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Exergetic efficiency of NF, RO and EDR desalination plants

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HIGHLIGHTS

- Exergetic analysis of a commercial-scale brackish water desalination plant is investigated.
- The plant contains nanofiltration, reverse osmosis and electrodialysis reversal units subject to the same source water.
- The correct definition of exergetic efficiency for such systems was discussed.
- It is shown that the calculated second-law efficiencies are very low.
- It is demonstrated that the highest efficiency occurred through use of a pressure exchanger.
- The pressure retarded osmosis option investigated had efficiencies approximately equal to the hydro-turbine.

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ABSTRACT

Exergetic analysis of a 2250 gpm brackish water desalination plant in California was performed using its operational data. The plant contains nanofiltration, reverse osmosis and electrodialysis reversal units subject to the same source water. The correct definition of exergetic efficiency for such systems was discussed. The effect of feed salinity was also used for further illustrating the difference in the second-law efficiency definitions. The preferred definition can be used to determine the specific energy consumption and makes thermodynamic sense. The nanofiltration, reverse osmosis and electrodialysis reversal units had efficiencies of 0.087%, 0.066% and 0.078%, respectively, which are very low. Various energy recovery devices including a pressure retarded osmosis unit (having infinite area) were applied to the system to see relative increase in second-law efficiency. For the preferred definition, it was seen that the nanofiltration unit had the best efficiency. In terms of alternative designs using energy recovery devices, the pressure retarded osmosis option had efficiencies approximately equal to the hydro-turbine while the highest efficiency occurred through the use of a pressure exchanger at the plant inlet salinity. Therefore, it does not seem to be a practical energy recovery method for the investigated desalination systems.

1. Introduction

Approximately 20% of the world's population lacks drinking water. About 25% may be living in water scarce areas by 2020 [1]. With the current world population above 7 billion and expected to reach 9 billion before 2050 [2], the need for potable water is expected to rise significantly. Desalination has been providing drinking water for decades and is used in 150 countries worldwide [3]. Desalination technologies include multi-stage flash distillation (MSF), nanofiltration (NF), reverse osmosis (RO), electrodialysis (EDR), multiple-effect distillation (MED) and vapor compression (VC). From these, reverse osmosis, which is a commercialized membrane-based process [4], represents 60% of total installed capacity [5]. For membrane-based technologies, the energy requirement of these systems can be lowered by combining it with other systems [6–12], producing enhanced membranes [13–15], using more efficient pumps and/or incorporating new or improved energy recovery methods [16–19]. Commercialized energy recovery devices include the Pelton turbine, turbocharger and pressure exchanger wherein the Pelton turbine is probably used the most [20].

Both the first-law (energy) as well as second-law basis (exergy) can be used to evaluate desalination plants with existing or new energy recovery devices. First law analysis focuses on the quantity of energy spent. In desalination systems, the specific energy consumption (SEC), which is the power consumed per cubic meter of fresh water produced, may be taken as a quantitative measure of the energy consumed. Second law analysis focuses on the quality aspect of the energy consumed (i.e. exergy). The reversible work that be done by a system is characterized by its exergy with respect to a dead state or the environment. Exergy analysis not only highlights component irreversibilities

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but also assesses the efficiency of the overall system. Fitzsimons et al. [21] reviewed six exergy model approaches with focus on the chemical exergy term. They showed that the choice of exergy model can have a significant effect on the results, which coincides with the conclusions of Sharqawy et al. [16,22]. Also, they mentioned some concerns regarding three of the models such as that used by Cerci [23,24]. Second-law (exergetic) efficiency is found in the literature to be often defined in two ways. The first method says that it is the ratio of total exergy leaving divided by total exergy entering the system. The second is defined as the ratio of the product to fuel exergies [25,26]. For example, Kahraman et al. [27] and Sharqawy et al. [16] applied the first definition while Demirel [28] and Mistry et al. [29] used the second method. Section 2.2 focuses on resolving this issue. Other definitions such as the rational efficiency have been mentioned in the context of thermal plants by Kotas [30] and compared to the above and other efficiency definitions by Cornelissen [31] and Fitzsimons [32].

Many researchers have performed exergy analyses of membrane-based desalination plants and identified the sources of irreversibility in them. For example, Kahraman et al. [27] performed exergy analysis of a two-stage RO, NF and EDR desalination plant located in California with brackish water feed and no ERD. The second-law efficiencies were found to be 8%, 9.7% and 6.3% with the largest amount of exergy destruction occurring in the RO modules (36.2%–48.6%) and pumps (23.6%–54.1%). Second-law analysis of a two-stage RO desalination plant with brackish water feed was performed by Aljundi [33]. With no energy recovery device, the exergetic efficiency was found to be 4.1%. Exergy destruction in the four throttle valves was about 57% and approximately 21% in the RO modules. A two-stage industrial RO unit was analyzed by Gasmi et al. [34] and it was found that approximately 55% of the exergy destruction came from the pumps while the RO modules constituted 37%. Using seawater as feed, Blanco-Marigorta et al. [35] performed second-law analysis of a two-stage RO desalination plant. The exergetic efficiencies were determined to be 26.8%, 28.4% and 32.8% when the ERD used was a pressure exchanger, a Pelton turbine and a Dual Work Exchange Energy Recovery system, respectively. The RO modules and the high-pressure pump were reported as the main sources of irreversibility. Liu et al. [36] did exergy analysis of a dual-stage nanofiltration seawater desalination unit. The exergetic efficiency was found for three scenarios: i) no ERD (38.88%), ii) with ERD (51.82%), and iii) with ERD and blending (46.11%). The membrane modules and throttle valves were locations of the largest exergy destruction. Exergy analyses of single-stage systems indicated similar results [16–18,24,37,38]. Also, it should be noted that these diverse exergetic efficiency values are due to differences in some or all of the following factors: feedwater salinity, flow rate, pump efficiency, choice of energy recovery device, efficiency definition and exergy destruction in the throttle valves.

In this paper, the modeling of the energy recovery devices is done in Section 2 along with selection of the appropriate definition of the second-law efficiency for membrane-based desalination plants. Then its link to the specific energy consumption is established. In Section 3, the second-law efficiency and specific energy consumption for a case study dealing with (two-stage) reverse osmosis, (two-stage) nanofiltration and electrodialysis desalination plants are determined. Then various energy recovery devices are applied to the original systems including pressure retarded osmosis for comparative analysis.

2. Modeling

The assumptions made are as follows:

- In the ERDs, pressure drops in the lines are not considered.
- Fluid in the ERD is considered at a constant environmental temperature of 15 °C.
- Seawater properties are determined from the correlations given by Sharqawy et al. [39].
- The efficiency of the turbocharger is taken as 70% [20] while it is assumed to be 85% for the turbines [20,40].
- Leakage is assumed to be zero in the pressure exchanger while its efficiency is taken as 96% [41] unless otherwise indicated.
- The properties of the PRO intake are the same as that at the main feed pump i.e. $T_0 = 15\,°C, P_0 = 101.325\ \ kPa, S_0 = 0.9\ \ g/kg$(dead state).
- Effect of reverse salt diffusion and concentration polarization are ignored in the PRO.
- For the PRO modules, an infinite area (unit effectiveness) is assumed.

2.1. First-law analysis

For the purpose of understanding the two definitions of the exergetic efficiency discussed in Section 2.2, modeling of the above systems involve applying mass and solution balances (Eqs. (1) and (2), respectively, below) on the RO and PRO module as well as between any two consecutive states.

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

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

The electrical input to the pumps is related to the ideal pumping power by its isentropic efficiency while the turbine power produced is found by multiplying its isentropic efficiency with the ideal turbine power.

$$\dot{W}_{pp} = \frac{\dot{W}_{is,pp}}{\eta_{is,pp}} \tag{3a}$$

$$\dot{W}_t = \eta_{is,t}\dot{W}_{is,t} \tag{3b}$$

As in the turbine, power extracted from the turbocharger is found by using its efficiency in Eq. (3b).

The efficiency of the pressure exchanger is defined as [42]:

$$\eta_{px} = \frac{\sum_{out}\left(\dot{V}P\right)}{\sum_{in}\left(\dot{V}P\right)} = \frac{\dot{V}_{B,o}P_{B,o} + \dot{V}_{f,o}P_{f,o}}{\dot{V}_{B,i}P_{B,i} + \dot{V}_{f,i}P_{f,i}} \tag{4}$$

In the PRO unit working as an ERD, the mixing (or mass) ratio (MR) is defined as the ratio of the mass flow rates of the draw solution to the incoming feed water [43].

$$MR = \frac{\dot{m}_{d,i}}{\dot{m}_{f,i}} \tag{5}$$

For the PRO unit, the maximum recovery ratio (see Eq. (6) below) is used at the chosen mass ratio. The model developed by Sharqawy et al. [43] is used to find this maximum for an optimized hydraulic pressure difference calculated using a program written in EES [44].

$$R_{PRO} = \frac{\dot{m}_p}{\dot{m}_{f,i}} \tag{6}$$

Lastly, the specific energy consumption of the desalination unit is calculated by dividing the net power requirement by the permeate flow rate.

$$SEC = \frac{\dot{W}_{in}}{3600\dot{V}_p} \tag{7}$$

This concludes mentioning of the key equations required for system modeling.