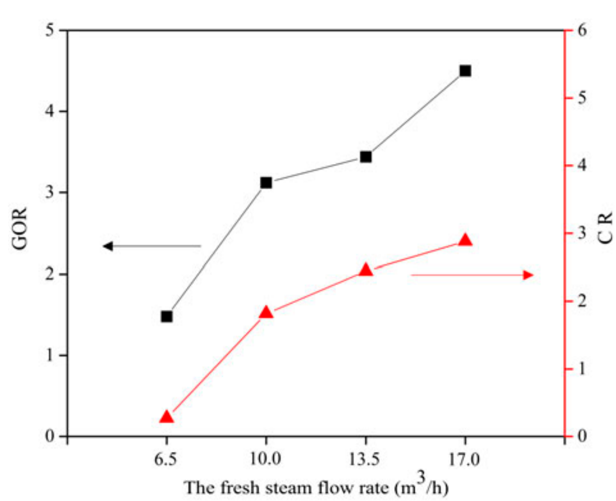

Fig. 7. Variations of CR and GOR with different fresh steam flow rate.

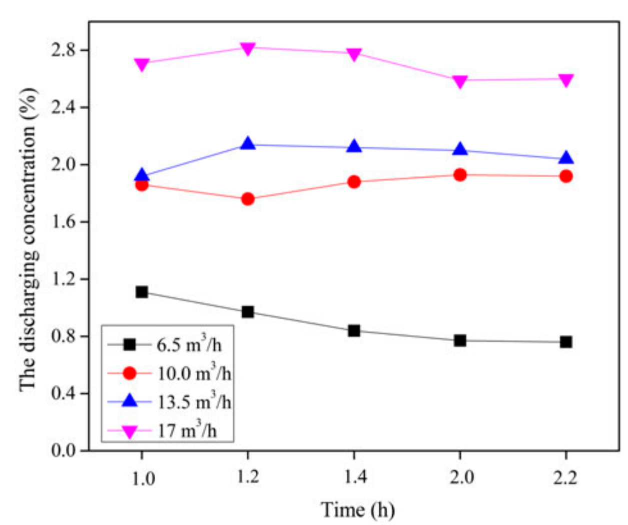

Fig. 8. The discharging concentration of the different fresh steam flow rate.

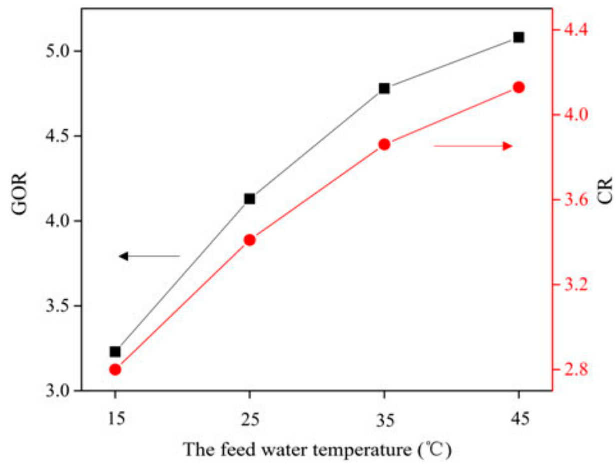

Fig. 9. Variations CR and GOR with different feedwater temperature.

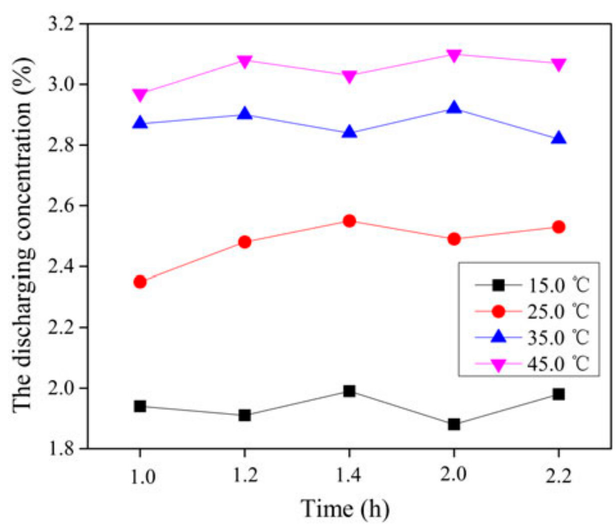

Fig. 10. The discharging concentration of the different feedwater temperature.

any increase in feedwater temperature would raise the CR, GOR, and discharging concentration amounts. This was because the feedwater enthalpy would increase with the increase of feedwater temperature. Moreover, the steam used to preheat the feedwater would be reduced due to the high feed temperature, and more steam used to warm the feedwater to reach the boiling point. So the optimal feedwater temperature was 45℃. However, the additional heat source needed to raise the feed temperature to upgrade the distillated product was at the expense of external heat source. Therefore, the appropriate feed temperature should be chosen in practical applications.

4. Conclusions

In summary, optimal operation schemes and parameters were determined in a lab-scale MED system. First, the FFC system was considered as the optimal scheme owing to the higher CR and GOR by comparing five different schemes for salinity wastewater treatment performance. Experimental results demonstrated that the higher CR and GOR were synchronized by increasing the number of effects, the flow rate of fresh steam, and the temperature of feedwater, while decreased by increasing the salinity and flow rate of the feedwater. It was found that the optimal operation parameters consisted of the feedwater with salinity (0.6%), flow rate (75 kg/h), and temperature (45℃), and the fresh steam with flow rate (17 m^3/h). The maximum CR and GOR were 5.08 and 4.13, respectively. It was considered that the MED system was more suitable for dealing with the low salinity wastewater, which could be used as the optimal pretreatment before the wastewater crystallization in petrochemical enterprises. Moreover, the risk of device fouling would rise with the increase of CR. Therefore, taking into account the risk of fouling and the economic performance of the system, appropriate CR should be better designed in the future.

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