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Study of steam parameters on the performance of a TVC-MED desalination plant

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ABSTRACT

For a dual-purpose power plant with low temperature multi-effect distillation (LT-MED) desalination plant, the heating steam is normally extracted from steam turbine with pressure much higher than needed. In order to use the steam energy more efficiently, the thermal vapor compressor (TVC) is normally adopted to form the vapor recirculation utilization. A mathematical model for a multi-effect desalination with thermal vapor compression (MED-TVC) desalination plant was developed and the model validity was examined by comparing with a commercial MED-TVC plant which showed good results in this paper. It also presents the performance calculation of the MED-TVC desalination system with different steam pressures and temperatures. With higher steam pressure, the gained output ratio (GOR) of the desalination plant could get higher values. The recirculation position of vapor in a multi-effect distillation system has a great effect on the GOR as well.

Keywords: Desalination; Multi-effect distillation; Thermal vapor compressor; Gained output ratio

1. Introduction

During the last few years, rapid developments have occurred in the MED desalination system because new designs with operation at a lower top brine temperature (TBT) and the uses of cheaper material and TVC solved the scaling problem and reduced the expenditure cost. It has a lower need for heating steam and electricity in comparison with the other desalination system such as multi-stage flash (MSF) and reverse osmosis (RO) [1]. Many researches have been carried out for the related topics. Darwish and El-Dessouky [2] compared the economy of the MED, MSF, and MED–TVC system, and the results show the lowest unit product cost for MED–TVC, followed by MEE and MSF successively. El-Dessouky and Ettouney et al studied the single effect thermal vapor compression, single effect vapor compression systems, MED combined with heat pumps, and mechanical vapor compression, [3–6]. Results of these studies show a large enhancement in the performance of MED systems combined with vapor compression in comparison with stand-alone MED and the advantage of MED-TVC for high-capacity desalination systems.

Hamed performed the study of the effect of different process variables on the performance of the MED system as number of effects, TBT, inlet seawater and the amount of product. The dependence of the water production cost on the performance of the plant was also studied [7]. The results show that the performance ratio is highly depen-

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dent on the number of effect, and both the inlet seawater temperature and TBT are slightly affected on the plant performance ratio. Ameri et al. [8] presented a conceptual design for a four-effect MED system with TVC. The results show that when the heating steam temperature is assumed to be constant, TBT has a minor effect on the performance ratio (PR), while heat transfer surface significantly decreases with increasing TBT. Ameri [9] studied effect of inlet steam pressure on PR, the required heat transfer surface area of the plant and the cooling seawater mass flow rate for a MED-TVC desalination system with a production rate of 2000 m^3/d. The results show that an increase in boiler pressure increases the performance ratio, decreases the cooling seawater mass flow rate, and brings about the increase at 1% in total heat transfer area. The selection of the best value for boiler pressure requires economical optimization including the effect of pressure on the boiler's capital and operation costs. Kamali et al. [10,11] developed a mathematical simulation model for MED-TVC systems and analyzed the effect of the number of evaporators, heating steam temperature of the first effect evaporator, and concentration ratio on the GOR respectively. Amer [12] developed a steady state mathematical model of the MED-TVC desalination system, and solved an optimization problem of the mathematical model using a MATLAB algorithm. The optimum operating and design conditions of the system are the maximum gain ratio varied between 8.5 and 18.5 for 4 and 12 effects with the optimal top brine temperature ranging between 55.8 and 67.5°C.

The MED desalination plant is normally built with a power plant to form a dual-purpose power plant for its economy and thermal efficiency. In this case, the heating steam for a MED desalination plant is extracted from steam turbine normally with much higher pressure and temperature than the desalination plant needed. For the enhancement of the energy utilization efficiency, a TVC could be used to make the vapor recycle as the pressure reducer. Since the performance of a TVC is controlled by the pressures of entrained vapor and motive steam, the thermodynamic state of the heating steam and the position of TVC in a MED desalination plant will affect its performance significantly and will decide the GOR of a MED-TVC desalination plant. Therefore the heating steam parameters and the TVC suction position in a MED system are concerned by both academic researchers and engineers. This paper presents the effect of heating steam pressure and temperature on the performance of a MED-TVC desalination plant. In addition, the influence by the various recirculation position of vapor on the GOR is also analyzed. The parallel feed MED model by El-Dessouky and Ettouney [13] and the TVC model by Shen [14,15] provide the basis for the development of the MED-TVC simulation.

2. Process description

A schematic of the MED-TVC desalination system is shown in Fig. 1. It includes mainly evaporators, a TVC and an end condenser. Other auxiliary equipments include distillate flashing boxes, brine flashing boxes, a venting system, sea water feeding, and brine and distillate expelling facilities.

For a low temperature MED desalination plant, the heating steam should be saturated and the temperature should not be higher than 70°C. As the external heat, the

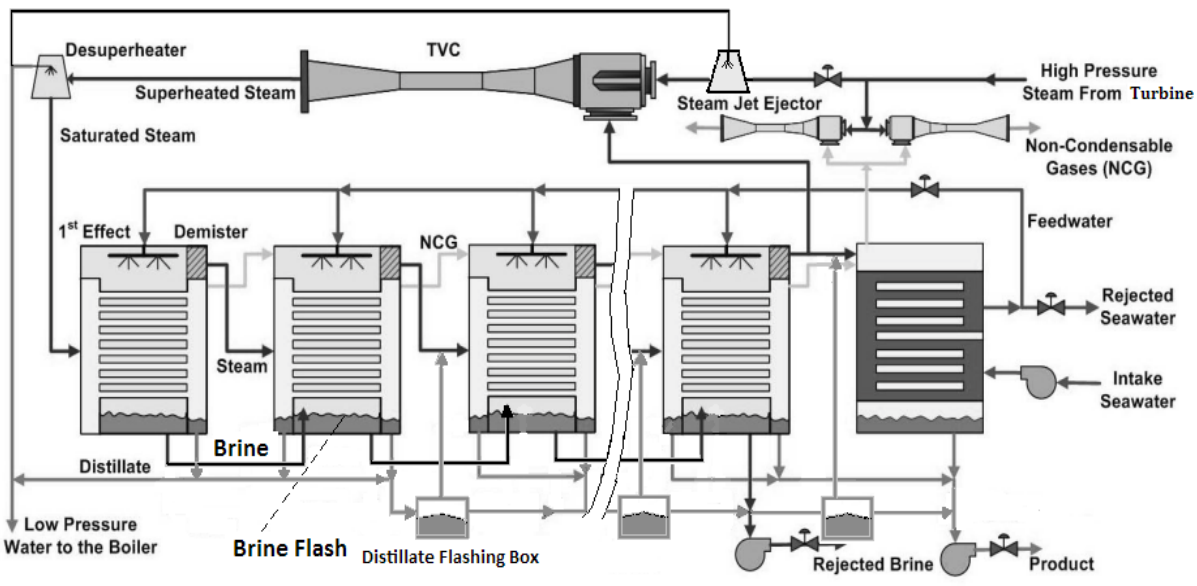

Fig. 1. Schematics of the MED-TVC system.

steam extracted may be from a turbine or other steam supplier, so it is normally much higher than needed. The high pressure steam will be taken as the motive steam of the TVC. The mixture of motive steam and vapor sucked by the TVC from *k*-effect evaporator is taken as the heating steam of the first effect evaporator of the MED desalination plant. This entrainment process of the TVC reduces the need for external steam by reusing vapor as the heating steam. Therefore it reduces the consumption of input energy. The entrainment ratio of a TVC is defined as the mass flow ratio of the entrained vapor to the motive steam. The higher the entrainment ratio, the lower the consumption of external steam for a certain amount of heating steam. The pressure of the mixed steam at the discharge connection is set to that corresponding to the saturation temperature of steam for the first effect evaporator, which is higher than the suction vapor pressure and lower than motive steam pressure. The discharge steam, which is superheated, passes through the desuperheater and leaves as saturated steam by mixing with the saturated water. Though the process in a TVC is not high efficient, the thermal compressor increases the GOR of the desalination plant and reduces the steam consumption significantly.

3. Mathematical modeling

A mathematical model of the MED-TVC desalination system as shown in Fig. 1 is presented in this section. To simplify the analysis, it is assumed that the system is operated at steady-state conditions. Features of the developed mathematical models are as follows:

- Thermodynamic losses are considered in the model, which include the boiling point elevation with the temperature and salinity, non-equilibrium allowance inside evaporators and flashing boxes, temperature depression corresponding to the pressure drop from evaporation to condensation.
- As the standard practice in design of desalination plant, constant and equal heat transfer areas in all effect evaporators before TVC suction point (vapor recirculation position) and evaporators behind TVC suction point respectively are considered.
- Physical properties of water and vapor are taken as a function of temperature and pressure, and variable physical properties of seawater and brine with temperature and salinity are considered.

Based on the assumptions above, the mass and energy conservation equations for each effect evaporator are developed, similar to those presented by El-Dessouky et al. [13] for parallel/cross flow system. The calculations of some parameters are presented in this paper, which deserve to pay special attention for a MED system with the TVC.

The heating steam flow rate of the first effect evaporator is as follows:

$$M_1 = M_m + M_s + M_w \tag{1}$$

where M is the mass flow rate. The subscripts m, s and w are the motive steam, the suction vapor and saturation water sprayed in the desuperheaters. The value of M_w depends on the superheating degree and flow rate of the discharge steam and the motive steam of the TVC.

The heating steam flow rate of the first effect evaporator behind the vapor recirculation position is

$$M_{k+1} = M_{e,k} + M_{b,k} + M_{d,k} - M_s \tag{2}$$

The subscripts k, e, b, d, s are respectively the effect number of the evaporators at the vapor recirculation position, vapor generated on the surface of horizontal tube bundles, vapor from brine flashing in number k evaporator and from number k distillate flashing box, and vapor sucked by the TVC.

The inlet seawater mass flow rate of the condenser is as follows:

$$M_{con} = M_f + M_r \tag{3}$$

where the subscripts con, f and r are the inlet seawater of the condenser, the feed seawater into the evaporators and the rejected seawater which takes some heat away from the condenser. As for a system with constant production capacity and concentration ratio, M_{con} is an indicator for reflecting the thermal loss of the condenser because the feed seawater remains the same.

Some evaluation parameters for a MED desalination plant are as follows. The gained and output ratio is

$$\mathrm{GOR} = \frac{M_D}{M_m + M_{NCG}} \tag{4}$$

where M_{NCG} and M_{D} are respectively the mass flow rates of the steam extracting the non-condensable gases and the total distillate. The specific energy consumption is

$$\gamma_{en} = \frac{M_m\left(h_m - h_0\right)}{M_D} \tag{5}$$

where h_m and h_0 are specific enthalpy of the motive steam and the condensate in the environmental condition. The definition of specific exergy consumption is

$$\gamma_{ex} = \frac{E_{x,m}}{M_D} = \frac{M_m\left[\left(h_m - h_0\right) - T_0\left(s - s_0\right)\right]}{M_D} \tag{6}$$

where $E_{x,m}$ and s are exergy and entropy of the motive steam. s_0 is entropy of the outlet condensate as saturated liquid at the ambient temperature. The specific heat transfer area as the equipment cost criteria is

$$A_{SHTA} = \frac{A}{M_D} = \frac{\sum_{i=1}^{n} A_i + A_c}{M_D} \tag{7}$$

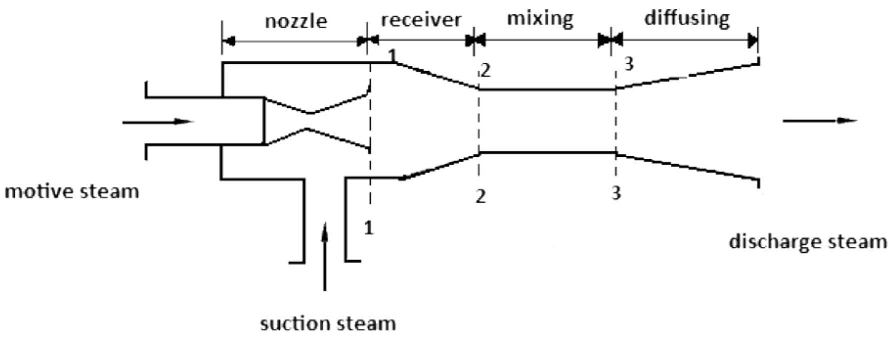

Fig. 2. Schematics of the thermal compressor.

where A is the total heat transfer area, including the heat transfer areas of evaporators $\sum_{i=1}^{n} A_i$ and the heat transfer area of condenser A_c.

The diagram of the TVC adopted in this system is shown in Fig. 2. The mathematical model for its performance calculation was developed in the previous publication [14,15].

The definition of entrainment ratio ε:

$$\varepsilon = \frac{M_s}{M_m} \tag{8}$$

The calculation formula of entrainment ratio ε is

$$\varepsilon = \frac{K_1 \dfrac{a_{m^*}}{a_{d^*}} \lambda - K_3 \lambda_{d3}}{K_4 \lambda_{d3} - K_2 \dfrac{a_{s^*}}{a_{d^*}} \lambda_{s2}} \tag{9}$$

where Ki $(i = 1 - 4)$ is velocity coefficient, a is critical velocity, "*" is critical value, λ is superficial isentropic velocity. The subscripts d and s mean the discharge steam and suction vapor respectively. Besides, the subscripts 2 and 3 are the section positions in Fig. 2.

4. Solution procedure

A computer program is developed based on the mathematical model using Visual Basic 6.0, whose flow chart is shown in Fig. 3.

The validation of the simulation results was accomplished by comparing with the MED plant built in Huanghua, China. Its distillate production is 10,000 t/d with 4 effect evaporators. The results of the comparison are listed in Table 1.

At the same given parameters, the relative errors of parameters including distillate production, GOR and heat transfer area of evaporator are –0.02%, 1.08% and –5.06% respectively. The results of the mathematical model simulations show a good agreement with the actual plant. Thus it can be verified that the calculation method is accurate and reliable for engineering practice.

A 10-effect desalination system with 10,000 m^3/d production is taken as the example to study effects of steam parameters and recirculation position (pressure) of vapor on the system performance. The required input variables are summarized in Table 2.

Table 1
Mathematical model simulations against the commercial plant

Parameters	Actual	Model	Error (%)
Number of evaporator effect	4	4	
Seawater temperature, °C	25	25	
Seawater salinity, ppm	36,000	36,000	
Feed water temperature, °C	52.6(1th)/48(2th–4th)	52.6(1th)/48(2th–4th)	
Heating steam temperature, °C	65	65	
The last effect temperature T_n, °C	51.8	51.8	
Distillate production, t/d	10,000	9998.4	–0.02
GOR	8.33	8.42	1.08
Heat transfer area of evaporator, m^2	10,188	9672	–5.06

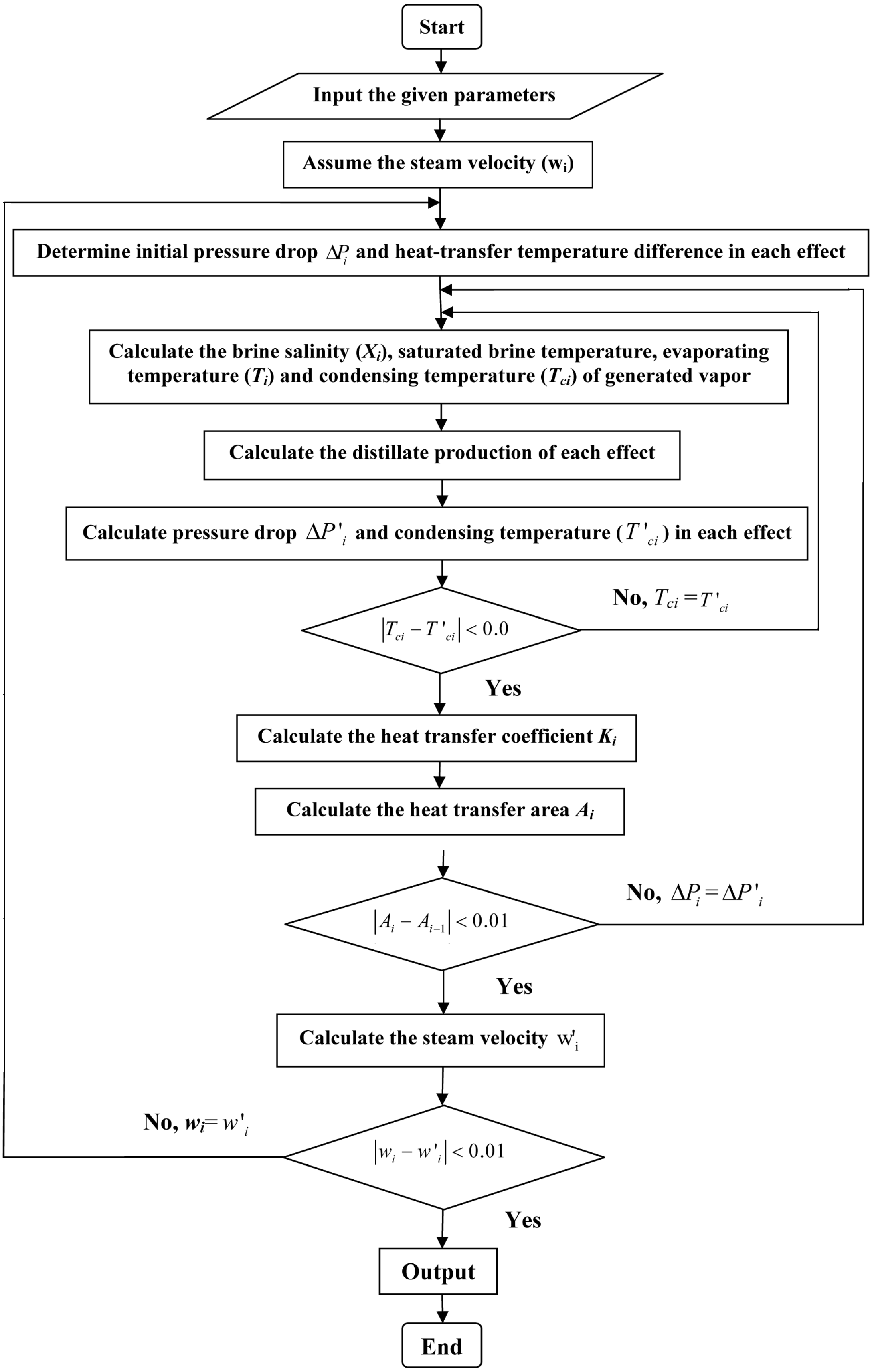

Fig. 3. A schematic of programming flow chart.

Table 2
The required input parameters for the program

Parameters	Value
Production capacity, m^3/d	10000
Number of evaporator effect	10
Seawater temperature, °C	20
Seawater salinity(X_f), ppm	32,000
Feed water temperature, °C	38
Concentration ratio	2.0
Heating steam temperature, °C	68
Motive steam pressure, MPa	0.3–1.0
Motive steam temperature, °C	133–300
Recirculation position of vapor	6–10
Heat transfer tubes length, m	8.0
Tube outer radius, m	0.025
Radiation loss, %	2.0
T_n in the last effect, °C	43

5. Results and discussion

The effects of motive steam pressure on the performance of MED-TVC system are shown in Figs. 4–7. The recirculation position of vapor is set behind the 6th effect evaporator. The motive steam temperature is corresponding to the saturation pressure.

In Fig. 4, the entrainment ratio ε of TVC and the GOR of the desalination plant increase with the enhancement of motive steam pressure. The motive steam with higher pressure will have higher working ability to enhance the vapor recycling amount. With more recirculation vapor amount, the thermal loss in the end condenser will be reduced and less motive steam is needed. This makes the GOR of the desalination plant increased. With higher motive steam pressure, although the amount of required external steam is decreased, the heating steam M1 to the first effect evaporator increases. This means that the evaporators before the recirculation position will be larger and the evaporators behind the recirculation position will be smaller.

The effects of motive steam pressure on specific exergy consumption and specific energy consumption are shown in Fig. 5. As is shown that, with higher motive steam pressure, the specific energy consumption becomes lower, while specific exergy consumption increases. The specific enthalpy of motive steam increases with the rising pressure correspondingly. The increasing rate of the specific enthalpy is less than the decreasing rate of the amount of required motive steam, so that the specific energy consumption decreases. The specific energy consumption and the specific exergy consumption reflect the energy consumption characteristics of the MED-TVC system from quantity and quality aspects respectively. For a dual purpose power plant, the exergy consumption of a MED desalination plant could probably be taken as a better energy consumption index since the exergy consumption is positive to the power generation.

The increasing of the entrainment ratio increases the amount of steam sucked out from the 6th effect evaporator and decreases the flow rate of steam to the condenser, which cuts down the condenser inlet seawater mass flow rate as it is shown in Fig. 6.The effect of motive steam pressure on specific heat transfer area is shown in Fig. 7. It demonstrates a small reduction of specific heat transfer area by 2% approximately with the increase of motive steam pressure from 0.3 MPa to 1.0 MPa. With motive steam pressure rising, the raised entrainment ratio of TVC causes the cutdown of the generated vapor in the last effect evaporator, which results in the decreasing of the heat transfer area of the condenser. As mentioned before, the area of evaporators before the vapor recircula-

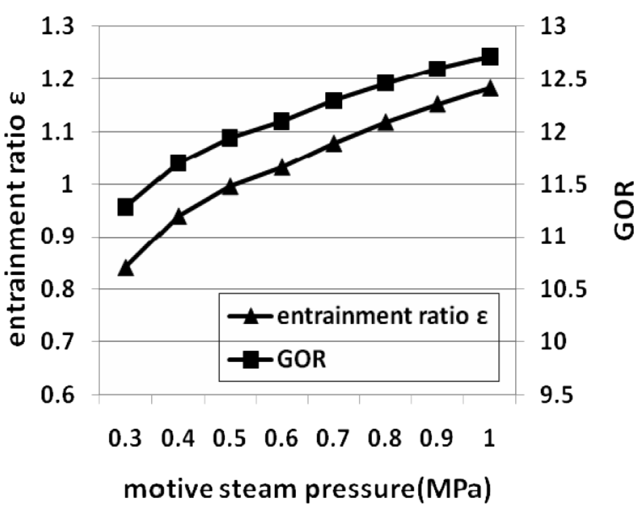

Fig. 4. Effect of motive steam pressure on entrainment ratio ε and the GOR.

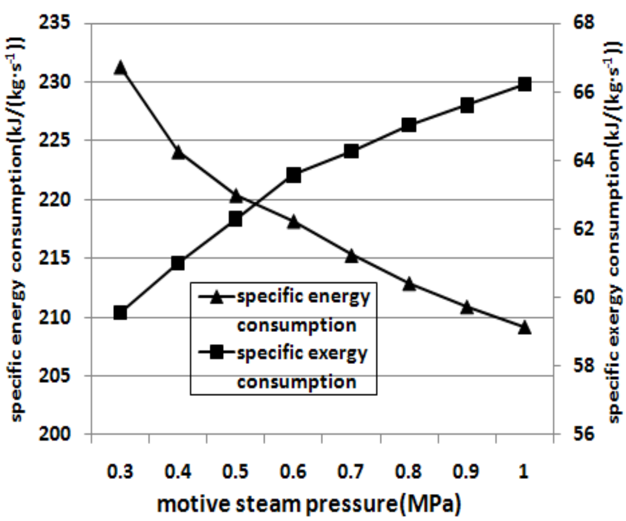

Fig. 5. Effects of motive steam pressure on specific exergy consumption and specific energy consumption.

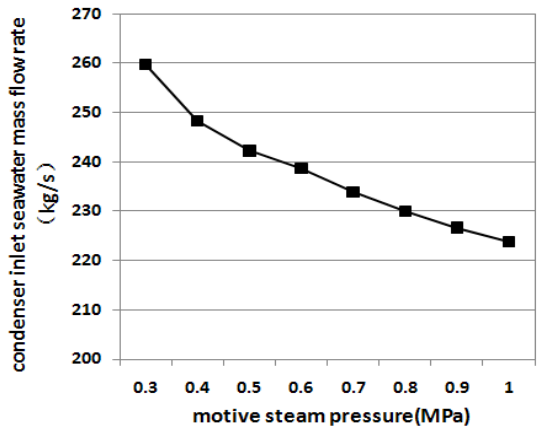

Fig. 6. Effects of motive steam pressure on condenser inlet seawater mass flow rate.

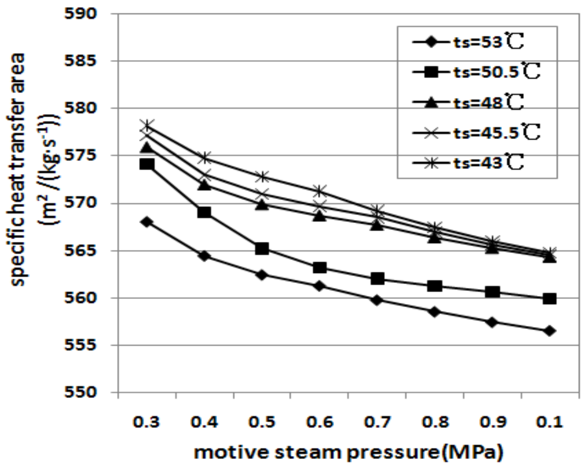

Fig. 7. Effects of motive steam pressure and suction steam temperature on specific heat transfer area.

tion position is larger and the area of evaporators behind the vapor recirculation position is smaller. As a result, the specific heat transfer area decreases.

Obviously, the advantages of increasing motive steam pressure include the increase of the GOR, the reduction of specific energy consumption and cooling seawater mass flow rate and specific heat transfer area. On the other hand, its disadvantage is the increase in specific exergy consumption, which also affects the power production for a dual-purpose power plant. Therefore, further analysis and evaluation for the parameter is necessary.

The optimal range of TVC compression ratio is between 1.81 and 3.68 for 4–12 effects of the MED-TVC system [12]. Referring to the literature, the applicable range of suction steam pressure is between 0.00806 and 0.0158 MPa when the motive steam pressure is set at 1.0 MPa in this paper. Therefore, the recirculation positions of vapor are behind the 10th–6th effect, corresponding to the suction steam temperature ts of 43, 45.5, 48, 50.5 and 53°C respectively. The influences of vapor recirculation position on the performance of the MED-TVC desalination system are demonstrated in Figs. 7–11. The parameters of motive steam are 1.0 MPa and 300°C in Figs. 8, 9 and 11. The motive steam pressure of Fig. 10 is 1.0 MPa.

As shown in Fig. 8, with suction steam temperature increasing, the entrainment ratio ε gets higher values and the motive steam mass flow rate decreases. It is shown in Fig. 9 that both specific energy consumption and specific exergy consumption become lower with suction steam pressure increasing. Based on Eqs. (5) and (6), it is caused by the decreasing motive steam mass flow rate at the same motive steam pressure and production capacity.

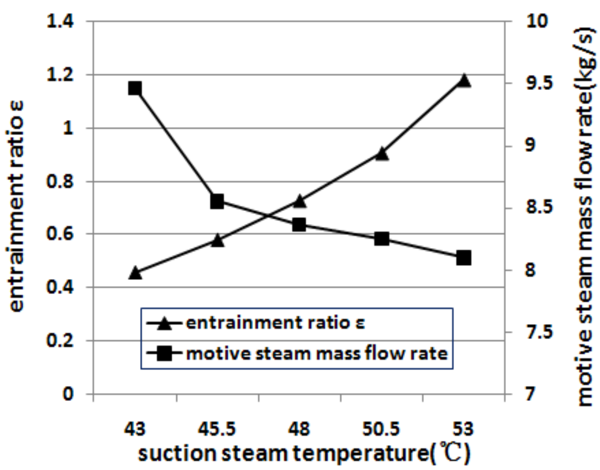

Fig. 8. Effects of suction steam temperature on motive steam mass flow rate and entrainment ratio ε.

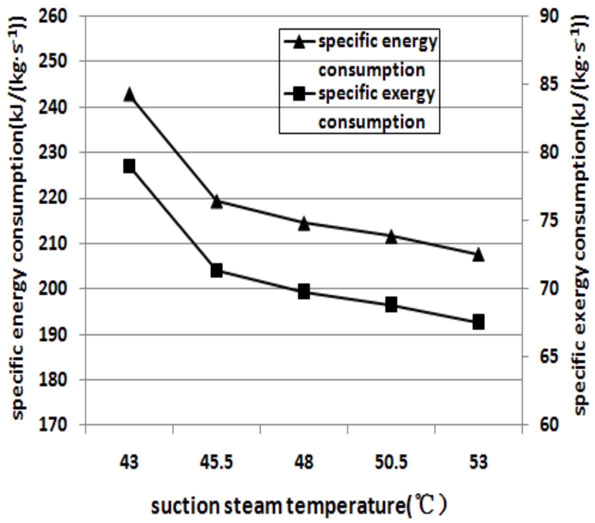

Fig. 9. Effects of suction steam temperature on specific exergy consumption and specific energy consumption.

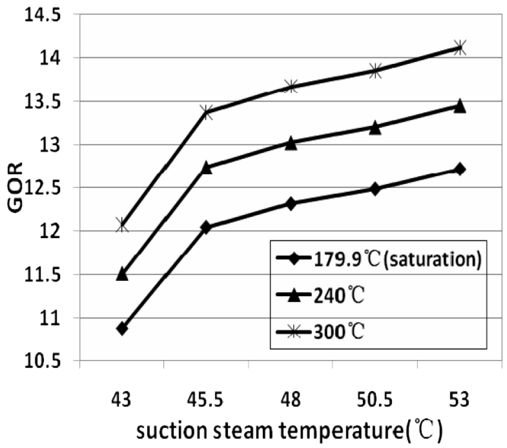

Fig. 10. Effects of suction steam temperature and degree of superheat of motive steam on the GOR.

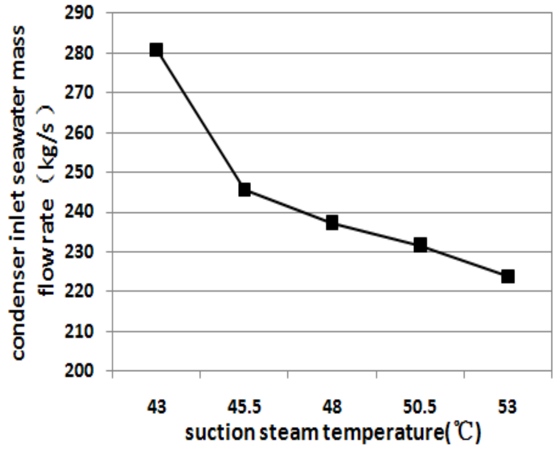

Fig. 11. Effect of suction steam temperature of the condenser inlet seawater mass flow rate.

The effect of suction steam temperature on specific heat transfer area is also shown in Fig. 7. The decrement of specific heat transfer area is due to the raised entrainment ratio as the suction steam pressure is higher, similar to that of the motive steam pressure increasing. Actually, it reduces the amount of vapor entering the condenser so that the heat transfer area of the condenser also decreases.

The change trends of the GOR with superheating degrees of motive steam and suction steam temperature are demonstrated in Fig. 10. The GOR becomes higher when the superheating degree of motive steam is raised. The value of the GOR arises with the increases in suction steam temperature, but the growing rate decreases gradually. It is caused by two reasons: (1) The increasing entrainment ratio with suction steam temperature results in higher reuse of the produced vapor, which will cause a higher GOR. (2) The evaporators ahead of the recirculation position have more contribution to distillate production than the ones behind it due to the existence of the suction vapor. The further forward the recirculation position, the less the number of evaporators ahead of the recirculation position, which may make the growing rate of the GOR decrease.

The effect of suction steam temperature on the condenser inlet seawater mass flow rate is shown in Fig. 11. The increasing entrainment ratio with the growth of suction steam temperature increases the vapor recirculation amount and decreases the cooling load of the condenser. According to Eq. (3), the thermal loss in the condenser is decreasing as a result. Due to the given production capacity and concentration ratio, the demand for the feed seawater of the desalination system is 231.5 kg/s. The values in Figs. 6 and 11 are calculated according to the thermal balance of the condenser. Therefore, the point with lower values than the demand in Figs. 6 and 11 should be revised to 231.5 kg/s in the practical operation. With a TVC in the MED desalination plant, most, or even the total, of the cooling water of condenser will be used as the feeding water. The thermal loss by cooling water is less than the simple MED system.

It is observed that the GOR gets higher and the specific heat transfer area and the cooling water of condenser are cut down as the suction steam pressure rises. Therefore, the optimal suction steam temperature is 53°C behind the 6th , in the applicable range of the TVC and the maximum gained output ratio is 14.1 correspondingly for a given system as Table 2.

6. Conclusions

A mathematical model of the MED-TVC desalination system was developed in this paper and its validity is examined by comparing with a commercial MED desalination system which showed good coherence. From the calculation, the following are concluded for the 10-effect MED-TVC desalination system as Table 2:

1. The enhancement of the motive pressure will increase the GOR, decrease the condenser inlet seawater mass flow rate, the specific energy consumption and the specific heat transfer area, which could reduce the expenditure cost. The increasing of superheating degrees of motive steam can also benefit for the GOR.
2. The motive steam with high pressure and high temperature will raise the specific exergy consumption. For a dual purpose plant, the optimal motive steam pressure and temperature needs to balance the electricity generation and the performance of TVC-MED system. Therefore, an economical analysis for the whole system is necessary in further analysis.
3. An increase in suction steam temperature cuts down the specific energy consumption, the specific exergy consumption, the cooling load of the condenser and

the specific heat transfer area. The value of the GOR arises with the increases in suction steam temperature. The optimal suction steam temperature is 53°C, behind the 6th, in the applicable range of the TVC and the maximum gained output ratio is 14.1 for the given system.

Symbols

A	—	Heat transfer area, m^2
a	—	Critical velocity, m/s
Ex	—	Exergy, kJ
h	—	Specific enthalpy, kJ/kg
K_i	—	Velocity coefficient (i = 1 – 4)
M	—	Mass flow rate, kg/s
s	—	Specific entropy, kJ/(kg·°C)
T	—	Temperature, °C

Greek

ε	—	Entrainment ratio
γ_{en}	—	Specific energy consumption, kJ/kg
γ_{ex}	—	Specific exergy consumption, kJ/kg
λ	—	Superficial isentropic velocity, m/s

Subscripts

b	—	Vapor from brine flashing in evaporators
c	—	Condenser
d	—	Vapor from distillate flashing box
dis	—	Discharge steam
e	—	Vapor generated on the surface of horizontal tube bundles
k	—	Number of the effect in the recirculation position of vapor
m	—	Motive steam
s	—	Suction steam
w	—	Water sprayed in the superheater
0	—	The environmental condition
*	—	Critical value

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