Energy 93 (2015) 256–265

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Exergetic analysis of a brackish water reverse osmosis desalination unit with various energy recovery systems

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ARTICLE INFO

Article history:
Received 20 June 2015
Received in revised form
1 September 2015
Accepted 2 September 2015
Available online 4 October 2015

Keywords:
Exergy analysis
Brackish water
Pressure retarded osmosis
Energy recovery device
Reverse osmosis
Desalination

ABSTRACT

Exergetic analysis of a reverse osmosis desalination unit is performed for brackish water feed using different energy recovery methods. This includes single and two-stage pressure retarded osmosis units (for infinite area). The correct definition of exergetic efficiency for such systems is also discussed. A clear connection is seen between specific energy consumption and the efficiency definition chosen such that one can be determined from the other. The program written is validated against experimental and numerical data from the literature with nearly zero percent error. The effect of salinity, turbine and pump efficiency as well as mass ratio is studied. In all cases, it is seen that the reverse osmosis unit has the best efficiency when a pressure exchanger is used as an energy recovery device (~16% maximum). All pressure retarded osmosis options investigated had efficiencies below or approximately equal to the hydroturbine. Since finite area and concentration polarization would further decrease the efficiency, therefore, it does not seem to be a viable energy recovery method for reverse osmosis units with brackish water feed.

1. Introduction

Around one-fifth of the world's population lives without potable water while a quarter of the world's population may be living in water scarce areas by the next decade [1]. Reverse osmosis (RO), a membrane-based process that was commercialized in the 1970s [2], is one method of desalting brackish and sea water to alleviate this problem. These membranes are often in the form of spiral-wound modules, which are typically parallel pressure vessels containing a series of membranes. Recovery rates of water (called permeate) from brackish water sources is 75–90% while it is 35–50% for sea water [2,3]. Besides the RO module itself, the desalination unit consists of a pre-treatment and post treatment system along with pumps that are often coupled with energy recovery devices (ERD).

The energy cost of these desalination systems can be reduced by coupling it with other systems [4–10], developing better membranes [11–13], using higher efficiency pumps and/or employing improved or new energy recovery technologies [14–17]. Energy recovery devices that are in commercial use include the Pelton turbine, turbocharger and, the comparatively more recent, pressure exchanger. The Pelton wheel is a concept that is more than 100 years old and, therefore, probably the ERD which is used the most [18]. A shaft connected to the wheel turns as the brine stream impinges onto buckets coupled to it. The shaft, which is directly connected to the pump, reduces its load and the energy requirement reduces. The turbocharger is, in essence, a stand-alone device wherein a turbine is coupled to a pump. It uses the turbine to extract energy from the brine stream, then rotates a shaft to which the impeller of a pump is connected and, thus, raises the fluid pressure on the other side received from the main pump. In a pressure exchanger, the feed stream is pressurized directly by the brine flow. The only moving part is a ceramic rotor, which spins on a thin film of leaked brine water, with ducts filled with low pressure feed water that are pressurized by rotating them into direct contact with the high-pressure brine flow.

Evaluation of RO desalination units with existing or new energy recovery technologies can be performed on a first-law as well as second-law basis. The first one provides an energy-based analysis emphasizing the quantity of energy expended on the process. In desalination systems, the specific energy consumption (SEC), defined as the power consumed per cubic meter of permeate

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http://dx.doi.org/10.1016/j.energy.2015.09.003
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produced, may be considered as a quantitative measure of the process. The second one focuses on the quality aspect of the energy expended often termed as exergy. The true potential of a system to perform work is represented by its exergy with respect to the environment or a dead state. Exergy analysis not only pin-points the components with the highest exergy destruction (irreversibility) but also evaluates the overall system through the use of a second-law or exergetic efficiency. The higher the efficiency, the closer the system is to its reversible counterpart. In the literature, second-law efficiency is often defined in two ways. The first one is defined by saying that it is the ratio of total exergy leaving divided by total exergy entering the system. The second is mentioned as the ratio of the product to fuel exergies [19,20]. Al-Sulaiman et al. [21] specifically studied a novel hybrid desalination system consisting of a humidification-dehumidification system combined with reverse osmosis. They indicated that the use of second-law efficiency (using the second method) was found to be misleading but this was based on a new concept termed the equivalent electricity consumption. This term was evaluated based upon assumed values for a Rankine power plant that theoretically would be using the steam to produce this electricity. Furthermore, the system that produced the actual steam was not considered in the control volume. For RO desalination systems, authors such as Kahraman et al. [22] and Sharqawy et al. [14] used the first method while Demirel [23] and Mistry et al. [24] defined it in the second manner. Mistry and Lienhard V [25] then generalized the usage of the second method to consider input in the form of work, heat and chemical fuel. This issue is further discussed and resolved in Section 2.2.

Besides the theoretical work of Spiegler and El-Sayed [26], several works in the literature are available regarding exergy analysis of RO desalination plants: Cerci [27] performed exergy analysis of a brackish RO desalination plant in California. It was a single-stage system with brackish water feed and no ERD. The second-law efficiency was found to be 4.3% with the highest source of exergy destruction being the RO module (~74%) and throttling valves (~15%). However, Sharqawy et al. [14–16] pointed out that the chemical exergy was being evaluated incorrectly. They re-evaluated the same plant and found the efficiency to be 1.5%. Furthermore, the authors proposed a pressure retarded osmosis unit [28,29] with turbines as an alternate ERD, which was said to increase the efficiency to approximately 2%. This proposal, however, will be re-evaluated in the current work based on a different second-law definition (See Section 2.2). Kahraman et al. [22] performed exergy analysis of a two-stage RO desalination plant in California with brackish water feed and no ERD. The second-law efficiency was found to be 8% with one of the highest sources of exergy destruction being the RO modules (~36%). Romero-Ternero et al. [30] studied a single-stage RO desalination plant in Spain for the purpose of exergy analysis. It had sea water as feed and a Pelton turbine as an energy recovery device. The second-law efficiency was found to be 48.5% with the highest sources of exergy destruction being the RO modules (~35%) followed by the Pelton turbine (~24%). Aljundi [31] did exergy analysis of a two-stage RO desalination plant in Jordan with brackish water feed and no ERD. The second-law efficiency was found to be 4.1%. The four throttle valves constituted approximately 57% of the exergy destruction followed by the RO modules (~21%). Gasmi et al. [32] studied a two-stage industrial RO unit and found that the pumps contributed to approximately 55% of the exergy destruction while the RO modules destroyed 37% of the exergy. Blanco-Marigorta et al. [33] performed exergy analysis of a two-stage RO desalination plant in Spain with sea water feed and three ERD. The second-law efficiencies were found to be 32.8%, 28.4% and 26.8% when the ERD used was a Dual Work Exchange Energy Recovery (DWEER) system, a Pelton turbine and a pressure exchanger, respectively. The main locations of exergy destruction were reported to be the RO modules and the high-pressure pump.

Banchik [17] evaluated the viability of PRO coupled with a pressure exchanger for the purpose of energy recovery with sea water as feed. It was found that decrease in power requirement only occurred when the wastewater inlet salinity was less than 20 g/kg. Therefore, the objective of the current work is to evaluate the viability of different PRO-based systems for energy recovery by using second-law efficiency as a guide and comparing with various energy recovery devices for brackish water reverse osmosis desalination units using accurate sea water properties. In this regard, the appropriate definition for the second-law efficiency is selected and compared to variations in specific energy consumption as well.

2. Description of systems and models

A reverse osmosis desalination unit is considered with seven different configurations as energy recovery devices (ERD). Fig. 1(a)-(d) represent the well-known ERD while Fig. 2(a)-(c) represent ERD options using pressure retarded osmosis. The authors did not find the systems shown in Fig. 2(b)-(c) as ERD alternatives for brackish water in the literature. Overall, these ERD include a throttling valve (TV), turbocharger (TC), hydroturbine (T), pressure exchanger (PX), pressure retarded osmosis unit with hydroturbines (PRO-T), pressure retarded osmosis with hydroturbine and pressure exchanger (PRO-PX) and two-stage pressure retarded osmosis unit (2S-PRO-T). The first configuration (Fig. 1(a)) is the base case with no ERD [27] while the last two are new alternatives investigated for brackish water in order to compare with the rest. The main assumptions that have been made are:

- All pressure drops in the ERD lines are considered negligible.
- Leakage is taken as zero in the pressure exchanger.
- Complete system is considered at a constant temperature equal to the environment temperature of 15 °C.
- The dead state is taken as the condition of the feed water i.e. $T_0 = 15\,^{\circ}C,\ P_0 = 101.325\ kPa$ with $S_0 = 1.55\ \ g/kg$ in situations where feed salinity is not being varied.
- Accurate thermophysical properties of sea water are based on correlations provided by Sharqawy et al. [34].
- Effect of concentration polarization and reverse salt diffusion are ignored.
- The efficiency of the pressure exchanger is fixed at 96% [35] while it is 70% for the turbocharger [18].
- Recovery ratio of the RO unit is fixed at 77.5% [27].
- The permeate is assumed to have a salinity of 0.23 g/kg [27].
- PRO modules are assumed to have infinite area (unit effectiveness).

2.1. First-law analysis

Modelling for all of the above systems is performed by applying mass balances (Eq. (1) below) and solution balances (Eq. (2) below) on the RO and PRO modules as well as between any two sequential states for the purpose of a theoretical study.

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

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

The actual pumping power is determined by dividing the ideal pumping power by its isentropic efficiency while the turbine power