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Performance analysis of mixed feed LT-MED desalination system with thermal vapor compressor

Xiaohua Liu, Dawei Liu, Shengqiang Shen*, Yong Yang, Feng Gao

School of Energy and Power Engineering, Dalian University of Technology, Dalian, 116024, P.R. China
Tel. +86 131 3040 1799; email: lxh723@dlut.edu.cn

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ABSTRACT

Seawater desalination has emerged as an important source of fresh water. Low-temperature multi-effect distillation (LT-MED) is one of main methods of seawater desalination. LT-MED desalination system consists of a few types, such as forward feed configuration, backward feed configuration, parallel feed configuration and mixed feed configuration. Among them, the mixed feed configuration can process higher concentration ratio of seawater than that of the others and the spray density of this configuration can be easily designed to achieve a reasonable range which are important for operation. In this study, a mathematical model of mixed feed LT-MED desalination system with thermal vapor compressor (TVC) has been established based on the mass and energy conservation. In this model, the temperature losses are calculated in terms of boiling point elevation (BPE) of sea water and steam flow pressure drop during tube bundle, demisters and pipelines. To develop this model, the property parameters of seawater are considered as the functions of temperature and concentration, and the property parameters of fresh water and saturated steam are considered as the functions of temperature. The model simulation is based on the system with a rated water production of 3500 t d^{-1}. Taking actual operation into account, some related factors on the system performance have also been analyzed such as entrained steam position of TVC, heating steam temperature of the first effect, motive steam parameters of TVC, and position of preheater. The results show that when the entrained steam position of TVC is located at the effect just behind the mixed feed position, the gained output ratio (GOR) reaches the maximum value and the total area of evaporators reaches the minimum value, which will benefit to reduce the water cost. It is also observed that the impact of motive steam parameters of TVC on GOR is greater than on total area of evaporators. The increase of motive steam parameters and a design with the preheater before the entrained steam position of TVC will greatly contribute on reducing the cost of water.

Keywords: Seawater desalination; Low-temperature multi-effect distillation; Thermal vapor compressor; Mixed feed; Boiling point elevation

1. Introduction

Water is available in large quantities on earth. It covers about 3/4 area of the earth surface, while only 3% of which is available for drinking. About 25% of the world's people lack the quality and quantity of freshwater supplies. More than 80% of the countries are facing serious water problem [1]. The oceans represent the earth's major water reservoir. By removing salt from the virtually unlimited supply of seawater, desalination has emerged as an important source of fresh water [2–4]. A variety of desalination technologies has been developed

*Corresponding author.

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over the years on the basis of thermal distillation, membrane separation, freezing, electrodialysis, etc. [4–11]. Researchers show that three processes of desalination—multi-stage flash distillation, reverse osmosis, and multi-effect distillation (MED)—will be dominant and competitive in the future [12,13].

The MED process is the oldest desalination method. In the middle stage of 1980s, large scale plant of LT-MED appeared. The character of LT-MED system is that the range of the heating steam temperature of the first effect is 65 ≈ 75°C [14], which reduces the potential for scale formation and corrosion. Most of LT-MED plants are built combined with power plant, which is called Dual Purpose Power Plant, so that the cost of water can be reduced greatly.

According to brine flow direction and the vapor flow direction, flow configuration in a MED system can be classified into four types: forward feed configuration, backward feed configuration, parallel feed configuration and mixed feed configuration [15]. In the forward feed configuration, both feed seawater and heating steam to the evaporators flow in the same direction, hence the least salinity is in the first effect with the highest temperature. In the backward feed system, the flow directions of heating steam and seawater feed are opposite to each other. This is rarely used in desalination since the first effect has the highest temperature and salinity [16]. In the parallel feed arrangement, the feed seawater is divided and distributed almost equally to each effect [17]. In the mixed feed configuration, the ways of feed seawater entering into the effects before and behind the mixed feed position are both parallel, but for the mixed feed position, the total flow arrangement including seawater flowing into effects before mixed feed position and the feed seawater entering into the left effects is current. However, not so much researches have been done in the mixed feed configuration. As a potential configuration, its concentration ratio of seawater can be higher than that of other configurations and the spray density can be easily designed to achieve a reasonable range which is important for operation purpose.

2. The mixed feed LT-MED desalination system with thermal vapor compressor

The mixed feed LT-MED desalination system with TVC is shown in Fig. 1. In this figure, the mixed feed position is between the second and the third effect. The first two effects' feed seawater flow from the condenser and the way of feed seawater enters into each effect is parallel. The feed seawater of the left No.3 to No. *n* effects is the concentrated brine discharged from the first two effects and the way of feed seawater enters into the left No.3 to No. *n* effects is also parallel. Because the temperature of the concentrated brine discharged from the effects before the mixed feed position is higher, a brine cooler is used at the mixed feed position which makes use of the heat of brine to heat the sea water directly from condenser. The mixed feed position can be selected between No.1 to No. *n* effect.

For Dual Purpose Power Plant, high pressure and temperature steam extracting from turbine is used as the motive steam of TVC. Part of the secondary steam from certain effect of LT-MED system is used as the entrained steam of TVC. The steam from the outlet of TVC is usually desuperheated and then used as the heating steam of the first effect of LT-MED system. Theoretically, when the number of total effects is n, the number of optional mixed position is $n - 1$ and the number of optional entrained steam position of TVC is n. So the number that the optional configurations of the mixed feed LT-MED desalination system with TVC is $n^2 - n$.

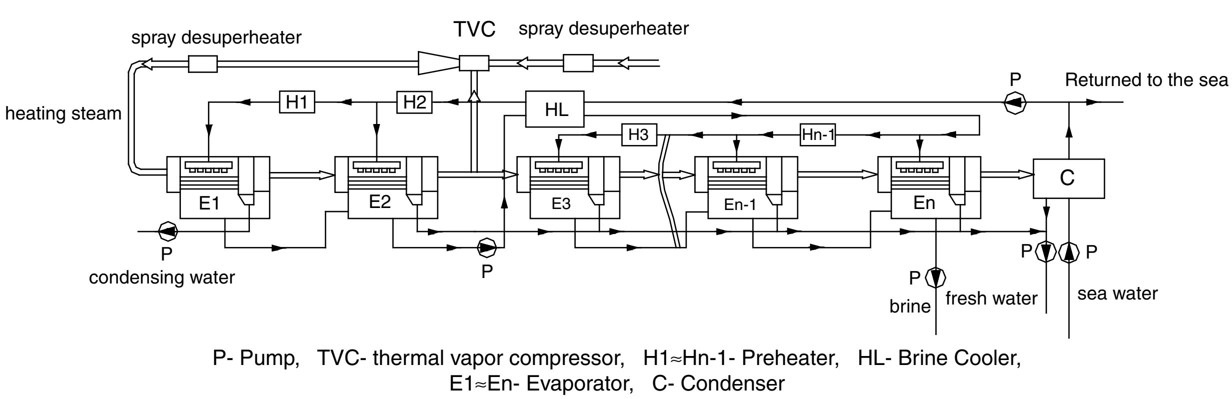

Fig. 1. Schematic diagram of mixed feed LT-MED desalination system with TVC.

3. Mathematical model

Based on the mass and energy conservation, a mathematical model of the mixed feed LT-MED desalination system with TVC has been established. The temperature losses are evaluated in term of BPE of sea water and the flow resistance when steam flowed through the tube bundle, demisters and pipelines. The property parameters of sea water are considered as the function of temperature and concentration, and the property parameters of fresh water and saturated steam are considered as the function of temperature. A software is designed using Visual Basic to simulate this mathematical model.

3.1. Evaporator

The mass conservation, salt balance and energy conservation equations of the No. *i* effect evaporator are defined by Eqs. (1)–(3) separately:

$$M_{\text{b.in}} = M_{\text{b.out}} + M_{\text{vi}} \tag{1}$$

$$X_{\text{b.in}} \times M_{\text{b.in}} = X_{\text{b.out}} \times M_{\text{b.out}} \tag{2}$$

$$(M_{\text{v}(i-1)} \times \lambda_{i-1} + M'_{\text{v}(i-1)} \times \lambda'_i + M_{\text{b.out}(i-1)} \times C_{\text{pb.out}(i-1)} \times t_{\text{b.out}(i-1)} - M_{\text{b.in}} \times C_{\text{pb.in}} \times t_{\text{b.in}}) \times \eta = M_{\text{v}i} \times h_i \tag{3}$$

where *M*, *X*, λ, *h*, η, *t* and Cp denote mass flow rate (kg s^{-1}), salt concentration (kg kg^{-1}), latent heat of vaporization (kJ kg^{-1}), enthalpy (kJ kg^{-1}), adiabatic efficiency of evaporator, temperature (°C), and the specific heat (kJ (kg°C)$^{-1}$), respectively. The subscripts b, v, *i*, in, out denote brine, steam, the number of effects, inlet, and outlet, respectively. The superscript′ denotes flash distillation.

For the first effect, there is no flash vapor. The energy balance equation is as follows:

$$(M_{\text{v}0} \times \lambda_0 + M_{\text{b.out}0} \times C_{\text{pb.out}0} \times t_{\text{b.out}0} - M_{\text{b.in}} \times C_{\text{pb.in}} \times t_{\text{b.in}}) \times \eta = M_{\text{v}1} \times h_1 \tag{4}$$

The temperature of secondary steam of the No. *i* effect (t_{vi}) and the temperature of the heating steam that enters the next effect (t_{ci}) are defined as follows:

$$t_{\text{v}i} = t_{\text{b}i} - \text{BPE}_i - \Delta t_{\text{j}i} \tag{5}$$

$$t_{\text{c}i} = t_{\text{v}i} - \Delta t_{\text{h}(i-1)} - \Delta t_{\text{d}(i-1)} - \Delta t_{\text{t}(i-1)} \tag{6}$$

where BPE is the boiling point elevation of seawater (°C), a function of temperature and concentration of sea water. In this case, the temperature loss caused by static pressure of liquid layer Δt_{ji} is zero (°C), because the liquid film thickness is very thin in the horizontal tube falling film evaporator. The subscripts h, d and t denote tube bundle, demister and pipeline, respectively. The Δt_h, Δt_d and Δt_t denote the steam temperature loss (°C) caused by the steam flow resistance during tube bundle, demisters and pipelines, respectively.

The heat transfer equation of the No. *i* effect is written as follows:

$$M_{\text{v}(i-1)} \times \lambda_{i-1} + M'_{v(i-1)} \times \lambda'_i = A_i \times k_i \times (t_{\text{c}i} - t_{\text{b.in}}) \tag{7}$$

where *A* denotes heat transfer area (m^2), and *k* denotes heat transfer coefficient (W (m^2 °C)$^{-1}$).

3.2. Preheater

The system studied in this paper uses external heat source to preheat feed seawater. The energy conservation equation of the No. *i* effect preheater can be expressed as follows:

$$Q_{\text{out}} = M_{\text{r}} \times (C_{\text{pr}i} \times t_{\text{r}i} - C_{\text{pr}(i+1)} \times t_{\text{r}(i+1)}) \tag{8}$$

Also, the heat transfer equation of the No. *i* effect preheater is as follows:

$$Q_{\text{out}} = k_{\text{p}i} \times A_{\text{p}i} \times (\text{LMTD})_{\text{p}i} \tag{9}$$

where the subscripts r and p denote feed seawater and preheater, respectively; LMTD denotes logarithmic mean temperature difference (°C); Q_{out} denotes the amount of external heat (kJ).

3.3. Condenser

The energy conservation equation of condenser is defined using Eq. (10):

$$M_{\text{last}} \times \lambda_{\text{last}} = M_{\text{cw}} \times (C_{\text{pbout}} \times t_{\text{out}} - C_{\text{pbin}} \times t_{\text{in}}) \tag{10}$$

The heat transfer equation of condenser is defined using Eq. (11) as follows:

$$M_{\text{last}} \times \lambda_{\text{last}} = k_{\text{c}} \times A_{\text{c}} \times (\text{LMTD})_{\text{c}} \tag{11}$$

where M_{last} and M_{cw} denote the mass flow rate of steam that enters into the condenser and the mass flow rate of sea water (kg s^{-1}), respectively; the subscripts last, c, out and in denote the last effect evaporator, condenser, outlet and inlet, respectively.

4. Flash distillation process

The energy conservation equation of the No. i effect is:

$$M'_{vi} \times \lambda'_i = M_{f(i-1)} \times C_{pf(i-1)} \times t_{c(i-1)} - M_i \times C_{pfi} \times t_{i.out} \tag{12}$$

$$t_{i.out} = t_{vi} + (NEA)_i \tag{13}$$

The mass conservation equation of the No. i effect is as follows:

$$M_{vi}' = M_{f(i-1)} - M_{fi} \tag{14}$$

The non-equilibrium temperature rise of flash is as follows [18]:

$$(NEA)_i = 0.33 \frac{t_{c(i-1)} - t_i'}{t_{vi}} \tag{15}$$

where, the subscript f denotes fresh water.

4.1. Brine cooler

The energy conservation equation is as follows:

$$M_{qr} \times (C_{pqout} \times t_{out} - C_{pqin} \times t_{in}) = M_{gr} \times (C_{pgout} \times t_{out} - C_{pgin} \times t_{in}) \tag{16}$$

The heat transfer equation is as follows:

$$M_{qr} \times (C_{pqout} \times t_{out} - C_{pqin} \times t_{in}) = k_l \times A_l \times (LMTD)_l \tag{17}$$

where, the subscripts q, g and l denote the effect before the mixed feed position, effect behind the mixed feed position and brine cooler, respectively.

4.2. Thermal vapor compressor

As shown in Fig. 2, TVC includes nozzle(1–3), suction chamber(3–4), mixing chamber(4–5) and diffuser(5–6). Mach number of nozzle exit is defined as Eq. (18):

$$Ma_3 = \sqrt{\eta_n \frac{2}{\gamma - 1}\left(\left(\frac{p_1}{p_3}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)} \tag{18}$$

where, P_3, γ and η_n denote the pressure of the steam of nozzle exit (MPa), polytropic exponent of steam at nozzle exit and isentropic efficiency, respectively. The saturated motive steam expands in nozzle, and its temperature is T_1 (°C), pressure is P_1 (MPa), and speed is 0 (m s^{-1}).

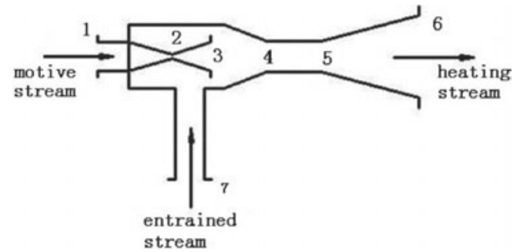

Fig. 2. Schematic of TVC.

Based on momentum and energy equations, Mach number of mixing chamber exit can be reformulated as follows:

$$Ma_4^* = \frac{\eta_m r Ma_3^* + Ma_{3v}\sqrt{T_{7v}/T_{1s}}}{\sqrt{(r+1)(r + T_{7v}/T_{1s})}} \tag{19}$$

$$Ma^* = \sqrt{\frac{\gamma+1}{2} Ma^2 \Big/ \left(1 + \frac{\gamma-1}{2} Ma^2\right)} \tag{20}$$

where Ma^* denotes the ratio of steam flow rate and the sound speed when the Mach number of mixing chamber is 1, r denotes mass flow rate ratio of motive steam and entrained steam, η_m denotes mixing efficiency.

Mach number of diffuser inlet and pressure ratio of outlet and inlet of mixing chamber are as follows:

$$Ma_5 = \sqrt{\left(\frac{2}{\gamma-1} + Ma_4^2\right) \Big/ \left(\frac{2\gamma}{\gamma-1} Ma_4^2 - 1\right)} \tag{21}$$

$$p_5/p_4 = \frac{1 + \gamma Ma_4^2}{1 + \gamma Ma_5^2} \tag{22}$$

The pressure ratio of outlet and inlet of diffuser is as follows:

$$p_6/p_5 = \left(\eta_d \frac{\gamma-1}{2} Ma_5^2 + 1\right)^{\frac{\gamma}{\gamma-1}} \tag{23}$$

where, η_d denotes diffusion process efficiency.

4.3. GOR

The GOR of the system is as follows:

$$GOR = \frac{M_f}{M_s} \tag{24}$$

where M_f and M_s denote the mass flow rate of the total freshwater production and the mass flow rate of heating steam (kg s^{-1}), respectively.

5. Results and discussion

Based on N300-16.17/550/550 condensing turbine, the steam that come from 3, 4, 5, 6 extraction ports is chosen as the motive steam of TVC. Parameters of motive steam are listed in Table 1. The total effects number of the LT-MED desalination system is 7 with the rated fresh water production 3500 t d^{-1}. The temperature difference between adjacent effects is 3°C. Taking the actual operation into account, spray density of seawater inside evaporator with the range of 0.03–0.08 kg (m•s)$^{-1}$ are selected. The selected parameters of system performance are GOR and the total area of evaporators which are the most important factors for the total cost of water [19,20]. The factors impacting on the system performance are analyzed in term of the entrained steam position of TVC, the heating steam temperature of the first effect, the motive steam parameters of TVC, and the position of preheater.

The heating steam temperature of the first effect is 65°C. The steam coming from No.4 extraction port is used as the motive steam. The variations of GOR and the total area of evaporators with the entrained steam position of TVC are shown in Figs. 3 and 4 (TVC $n + m$ represents the entrained steam position of TVC is just behind the No. n effect and the whole number of effects is $n + m$. Mixed feed $n + m$ represents the mixed feed position is just behind the No. n effect and the whole number of effects is $n + m$). With the entrained steam position of TVC moving from front effect to back effects, GOR increases firstly and then decreases. When the entrained steam position of TVC is at the effect just behind the mixed feed position, GOR reaches the maximum value. With the entrained steam position of TVC moving from front effect to back effect, the total area of evaporators changes unsteadily. When the entrained steam position of TVC is at the effect just behind the mixed feed position, the total area of evaporators reaches the minimum value. Therefore, to lower the cost of water, the optimal position of the entrained steam of TVC is just behind the mixed feed position.

The steam coming from No.4 extraction port is used as the motive steam. The processes that TVC3 + 4 and mixed feed 2 + 5, TVC4 + 3 and mixed feed 3 + 4 and TVC5 + 2 and mixed feed 4 + 3 are selected to analyze the variations of GOR and the total area of evaporators with the heating steam temperature of the first effect. The results are shown in Figs. 5 and 6. With the increasing of

Table 1
Extraction steam parameters of turbine [21]

Extraction port number	3	4	5	6
Pressure (MPa)	1.63	0.803	0.341	0.314
Temperature (°C)	436.6	337.4	237.1	145

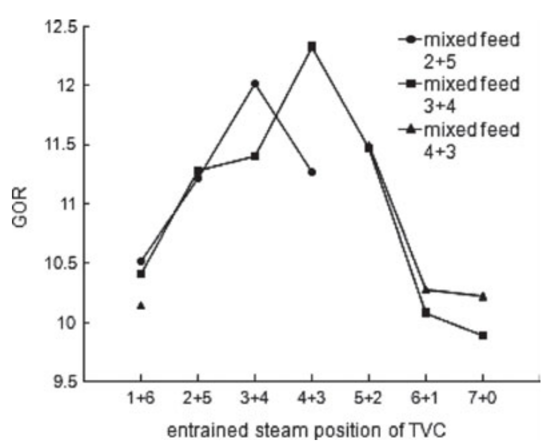

Fig. 3. Variation of GOR with entrained steam position of TVC.

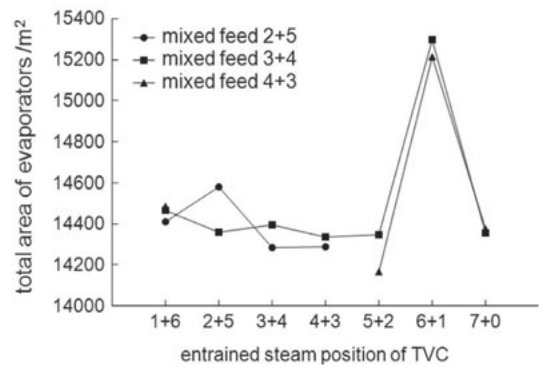

Fig. 4. Variation of the total area of evaporators with entrained steam position of TVC.

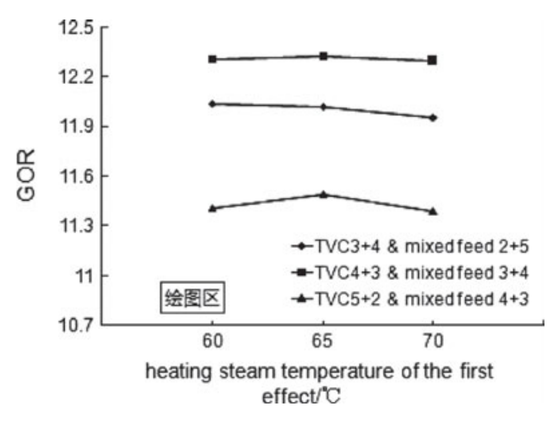

Fig. 5. Variation of GOR with heating steam temperature of the first effect.

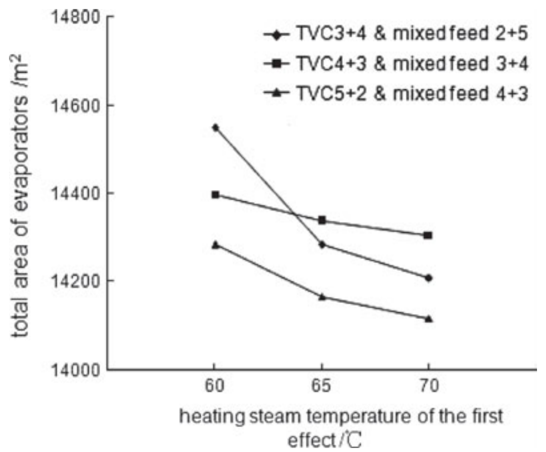

Fig. 6. Variation of the total area of evaporators with heating steam temperature of the first effect.

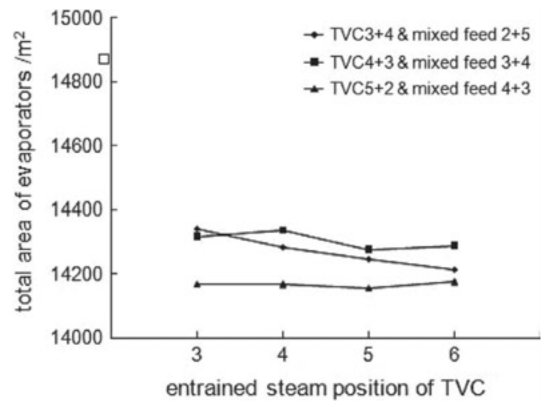

Fig. 8. Variation of the total area of evaporators with motive steam parameters of TVC.

the heating steam temperature of the first effect, GOR of TVC3 + 4 and mixed feed 2 + 5 reduces gradually. When the heating steam temperature of the first effect is 70°C, GOR reaches the minimum value. GOR of TVC4 + 3 and mixed feed 3 + 4 and TVC5 + 2 and mixed feed 4 + 3 firstly increases and then decreases. When the heating steam temperature of the first effect is 65°C, it reaches the maximum value. With the increasing of the heating steam temperature of the first effect, all the total areas of evaporators reduce.

The heating steam temperature of the first effect is 65°C. The processes that TVC3 + 4 and mixed feed 2 + 5, TVC4 + 3 and mixed feed 3 + 4 and TVC5 + 2 and mixed feed 4 + 3 are selected to analyze the relationship of GOR and the total area of evaporators with the motive steam parameters of TVC. The results are shown in Figs. 7 and 8. With the decrease of the temperature and pressure of motive steam, GOR of the three processes are all reduced and the total area of evaporators changes slightly. The impact of motive steam parameters of TVC on GOR is greater than on total area of evaporators. Hence, it is suggested to increase the parameters of motive steam for reducing the cost of water.

External heat source is used to preheat feed water. The steam comes from No.4 extraction port. The heating steam temperature of the first effect is 65°C. The number of the preheaters is 1 and the quantity of external heat source is 500 kW. The configurations that TVC3 + 4 and mixed feed 2 + 5, TVC4 + 3 and mixed feed 3 + 4 and TVC5 + 2 and mixed feed 4 + 3 are selected to analyze the variations of GOR and the total area of evaporators with the position of preheater. The results are shown in Figs. 9 and 10. With the position of preheater changes from H1 to H6, GOR of TVC3 + 4 and mixed feed 2 + 5 and TVC4 + 3 & mixed feed 3 + 4 decreases firstly and then increases, and GOR of TVC5 + 2 and mixed feed

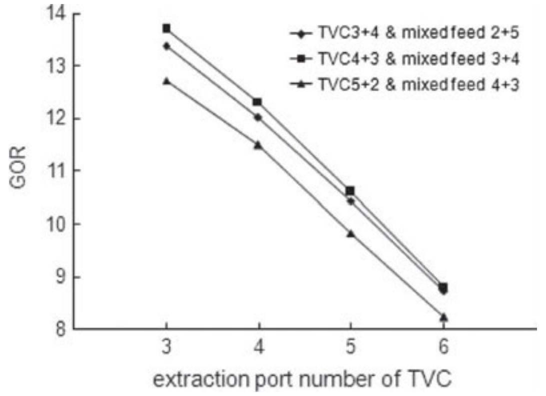

Fig. 7. Variation of GOR with motive steam parameters of TVC.

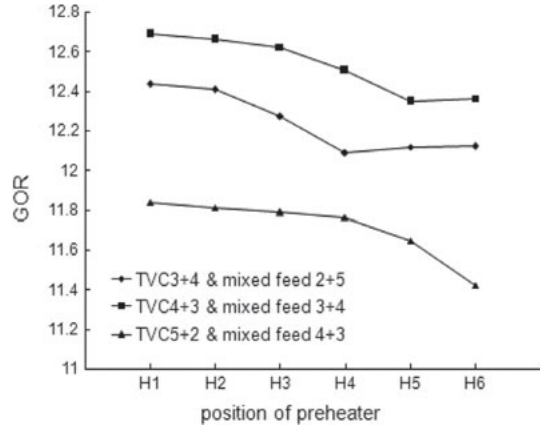

Fig. 9. Variation of GOR with position of preheater.

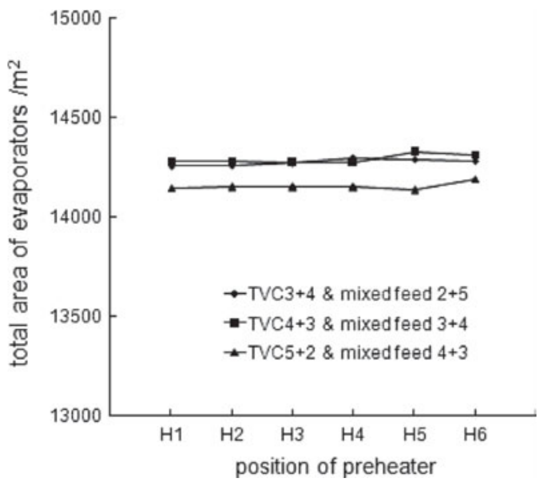

Fig. 10. Variation of the total area of evaporators with position of preheater.

4 + 3 decreases gradually. When the position of preheater is put at the effect just behind the entrained steam position of TVC, GOR of all the three configurations reaches the minimum value. GOR for the position of preheater before the entrained steam position of TVC is higher than that of the position of preheater behind the entrained steam position of TVC. The total area of evaporators changes slightly when the position of preheater changes from H1 to H6. The total area of evaporators for the position of preheater behind the entrained steam position of TVC is higher than that of the position of preheater before the entrained steam position of TVC. Therefore, the optimal position for preheater is before the entrained steam position of TVC, which is benefit to reduce the water cost.

6. Conclusions

The study is based on the mixed feed LT-MED system with TVC, and the rated water production is 3500 t d^{-1}. Taking the actual project into account, some factors impacting on the system performance are analyzed such as the entrained steam position of TVC, the heating steam temperature of the first effect, the motive steam parameters of TVC, and the position of preheater. According to the simulation results, we can conclude:

1. When the entrained steam position of TVC is at the effect just behind the mixed feed position, GOR reaches the maximum value and the total area of evaporators reaches the minimum value, which is benefit for reducing the cost of water.
2. With the increasing of the heating steam temperature of the first effect, GOR of TVC3 + 4 and mixed feed 2 + 5 reduces gradually, when the heating steam temperature of the first effect is 70°C, it reaches the minimum value. GOR of TVC4 + 3 and mixed feed 3 + 4 and TVC5 + 2 and mixed feed 4 + 3 firstly increases and then decreases, when the heating steam temperature of the first effect is 65°C, it reaches the maximum value. With the increasing of the heating steam temperature of the first effect, all the total areas of evaporators reduce.
3. With the temperature and pressure of motive steam reducing, GOR of the three processes are all reduced and the total area of evaporators changes slightly. The impact of motive steam parameters of TVC on GOR is greater than that of total area of evaporators. It is better to increase the parameters of motive steam for reducing the cost of water.
4. When external heating source is used to preheat feed water, the optimal position of preheater is before the entrained steam position of TVC, which is benefit to reduce the water cost.

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Symbols

M	—	mass flow rate, kg s^{-1}
X	—	salt concentration, kg kg^{-1}
λ	—	latent heat of vaporization, kJ kg^{-1}
h	—	enthalpy, kJ kg^{-1}
η	—	adiabatic efficiency of evaporator
t	—	temperature, °C
Cp	—	the specific heat, kJ $(kg°C)^{-1}$
BPE	—	the boiling point elevation of seawater, °C
Δt_{ji}	—	the temperature rise caused by static pressure of liquid layer, °C
Δt_h	—	the steam temperature loss that is caused by the flow resistance when steam flowing in tube bundle, °C
Δt_d	—	the steam temperature loss that is caused by the flow resistance when steam flowing in demisters, °C
Δt_t	—	the steam temperature loss that is caused by the flow resistance when steam flowing in pipelines between adjacent effects, °C

A	—	heat transfer area, m^2
k	—	heat transfer coefficient, $W(m^2 \cdot °C)^{-1}$
LMTD	—	logarithmic mean temperature difference, °C
Q_{out}	—	the amount of external heat, kJ
M_{last}	—	the mass flow rate of steam that enters into the condenser, kg s^{-1}
M_{cw}	—	the mass flow rate of sea water, respectively, kg s^{-1}
P	—	pressure, MPa
T	—	temperature, °C
	—	polytropic exponent of steam
η_n	—	isentropic efficiency
Ma^*	—	the ratio of steam flow rate and the sound speed
r	—	mass flow rate ratio of motive steam and entrained steam
η_m	—	mixing efficiency
η_d	—	diffusion process efficiency
M_f	—	the mass flow rate of the total freshwater production, kg s^{-1}
M_s	—	the mass flow rate of heating steam, kg s^{-1}

Subscripts

b	—	brine
v	—	steam
i	—	the number of effects
in	—	inlet
out	—	outlet
0	—	the original parameter of brine that enters the first effect
h	—	tube bundle
d	—	demister
t	—	pipeline
r	—	feed water
p	—	preheater
last	—	the last effect evaporator
c	—	condenser
f	—	fresh water
q	—	the effects which are front of the mixed feed position
g	—	the effects behind the mixed feed position
l	—	brine cooler

Superscript

′	—	flash distillation

References

[1] I.C. Karagiannis and P.G. Soldatos, Water desalination cost literature: review and assessment, Desalination, 223 (2008) 448–456.
[2] G. Ruan and H. Feng, Technical progress in seawater desalination technology at home and abroad, China Water Wastewater, 10 (2008) 86–90.
[3] A.A. Alawadhi, Regional Report on Desalination-GCC Countries, in: Proceedings of the IDA World Congress on Desalination and Water Reuse, Manama, Bahrain, 2002, pp. 8–13.
[4] A.D. Khawaji, I.K. Kutubkhanaha and J.-M. Wieb, Advances in seawater desalination technologies, Desalination, 221 (2008) 47–69.
[5] E.D. Howe, Fundamentals of Water Desalination, Marcel Dekker, New York, 1974.
[6] O.K. Buros, The U.S.A.I.D. Desalination Manual, International Desalination and Environmental Association, Englewood Cliffs, NJ, 1980.
[7] K.S. Spiegler and A.D.K. Laird, Principles of Desalination, 2nd edn., Academic Press, New York, 1980.
[8] A. Porteous, Desalination Technology, Applied Science Publishers, London, 1983.
[9] H.G. Heitmann, Saline Water Processing, VCH Verlagsgesellschaft, Germany, 1990.
[10] K.S. Spiegler and Y.M. El-Sayed, A Desalination Primer, Balaban Desalination Publications, Santa Maria Imbaro, Italy, 1994.
[11] B. Van der Bruggen, Desalination by distillation and by reverse osmosis—trends towards the future, Membr. Technol., 2 (2003) 6–9.
[12] R. Rantenbach, J. Widua and S. Chafer, Reflections on Desalination Processes for the 21st Century, in: Proceedings of IDA World Congress on Desalination and Water Sciences, Vol. I, Abu Dhabi, U.A.E., November 18–24, 1995, pp. 117–136.
[13] R. Rautenbach, Progress in Distillation, in: Proceedings of the DESAL '92 Arabian Gulf Regional Water Desalination Symposium, Al Ain, U.A.E., November 15–17, 1992.
[14] X. Liu, S. Shen, K. Genthner and C. Jiang, Dimulation and optimization of MEE seawater desalination system, J. Petrochem. Univ., 12 (2005) 16–19.
[15] M. Al-Shammiri and M. Safar, Multiple-effect distillation plants: state of the art, Desalination, 126(1–3) (1999) 45–59.
[16] M.A. Darwish, F. Al-Juwayhel and H.K. Abdulraheim, Multi-effect boiling systems from an energy viewpoint, Desalination, 194 (2006) 22–39.
[17] M.A. Darwish and H.K. Abdulrahim, Feed water arrangements in a multi-effect desalting system, Desalination, 228 (2008) 30–54.
[18] O. Miyatake, K. Murakami, Y. Kawata and T. Fujii, Fundamental experiments with flash evaporation, Heat Transfer Japan, 10 (1973) 89–100.
[19] H. Glade, Scaling in Multiple-Effect Distillers: New Approach to Study Mechanism and Control, in: Proceedings of the IDA Conference, Bahamas, 2003.
[20] T.B. Scheffler and A.J. Leao, Fabrication of polymer film heat transfer elements for energy efficient multi-effect distillation, Desalination, 222 (2008) 696–710.
[21] T. Ye, Thermal power plant, China Electric Power Press, 2006, pp. 81–82.