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Performance Analysis of Thermal Vapor Compression Integrated with Reverse Osmosis Desalination System

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Based on the thermal and membrane desalination technology, this study presents an analysis of an integrated single stage TVC-RO system. The hybrid system produces fresh water with an adjustable salinity in parallel operation. A steam ejector and a pressure exchanger are applied as the energy recovery devices. For comparison, a coupling system without energy recovery process is also modeled in the steady-state condition. System performance is evaluated by specific energy consumption and production ratio. The effects of several design parameters on system performance are investigated including boiling temperature, compression ratio, motive steam pressure, and target recovery rate. Results of the analysis indicate that the product salinity is adjustable in the TVC-RO system, and the system performance is largely dominated by system configurations and design parameters. To improve the system performance, the use of energy recovery device is necessary, and the membrane operation is recommended if the process is less demanding on product purity. A better performance can be obtained by increasing the target recovery rate of the RO membrane and decreasing compression ratio and motive steam pressure of the ejector. As the boiling temperature increases, one can expect that the production rate increases at a cost of a higher specific energy consumption.

1. Introduction

The global development is highly connected with freshwater resource and energy. Freshwater is not only indispensable for biological activity, but also vital for various energy generation processes, such as extraction, cooling, washing, diluting and fuel conversion. In coastal regions, desalination has chosen to be a prior method to deal with fresh water shortage.

Desalination is an energy-intensive process, it can be classified into two types according to whether they are involving phase-change or not. The Multi-effect (ME) distillation, Multistage flash (MSF) distillation and Vapor compression (VC) distillation are the most well-known thermal processes involving phase change, thus consuming energy to provide heat for evaporation. Whereas the RO (Reverse Osmosis) is the widely-applied membrane process that uses high pressure as the driving force to produce the permeate flow.

Compared with the standalone desalination system, the integration of thermal and membrane desalination allows for the integrated pre-treatment and post-treatment operation with less capital cost and chemicals (Hamed, 2005). The practical selection of desalination process depends on many factors including energy cost, water quality demand, local circumstances and environmental constraints.

Many studies have been conducted to examine the system performance of the TVC process and RO process respectively. With the emerging integration method, most studies discussing the energy consumption issue mainly focuses on system coupling between the same types, such as MED-TVC (Al-Mutaz and Wazeer, 2014), SWRO-PRO process (Wan and Chung, 2016), membrane process with multiple stages (Qi et al., 2012), integration of thermal process with cogeneration cycle (Asiedu-Boateng et al., 2012) and with solar thermal systems (Sharan and Bandyopadhyay, 2015). A hybrid MSF-RO desalination system was studied by (Marcovecchio et al., 2005), the basic design of such a desalination process was provided based on the solution of the mathematical model. In combination of desalination with site utility in process industries, an MED-RO system was proposed through exergoeconomic optimization (Manesh et al., 2013).

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This study presents a TVC-RO hybrid system with a boiler as heat source. Such arrangement allows using common seawater intake and product output, and the salinity of the product freshwater is therefore adjustable to the purity demand. A parametric study of the system performance is carried out by modelling, simulation, and analysis of the hybrid system. The steady state thermal dynamic model is used to describe the desalination process. And the correlation between system performance with product salinity, boiling temperature, compression ratio, motive steam pressure, and target recovery rate are evaluated. In addition, the effect of utilizing energy recovery device is also discussed.

2. Description and modelling of the system

2.1 Process description

Figure 1a shows a schematic diagram for the proposed integrated TVC-RO desalination system. The main components of the system are the evaporator, the condenser, the primary steam boiler, the RO module and high-pressure pump. The dotted lines represent for the energy recovery process by adding a steam jet ejector and an isobaric pressure exchanger for the coupling system. With parallel operation, the intake seawater splits into two feed streams from a common seawater intake. According to different distribution ratio, one feed stream enters TVC system as feed water, and the remaining stream enters RO system. Similarly, the product streams from the two systems joint together as the fresh water which enables the dual water distribution.

The TVC feed water flows through the tubes of the condenser where it is heated by the condensing vapor generated from the evaporator on the shell side. The feed water temperature is maintained at a lower temperate than the boiling temperature in the evaporator tubes. A part of the feed water, known as the cooling seawater, is dumped back to the sea to remove part of the excess heat added to the system. When the remaining feed water flows down along the inner wall from the top of vertical tubes inside the evaporator, it absorbs the latent heat from compressed steam condensing on the shell side. A part of the feed water vaporizes and passes through the demister, the entrained brine droplets is filtered and discharged with the remaining high concentrate seawater thereby making the departing vapor is free of salt. Due to the temperature depression caused by pressure loss in the demister, the saturation temperature of the vapor is slightly lower than the boiling temperature. Part of the condensed vapor is used to preheat the intake seawater flowing inside the tubes of the condenser, while the rest of the vapor is entrained by the steam ejector which compresses it to a higher outlet pressure and temperature with the mixing of motive steam. After the heat transfer process in the evaporator, the condensed heating steam is divided into the primary flow recycled by boiler and the distillate flow collected together as the product.

To overcome the osmotic pressure, the external pressure is applied to the RO feed water by the high-pressure pump. The added driving force enables the pure water to permeate through the semi-permeable membrane, however, this pressurization is one of the main energy consuming process in RO system. An isobaric pressure exchanger can be used to recover the high pressure from the salt rejection flow. After transferring pressure to feed seawater, the salt rejection flow is discharged when exposed to the inflow seawater.

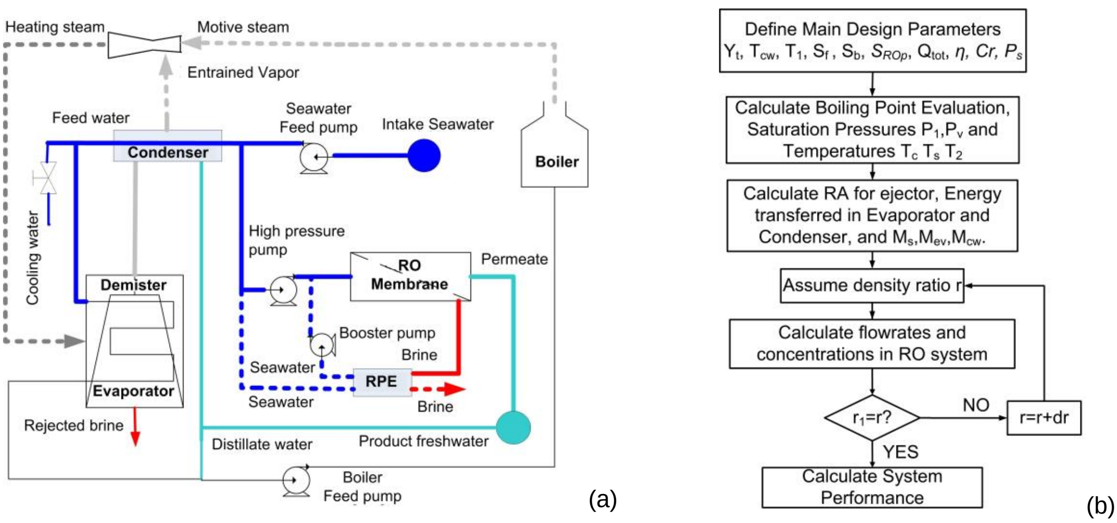


Figure1: Schematic of a Single Effect TVC-RO desalination system with energy recovery devices (a) and solution procedure (b)

2.2 Process Modelling

In the distillation process, the feed seawater ends up in the distillate product and rejected brine. The overall mass and salt balance equations are given by,

$$M_f = M_b + M_d \tag{1}$$

$$M_f \cdot S_f = M_b \cdot S_b \tag{2}$$

In the above equations, *M* is the mass flow rate; *S* is the salt concentration, Subscripts f, d and b denote the feed water, product fresh water and brine respectively.

The total energy consumed in the evaporator is supplied by the saturated heating steam from the ejector. It is used to raise the feed water temperature to the boiling temperature, T_1 and to provide the latent heat for the evaporation on shell side. It can be written as,

$$Q_e = M_f \cdot C_p \cdot (T_1 - T_f) + (M_d \cdot \lambda_e) = A_e \cdot U_e \cdot (T_m - T_1) \tag{3}$$

where C_p is the specific heat at constant pressure of the seawater and is calculated by an empirical correlation (El-Dessouky et al, 2000), λ_e is the latent heat of evaporation, *A* is the required heat transfer surface area, *U* is the overall heat transfer coefficient. Subscripts e and m denote the evaporator and the heating steam.

Due to the salts dissolved in the water, the temperature of the formed vapor T_v is less than the boiling temperature by the boiling point elevation. The elevation varies with temperature and salinity of seawater at a given pressure, the value can be calculated empirically in the common operating ranges of TVC system.

Similarly, the thermal load of the evaporator can be written as,

$$Q_c = (M_f + M_{cw}) \cdot C_p \cdot (T_f - T_{cw}) = (M_d - M_{ev}) \cdot \lambda_c = A_c \cdot U_c \cdot (LMTD)_c \tag{4}$$

where subscript c, cw and ev denote the condenser, the cooling water and entrained vapor. The definition of the logarithmic mean temperature difference $(LMTD)_c$ can be found in the literature (El-Dessouky and Ettouney, 1999). By calculating the pressure loss while the vapor is flowing through the demister at the top of evaporator, the temperature depression and pressure of entrained vapor are obtained.

The steam ejector performance can be evaluated by using turbomachinery analog (Chabukswar and Garris, 2009). Other methods for performance evaluation of steam ejector include chart, empirical correlation, gas dynamic method and CFD method (Ji et al., 2007). The method used in this work is correlation developed by (El-Dessouky and Ettouney, 1999) which is based on the chart developed by (Power, 1994). As the main data required from analyzing a steam jet ejector, the entrainment ratio (*Ra*) is defined as the mass of motive steam per mass of entrained vapor, and it is obtained with the given pressure of discharge mixture (P_m), entrained vapor (P_{ev}), and motive steam (P_s). The ejector entrainment is defined as,

$$Ra = 0.296 \frac{(P_m)^{1.19}}{(P_c)^{1.04}} \left(\frac{P_s}{P_c}\right)^{0.015} \left(\frac{PCF}{TCF}\right) \tag{5}$$

where *P* is the pressure, *PCF* and *TCF* are pressure and temperature correction factors respectively. It is mentioned that Eq (5) is valid in the most common operating ranges in TVC desalination systems.

The energy supplied to the boiler Q_b can be calculated as follows,

$$Q_{Boiler} = M_s \cdot (h_1 - h_2) \tag{6}$$

where *h* is the specific enthalpy of different sections, kJ/kg.

In the membrane process, the mass and salt balance are also developed for the entire process. As discussed in section 2.1, the main energy consumed in RO process is associated with pumps. The total consumption equals to the sum of pump work W_{pump},

$$W_{pump} = \frac{Q \cdot \Delta P}{\eta} \tag{7}$$

where *P* and *Q* are the pressure and volumetric flow rate of the pressurized flow, η is the pump efficiency.

Considering the thermodynamic restriction and concentration polarization (Qi et al., 2012), the specific energy consumption (*SEC*) for RO system is introduced as the energy required to produce a cubic meter of permeate,

$$SEC_{RO,ERD} = \frac{(Y_t + \beta \cdot (1 - Y_t) \cdot R_t) \cdot \pi_0}{Y_t \cdot (1 - R_t \cdot Y_t) \cdot \eta_{HP}} + \frac{(1 - \eta_E)(1 - \beta)(1 - Y_t) \cdot R_t \cdot \pi_0}{Y_t \cdot (1 - R_t \cdot Y_t) \cdot \eta_{BP}} \tag{8}$$

where Y_t is the targeted recovery rate of the RO membrane, R_t is the rejection rate, β is the initial leakage ratio, E, HP and BP represent the PX pressure exchanger, high pressure pump and the booster pump, π_0 is the osmotic pressure for membrane process (Hyung and Kim, 2006).

The total energy consumed in the TVC-RO hybrid system is calculated as the energy supplied to the boiler, the high-pressure pump, the feed pumps and the booster pump. The system performance is evaluated by the total *SEC*, and the water production/seawater consumption ratio (*PR*). For comparison, the system performance is also analyzed when energy recovery devices are removed. We assume that the system is operated at steady state; negligible energy loss in the pipelines; primary and entrained flow are ideal gas and undergo a complete mixing in the ejector. In the modelling process, we use the Matlab R2010a to solve the model and iteration process. Several known parameters are given in Table 1. The solution procedure for solving the systematic model is shown in Figure 1b. A subroutine code for calculating the water and water vapor properties are also calculated in the simulation.

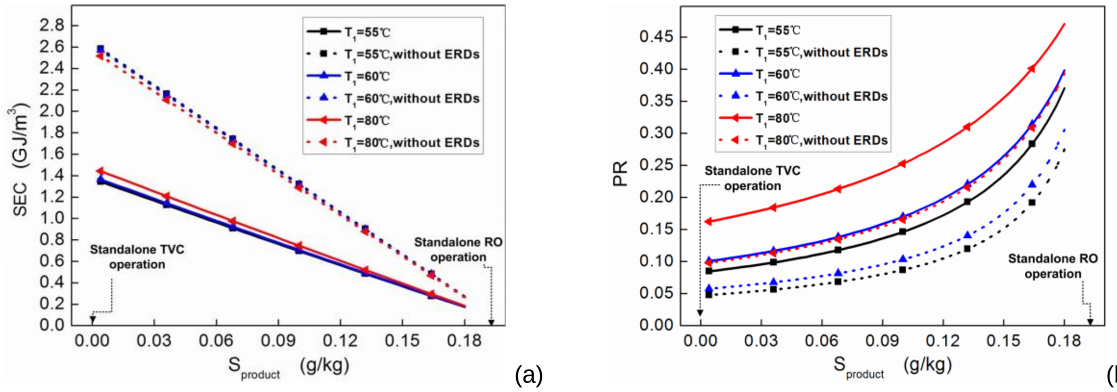
Table 1: Parameters used in the simulation

Seawater temperature, T_{cw}	Seawater salinity, S_f	Rejected brine salinity, S_b	PX mixing rate, *m*	PX leakage ratio, *l*	PX efficiency, η_E	Total production rate, Q_{tot}
°C	g/kg	g/kg	%	%	%	kg/s
25	35	70	4.5	1	90	10

3. Results

Figure 2 to Figure 4 show the variations of the system performance with the boiling temperature, the target recovery rate, the compression ratio, *Cr*, and the pressure of the motive steam.

As is shown in Figure 2a, a higher purity of product water corresponds to a higher specified energy consumption. Two arrows point to extreme cases of standalone operation. Dotted lines represent for the system performance when operates without energy recovery devices. It is seen that the use of energy recovery devices decreases the system *SEC* significantly, especially when producing the freshwater at a lower salinity. With the increase in boiling temperature, the *SEC* of the system with no ERDs decreases slightly, while it shows an opposite trend in the system with ERDs. This is caused by the variation of energy consumed in the boiler. In no ERDs case, the heating steam temperature remains unchanged, and therefore less heating steam is needed as the heat transfer amount in the evaporator decreases. However, the temperature of the heating steam is increased at ejector outlet with a higher temperature in the entrained flow. As a result, more steam is needed as the latent heat of evaporation for feed seawater decreases. Figure 2b shows the production ratio of the desalination system at different product salinities. A larger production ratio is obtained at a higher product salinity. The benefit of introducing the ERDs for improving system performance is also observed.



(a) (b)

Figure 2: SEC variations (a) and PR variations (b) versus the product salinity at different boiling temperatures and configurations

As is shown in Figure 3, the correlation between system performance and product salinity at different boiling temperatures is similar to the previous findings. The higher purity of product water is obtained at a cost of the lower system performance. At a boiling temperature of 60 °C, there is no obvious effect of the target recovery rate on *SEC* compared to the production ratio.

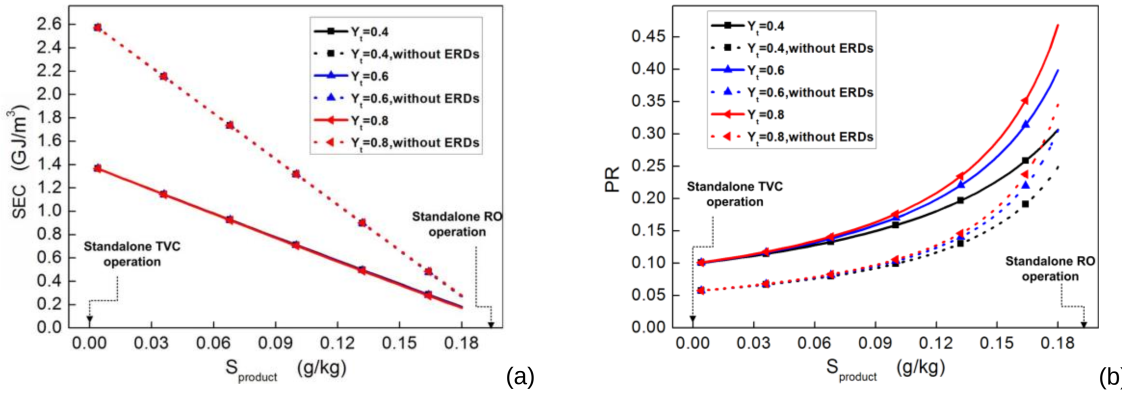


Figure 3: SEC variations (a) and PR variations (b) versus the product salinity at different recovery rates and configurations

Figure 4 reveals the effect of design parameters on the system performance. In Figure 4a, the higher *SEC* values are observed at the high boiling temperatures and low target recovery rates. It is also observed that the production ratio increases with the boiling temperature and target recovery rate in Figure 4b. This can be explained by the fact that, as the increase in the amount of vapour generated in the boiler, more heat is added to the evaporator, and more distillate water is produced. Meanwhile, the increase in the target recovery rate requires a larger driven force to permeate more fluids, which in turn raises the energy consumption of the system. As a thermal process, energy consumption of the system is more sensitive to the design parameters of TVC system. In Figure 4c and Figure 4d, it is observed that the higher system performance is obtained at low compression ratio (discharge pressure/suction pressure) and motive steam pressure. The increase in compression ratio requires more heating steam to compress the entrained vapour. In this case, more additional energy is supplied to the boiler, and the same reason applies at the high motive steam pressure.

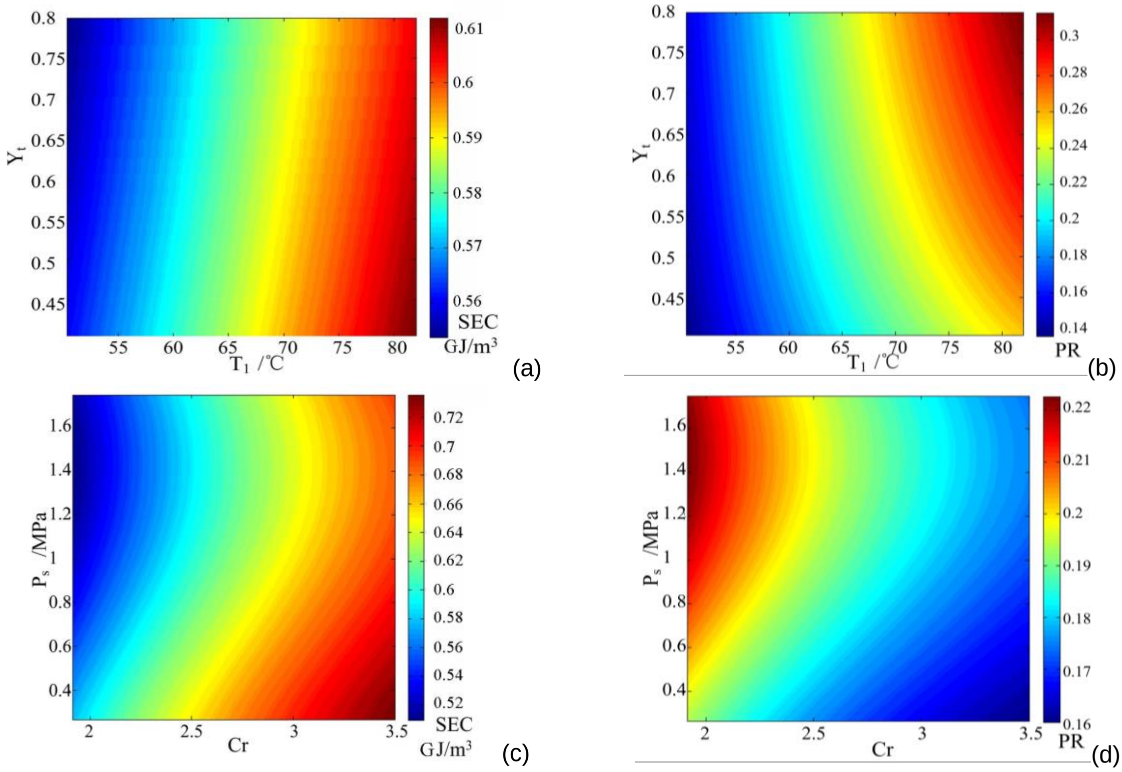


Figure 4: System performance at different recovery rates and boiling temperatures (a-b), and compression ratios and motive steam pressures (c-d)

4. Conclusion

From this study, it can be concluded that an adjustable product salinity is obtained with the coupling of TVC-RO system, and the higher purity of product water leads to the higher specified energy consumption and lower production rate. With the use of energy recovery devices, the system performance can be significantly improved. Moreover, the increase of the target recovery rate of the RO membrane decreases the *SEC* and increases the production rate. In comparison, the system performance is more sensitive to variations of thermal parameters of TVC system. It is shown that both *SEC* and production rate vary proportionally with increase in the boiling temperature, and a better system performance is obtained at low compression ratio and motive steam pressure of the ejector.

Acknowledgments

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