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Effect of feed flow arrangement and number of evaporators on the performance of multi-effect mechanical vapor compression desalination systems

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ABSTRACT

The current study provides a detailed analysis of multi-effect mechanical vapor compression desalination systems. Three different feed flow arrangements including forward-feed (FF), parallel-feed (PF) and parallel-crossfeed (PCF) are analyzed and compared in terms of energy consumption, exergy destruction, heat transfer area and product cost. For this purpose, energy, exergy, and economic models are simultaneously solved numerically. In this regard, a component-based exergo-economic model is used to calculate the fresh water cost. It is observed that FF has the highest energy consumption followed by PF and PCF. While, the heat transfer area is calculated to be the highest for PCF followed by PF and FF, respectively. Finally, the product cost is estimated to be 0.867 for FF, 0.865 for PCF, and 0.842 \$/m^3 for PF MVC systems operating with 4 evaporators.

1. Introduction

Evaporation-based multi-effect desalination (MED) systems are best suited (compared to the membrane-based systems) while treating high temperature and salinity feeds [1]. These systems exist in various configurations including stand-alone MEDs [2], dual purpose or co-generation plants [3], integrated systems [4], and hybrid units [5,6]. Multi-effect desalination system integrated with mechanical vapor compressor (MVC) is reported to be an attractive option especially for small and intermediate capacities [7,8]. The specific power for conventional MVC units is estimated to be ranging between 10 to 18 kWh/m^3 [9–11].

Various efforts have been made to improve the performance of conventional MVC systems. Alasfour and Abdulrahim [12] presented an MSF-MVC hybrid desalination model and showed that a reduction in the stage temperature cuts the distillate water flow rate and increases the specific energy consumption (SEC) and exergy destruction. Meanwhile, Karameldin and Mekhemar [13] and Zejli et al. [14] optimized wind/PV driven MVC systems and calculated the product cost to be 0.7 €/m^3. Askalany [15] proposed a mechanical vapor compression adsorption (MVC-AD) desalination system consisting of an evaporator, two adsorption beds (working in different phases), compressor, condenser and desalinated water collecting tank. He showed that the hybrid system has higher coefficient of performance and product flow rate compared to simple adsorption systems. Meanwhile, Han et al. [16] proposed a zero-emission based MVC desalination system and showed that the compression work for such systems can be reduced up to 15% by increasing the number of effects. Likewise, Onishi et al. [17] developed and optimized an MVC system for shale gas flow back water desalination. They estimated the fresh water cost to be 6.70 \$/m^3 for a recovery ratio of 77% when the brine approaches a condition of zero liquid discharge. Gude [18] reviewed and highlighted the energy storage opportunities for the desalination technologies that require uninterrupted energy supply like MED and MVC systems. Different technologies were compared in terms of design, sizing, environmental impacts and cost. Sharaf et al. [19] analyzed solar assisted parallel-cross-feed MED systems with thermal and mechanical vapor compressors using Solar Desalination Systems (SDS) software. They revealed that PCF MVC when operated within 2 to 4 effects, shows promising results; however, it is not competitive at higher effects.

Beside seawater, the MVC systems have also been reported an attractive option for high salinity (produced water/hypersaline) feeds. Chung et al. [20] analyzed single as well as two effect MVC system for brine management under zero liquid discharge desalination. The Second-Law efficiency for single- and two-effect systems was reported to be 8.5% and 11.6%, respectively. Likewise, Thiel et al. [21] revealed that for a fixed brine salinity, the MVC systems show only a small increase in energy consumption with an increasing feed salinity. While

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the efficiency of these systems increases with increasing feed salinity, thus making them favorable for high salinity feeds. Recently, Jamil and Zubair [22] reported the SEC, Second-Law efficiency and product cost for a single-stage MVC system with and without bine recirculation. In another study [23], they provided a detailed exergoeconomic model for a forward-feed MVC system and showed that addition of multiple evaporators improves the performance of MVC systems, both thermally as well as economically.

From the literature, it is observed that most of the studies are dedicated to analyze and improve the performance of a fixed plant layout (forward-feed). While Darwish and Abdulrahim [24] showed that flow sheet arrangement has a considerable effect on the performance of MED systems and must be selected carefully. Keeping in view the importance of feed-flow arrangement, the current study is focused to: (a) provide a complete numerical model for the analysis of MVC systems operating under three different feed-flow arrangement, (b) compare the performance of MVC systems under forward-feed, parallel-feed, and parallel-cross-feed arrangements from First-and-Second-Law analysis viewpoint, (c) provide a detailed design data for the evaporators and preheaters used in these systems, (d) provide a component-based exergoeconomic analysis highlighting the exergetic as well as monetary cost of various streams in the system for all feed-flow arrangements, and (e) study of output parameters as a function of important plant inputs such as number of evaporators, compressor efficiency, pump efficiency, electricity cost and cost index factor for all the feed-flow arrangements.

2. System description and assumptions

A multi-effect MVC system with a product flow rate of 35 kg/s is analyzed in the current study. Three different feed flow arrangements including forward, parallel, and parallel-cross are compared from thermodynamic and economic viewpoint [25].

In thermal desalination systems, steam is used to separate freshwater from the feed. For example, in multi-effect desalination, the steam is taken from the external source (boiler/steam generator). However, in MVC systems, a compressor is used to compress the produced vapor which is used in the cycle. The plant operates with a seawater intake having total dissolved salts (TDS) of 35 g/kg (primarily sodium and chloride ions along with small amounts of sulfate, bicarbonate, and iron [26]), is supplied to the two preheaters to raise its temperature by taking heat from the brine and distillate streams. The feed from preheaters is then sprayed on the evaporator tubes where it evaporates partially and the remaining leaves as brine. The vapor produced is directed to the compressor in case of single effect systems and to the next effects in multi-effect systems. The feed and brine in each evaporator flow differently depending on the feed-flow arrangement, as described in the following subsections:

2.1. Forward-feed (FF)

In this case, the feed water is sprayed in the first evaporator, while brine from the evaporator serves as a feed for the next effect. In this configuration, feed undergoes sensible heating before evaporation in the first effect, only. In the subsequent effects, the feed is sprayed as a saturated liquid and evaporates immediately. Finally, brine from N^{th} effect exchanges its heat with the intake seawater in the preheaters, as shown in Fig. 1(a).

2.2. Parallel-feed (PF)

In this arrangement, the feed water is evenly distributed among all evaporators at an identical feed temperature T_F. The sprayed water is sensibly heated before evaporation in each effect and the brine is directed to the brine preheater as, demonstrated in Fig. 1(b).

2.3. Parallel-cross-feed (PCF)

This feed-flow arrangement is a combination of PF and FF, as shown in Fig. 1(c). Feed water is equally distributed in all evaporators and the brine from each effect is directed to the next effect which causes flashing, thus producing additional vapor. Like FF, brine from the last effect enters the brine preheater at a temperature equal to its evaporation temperature.

In all three configurations stated above, the vapor produced in an effect is used to evaporate feed water in the next effect and so on. Finally, vapor from the last effect is compressed and directed to the first evaporator and the process continues.

The current study is based on the following assumptions [6,8,27]: (a) steady flow process, (b) insignificant energy losses in pumps, pipelines, and heat exchangers, (c) negligible product water salinity i.e. ≤ 0.005 g/kg, (d) feed stream leaves both preheaters at the same temperature, (e) the reference (dead) state is taken as, i.e., $P_0 = 101.325$ kPa, $T_0 = 21$ °C, $S_0 = 40$ g/kg, (f) heat transfer in evaporators is governed by phase change (latent heat), (g) efficiencies of the various components are, $\eta_{Pump} = 78\%$, $\eta_{Motor} = 92\%$, $\eta_{Compressor} = 70\%$, $\eta_{gen} = 95\%$ and $\eta_{TB} = 85\%$, (h) in case of FF, heat transfer per unit area is uniform in all evaporators, and in PF and PCF, an equal temperature drop is considered among the evaporators.

The governing equations for energy, exergy, and cost analysis are simultaneously solved using Engineering Equation Solver (EES). For the solution of the economic model, Gauss-Seidel method is used because of nonlinearity of the problem.

3. Methodology

3.1. Thermodynamic analyses

These are carried out to assess the plant performance from energy and exergy viewpoint. For this purpose, energy consumption and exergy destruction in each component are calculated. Finally, SEC and Second-Law efficiency are estimated to compare the plant performance operating under different conditions. The mathematical model for this analysis of MVC systems is provided in Appendix A, while additional details are given by Jamil [25].

3.2. Heat exchanger analysis

The heat exchangers (HXs) are of critical importance because of their significant effect on the plant capacity, performance as well as investment cost. The HXs used in MEE-MVC systems include two preheaters and multiple evaporators. The formulations used in the heat exchanger design are provided in detail by the authors [22,23].

3.3. Exergoeconomic model

The current study presents an exergoeconomic model to estimate the product water cost by solving exergy-and-cost equations for each component, simultaneously. It works on the cost-flow method which estimates the local stream cost while it enters and leaves different components of the system. Further details regarding this analysis are given in the following section.

3.4. Purchased equipment cost

First, the purchased equipment cost Z ($) is calculated which reflects the fixed cost of the component. The correlations used are listed in Table 1.

3.5. Rate of fixed cost

In the next step, the purchased equipment cost is converted to the annual rate of fixed cost Z_{Annual} (in $/yr) by multiplying with the capital recovery factor (CRF) as given below [28]: