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Energy-exergy analysis of seawater reverse osmosis plants

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HIGHLIGHTS

- Energy-exergy analysis of reverse osmosis units is done for seawater applications.
- Various energy recovery devices including pressure retarded osmosis are evaluated.
- Effect of salinity, pump and turbine efficiencies as well as mass ratio are studied.
- Van't Hoff constants for a range of seawater temperatures are also determined.
- It is demonstrated that the pressure exchanger is the best energy recovery device.

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ABSTRACT

In this paper, a seawater reverse osmosis desalination plant with various energy recovery systems is studied using exergy analysis. These energy recovery devices include turbines and pressure exchangers as well as infinite area based single and two-stage pressure retarded osmosis units. The appropriate exergetic efficiency definition for such systems is mentioned. The effect of pump and turbine efficiency, salinity, temperature and mass ratio is studied using a validated program. In this regard, modified Van't Hoff constants for a large range of seawater surface temperatures are also determined. The best efficiency was obtained using the pressure exchanger for all systems investigated. Use of pressure retarded osmosis units as energy recovery devices provided efficiencies nearly equal to or less than the hydro-turbine. Thus, for the range investigated, it does not seem to be a viable energy recovery method for reverse osmosis units with seawater feed since constraints such as concentration polarization and finite area would further decrease performance.

1. Introduction

Living without drinking water or in areas where it is difficult to obtain is a reality that many people face [1]. Technology can help to improve this situation. One such technology is reverse osmosis, which is a process that uses membranes to separate salt from seawater [2]. Typically, it uses pressure vessels (in parallel) housing these membranes that are often spirally wound. 35–50% of (potable) water can be recovered from seawater fed into the desalination plant [2,3]. Other important parts of the plant typically consist of pre-treatment, energy recovery system, pumps and post-treatment system.

The running of these desalination plants incurs a cost due to the energy they consume. There are many ways to reduce this such as: i) coupling the plant with other systems [4–10], ii) developing superior membranes [11–13], iii) using higher efficiency pumps, and iv) employing new or improved energy recovery technologies [14–17]. Commercially used energy recovery devices (ERD) comprise the Pelton turbine, turbocharger and pressure exchanger. It should be noted that the Pelton turbine is probably the most used ERD. Details regarding the working of these devices may be obtained from [18].

Performance of seawater reverse osmosis (SWRO) plants can be assessed using the first and second laws of thermodynamics. Use of the first-law requires quantifying the energy needed to run the plant. The performance metric used, in this case, is the specific energy consumption (SEC), which is determined by dividing the (fluid or electrical) power consumed by the volumetric flow of potable water recovered in cubic meters per hour. Due to SEC having a relation to electrical power consumption, it is also an economic indicator. Now, use of the second-law entails concentrating on the quality of energy consumed by the plant. This is done by using the concept of availability, which is also called exergy. The concept of exergy can be used to measure the ability of a system (or process) to perform reversibly based on a chosen reference state, called the dead state. The performance metric used, in this case, is the exergetic

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or second-law efficiency. A correctly defined efficiency varies between 0 and 1 where the former represents a completely irreversible process/system and the latter a completely reversible process/system. In desalination systems, two definitions are commonly encountered in the literature. One uses a total exergy out over total exergy in ratio while the second uses a product-to-fuel ratio [19,20]. Some researchers have used the first method such as Kahraman et al. [21], Eshoul et al. [22] and Sharqawy et al. [14] while others have advocated the second method [23–26]. Further discussion of this issue is given in Section 2.

Exergetic analysis of some SWRO plants can be found in the literature that points out the common sources of irreversibility. For example, exergy analysis of a single-stage reverse osmosis plant using a turbine as an ERD was performed by Romero-Ternero et al. [27]. The exergetic efficiency was calculated as 48.5% while the locations for the highest exergy destruction were the RO modules (~35%) and the turbine (~24%). Exergy analysis of a two-stage reverse osmosis plant was performed by Blanco-Marigorta et al. [28] using three energy recovery devices. The exergetic efficiencies were calculated as 26.8%, 28.4% and 32.8% when the energy recovery device was a pressure exchanger, a turbine and a Dual Work Exchange Energy Recovery (DWEER) system, respectively. The locations for the highest exergy destruction were the RO modules and the high-pressure pump. Besides these, exergetic analysis of desalination plants using brackish water feed has also been performed. These include the investigation by Cerci [29] and Sharqawy et al. [14–16] of a single-stage RO plant and those by Kahraman et al. [21], Aljundi [30] and Gasmi et al. [31] of two-stage RO plants. The sources of high exergy destruction reported in these studies are similar to those of seawater RO plants. Other works such as [32] may be consulted for further information on desalting brackish water.

The objective of this work is to evaluate the feasibility of different PRO-based ERD for seawater feed by comparing with well-known ERD using an exergetic efficiency that makes thermodynamic and economic sense coupled with accurate seawater properties. For this purpose, Section 2 has all configurations described and modeled as well as the selection of the exergetic efficiency formula. Accurate seawater properties will be used to compare the different PRO-based ERD to commercial ERD for SWRO desalination plants in Section 3. Finally, Section 4 contains the conclusions.

2. Description of systems and models

A SWRO desalination plant is studied using several energy recovery devices (ERD). Fig. 1(a)–(b) shows the common ERD while Fig. 2(a)–(b) are schematics of ERD using pressure retarded osmosis units. It should be noted that the configurations in Fig. 2(a)–(b) were not found in the literature for SWRO by the authors. These devices include: i) throttling valve (TV), ii) turbocharger (TC), iii) hydroturbine (T), iv) pressure exchanger (PX), v) pressure retarded osmosis unit coupled with hydroturbines (PRO-T), vi) pressure retarded osmosis unit coupled with a hydroturbine and pressure exchanger (PRO-PX), and vii) two-stage pressure retarded osmosis (2S-PRO-T). The first system in Fig. 1(a) represents the base case with no ERD whereas the last two are new alternatives to be investigated and compared with the others. The following assumptions were made:

- There is negligible pressure drop in the ERD lines.
- Pressure exchanger has no leakage.
- PRO units have counter-flow configuration and unit effectiveness (i.e. infinite area).
- Effect of reverse salt diffusion and concentration polarization is ignored.
- The whole system is at the same temperature.
- Correlations given by Sharqawy et al. [33] are used to determine thermophysical properties of seawater.
- The condition of the feed water is taken as the dead state. This dead state is: $T_0 = 21.4\ °C, P_0 = 101.325\ kPa$ with $S_0 = 36.888\ g/kg$ [27] except where any of these parameters are varied.
- Turbocharger efficiency is taken as 70% [18] whereas it is assumed to be 96% [34] for the pressure exchanger.
- The SWRO plant is assumed to have a recovery ratio of 42% [27].
- The salinity of the permeate is taken as 0.4 g/kg [27].

We now proceed with the energy analysis. The ratio of the product to inlet feed water mass flow rates is taken as the recovery ratio, R:

$$R = \frac{\dot{m}_p}{\dot{m}_{f,i}}. \tag{1}$$

The mixing ratio (MR) for PRO units is defined as the ratio of the draw to feed water inlet mass flow rates [35]:

$$MR = \frac{\dot{m}_{d,i}}{\dot{m}_{f,i}}. \tag{2}$$

Eq. (3) comprises of a general solution balance. Mass balances are similarly applied. All system components and processes are modeled using them.

$$\sum_{in} \dot{m}S = \sum_{out} \dot{m}S \tag{3}$$

The isentropic efficiency is used to determine the actual power for the turbine as well as the pump (see Eqs. (4a)–(4b) below). Also, the power provided by the turbocharger is calculated in a way similar to that of the turbine.

$$\dot{W}_t = \eta_{is,t} \dot{W}_{is,t} \tag{4a}$$

$$\dot{W}_{pp} = \frac{\dot{W}_{is,pp}}{\eta_{is,pp}} \tag{4b}$$

Efficiency of the pressure exchanger is taken as [36]:

$$\eta_{px} = \frac{\sum_{out} (\dot{V}P)}{\sum_{in} (\dot{V}P)} = \frac{\dot{V}_{B,o}P_{B,o} + \dot{V}_{f,o}P_{f,o}}{\dot{V}_{B,i}P_{B,i} + \dot{V}_{f,i}P_{f,i}}. \tag{5}$$

Furthermore, at the desired mixing ratio, the maximum possible recovery ratio is used, which is calculated from the dimensionless model of Sharqawy et al. [35]. Lastly, the specific energy consumption (SEC) of the plant is calculated by dividing the net power input by the volumetric flow rate of permeate.

$$SEC = \frac{\dot{W}_{in}}{3600\dot{V}_p} \tag{6}$$

We can say that, because of the way SEC is defined, it is intrinsically an economic indicator [37–39]. One may refer to Appendix A, which contains an application of the above equations to one of the configurations. Now, experimental data from the literature was used to validate different parts of the program written in EES [40] (see Table 1) resulting in excellent agreement. Furthermore, appropriate portions of Tables 1 and 2 of Sharqawy et al. [14] were used to check that the specific exergy values were being calculated correctly. The percentage error encountered was nearly zero for all states.

Now, comparison of all system configurations will be done not only on a first-law basis using SEC as a measure but also on a second-law basis using exergetic efficiency. There are two definitions of exergetic efficiency that are commonly encountered. The first one is defined as