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Analysis of adjusting method for load performance of TVC-MED desalination plant

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ABSTRACT

Multi-effect distillation (MED) desalination with thermal vapor compressor (TVC) is widely used in a dual-purpose power plant configuration. Due to the variety of extraction pressure and water demand, it works under a wide range varying from over-rated load to less than half-rated load. The adjusting method of load performance is presented to obtain the optimal performance of MED-TVC desalination plant based on the operating characteristics of TVC and MED. With adjustable TVC, the thermodynamic performance of MED-TVC is analyzed when water load and extraction pressure varies. The effect of the variation in feed seawater flow rate, together with the heating steam temperature of the first evaporator, is also investigated. The results of the analysis are fairly close to the data of a practical MED-TVC plant, which justifies the expectation that the analytical method is accurate and reliable.

Keywords: Multi-effect distillation; Thermal vapor compressor; Adjusting method; Load performance

1. Introduction

The process of multi-effect distillation (MED) combined with thermal vapor compression (TVC) is widely used in large-scale thermal desalination industry. TVC is a device to transfer, compress or mix gas, vapor, liquid, or solids, in which the pressure energy is conversed into velocity by means of nozzles. The TVC method is used due to its absence of moving parts, high reliability of operation, inexpensive maintenance, simple geometry as well as being insensitive to fouling. It is suitable for a wide range of volume flow rates. As TVC is powered by steam, it is obviously less expensive to run than electrical- or mechanical-related power. The power plants often have steam available for several operations, which provides a relatively cheap and steady source of energy for TVC. In addition, the TVC-MED configuration is less expensive in investment costs. Because of the conversion of TVC to a practical purpose, the higher gained output ratio (GOR) of TVC-MED can be obtained with fewer effects. For instance, GOR of a TVC-MED desalination plant with a four-effect evaporator can attain an eight while a MED desalination plant alone requires at least the same size ten-effect evaporator to reach the same GOR. Therefore, TVC-MED in a dual-purpose power plant becomes the main technology for desalination plants.

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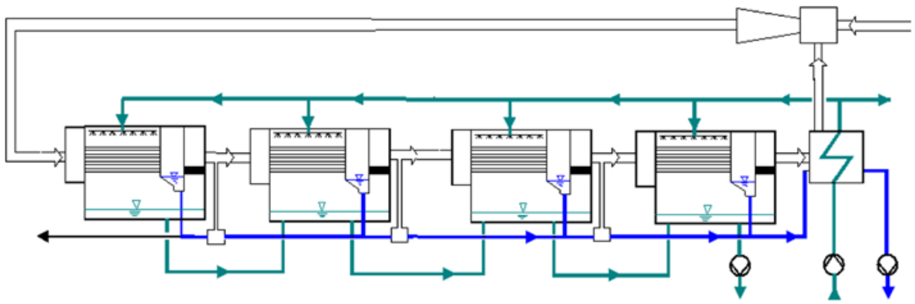

Fig. 1. Schematic diagram of TVC-MED.

Much theoretical and experimental research work has been carried out to study the performance of TVC-MED. Theoretical models have been proposed, and experiments have been investigated to understand flow phenomena and mixing processes of TVC [1–3]. The performance parameters of TVC, mainly on the entrainment ratio and the pressure ratio, were studied [4,5]. Thermodynamic analysis and thermoeconomic optimization on TVC-MED have been developed [6–11]. In addition, research on MED driven by new energy is explored [12–15].

The adjustable method is important. The extraction pressure keeps variable as the steam turbine often works at off-design conditions, and the water demand varies with seasons. Thus MED-TVC works under a wide range, from over-rated load to less than the half-rated load. It is of great importance to obtain the optimal performance by adjusting method. However, there appears to be little information in the literature about the adjusting method for load performance. Based on our previous research on the operating characteristics of TVC [2,16–19] and MED [20–22], adjusting methods for load performance were presented and thermodynamic performance of TVC-MED was analyzed. Compared with the data of a practical TVC-MED plant, the validity of the adjusting method was justified.

2. Process description

The process of TVC-MED is illustrated in Fig. 1. The main components are evaporators, TVC, and a final condenser. Seawater is fed to final condenser where the vapor produced in the last effect evaporator is condensed. The pre-heated seawater in the final condenser is divided into two parts. The first part is fed to the evaporators in parallel configuration. The second is rejected and it is known as cooling seawater. The feed seawater is sprayed in the form of thin film on the outside of the succeeding rows of tubes which are arranged horizontally. The brine is heated to its saturated temperature before a small portion of it is evaporated. The vapor produced in each effect is condensed in the next effect after being passed through a demister to remove the entrained brine droplet. The rest part of the brine is introduced into the next effect. Pressure difference causes the brine to cascade between successive evaporators. Part of the steam produced in the last effect is condensed by sea water, and the remaining vapor is sucked and compressed by TVC, and TVC is operated by extraction, which is known as motive steam. On leaving the TVC, the mixture of the motive steam and entrained vapor is referred to as heating steam, and this is fed into the heating bundle of the first effect. The condensate of the heating steam returns the boiler feed water. A vacuum system continuously works to extract non-condensable gases that are produced during the process of falling film evaporation. The discharge steam of TVC is used as a heating steam of MED, and the adjustment of TVC is closely related to the load performance of TVC-MED. When motive steam pressure decreases, the discharge steam pressure and the suction steam decrease simultaneously. As a result, the load of MED is reduced.

TVC normally consists of four main parts: the motive nozzle, suction chamber, mixing chamber, and diffuser. The thermodynamic process of TVC is shown in Fig. 2. As the motive steam expands in the nozzle, its static pressure energy is converted to kinetic energy and exits the nozzle at a high velocity and low pressure. The nozzle is a kind of Laval-noz-

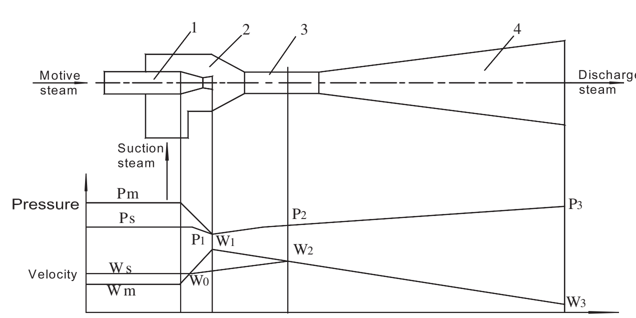

Fig. 2. Schematic pressure and velocity profile in TVC.

zle with a divergent outlet that expands the steam to supersonic velocity in the divergent part, and it also expands the steam to the sonic velocity in the smallest part of the nozzle. The suction chamber is to entrain the suction steam. The suction steam pressure enters the suction chamber at pressure P1 where it mixes with the motive steam. The two streams completely mix in the mixing chamber. The result of this action is the mixture of motive steam and entrained steam at a mean velocity. The mixture experiences a self-compression as it passes through the diffuser, where its cross-sectional area increases. In the diffuser, the kinetic energy is converted to static pressure energy. As a result, the pressure of discharge steam increases to an outlet pressure that is higher than the suction pressure.

3. Adjusting method of load performance

The conventional method to influence the operational behavior of TVC is to throttle the motive steam pressure by a control valve. In the TVC-MED system, the expansion pressure ratio, p_d/p_s, is sufficient to achieve critical pressure ratio. The exact critical pressure and sonic speed are achieved in the throat section of the nozzle. Due to the blocking of the velocity of the sonic speed in the throat section, the mass flow rate of the nozzle, m, depends on the pressure of motive steam in front of the nozzle, p_m and the diameter of the throat section, d, $m = \text{const} \times d \times p_m$. A decrease in motive steam pressure results in a similar decrease in the motive steam flow rate. The efficiency of TVC is obviously decreased owing to the reduction in motive steam pressure.

A spindle in the nozzle is installed in a TVC known as adjustable TVC. The nozzle spindle controlled TVC is shown in Fig. 3. By adjusting the spindle position in the nozzle, the motive steam flowing area in the throat is changed and thereby the mass flow rate of motive steam is controlled while the motive steam pressure is not influenced. In contrast to the throttle control in the conventional TVC, the motive mass flow is changed without changing the motive pressure that is the key parameter for the compression efficiency of TVC. Thus, the efficiency of adjustable TVC for a partial load is higher than the conventional TVC with a throttle control valve.

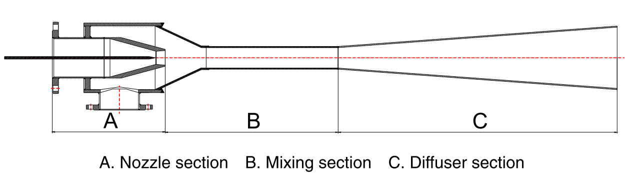

Fig. 3. Schematic diagram of adjustable TVC.

The output of a TVC-MED desalination plant can be adjusted within the range of 40–110% of rated load, and the plant can be operated normally within such a range. For the throttle control in the conventional TVC, the motive steam mass flow rate is reduced by a control valve. The throttling motive steam pressure, together with the reduction in the suction steam pressure, deteriorates the efficiency of TVC. Therefore, the MED combined with conventional TVC works within a narrow range of rated load. For adjustable TVC, the motive steam flow rate is influenced by changing the nozzle throat area rather than the motive steam pressure. Thus, the MED combined with adjustable TVC can operate within a wide range of both operating load and motive pressure.

The load of TVC-MED is proportional to the temperature difference between heating steam and the discharged brine in the last effect evaporator. The temperature difference is controlled by changing the spindle position in the nozzle, and the motive steam flow rate is adjusted. With a decrease in motive mass flow rate, the discharge steam pressure is reduced. Thus, both the saturated temperature and the flow rate of heating steam are reduced simultaneously. The heating steam flow rate and discharge steam flow rate are reduced as well.

MED desalination uses falling film evaporation over the outer surface of a vertical column of horizontal steam-heated tubes. It is necessary to keep thin and even film on the outside of the tube to achieve high efficient heat transfer simultaneously. At the same time, the feed seawater is kept at least 3 times greater than the rated distillation load in order to control scaling and corrosion on the outside of the tube. Balancing the above-mentioned two sides, the feed seawater flow rate is usually kept constant for partial load.

4. Results and discussion

A 4-effect TVC-MED practical desalination plant with rated load of 10,000 ton/day in China is driven by extraction shown in Fig. 1. Adjustable TVC is combined with MED in this desalination plant. Its design starts with the given parameters listed in Table 1.

The comparison of thermodynamic performance between the practical and calculated data is shown in Tables 2–4. It can be seen that the calculated thermodynamic performance is found to be fairly close to the

Table 1
Given designing parameters

Item	Unit	Data
Seawater temperature	℃	25
Heating steam temperature	℃	65
Motive steam pressure	MPa	0.55
Motive steam temperature	℃	320
Rated load	ton/day	10,000

Table 2
Comparison of thermodynamic performance at rated load

Item	Unit	Practical Data				Calculating Data			
GOR		8.33				8.42			
Entrainment ratio of TVC		1.13				1.07			
Heat transfer area per effect	m^2	10,188				9,672			
Motive steam flow rate	t/h	50.0				49.5			
Evaporation temperature	℃	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
		61.6	58.3	55.1	51.8	61.7	58.4	55.2	51.8

Table 3
Comparison of thermodynamic performance at condition of 110% rated load

Item	Unit	Practical data				Calculating Data			
GOR		8.20				8.28			
Entrainment ratio of TVC		1.08				1.02			
Motive steam flow rate	t/h	55.9				55.4			
Evaporation temperature	℃	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
		64.5	61.0	57.6	54.1	64.5	61.0	57.7	54.5

Table 4
Comparison of thermodynamic performance at condition of 40% rated load

Item	Unit	Practical Data				Calculating Data			
GOR		6.75				6.79			
Entrainment ratio of TVC		0.78				0.75			
Motive steam flow rate	t/h	24.7				24.5			
Evaporation temperature	℃	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
		43.6	41.9	40.4	39.1	43.7	42.0	40.5	39.1

practical data at three conditions that are rated load, 110% rated load, and 40% rated load. The expectation is justified that the adjusting method for adjustable TVC is reliable, and the analytical model of adjustable TVC is accurate.

The run for entrainment ratio of adjustable TVC and GOR is illustrated in Figs. 4 and 5 for a constant value of the rated load and increasing motive pressure. The entrainment ratio and GOR increase with an increase in motive pressure. For traditional TVC when

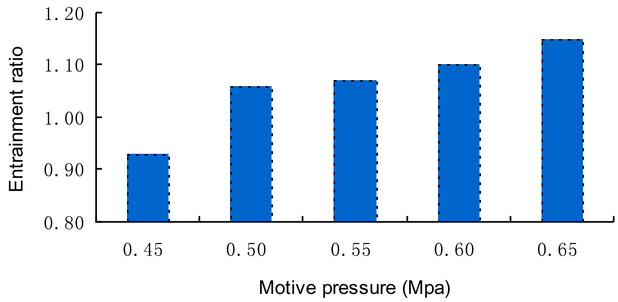

Fig. 4. Effect of motive pressure on entrainment ratio.

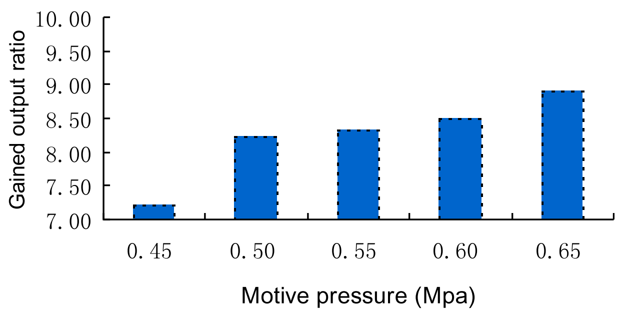

Fig. 5. Effect of motive pressure on GOR.

motive pressure is higher than the designed motive pressure, the motive pressure is throttled, and thereby the entrainment ratio and GOR are decreased. Both the entrainment ratio and motive steam mass flow rate are reduced when motive pressure is lower than the designed pressure. Therefore, the utilization of adjustable TVC makes TVC-MED to work at rated load and obtain high efficiency under a wide range of motive pressure.

5. Conclusion

The adjusting method for load performance is presented to obtain the optimal performance of MED-TVC desalination plant based on the operating characteristics of TVC and MED. From the thermodynamic analysis and performance comparison, the following conclusions can be drawn.

The calculated thermodynamic performance demonstrates satisfactory agreement with the practical data for different load, which justifies the expectation that the adjusting method for adjustable TVC is reliable and the analytical model of adjustable TVC is accurate.

It is found in the analysis that adjustable TVC makes TVC-MED system adapt to a wide range of motive pressure at rated load and obtains high efficiency.

Acknowledgements

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References

[1] T. Sankarlal, A. Mani, Experimental investigations on ejector refrigeration system with ammonia, Renew. Energ. 32 (2007) 1403–1413.
[2] S.Q. Shen, K. Zhang, Calculation of performance of adjustable steam ejector, Int. J. Energy Machinery 1 (2007) 20–26.
[3] Y. Bartosiewicz, Y. Mercadier, P. Proulx, Numerical investigations on dynamics and heat transfer in a turbulent underexpanded jet, AIAA J 40(11) (2002) 2257–2265.
[4] K. Chunnanond, S. Aphornratana, An experimental investigation of steam-ejector refrigerator, the analysis of pressure profile along ejector, in 4th the Asia-Pacific Conference on Sustainable Energy and Environment Technologies, Mie, 8–10 May 2003.
[5] S. Aphornratana, I.W. Eames, A small load steam-ejector refrigerator: Experimental investigation of a system using ejector with movable primary nozzle, Int. J. Refrig. 20(5) (1997) 352–358.
[6] H. Sayyaadi, A. Saffari, A. Mahmoodian, Various approaches in optimization of multi effects distillation desalination systems using a hybrid meta-heuristic optimization tool, Desalination 254 (2010) 138–148.
[7] K. Ansari, H. Sayyaadi, M. Amidpour, Thermoeconomic optimization of a hybrid pressurized water reactor (PWR) power plant coupled to a multi effect distillation desalination system with thermo-vapor compressor (MED-TVC), Energy 35(5) (2010) 1981–1996.
[8] H. Sayyaadi, A. Saffari, Thermoeconomic optimization of multi effect distillation desalination systems, Appl. Energy 87 (4) (2010) 1122–1133.
[9] H. Raach, J. Mitrovic, Simulation of heat and mass transfer in a multi-effect distillation plant for seawater desalination, Desalination 204 (2007) 416–422.
[10] P. Fiorini, E. Sciubba, Modular simulation and thermoeconomic analysis of a multi-effect distillation desalination plant, Energy 32(4) (2007) 459–466.
[11] L. Yang, S. Shen, Assessment of energy requirement for water production at dual-purpose plants in China, Desalination 205 (2007) 214–223.
[12] D.C. Alarcón-Padilla, L. García-Rodríguez, J. Blanco-Gálvez, Design recommendations for a multi-effect distillation plant connected to a double-effect absorption heat pump: A solar desalination case study, Desalination 262 (2010) 11–14.
[13] D.C. Alarcón-Padilla, L. García-Rodríguez, J. Blanco-Gálvez, Application of absorption heat pumps to multi-effect distillation: A case study of solar desalination, Desalination 212 (2007) 294–302.
[14] K. Zhao, Y. Liu, Theoretical study on multi-effect solar distillation system driven by tidal energy, Desalination 249 (2009) 566–570.
[15] J. Jiang, H. Tian, M. Cui, Lijian Liu, Proof-of-concept study of an integrated solar desalination system, Renew. Energ. 34(12) (2009) 2798–2802.
[16] S. shengqiang, Z. Kun, L. Jia, Y. Yong, Experimental investigation on performance of adjustable ejector, J. Chem. Ind. Eng. (China) 60(6) (2009) 1398–1401.
[17] S. shengqiang, Z. Kun, Study and calculation of performance of adjustable ejector, J. Therm. Sci. Technol. (China) 6(3) (2007) 1398–1401.

[18] S. shengqiang, Z. Kun, Study and calculation of performance of adjustable ejector, J. Petrochemical Universities (China) 20 (1) (2007) 74–76.
[19] S. shengqiang, S. Yu, Z. Kun, Y. Yong, Performance calculation of adjustable nozzle steam ejector, J. Therm. Sci. Technol. (China) 9(1) (2010) 64–68.
[20] L. Yang, S. Shen, Experimental study of falling film evaporation heat transfer outside horizontal tubes, Desalination 220 (2008) 654–660.
[21] L. Yang, S. Shen, X. Chen, Heat transfer of film condensation inside horizontal-tube in the presence of non-condensable gas, Desalination for the Environment: Clean Water and Energy, Baden-baden, Germany, 17–20 May 2009.
[22] L. Yang, S. Shen, X. Chen, Thermoeconomic analysis of a CHP-based dual-purpose power plant, Desalination for the Environment: Clean Water and Energy, Baden-baden, Germany, 17–20 May 2009.