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Exergo-economic analysis of a seawater reverse osmosis desalination plant with various retrofit options

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HIGHLIGHTS

- Seawater reverse osmosis desalination plant with four different retrofit options is studied.
- First- and second-law analyses are carried out to estimate energy requirements and second-law efficiency.
- The product cost is compared by performing exergo-economic analysis using reliable seawater properties.
- Analysis revealed that with a pressure exchanger, energy consumption can be reduced by 24%.
- It is also shown that post-treatment and distribution sections increase the product cost by about 20%.

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ABSTRACT

The current study is focused on carrying out exergo-economic analysis of a seawater reverse osmosis (SWRO) desalination plant. The main objective is to compare the performance as well as the product cost of an existing SWRO plant, including post-treatment and distribution sections, for four different retrofit options made by coupling high-efficiency pressure exchangers (PXs) in place of conventional energy recovery turbines. For this purpose, first- and second-law analysis is carried out to estimate the energy requirements and second-law efficiency for each retrofit option. Finally, the product cost is compared by performing an exergo-economic analysis using appropriate seawater properties for the calculations. The analysis revealed that, by introducing a PX, the specific energy consumption (SEC) can be reduced by about 24%; thus, increasing the second-law efficiency. Besides this, it is also demonstrated that the addition of post-treatment and distribution sections enhances the product cost by almost 20%. Furthermore, the study suggested that using a booster pump with a PX (as used in retrofit # 3) is best suited for enhancing the plant capacity compared to retrofit # 4 in which a PX is used in place of the pump. It has the least product water cost among all the options discussed.

1. Introduction

Reverse osmosis (RO), a membrane-based desalination system is one of the most frequently used techniques for treatment of seawater. From 1970 till today, this technology has been widely used, studied and improved over the time [1]. It has lower start-up time, decreased environmental impacts (in terms of emissions) and easier operation and maintenance. Energy analysis of RO systems operating under different capacities with and without energy recovery devices (ERDs) reveals that their energy consumption can be greatly reduced by coupling ERDs [2–6]. Coupling of Pelton turbines (as energy recovery turbines "ERTs") with RO systems is one of the oldest energy recovery methods [7,8]. Isobaric pressure exchangers (PXs) are relatively modern and better devices in this regard [9]. A detailed discussion of the working and selection of ERDs is carried out by various investigators [10–15].

Besides this, exergy analysis has been used as one of the most important tools by researchers [16,17] frequently to identify the components with the greatest exergy destruction. Cerci [18] and Aljundi [19] analyzed two different RO plants using actual plant data and reported the throttling valves and membrane modules to be the primary locations for exergy destruction. Romero et al. [20] carried out a similar study for a complete plant including pre-treatment, post-treatment and distribution sections. The above studies proposed that the second-law efficiency of the plants can be improved by installing pump-motors equipped with variable frequency drives and replacing throttle valves on the brine stream with a PX.

Another useful way of analyzing the desalting systems is to combine the exergy and cost analysis known as exergo-economic analysis. Lozano and Valero [21] presented the theory of exergetic costs which is considered to be one of the major approaches in this field. Based on

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this theory, Romero et al. [22] carried out an exergo-economic analysis of an RO plant and reported the product cost to be 0.70 €/m^3. El-Emam and Dincer [23] performed a similar analysis for different seawater salinities and estimated the product cost to be 2.45 \$/m^3 for a salinity of 35 g/kg. Spiegler and El-Sayed [24,25] contributed significantly to the field of thermo-economics by developing the correlations for the rate of fixed cost of various components of desalination systems. They suggested that the main focus should be on the exergy destruction which constitutes mainly the operating resources of any desalination system rather than the making resources (fixed cost). Some studies [26–28] were focused on analyzing solar-powered desalination systems. The unit product cost for a small-scale solar-powered membrane distillation unit was reported to be 15 \$/m^3 by [26] which is much higher than conventional systems. However, the unit product cost for a large scale PV/RO system was estimated as 1.3 \$/m^3 by [27], which is slightly higher than conventional systems (0.75 \$/m^3) due to higher electricity cost. Penate and Rodriguez [29] proposed and analyzed four different retrofit options to provide upgradation opportunities for existing SWRO plants working with conventional ERTs. The results of energy, exergy and thermo-economic analysis for all the retrofit options were compared to identify the best one with a minimum product cost.

1.1. On exergy calculation model

Fitzsimons et al. [30] examined and compared six different exergy calculation models and showed that these models affect the final results significantly. The study suggested that, among these, the electrolyte model approach is not suitable because seawater is not an ideal mixture. Similarly, the approaches used by Cerci [18] and Drioli et al. [31–33] are not suitable for desalination system analysis because of ideal mixture assumptions and specific separation assumptions, respectively. Sharqawy et al. [34] functions and Pitzer et al. [35,36] equations can be used to calculate thermodynamic properties of seawater and other electrolytes, respectively. A similar issue regarding the definition of second-law efficiency is highlighted by various authors [17,37–39] in their studies. Some of them [14,40] define it as the ratio of the total exergy leaving to the total exergy entering the system, while others [16,17] as the ratio of product to fuel exergies. Qureshi and Zubair [41] discussed the applicability of these definitions and suggested that the second one is more appropriate for desalination systems.

Based on the above discussion, the current study is focused on reassessing and improving the work of Penate and Rodriguez [29] by considering the following: (a) post-treatment and distribution sections in the current analysis, (b) use of reliable and updated seawater properties recently compiled by Sharqawy et al. [34], (c) an appropriate definition of the second-law efficiency suggested by Qureshi and Zubair [41], and (d) plant performance as a function of important input parameters such as unit electricity cost, feed salinity and high-pressure pump (HPP) efficiency.

2. System description and modeling

The system under consideration consists of a 10,000 m^3/d seawater reverse osmosis (SWRO) plant equipped with two membrane modules of the same capacity coupled with two identical ERTs. The schematic for this configuration is shown in Fig. 1, in which one HPP per train is used to raise the feed pressure. The system is analyzed under four different possible retrofit options, calculations for each retrofit option are performed and the results are compared with the standard configuration. In the first two retrofit options, the plant capacity remains the same while the focus is to minimize the energy consumption by replacing ERTs with a PX. The last two options are proposed to increase the plant capacity as well as minimize the energy consumption. The data used for analysis of the plant is listed in Table 1. The analysis presented in the paper is based on the following assumptions that are also considered by [29,41]: (a) the dead state is taken as the conditions of the feed, i.e., $P_0 = 101.325$ kPa, $T_0 = 20$ °C, $S_0 = 35$ g/kg and operating temperature is considered constant throughout the system, (b) an overall pressure drop in RO modules, pipes and valves is considered to be 160 kPa, (c) feed water pressure at HPP inlet is taken as 351.325 kPa and the recovery ratio is 45%, (d) effect of permeate back pressure, reverse salt diffusion, concentration polarization and system leakages are considered negligible, (e) thermo-physical properties of seawater are based on the correlations provided by Sharqawy et al. [34], and (f) efficiencies of the various components are, $\eta_{HPP}=78\%$, $\eta_{BP}=77\%$, $\eta_{FP}=78\%$, $\eta_{DP}=78\%$, $\eta_{Motor}=92\%$, $\eta_{PX}=90\%$ [29].

For numerical simulation, engineering equation solver (EES) software is used with updated seawater properties compiled by Sharqawy et al. [34].

2.1. First-law analysis

To carry out the first-law analysis, the mass balance (Eq. (1)) and the solution balance (Eq. (2)) are applied. For a steady-state system, these can be expressed as,

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \tag{1}$$

$$\sum_{in} \dot{m}S = \sum_{out} \dot{m}S \tag{2}$$

Pump and turbine work is calculated using Eq. (3) and Eq. (4), respectively as,

$$\dot{W}_{Pump} = \frac{\dot{Q}\Delta P}{\eta_{Pump}} \tag{3}$$

$$\dot{W}_{TB} = \eta_{TB}\,\dot{Q}\Delta P \tag{4}$$

The PX efficiency is described as [41,42]:

$$\eta_{PX} = \frac{\dot{Q}_{B,o}P_{B,o} + \dot{Q}_{F,o}P_{F,o}}{\dot{Q}_{B,i}P_{B,i} + \dot{Q}_{F,i}P_{F,i}} \tag{5}$$

Specific energy consumption (SEC) is one of the important parameters for comparing plants working under different capacities because it compares the energy requirement for a unit product. It can be expressed as [41]:

$$SEC = \frac{\dot{W}_{in}}{3600\sum_{out} \dot{Q}_p} \tag{6}$$

2.2. Second-law analysis

This analysis measures the extent of irreversibility in terms of exergy destruction, which is calculated by applying exergy-balance on each component, separately:

$$\sum_{fuel} \dot{X} - \sum_{products} \dot{X} = \dot{X}_D + \dot{X}_L \tag{7}$$

The second law efficiency is calculated, as described in [17,41]:

$$\eta_{II} = \frac{\dot{W}_{l,min}}{\dot{W}_{in}} \tag{8}$$

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