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On thermoeconomic analysis of a single-effect mechanical vapor compression desalination system

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ABSTRACT

The current study is focused on thermoeconomic analysis of a single effect mechanical vapor compression (MVC) desalination system operating with and without brine recirculation. For this purpose, first- and second-law analyses are carried out to estimate the energy consumption and second-law efficiency of the plant. A single stage seawater reverse osmosis plant is also presented for the sake of comparison. For thermal systems, a detailed heat exchanger design is provided to calculate an overall heat transfer coefficients, heat transfer areas, and the pressure drops on the cold- and hot-sides of the heat exchangers. Besides, the product cost is calculated and compared by using two different cost estimation methods. Moreover, it is demonstrated that the cost-flow method of economic analysis is more elaborative and useful because it enables the component level cost optimization. The calculations reported the values of specific energy consumption (SEC), second law efficiency and product cost to be 10 to 13 kWh/m^3, 8 to 9% and 1.7 to 2.3 \$/m^3, respectively. Furthermore, it is shown that the input parameters like cost index factor, electricity cost, compressor efficiency and the heat transfer areas have a remarkable influence on the product cost and must be selected carefully for accurate cost estimation.

1. Introduction

About one-fifth of the world's population is living in water scarce areas. The situation will become even worse as it is expected to grow to 9.1 billion in 2050 [1]. To handle this water deficit, a number of desalination technologies are working on local as well as commercial scale in the given proportion [2]: reverse osmosis (RO) ~ 60%, multistage flash (MSF) ~ 26%, multi-effect desalination (MED) with or without vapor compression ~ 8%, electrodialysis (ED) ~ 3% and others ~ 3%.

Mechanical vapor compression (MVC), a thermal-based desalination system is known to be an effective and viable option for production capacities ≤ 5000 m^3/d [3,4]. Various studies have been carried out to analyze and improve its performance since it was commercialized in 1969. Ayber [5] investigated a low-temperature MVC system and reported the SEC to be 11.47 kWh/m^3 for a single tube model. In the meantime, Aly [6] and Bahar et al. [7] analyzed two pilot plants with production capacity of 5 and 1 m^3/d and the compressor work and performance ratio were reported to be ~50 kJ/kg and 2.52, respectively. Lara et al. [8] studied a combined-cycle cogeneration plant operating at a very high temperature to ensure dropwise condensation and pool boiling. They reported the product cost to be 0.4 \$/m^3. Alasfour et al. [9] showed that for an MSF-MVC hybrid desalination system, the temperature drop across the stage decreases the distillate water and increases the SEC as well as exergy destruction. Some other studies [10–13] have also been made to execute entropy generation calculation, first- and second-law analyses and parametric study of the systems.

Shen et al. [14,15] revealed that an injection of < 5% mass fraction of water in a water injected twin-screw compressor substantially reduces its power. They recommended it's use for a product capacity of ≤ 600 (m^3/d). Beyond seawater treatment, the scope of MVC systems has also been reported suitable for waste water treatment in the recent years. The major reasons for adopting this technology include [16–18]: high thermodynamic efficiency, compact equipment, no requirement of an external heat source or condenser, as well as flexible and reliable at low-temperature operation. The specific power consumption and heat transfer areas for such systems turned out to be ranging between 40 to 60 kWh/t and 150 to 200 m^2, respectively.

Beside the above-mentioned efforts, some noticeable attempts have also been made to provide MVC systems operating on renewable energy. For instance, Karameldin et al. [19] proposed a wind driven MVC system wherein they resolved the issue of variable wind speed by introducing an electrical-mechanical system that interconnected the system to a local electrical grid. Optimization of a similar plant driven by wind/PV has also been carried out recently by Zejli et al. [20]. The product cost for this configuration was reported to be 0.7 €/m^3. Some

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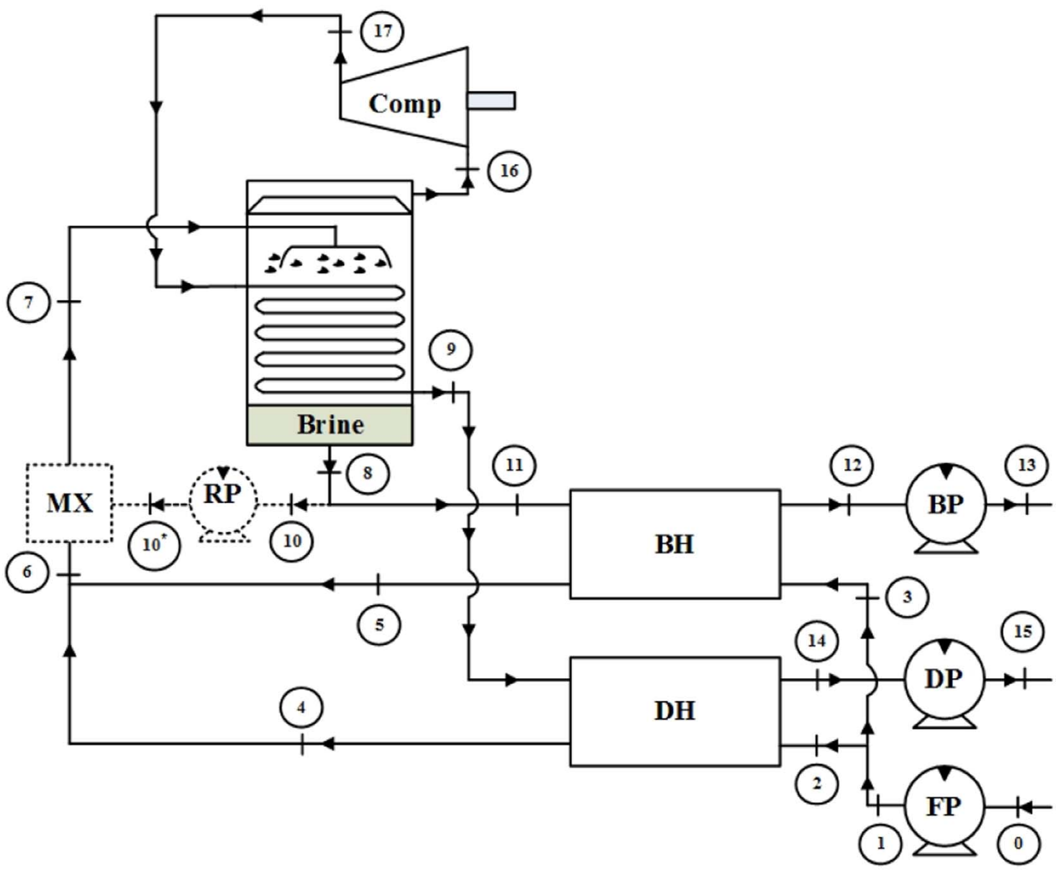

Fig. 1. Schematic of a single-effect MVC system.

other recent studies in this regard include MVC-AD hybrid system analysis [21], a zero-emission system based on MVC model [22], and single vs multiple-effect evaporation with vapor recompression cycle and thermal integration for shale gas flow back water desalination [23].

1.1. Cost analysis

The unit product cost for MVC systems is generally estimated by treating the whole plant as a single unit [24–26] in which the total cost consisting of purchased equipment cost, the chemical cost, operation and maintenance costs is divided by the plant capacity. Meanwhile, another method implementing the economic analysis on a component level to estimate the local product cost of each component also exists. Mabrouk et al. [27,28] followed this pattern and used Visual Design and Simulation (VDS) package to analyze a newly proposed MSF-MVC hybrid system along with some other existing systems as well. About 25% reduction in the product cost was reported for this hybrid system compared to MSF and MVC standalone systems. Nafey et al. [26] used the same VDS package to analyze MVC system with brine recirculation and the product cost was reported to be 2.13 $\$/m^3$.

A review of existing studies suggests that MVC systems hold a clear advantage for water treatment especially when dealing with harsh feeds and remote locations. Keeping in view the demand for these systems, the current study is focused to add value to the existing studies by providing (a) a detailed design and analysis of evaporator as well as preheaters used in MVC systems, (b) component based exergy analysis using updated seawater properties [29] (c) second-law efficiency calculations based on appropriate definition, recently suggested for desalting systems, (d) cost flow model for thermoeconomic analysis of the plant on a component level, (e) study of output parameters as a function of important plant inputs such as compressor efficiency, pump efficiency, unit electricity cost, and cost index factor.

2. System description and assumptions

The system considered in the current analysis consists of a single effect-evaporation mechanical vapor compression (SEE-MVC) desalination plant with a production capacity of 13 kg/s (1128 m^3/d) as shown in Fig. 1. The plant is studied in two configurations including once through system and with brine recirculation. For comparison, a seawater reverse osmosis plant (SWRO) operating under same capacity is also analyzed and presented. Various energy-recovery techniques are applied to optimize the performance and the results are discussed. The schematic diagram for SWRO plant is shown in Fig. 2.

The current analysis is based on following assumptions [4,30,31]: (a) system operates under steady-state conditions, (b) energy losses in pumps, pipelines and heat leaks in heat exchangers are negligible, (c) the product water salinity ranges between 0.001 and 0.005 g/kg and is neglected in material balance because of very high feed and brine salinities i.e. 40 and 80 g/kg, respectively, (d) outlet temperature of the feed stream from both preheaters is same, (e) the dead state is taken as the intake, i.e. P_0 = 101.325 kPa, T_0 = 21 °C, S_0 = 40 g/kg, (f) thermo-physical properties of vapors are a function of temperature and pressure, while that of seawater are function of temperature and salinity. These properties are calculated based on the correlations provided by Sharqawy et al. [29], (g) the effect of boiling point elevation (BPE) is considered in the analysis, (h) major portion of heat transfer in the evaporator takes place by phase change (latent heat) so the driving force for heat transfer is taken as distillate condensation and feed evaporation temperatures, (i) demister runs along the entire length of the evaporator, (j) efficiencies of various components are, η_{Pump} = 78%, η_{Motor} = 92%, $\eta_{Compressor}$ = 80%.

A Numerical code written in Engineering Equation Solver (EES) is used to solve the set of equations for each component. The properties of seawater and distillate are needed at each step of numerical