Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2013.855946

53 (2015) 1725–1734
February

Taylor & Francis
Taylor & Francis Group

Research for the adjustable performance of the thermal vapor compressor in the MED–TVC system

Yong Yang[a], Shengqiang Shen[a,*], Shihe Zhou[a], Xingsen Mu[a], Kun Zhang[b]

[a]*Key Laboratory for Sea Water Desalination of Liaoning Province, Dalian University of Technology, Liaoning, Dalian 116024, China*
[b]*College of Ocean and Civil Engineering, Dalian Ocean University, Dalian 116023, China*
Tel. +86 0411 84708464; Fax: +86 0411 84707963; email: zzbshen@dlut.edu.cn

Received 12 January 2013; Accepted 10 October 2013

ABSTRACT

As the expansion in the desalination industry, multiple-effect distillation (MED) with thermal vapour compression (TVC) system becomes more attractive than other thermal systems due to effectiveness, easier operation and maintenance, and good economic characteristics and is expected to take a considerable portion in the desalination field in the near future. The TVC is an essential part that governs the overall process in the MED–TVC system. The flow and heat transfer in the TVC is very complex due to the strong compressibility and supersonic turbulent flow of the stream. In this paper, based on gas-dynamic theory, a kind of semi-empirical calculation method of ejector, including calculation of the design point and variable operating condition of ejector, has been presented. The model gives the variation of the performance of the ejector as a function of the discharge pressure for different area values of throat and provides a foundation for the research for the performance of the adjustable ejector under variation condition. Furthermore, the necessity for the utilization of the adjustable TVC in the MED–TVC system and the performance for the adjustable TVC have been researched.

Keywords: Multiple-effect distillation (MED); Thermal vapour compressor (TVC); Adjustable ejector

1. Introduction

The provision of freshwater is becoming an increasingly important issue in many areas of the world. Rapid industrial growth and the worldwide population explosion have resulted in a large escalation of demand for freshwater, which makes more than 80% of the countries facing serious water problem [1]. Continuous progress and improvements in the seawater desalination technologies have made it a feasible alternative and quite competitive against water transportation. Among various seawater desalination technologies, the process of multi-stage flash (MSF), multi-effect distillation (MED) and reverse osmosis (RO) is the most dominant in the past few years [2,3]. Especially in China, the MED desalination method is more suitable for the power plant to solve the freshwater shorten problem in the northern coastal regions [4]. The need for heating steam and electrical energy in the MED system is lower in comparison with the other desalination systems such as MSF and RO. Especially, the low-temperature multiple-effect

*Corresponding author.

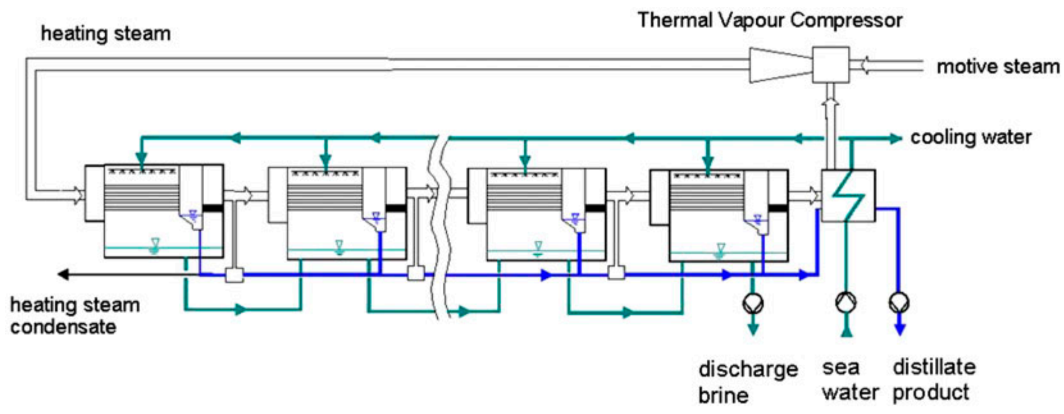

Fig. 1. Schematic of multi-effect distillation system with TVC conducting low pressure vapor from the final effect.

distillation (LT-MED) with thermal vapour compression (TVC) system becomes more attractive than other thermal systems due to effectiveness, easier operation and maintenance, and good economic characteristics, which is expected to take a considerable portion in the desalination field in the near future [5–7].

In the LT-MED desalination system, the top brine temperature (TBT) is usually lower than 70℃, so whenever the low-cost fuel or waste energy is available, the LT-MED system can be the best option for production of freshwater for industry or potable use. In the dual-purpose power plant, the heating steam for the MED desalination plant can be extracted from the steam turbine usually with much higher pressure and temperature than the first effect evaporator needed, so the thermal vapour compressor (TVC) is usually used in the desalination system to enhance the energy utilization [8,9]. As shown in Fig. 1, in the MED–TVC systems, the TVC works as the pressure reducer, which conducts low-pressure vapour from the rear effect of evaporator to gain steam with suitable pressure entering the first effect evaporator, using high-pressure vapour from turbine as motive steam. In the MED–TVC system, the TVC is an essential part that governs the overall process, so the thermodynamic state of the steam and the position of TVC in a MED desalination plant will affect its performance significantly. So accurate prediction of the TVC performance with different steam parameters, especially investigating the effect of entrained and motive steam on the discharging steam state and entrainment ratio of TVC are very significant for the optimization of the MED–TVC system.

The flow and heat transfer in the TVC is very complex due to the strong compressibility, turbulent flow and shock waves in the supersonic flow in it. In the TVC performance study, one-dimensional theoretical analyses have often been used, which is usually used for evaluating ejector characteristics under varying operation conditions for different refrigerants [10,11]. In these researches, the performances for the fix structure ejectors have been analysed. But the fixed structure ejector has only one optimum operating point, so the ejector should be designed at the operating conditions accurately to match the system; otherwise, the efficient of the system will be impaired or the ejector will not work at all. Deviations from the design point mostly result in a reduced efficiency for the TVC and the systems. Thus, a kind of adjustable TVC has been applied to fit for variable operating conditions of the refrigeration systems or the desalination systems [9,12,13].

In this paper, based on gas-dynamic theory, a kind of semi-empirical calculation method for TVC, including calculation of the design point and variable operating condition, has been presented. The model shows the variation of the performance of the ejector as a function of the discharge pressure for different area values of throat and provides a foundation for the performance of the adjustable ejector under variation condition. Based on the computational results, the necessary for the utilization of the adjustable TVC in the MED–TVC system and the performance for the adjustable TVC have been researched.

2. Mathematical modelling for adjustable TVC

2.1. Flow and mixing mechanism in adjustable TVC

As shown in Fig. 2, an adjustable TVC construction comprises four distinct parts: a convergent divergent primary nozzle with a removable axial spindle, a suction chamber, a mixing chamber attached to a constant area duct and a diffuser. As the same of the

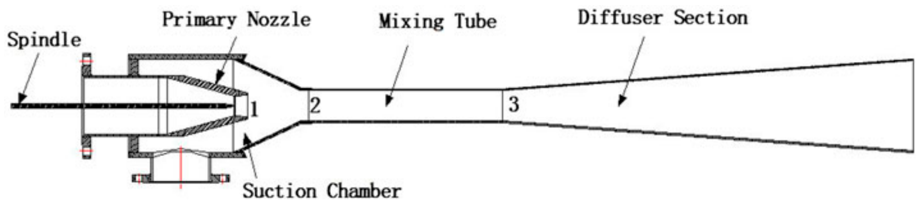

Fig. 2. Schematic diagram of the adjustable TVC construction.

traditional fixed structure TVC, the typical processes inside the adjustable TVC begin with high-temperature and high-pressure stream from the generator entering the ejector through the convergent divergent nozzle. This stream is accelerated and expanded to supersonic speed at the nozzle exit where it creates an aerodynamic duct to entrain the low pressure and low-temperature suction steam into the mixing chamber. The suction steam is accelerated to sonic velocity and mixes with the primary stream in the constant area duct. The region of supersonic flow is terminated by a normal shock wave further down the duct or in the diffuser. Based on Munday and Bagster's theory [14], two choking phenomena exist in the ejector performance, one in the primary flow through the nozzle and the other in the entrained flow. In addition to the choking in the nozzle, the second choking of an ejector results the acceleration of the entrained flow from a stagnant state at the suction port to a supersonic flow in the constant-area section.

According to the semi-empirical calculation method of ejector, the performance of the ejector is greatly influenced by the area ratio of primary nozzle exit cross-section to throat cross-section and the area ratio of mixing chamber section to the primary nozzle throat section. So different from the traditional fixed structure TVC, the adjustable TVC employs an adjustment spindle (as shown in Fig. 3), which axially extends into the primary steam nozzle (also name as motive nozzle in some literatures) and is actuated either manually or by an electric positioner. When the spindle is moved into the throat axially, nozzle throat cross-section changes. And by moving the position of the spindle, the two area ratios can be changed to make the performance of the TVC changing a lot.

The entrainment ratio (ω, the ratio of mass flow rate of secondary fluid to that of primary fluid) is the most important performance parameter of the TVC, and it is affected by many factors. The physical phenomena involve supersonic flow, shock interactions, and turbulent mixing of two streams inside the ejector enclosure. It is so complicated that the design of an ejector still heavily relies on trials and errors methods, although a number of gas-dynamic theories for ejector analysis were developed by several researchers. Fig. 4 gives the typical performance curve for fixed structure TVC [15]. The flow in the TVC device is usually in three modes: critical mode (with choking flow in the mixing chamber), subcritical mode (without choking flow in the mixing chamber) and malfunction mode (with reversed flow in the mixing chamber) depended on different back pressure (P_d, discharge pressure of TVC). As P_d below the critical value (P_d^*), the entrainment ratio remains constant. When P_d is increased higher than P_d^*, the entrainment ratio begins to fall down rapidly. A TVC should be operated at the critical mode to keep steady pumping

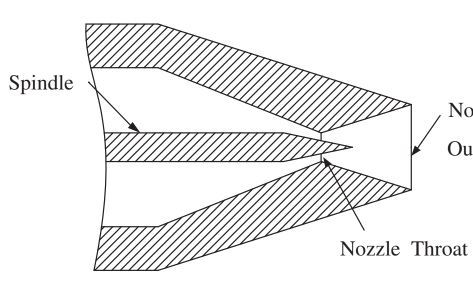

Fig. 3. Schematic diagram of the primary nozzle of the adjustable TVC.

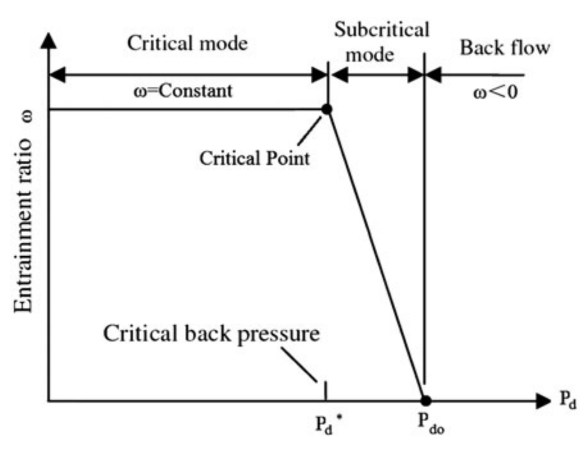

Fig. 4. Entrainment ratio as a function of discharge pressure.

performances, so it is very important to obtain thecritical point for an adjustable TVC in the theoretical analysis and engineering applications. As with the changing position of the spindle, the area of the nozzle throat will change and result in the changing of the entrainment ratio.

In the TVC system, the working characteristic of the TVC has great impact on the system performance, and a slight change of the inlet or back pressure will cause great change for the TVC entraining efficiency. For example, a minor change of the suction pressure can lead to a drastic change on the TVC operating performance and the increase in the primary steam pressure can slightly improve the performance of the TVC under a certain range [16,17]. So exploring the effect of steam pressure on the entrainment ratio is an urgent research task for the adjustable TVC.

2.2. Mathematical models establishment

2.2.1. The mathematical model for TVC

The general calculation equations for the adjustable TVC are mainly same as the traditional fixed structure ejector. The semi-empirical calculation method for ejector is used to describe the performance of the ejector [18], in which it is assumed that the mixing of primary flow and suction flow begins from the entrance of the mixing chamber. Based on the assumption, the momentum and mass flow equations can be written as following,

$$\varphi_2(G_m\omega_{m2} + G_s\omega_{s2}) - (G_m + G_s) = f_{m2}(p_3 - p_{m2}) + f_{s2}(p_3 - p_{s2}) \tag{1}$$

The mass flow rate equation can be written as following,

$$G_d = G_m + G_s = G_m(1 + u) \tag{2}$$

where the entrainment ratio u is calculated as following,

$$u = \frac{G_s}{G_m} \tag{3}$$

In Eqs. (1–3), as shown in Fig. 2, subscripts 1 denotes the outlet section of the working nozzle, while 2 and 3 denote the entrance and outlet section of the mixing chamber, respectively. Subscripts *m, s,* and *d* denote primary flow, suction flow (also named as secondary flow) and discharging flow, respectively. Thus, G_m, G_s and G_d are mass flow rate of primary flow, suction flow and mixing flow, respectively; ω_{m2}, ω_{s2} are velocity of primary flow and suction flow at the entrance of the mixing chamber; ω_3 is the velocity of mixing flow at the outlet of the mixing chamber; p_{m2}, p_{s2} are the static pressure of primary flow and suction flow at the entrance of mixing chamber; p_3 is the static pressure of mixing flow at the outlet of the mixing chamber; f_{m3} is the circulate area of the primary flow at the entrance of the mixing chamber; f_{s2} is the circulate area of the suction flow at the entrance of the mixing chamber; φ_2 is the velocity efficiency of the mixing chamber and the value of φ_2 is always below 1 considering the friction loss in the mixing chamber.

In Eq. (1), ω_{m2}, ω_{s2} are velocities of primary flow and suction flow at the entrance of the mixing chamber, which can be calculated as following,

$$\omega_{m2} = \varphi_1\, a_{m*}\lambda_{ms} \tag{4}$$

where

$$\lambda_{\mathbf{ms}} = \sqrt{\frac{k_{\mathbf{m}}+1}{k_{\mathbf{m}}-1}}\sqrt{1 - \Pi_{\mathbf{ms}}^{\frac{k_{\mathbf{m}}-1}{k_{\mathbf{m}}}}} \tag{5}$$

where Π refers the relative pressure, which is the ratio of the local static pressure to the stagnation pressure at the calculated section, calculated as following,

$$\Pi = \frac{P}{P_0} = \left(1 - \frac{k-1}{k+1}\lambda^2\right)^{\frac{k}{k-1}} \tag{6}$$

$$\Pi_{\mathbf{ms}} = \frac{P_s}{P_m} \tag{7}$$

As the similar, the velocity of suction flow at the entrance of the mixing chamber ω_{s2} and the velocity of mixing flow at the outlet of the mixing chamber ω_3 can be calculated as following,

$$\omega_{s2} = \varphi_4 a_{s*}\lambda_{s2} \tag{8}$$

$$\omega_3 = \frac{a_{d*}}{\varphi_3}\lambda_{d3} \tag{9}$$

$\varphi_1, \varphi_3, \varphi_4$ are the velocity efficiency for primary nozzle, diffuser and mixing chamber entrance, respectively, and φ_2 is the velocity efficiency of the mixing chamber. Usually, the value of φ is always below 1 considering the friction loss in the ejector flowing.

And a^* denotes the critical velocity of the calculated section, λ is the equivalent isentropic velocity.

Based on the aerodynamic theory, the critical flow section area can be calculated as follows:

$$f_* = \frac{G_{\mathbf{m}}*}{k\Pi_* P_0} \tag{10}$$

So the flow section area everywhere can be calculated as follows:

$$f = \frac{f_*}{q} \tag{11}$$

where q is the calculated mass flow velocity, which can be calculated as follows:

$$q = \frac{\omega\rho}{a * \rho^*} \tag{12}$$

And so f_{m2} and f_{s2} in Eq. (1) can be calculated as follows:

$$f_{m2} = \frac{G_m a_{m*}}{k_{\mathbf{m}} \Pi_{\mathbf{m}*} P_m q_{m2}} = \frac{G_m a_{m*}}{k_{\mathbf{m}} \Pi_{\mathbf{m}*} P_m q_{ms}} \tag{13}$$

$$f_{s2} = \frac{G_s a_{s^*}}{k_{\mathbf{s}} \Pi_{\mathbf{s}*} P_s q_{s2}} \tag{14}$$

where $q_{m2} = q_{ms}$, and q_{m2}, q_{s2} denote the calculated mass flow velocity for primary fluid and suction fluid at the section 2 (the entrance section of the mixing chamber), respectively.

In the mixing chamber, the circulate areas have the following relation equation,

$$f_3 = f_{m2} + f_{s2} = \frac{G_d a_{d^*}}{k_{\mathbf{d}} \Pi_{\mathbf{d}^*} P_d q_{ds}} = \frac{G_m a_{m^*}}{k_{\mathbf{m}} \Pi_{\mathbf{m}^*} P_m q_{ms}} + \frac{G_s a_{s^*}}{k_{\mathbf{s}} \Pi_{\mathbf{s}^*} P_s q_{s2}} \tag{15}$$

where q_{d3} is the calculated mass flow velocity for discharging flow at the section 3 (the outlet section of the mixing chamber).

Based on Eqs. (1–15), the general calculation equations for the TVC can be conducted as follows:

$$u = \frac{K_1 \frac{a_{m^*}}{a_{\mathbf{d}^*}} \lambda_{ms} - K_3 \lambda_{d3}}{K_4 \lambda_{d3} - K_2 \frac{a_{s^*}}{a_{\mathbf{d}^*}} \lambda_{s2}} \tag{16}$$

where K_1 and K_2 are the velocity coefficient for primary flow and suction flow. And K_1, K_2, K_3 and K_4 can be calculated as follows:

$$K_1 = \varphi_1 \varphi_2 \varphi_3 \tag{17}$$

$$K_2 = \varphi_2 \varphi_3 \varphi_4 \tag{18}$$

$$K_3 = 1 + \varphi_3 \frac{a_{m^*}}{a_{\mathbf{d}^*}} \frac{P_d}{P_m} \frac{\left(\Pi_{\mathbf{d}3} - \frac{P_s}{P_d}\right)}{K_m \Pi_{\mathbf{m}^*} \lambda_{d3} q_{ms}} \tag{19}$$

$$K_4 = 1 + \varphi_3 \frac{a_{s^*}}{a_{\mathbf{d}^*}} \frac{P_d}{P_s} \frac{(\Pi_{\mathbf{d}3} - \Pi_{\mathbf{d}2})}{K_s \Pi_{\mathbf{s}^*} \lambda_{d3} q_{s2}} \tag{20}$$

Based on Eq. (16), the entrainment ratio u can be calculated without the geometry parameters, and the equation is the basic equation for the designing of the TVC. While for calculating the performance of the TVC with given structure, the calculating equation should be given in another expression.

With the changing of the primary nozzle throat section, the mass flow rate will change at the same time. So in the model for the adjustable TVC, the mass flow rate can be calculated as follows:

$$G_m = \frac{k_m \Pi_{m*} P_m f_{m*}}{a_{m*}} \tag{21}$$

where G_m is the mass flow rate for the primary flow and f_{m*} is the section area of the primary nozzle.

To calculating the performance of the TVC, the static pressure of primary flow and suction flow at the entrance of mixing chamber p_{m2}, p_{s2} and the static pressure of mixing flow at the outlet of the mixing chamber p_3 should calculated as follows:

$$P_{m2} = \Pi_{m2} p_m,\ p_{s2} = \Pi_{s2} p_s,\ p_3 = \Pi_{d3} p_d \tag{22}$$

Based on Eqs. (1–22), the calculation model for the TVC performance can be conducted as follows:

$$\frac{P_d}{P_s} = \frac{1}{\Pi_{d3}} \left\{ \Pi_{m2} \frac{P_m}{P_s} \frac{f_{m2}}{f_3} + \Pi_{s2} \frac{f_{s2}}{f_3} + \frac{\Pi_{m^*} k_m}{\varphi_3} \frac{f_{m^*}}{f_3} \frac{P_m}{P_s} \left[K_1 \lambda_{m2} + K_2 u \frac{a_{s^*}}{a_{m^*}} \lambda_{s2} - (1+u) \frac{a_{d^*}}{a_{m^*}} \lambda_{d3} \right] \right\} \tag{23}$$

where P denotes pressure, k is heat capacity ratio, a^* denotes the critical velocity of the calculated section, λ is the equivalent isentropic velocity, u is the entrainment ratio of the ejector, φ is empirical coefficient and Π denotes the relative pressure at the calculated section, f denotes the cross section area and K_i (i = 1, 2) is the velocity coefficient for primary flow and suction flow (also named as secondary flow). Subscripts *m, s, d* denote primary flow, suction flow (also named as secondary flow) and discharging flow, respectively. And subscripts 2 and 3 denote the entrance and outlet section of the mixing chamber, respectively. Based on the equation, the changing of TVC performance caused by altering of the ratio of primary nozzle exit section to throat section and the area ratio of mixing chamber section to the primary nozzle throat section is conducted to calculate the performance of TVC.

2.2.2. The critical model of the TVC

As mentioned in the section of 2.1, the TVC device usually works in three critical models, when the choking happens in the suction chamber or in the constant area mixing tube or in the diffuser section. And TVC should be operated at the critical model to keep steady pumping performance. The first critical model occurs when the velocity of the suction flow reaches to the critical value at the entrance of the mixing chamber, and the second critical model occurs when the velocity of the suction flow reaches to the critical value in the mixing chamber, and the third critical model occurs when the velocity of the discharge flow reaches to the critical value at the outlet of the mixing chamber. And in the three different working models, the three different critical entrainment ratios are calculated as follows:

When the first critical model occurs, the flowing condition parameters are at the critical value, just as followings,

$$\omega_s = \omega_{s*},\ \lambda_s = \lambda_{s2} = 1,\ f_s = f_{s2} = f_{s*}$$

Similar to Eq. (21), the critical mass flow rate of the suction flow can be calculated as follows:

$$(G_s)_{\Pi m1} = \frac{k_s \Pi_{S*} P_s f_{s2}}{a_{s*}} \tag{24}$$

At the same section, the mass flow rate of the primary flow can be calculated as follows:

$$G_m = \frac{k_m \Pi_{m*} P_m f_{m*}}{a_{m*}} \tag{25}$$

So the entrainment ratio u can be calculated as follows:

$$(u_{\Pi m})_1 = \frac{(G_s)_{\Pi m1}}{G_m} = \frac{k_s}{k_m}\frac{\Pi_{s^*}}{\Pi_{m^*}}\frac{P_s}{P_m}\frac{f_{s2}}{f_{m^*}}\frac{1}{\sqrt{\theta}} \tag{26}$$

Based on Eq. (15),

$$f_{s2} = f_3 - f_{m1} = f_3 - \frac{f_{m^*}}{q_{m1}} \tag{27}$$

So the entrainment ratio of the first critical model can be calculated as follows:

$$(u_{\Pi m})_1 = \frac{k_s}{k_m}\frac{\Pi_{s^*}}{\Pi_{m^*}}\frac{P_s}{P_m}\left(\frac{f_3}{f_{m^*}} - \frac{1}{q_{mX}}\right)\frac{1}{\sqrt{\theta}} \tag{28}$$

where q is the calculation mass flow velocity,

$$q = \frac{\omega\rho}{a^*\rho^*} \tag{29}$$

where a^* is the critical velocity of the calculated section and ρ^* is the critical density at the critical velocity.

And in the second critical model, the velocity of the suction flow reaches to the critical value in the mixing chamber. Assumed that the critical state occurs at the *X-X* cross-section, the static pressure of the primary flow and the suction flow will achieve to the critical value of the suction flow.

$$P_X = P_{mX} = P_{sX} = \Pi_{s*} P_s$$

At the *X-X* cross-section, the mass flow rate of the suction flow can be calculated as follows:

$$(G_s)_{\Pi m2} = \frac{k_2 \Pi_{s*} P_s}{a_{s*}} f_{s*} \tag{30}$$

where

$$f_{s^*} = f_{mX} = f_3 - f_{mX} = f_3 - \frac{f_{m^*}}{q_{mX}} \tag{31}$$

Thus, the entrainment ratio of the second critical model can be calculated as following,

$$(u_{\Pi m})_2 = \frac{k_s}{k_m}\frac{\Pi_{s^*}}{\Pi_{m^*}}\frac{P_s}{P_m}\left(\frac{f_3}{f_{m^*}} - \frac{1}{q_{mX}}\right)\frac{1}{\sqrt{\theta}} \tag{32}$$

In the third critical model, the velocity of the discharge flow (mixing of the primary flow and the suction flow) reaches to the critical value at the outlet of the mixing chamber. Thus, the mass flow rate of the discharge flow can be calculated as following,

$$(G_d)_{\Pi m3} = G_m(1 + (u_{\Pi m})_3) = \frac{k_d \Pi_{d*} P_d}{a_{d*}} f_3 \tag{33}$$

Thus, the entrainment ratio of the second critical model can be calculated as following,

$$(u_{\Pi m})_3 = \frac{(G_d)_{\Pi m3}}{G_m} - 1 = \frac{k_d}{k_m}\frac{\Pi_{d*}}{\Pi_{m*}}\frac{P_d}{P_m}\frac{a_{m*}}{a_{d*}}\frac{f_3}{f_{m*}} - 1 \quad (34)$$

where $\theta = \frac{T_s}{T_m} = \frac{a_{s*}^2}{a_{m*}^2}$. And $(u_{\Pi m})_1, (u_{\Pi m})_2$ and $(u_{\Pi m})_3$ are the first critical entrainment ratio, the second entrainment ratio and the third entrainment ratio, respectively.

3. Performance of TVC in the MED–TVC system

3.1. Validation for the model: comparison vs. experimental values and literatures

Ji and Wang calculated the TVC performance for the MED–TVC system with fresh water production of 5 t/d [16]. To fit the variation for the pressures of the primary flow and suction flow in the MED–TVC system, they list five different working conditions for a fix structure TVC. To validate the capability and the accuracy of the calculating model, the five conditions were recalculated in the paper. And the validation for the calculation results was accomplished with the experiment data and Ji's results. As shown in Table 1, the calculation results in the paper show a good agreement between the result in literature [16] and the experiment data. The relative errors of calculation with the experiment data are below 3%. So the model selected in the paper can be used to predict the performance of the TVC in the MED–TVC system.

3.2. The necessary of the utilization of the adjustable TVC in the MED–TVC system

In the MED–TVC system, the primary vapour imported from the turbine system is always unsteady. Sometimes, the parameters of the primary vapour should be changed or the parameters of the suction steam will change if the suction position alters in the MED system. But for a fix structure TVC, the entrainment ratio will change a lot as the parameters altering.

In the traditional MED–TVC, the range of the primary steam pressure for the TVC is usually 0.3–1.0 MPa, while the suction steam pressure usually varies from 0.007 to 0.019 MPa, and the discharge pressure always alter from 0.016 to 0.058 MPa. For a 4–12 effect MED–TVC, the ideal interval for the Gained Output Ratio (GOR) of the system is 8.5–18.5 [19]. And in the LT-MED system, the inlet temperature of steam for the first effect of the MED is always below 70℃, so the relevant pressure for the discharge steam should blew 0.0312 MPa. In this range, we select P_m = 0.8 MPa, P_s = 0.01 MPa and P_d = 0.025 MPa as the design conditions. Based on the present model, we can calculate the structure of a fix structure TVC with f_3/f_{m*} = 61.7034 and f_{m1}/f_{m*} = 8.2695. And the critical entrainment ratio for the TVC is 0.7012. Figs. 5 and 6 show the performance of the fix structure TVC with the primary steam pressure changing from 0.3 to 1.0 MPa with discharge steam pressure changing.

As shown in Figs. 5 and 6, for the profile for the primary steam pressure P_m = 0.8 MPa, when the discharge steam pressure is below 0.025 MPa, the entrainment ratio of the TVC is 0.7018, which is almost equal to the design value 0.7012. When the discharge steam pressure is blow 0.025 MPa, the entrapment ratio keeps constant. While the discharge steam pressure is higher than 0.025 MPa, the performance for the TVC deteriorates quickly until to ω = 0.

At the same time, with the primary steam pressure changing from 0.8 to 1.0 MPa, the critical entrapment ratio drops down obviously. But the mass flow rate of discharge steam has an obvious increase. While the primary steam pressure decrease to 0.3 MPa, the critical entrapment ratio increases dramatically, but the adjustable range for the discharging steam becomes narrow. Based on the comparison between the different primary steam pressure, it can be seen that a little changing for the parameters of the steam, the performance for the fix structure TVC has an obviously

Table 1
Comparison between the results of the present paper and experiment data and Ji's result

Primary pressure P_m/MPa	Suction pressure P_s/MPa	Discharge pressure P_d/MPa	Entrainment ratio in experiment ω	Entrainment ratio calculated by Ji [16] ω	Entrainment ratio in present paper ω	Relative errors with experiment %
0.59	0.0112	0.0207	1.28	1.191	1.270	0.78
0.60	0.0135	0.0235	1.11	1.033	1.090	1.80
0.63	0.0135	0.0238	1.25	1.170	1.220	2.40
0.65	0.0135	0.0240	1.31	1.242	1.295	1.15
0.72	0.0156	0.0274	1.21	1.152	1.210	0.00

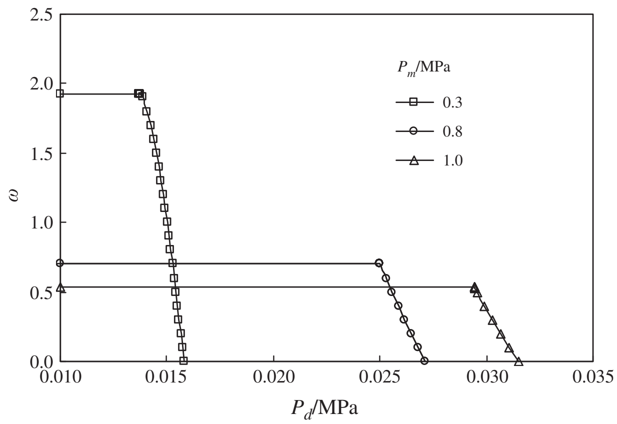

Fig. 5. The entrainment ratio of the fix structure TVC with different primary steam parameters.

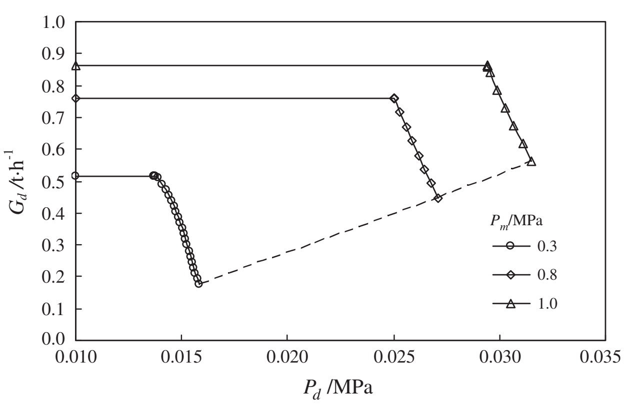

Fig. 6. The mass flow rate of discharge steam of the fix structure TVC with different primary steam parameters.

change. And the performance of the TVC has great effect on the GOR of the MED–TVC system.

3.3. The performance of the adjustable TVC

The performance of the ejector is greatly influenced by the area ratio of primary nozzle exit cross-section to throat section and the area ratio of mixing chamber section to the primary nozzle throat section. So the adjustable TVC employs an adjustment spindle into the primary steam nozzle. When the spindle is moved into the throat axially, the nozzle throat cross-section area f_m^* will change.

In this paper, an adjustable TVC was designed, and its performance was also revealed. The designed primary pressure for the TVC is 0.6 MPa, and the suction pressure is 0.2 MPa with the flow rate of discharge steam at 0.3 t/h. The original structure for the TVC is the primary nozzle outlet section is 71 mm^2, the nozzle throat area is 63.6 mm^2, and the cylindrical mixing chamber area is 201 mm^2. When the spindle is moving, the primary nozzle throat area f_m^* will change, and as shown in Fig. 7, four conditions are calculated to get the entrainment ratio profile for different nozzle throat areas with f_m^* value at 63.6, 50.3, 38.5, and 28.3 mm^2 with the same primary steam pressure and suction pressure.

As shown in Fig. 7, with the decrease in the nozzle throat section, the critical entrainment ratio becomes higher, and the relative discharge pressure reduces. When the nozzle throat area decreases from 63.6 to 28.3 mm^2, the critical entrainment ratio increases from 0.50 to 1.44, and at the same time, the discharge steam pressure drops from 0.28 to 0.2 MPa.

The mass flow rate flow in the primary nozzle will drop with the nozzle throat area decreasing. So the discharge flow rate G_d with the same entrainment ratio. The envelope line in Fig. 8 is the point for the entrainment ratio is 0 with different nozzle throat area. As shown in Fig. 8, at the subcritical mode, the mass flow rate becomes higher with the entrainment ratio when the discharge steam pressure drops. And with the bigger nozzle throat area, the adjustable range for the discharging steam is narrow.

As shown in Fig. 9, with discharge pressure decreasing, the temperature also decreases, but the steam is at the similar superheat condition. That means the nozzle throat area has little effect on the superheat temperature of the discharge steam. The envelope line in Fig. 8 is also the point for the entrainment ratio is 0 with different nozzle throat area. And when the discharge pressure drops to the critical point, the temperature will keep constant without any decreasing. And as shown in Fig. 9, with the smaller nozzle throat area, the discharge steam pressure and temperature of the critical point is always lower. As the discharge steam is always superheated, that means the vapour from the TVC cannot enter the first effect evaporator directly. In the practical application of the MED project, as the discharged steam from the TVC is always superheated state, to make sure the vapour entering into the MED desalination equipment always below than 70℃ at saturation state, the vapour discharging from the TVC should be sprayed saturation water at 70℃ or below 70℃ to make the TBT in the first effect evaporator below 70℃.

As shown in Figs. 7–9, when the spindle is inducted into the adjustable TVC, at different positions, the performance of the TVC always changes. The adjustable range for the discharge flow is much broader than any fix structure TVC. You can find that, the range of entrainment ratio, the mass flow rate, and the discharge steam temperature and pressure all

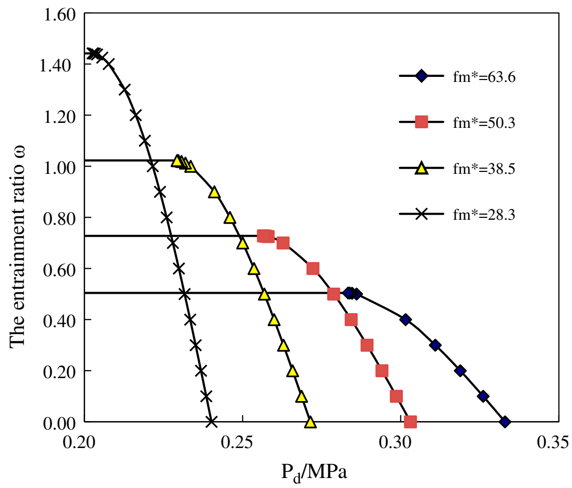

Fig. 7. Entrainment ratio as function of discharge pressure for different primary nozzle throat areas.

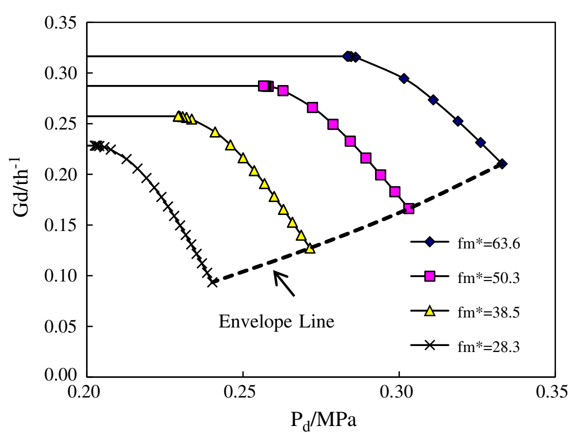

Fig. 8. Mass flow rate of discharge steam as function of discharge pressure for different primary nozzle throat areas.

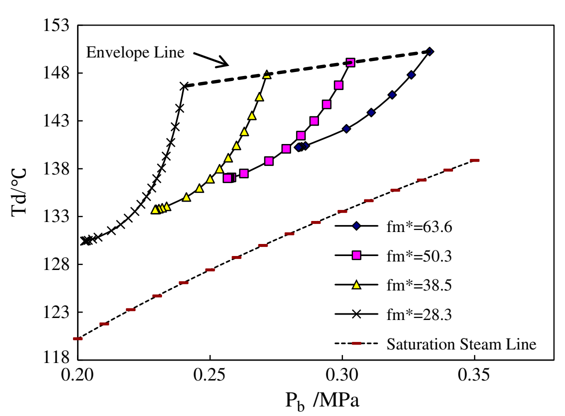

Fig. 9. Temperature of discharge steam as function of discharge pressure for different primary nozzle throat areas.

become much broader when the spindle is added to the fix structure TVC with f_m^* value at 63.6 mm^2. To some extent, the adjustable TVC is an aggregate for several fix structure TVCs. And if the primary steam pressure and the suction pressure change at some degree, the adjustable range for the TVC will be much broader.

4. Conclusions

In the present study, based on gas-dynamic theory, a kind of semi-empirical calculation method of ejector, including calculation of the design point and variable operating condition of ejector has been presented. The model gives the variation of the performance of the ejector as a function of the discharge pressure for different area values of throat, and provides a foundation for the research for the performance of the adjustable ejector under variation condition. Based on the computational results, the necessary for the utilization of the adjustable TVC in the MED–TVC system and the performance for the adjustable TVC have been researched. And the main conclusions were obtained as follows:

(1) The semi-empirical calculation method of ejector was validated with the experiment data and the computational results in literatures. And the results show reasonably good agreement with the latter ones. Therefore, the models could predict the ejector performance in a wide operating condition range of MED–TVC system.
(2) For a fix structure TVC, with the primary steam pressure increasing, the critical entrapment ratio drops obviously. And with the primary steam pressure decreasing, the critical entrapment ratio increases dramatically, but the adjustable range for the discharging steam becomes narrow.
(3) The performance of the ejector is greatly influenced by the area ratio of primary nozzle exit cross-section to throat section and the area ratio of mixing chamber section to the primary nozzle throat section. At the same operating conditions, when the nozzle throat area decreases from 63.6 to 28.3 mm^2, the critical entrainment ratio increases from 0.50 to 1.44, while the discharge steam pressure drops from 0.28 to 0.2 MPa.
(4) When the spindle is inducted into the adjustable TVC, at different positions, the performance of the TVC always changes.

The adjustable range for the discharge flow is much broader than any fix structure TVC. To some extent, the adjustable TVC is an aggregate for several fix structure TVCs. And with the primary steam pressure and the suction pressure changing at some degree, the adjustable range for the TVC will be much broader.

(5) In the LT-MED system, as the vapour discharging from TVC is always superheated, that means the vapour cannot enter the first effect evaporator directly. To make sure the vapour entering into the MED desalination equipment always below than 70℃ at saturation state, the vapour discharging from the TVC should be sprayed saturation water at 70℃ or below 70℃ to make the TBT in the first effect evaporator below 70℃.

Acknowledgments

The research is supported by the National Natural Science Foundation of China (No. 51206015), the Postdoctoral Science Foundation of China (No. 2012 T50253), and the Fundamental Research Funds for the Central Universities (DUT13JN09).

References

[1] I.C. Karagiannis, P.G. Soldatos, Water desalination cost literature: Review and assessment, Desalination 223 (2008) 448–456.
[2] M. Abdel-Jawad, Energy Options for Water Desalination in Selected ESCWA Member Countries, New York, NY, United Nations, 2001.
[3] R. Kouhikamali, N. Sharifi, Experience of modification of thermo-compressors in multiple effects desalination plants in Assaluyeh in Iran, Appl. Therm. Eng. 40 (2012) 174–180.
[4] L.P. Yang, S.Q. Shen, Assessment of energy requirement for water production at dual-purpose plants in China, Desalination 205 (2007) 214–223.
[5] R.K. Kamali, A. Abbassi, S.A. Sadough Vanini, A simulation model and parametric study of MED–TVC process, Desalination 235 (2009) 340–351.
[6] H.S. Choi, Y.G. Kim, S.L. Song, Performance improvement of multiple-effect distiller with thermal vapor compression system by exergy analysis, Desalination 182 (2005) 239–249.
[7] M.A. Sharaf, A.S. Nafey, G.R. Lourdes, Thermo-economic analysis of solar thermal power cycles assisted MED-VC (multi effect distillation-vapor compression) desalination processes, Energy 36 (2011) 2753–2764.
[8] S.Q. Shen, S.H. Zhou, Y. Yong, L.P. Yang, X.H. Liu, Study of steam parameters on the performance of TVC-MED desalination plant, Desal. Water Treat. 33 (2011) 300–308.
[9] I.S. Park, Robust numerical analysis based design of the thermal vapor compressor shape parameters for multi-effect desalination plants, Desalination 242 (2009) 245–255.
[10] B.J. Huang, C.B.F.F. Jiang, Ejector performance characteristics and design analysis of jet refrigeration system, J. Eng. Gas Turbines Power 107 (1985) 792–802.
[11] D.W. Sun, Comparative study of the performance of an ejector refrigeration cycle operating with various refrigerants, Energy Convers. Manage. 40 (1999) 873–884.
[12] S. Varga, O.C. Armando, X.L. Ma, S.A. Omer, W. Zhang, S.B. Riffat, Experimental and numerical analysis of a variable area ratio steam ejector, Int. J. Refrig. 34 (2011) 1668–1675.
[13] K. Zhang, S.Q. Shen, Y. Yang, X.W. Tian, Experimental investigation on adjustable ejector performance, J. Energy Eng. 138 (2012) 125–129.
[14] J.T. Munday, D.F. Bagster, A new ejector theory applied to steam jet refrigeration, Ind. Eng. Chem. Process Des. Dev. 6 (1977) 442–449.
[15] B.J. Huang, J.M. Chang, C.P. Wang, V.A. Petrenko, A 1-D analysis of ejector performance, Int. J. Refrig. 22 (1999) 354–364.
[16] J.G. Ji, L.X. Li, R.Z. Wang, Performance simulation and analysis of steam ejector under different operating condition, Chem. Eng. 35 (2007) 68–71.
[17] J.G. Ji, R.Z. Wang, L.X. Li, Performance computation and analysis of steam ejector, Ship Eng. 28 (2006) 46–49.
[18] E.I. Sokolov, N.M. Zinger, Jet Apparatuses (H. Qiuyun, Trans.), Science Press, Beijing, 1977, pp. 17–78.
[19] A.O. Bin, Development and optimization of ME-TVC desalination system, Desalination 249 (2009) 1315–1331.