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# Analysis of a hybrid Thermal Vapor Compression and Reverse Osmosis desalination system at variable design conditions

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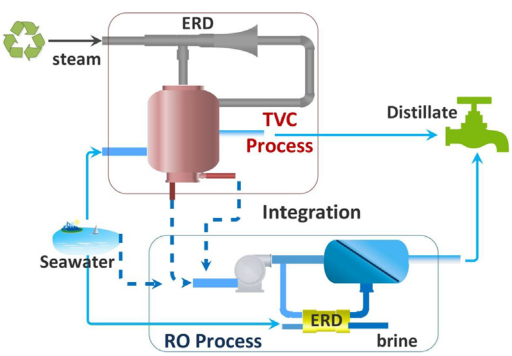
## GRAPHICAL ABSTRACT

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## ABSTRACT

This study proposes different configurations of TVC (Thermal Vapor Compression-Reverse Osmosis (TVC-RO) hybrid systems. The energy-based analysis is used as a quantitative measure to evaluate the system performance by Specific Energy Consumption (SEC) and Production Ratio (PR). The effects of the design parameters including boiling temperature, seawater temperature, compression ratio, motive steam pressure, leakage ratio and mixing rate of the pressure exchanger are obtained through a parametric study. Our results indicate that a better system performance can be achieved by the proposed serial TVC-RO system than the parallel and stand-alone system. A low sea temperature contributes to a better hybrid system performance, and a high boiling temperature results in a high PR. An optimum boiling temperature exists for the lowest SEC when seawater is above 11 °C. For the steam ejector, a low compression ratio helps to improve system performance, and SEC increases consistently while the PR increases first and then decreases with the increasing motive steam pressure. For the pressure exchanger in the RO process, a low mixing rate helps in improving the overall system performance, and a low leakage ratio is also advantageous as it has a more sensible improvement on SEC than on the PR.

## 1. Introduction

Water is not only a basic need for all living beings, but also a key material for various process industries. However, water scarcity is still a serious global challenge that nearly two-thirds of world's population is predicted to live in water-stressed countries by 2025 [1]. In this context, seawater desalination seems to be the most motivating technology for offering nearly unlimited water supply.

Desalination can be typically classified into thermal processes such as the Multi-effect (ME), Multistage flash (MSF) and Vapor Compression

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**Nomenclature**

| | |
|---|---|
| A | heat transfer area ($m^2$) |
| BPE | Boiling Point Elevation (°C) |
| $C_p$ | specific heat (kJ/kg °C) |
| Cr | compression ratio |
| h | specific enthalpy (kJ/kg) |
| m | ERD mixing rate |
| M | mass flow rate (kg/s) |
| L | thickness (m) |
| LMTD | logarithmic mean temperature difference (°C) |
| P | pressure (Pa) |
| PCF | pressure correction factors |
| q | heat energy (W) |
| Q | volumetric flow rate ($m^3$/s) |
| $R_t$ | salt rejection rate |
| Ra | entrainment ratio |
| S | salinity (g/kg) |
| SCF | salinity correction factors |
| TCF | temperature correction factors |
| $T_1$ | boiling temperature (°C) |
| U | overall heat transfer coefficient |
| V | vapor velocity (m/s) |
| $W_{pump}$ | rate of pump work (W/s) |
| $Y_0$ | reference recovery rate |
| $Y_t$ | target recovery rate |

*Subscripts*

| | |
|---|---|
| b | brine |
| bo | boiler |
| c | condenser |
| cw | cooling water |
| d | distillate |
| de | demister |
| e | evaporator |
| E | PX pressure exchanger |
| ev | entrained vapor |
| f | feed water |
| m | heating steam |
| p | permeate |
| s | motive steam |
| sea | intake seawater |
| T | thermal unit |
| tot | total desalted water |
| v | vapor |

*Greek symbols*

| | |
|---|---|
| β | ERD leakage ratio |
| η | efficiency |
| λ | Latent heat (kJ/kg) |
| π | osmotic pressure (Pa) |

(VC), and membrane process such as the Reverse Osmosis (RO) desalination. Since the widely-applied RO process can be thermally enhanced by using low-grade heat to increase flux through the membrane, it is thereby expected that the combination of RO and thermal desalination would lower the electrical energy consumption and achieve a higher water recovery [2]. Compared with stand-alone desalination process, the emerging hybrid desalination allows for, (1) the common pre-treatment and post-treatment facilities with less investment and chemicals, (2) an adjustable product quality in accordance with the salinity demand, (3) a reduction in maintain cost related to the lower boron requirements, (4) wide operating conditions with the possibility using a single stage RO process, (5) a higher flexibility in the production of water against seasonal variation [3].

As desalination is an energy-intensive process, many studies have been conducted to examine system performance for a more efficient water production with less energy cost. Considering the fact that the Thermal Vapor Compression (TVC) is easy to integrate with other thermal processes due to its simple form, El-dessouky and Ettouney [4] developed a mathematical model to analyze an open-loop single effect TVC process. The system performance was investigated in term of parameters that controlling the product cost. Ji et al. [5] presented a new thermodynamic model of the steam ejector, and the effects of intake seawater temperature and the mass flow rate of cooling water on system performance were investigated Apart from the conventional TVC process, Al-Ansari et al. [6] combined the VC with an adsorption heat pump. By this configuration, a higher thermal performance ratio was achieved according to the system performance calculation. Shen et al. [7] proposed a closed-loop mechanical vapor compression (MVC) process using water injected twin screw compressors, the Specific Energy Consumption (SEC) is around 9 kWh/$m^3$, which is comparable to 9.5–15 kWh/$m^3$ in other literature. For the RO membrane process, Al-Hawaj [8] discussed the design aspects of the energy recovery device (ERD) and predicted the SEC of the SWRO process employing such device. Zhu et al. [9–11] investigated the effect of multi-stage configurations, operating strategies and stream mixing on RO energy cost. They concluded that it would be feasible to refine the desalination process by targeting the operating condition. Qi et al. [12] presented a theoretical analysis considering the concentration polarization, and discussed the effects of system design parameters on energy consumption at the thermodynamic limit. In the field of hybrid desalination system, Wan and Chung [13] integrated SWRO process with the pressure retarded osmosis (PRO) process. They found that the optimal operating pressure is of vital importance to minimize the energy consumption of RO-PRO system. Qureshi and Zubair [14] performed an exergetic analysis of different RO-PRO systems, the coupling of pressure exchanger was found to be the best option. For the hybrid thermal-membrane system, Al-Sulaiman et al. [15] investigated a novel HDH-RO system they indicated that the specific exergy destruction could be significantly reduced when a high efficiency TVC was available. Manesh et al. [16] carried out an exergoeconomic optimization for the proposed MED-RO hybrid system, a site unity was integrated to provide the low-grade heating steam to improve RO performance. Similarly, Alzahrani et al. [17] presented a combining MED-TVC and RO system in parallel configuration. The effect of the main parameters of the integrated power plant on water production and exergy destruction rates was investigated. Sadri et al. [18] proposed a parallel-cross MED-RO system, the brine from RO process was recovered by the following MED process, the exergetic efficiencies and gain output ratio were improved by the hybrid system.

In view of the emerging integration of the desalination process, little analytical research has been conducted on the thermal and membrane hybrid system, especially for the capacity-flexible process, like RO and single effect evaporation. Besides, evaluations of the hybrid system are mostly focused on the quality aspect of the energy consumption, termed as exergy. This study includes modeling and performance evaluation of TVC-RO hybrid systems using energy recovery devices. The goal of this study is to identify possible improvements of the proposed hybrid system and to investigate key design parameters that affect system performance. For this purpose, an energy-based analysis was performed to quantitatively evaluate the system performance in terms of SEC and water production ratio (PR). Moreover, a parametric study was carried out to investigate system design parameters including intake temperature, boiling temperature, motive steam pressure, compression ratio of the ejector, and leakage ratio and mixing rate of the energy recovery