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Effects of different designs of pressure vessels on efficiency and energy consumption of reverse osmosis systems

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KEYWORDS

Pressure vessel; Reverse osmosis; Energy consumption; Efficiency; Seawater reverse osmosis; Brackish water reverse osmosis. **Abstract.** One of the cost-effective methods of water purification is reverse osmosis. In the present work, the effect of pressure vessels with different numbers of membranes in two types of reverse osmosis system design is investigated. Simulation results showed that pressure vessels with more membranes have lower energy consumption and higher efficiency in different simple and hybrid designs of reverse osmosis systems. Findings showed that the first design performs better in terms of energy consumption and efficiency than the second design. The study also showed that maximum efficiency was achieved using the first design of the hybrid two-stage brackish water reverse osmosis system. The least efficient system was the hybrid single-stage seawater reverse osmosis system.

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1. Introduction

In recent years, the use of membranes and membrane processes has constantly been increasing [1]. One of the main applications of membranes is desalination, one of the main methods of producing freshwater [2]. In addition, membranes are used in many fields, such as electrodialysis, electroosmosis processes, and drug purification [3–5]. Simulation techniques have been used directly and indirectly in most areas of

*. Corresponding author. Tel./Fax: +98-45-31505757 E-mail addresses: babapoor@uma.ac.ir and babapoor2006@yahoo.com (A. Babapoor) membrane processes [6–8]. Simulations of membranebased processes are useful in predicting processes and enable fast and cheap optimization [9]. Saltwater desalination has become an important method to overcome the global shortage of fresh water. Thanks to the development of water desalination methods, fresh water supply can be increased beyond what the hydrological cycle can provide [10]. The processes involved in Reverse Osmosis (RO) systems are welldeveloped and unparalleled in case of reliability and energy efficiency. Due to these reasons, they have become the most popular method of purifying water among other available technologies. Thus, many researchers are putting efforts into developing RO

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systems to make utilization of these systems as a reliable source of supplying freshwater feasible [11,12]. Currently, Multi-Stage Flash distillation (MSF), multieffect distillation, Vapor Compression (VC), RO, and electrodialysis (ED) are the most popular commercially available methods of desalination [13,14]. Most popular desalination processes rely on fossil fuels for energy [13– 17].

Ludwig [18] investigated the energy usage of SeaWater RO (SWRO) systems and analyzed the possibility of bettering their layout and function with Energy Recovery Instruments (ERIs). Data revealed that for purifying a seawater sample having a Total Dissolved Solids (TDS) equal to 35,000 ppm, approximately 3.5 W.h/m^3 of energy is typically used. Park et al. [19] theoretically analyzed low-energy SWRO plants. Methods of improving the energy efficiency of RO units have been divided into two groups: direct and indirect. An example of a direct method is diluting the feedwater, while an example of an indirect method is reducing the difference in osmotic pressure. Unlike thermal desalination methods, the amount of TDS in seawater predominantly affects SWRO desalination systems. Feed water salinity determines the osmotic pressure and pumps' workload. Thus, it affects the amount of energy consumption in SWRO plants. Based on prior studies, water with the highest quality can be produced using different Internally Staged Designs (ISD) with the full flow to the second pass. The cost of producing water using a system with permeate splitting mechanisms is estimated to be 8% lower than when a system with a full two-pass configuration is used. In addition, also by integrating permeate bypass mechanisms, the costs of water production can be lowered by 6% [20]. Research by Altaee et al. [21] demonstrated that for desalinating seawater, systems that utilize Forward Osmosis (FO) and RO have a higher recovery rate than conventional RO systems. Studies showed that the recovery rate does not exceed 50% by using less saline feed water due to scaling issues. However, since the draw solution in FO systems gets highly concentrated, these issues do not affect such systems, indicating that the recovery rate in FO-RO units can be increased beyond 50%. For purifying feeds like seawater, which contain high levels of TDS, high hydraulic pressures must be applied, increasing the amount of energy desalination plants consume. In such scenarios, lower levels of energy consumption can be achieved by lowering the feed's osmotic pressure.

In recent studies, researchers suggested several osmotic pressure reduction methods. Studies by Mustaqimah et al. [22], where ROSA was employed, demonstrated that applying higher feed water pressures yields permeate water containing more TDS. Based on results obtained using ROSA, it was found that the recovery rate and permeate TDS are higher in two-stage systems compared to single-stage ones. Joseph and Damodaran [23] dynamically simulated the SWRO process using LabVIEW to help understand the dynamics of processes involved in SWRO plants. Simplified functionaldecomposition approach modelings were employed to perform RO desalination process simulations to understand the dynamics of the processes. Comparing the results of dynamic simulations with transient ones and using operational data of real-world desalination plants, it was found that reasonably raising the feed's temperature reduces Specific Energy Consumption (SEC) for various recovery rates within RO systems. According to investigations by Al-Obaidi et al. [24], parameters such as feed flow rate and pressure could be adjusted to lower the permeate in brackishwater RO (BWRO) plants. The costs of desalinating highly saline feeds using BWRO plants can be lowered using Energy Recovery Devices (ERDs), as shown by Pearson et al. [25]. Through ROSA simulations, Oh et al. [26] validated that higher flow flux in RO plats increases permeate quality. However, doing so increases the overall energy consumption of RO plants. According to comprehensive pieces of information collected by Kim et al. [27] on factors affecting the energy consumption of SWRO plants, high SEC is the main issue of RO Wilf and Klinko [28] demonstrated that systems. upping the amount of high-rejection membranes and ERDs could be employed to cut the operational cost of RO systems. Figure 1 shows the processes that are involved in an SWRO plant.

Seawater desalination can be summarized in four steps: Pumping seawater to the plant, pretreatment of water, desalination in the RO system, and posttreatment of permeate. Seawater gets pressurized and pumped into the Pressure Vessel (PV) of the RO unit containing several RO membranes. For increasing the recovery rate of RO units, up to 8 RO elements are often placed inside PVs [29–32]. Technically, PVs are tanks, vessels, and pipelines that receive, carry, or store fluids, and their internal pressure differs from the outside pressure. Unlike tanks, PVs are not limited to atmospheric pressure [33].

As seawater moves through the PV, the desalination rate gradually decreases, leading to a steady increase in salinity, creating a highly saline solution at the PV outlet, causing scale formation on membranes located near membranes and consequently lowering the recovery rate. As a result, antiscalants, chemical softening of feed water, and membrane treatment typically must be employed in RO plants [31,32,34– 36]. Scale removal solutions are not always costeffective. Thus, central feeding was proposed as a substitute for conventional anti-scaling measurements in SWRO units [37]. In central feeding, a central port distributes feedwater evenly on both sides of the PV.



Figure 1. Processes involved in an SWRO desalination plant. Redrawn with permission from Ref. [29]. Copyright © 2009, Elsevier.

Table 1. Specifications of flow rate, flux inlet and produced water, and required membrane.

| | (gfd) | (\mathbf{gpm}) | $area (ft^2)$ | of membranes |
|------|-------|------------------|---------------|--------------|
| SWRO | 8.26 | 128.5 | 400 | 56 |
| BWRO | 16.51 | 55 | 400 | 12 |

Central feeding in SWRO plants reduces the likelihood of scale formation on the last membrane elements, but this design demands higher feed flow rates. Another method for controlling scale formation and fouling is using membranes modified using nanomaterials that prevent fouling [38]. Simulation performed by Altaee [32] showed that as the desalination capacity and feed's Silt Density Index (SDI) increase, using PVs with central feeding becomes more economical than using other designs. Investigations by Kim and Hong [39] showed that mixing the rejected brine of the last membranes with the feed water and returning it to the system improves the quality of permeate by 15%.

Despite the abundance of research on RO systems and the recent surge of publications, there remain essential deficiencies in studies of how different PV designs influence crucial factors such as RO plants' efficiency and energy consumption. Thus, in this paper, how two different PVs, each containing a different number of membranes, affect the energy consumption and efficiency of different RO systems is evaluated.

2. Materials and methods

In this paper, SWRO and BWRO plants having desalination capacities equal to $700 \text{ m}^3/\text{day}$ and $300 \text{ m}^3/\text{day}$, respectively, were assumed. Different hybrid and simple SWRO and BWRO systems, each having PVs with different numbers of membranes, were designed. Feeds used for BWRO systems were assumed to have a TDS ranging from 700 to 1450 ppm. SWRO systems were assumed to use feeds with a TDS ranging from 21500 to 42000 ppm. Commercially available BW400ES and BW400R were used in BWRO systems, and SW400GR and SW400R membranes were used in SWRO systems. For hybrid and simple single-stage BWRO systems, 3-element and 4-element PVs were used. BW400R membranes were used in 3-element PVs, and BW400ES membranes were used in 4-element PVs. In hybrid and simple two-stage BWRO systems, 4-element, 2element, and single-element PVs were used. In SWRO systems, 8-element and 7-element PVs were used. The model was validated under a frame of recommended guidelines. PVs with 4 membranes were used to save money and energy. The membranes' specifications are provided along with flow rate, inlet flux, and produced water in Table 1.

The number of required membranes was calculated using Eq. (1), which is provided in the following:

$$N = \frac{\text{Produced water} \times 1440 \text{ (gpm/gpd)}}{\text{Inletflux (gfd)} \times \text{membrane surface area (ft}^2)}. (1)$$

BWRO and SWRO unit simulations were performed assuming a well water sample with an SDI<3 is about to be desalinated. According to design guidelines, in such operating conditions, the value of inlet flux must be 16 to 20 GFD and 8 to 12 GFD for BWRO and SWRO systems, respectively [40]. Specifications of the investigated designs of simple and hybrid two-stage RO units are given in Tables 2 and 3.

| Type of design | Design 1 | Design 2 | No. membranes | No. PVs |
|---------------------|----------|----------|---------------|---------|
| Hybrid single-stage | * | - | 12 | 3 |
| Hybrid single-stage | _ | * | 12 | 4 |
| Simple single-stage | * | - | 12 | 3 |
| Simple single-stage | - | * | 12 | 4 |
| Hybrid two-stage | * | - | 12 | 3 |
| Hybrid two-stage | - | * | 12 | 8 |
| Simple two-stage | * | - | 12 | 3 |
| Simple two-stage | _ | * | 12 | 8 |

 Table 2. Investigated designs of the BWRO system.

| Table 3. | Investigated | designs | of the | SWRO | system. |
|----------|--------------|---------|--------|------|---------|
| | () | () | | | • (|

| Type of design | Design 1 | Design 2 | No. membranes | No. PVs |
|---------------------|----------|----------|---------------|---------|
| Hybrid single-stage | * | - | 56 | 7 |
| Hybrid single-stage | — | * | 56 | 7 |
| Simple single-stage | * | _ | 56 | 7 |

3. Results and discussion

3.1. Effects of different designs of PVs on energy consumption in simple and hybrid designs of RO systems

Figure 2 shows that a rise in the amount of TDS in feed water increases the amount of consumed energy in simple and hybrid single-stage SWRO systems. From Figure 2, it can be deduced that using feeds containing high amounts of TDS increases the osmotic pressure, ultimately increasing the pumps' workload and energy consumption [41–43]. Figure 2 also shows that there is not much difference in the amount of consumed energy in simple and hybrid single-stage SWRO systems.

Figure 3 shows the energy consumption in simple

and hybrid two-stage BWRO systems. Based on Figure 3, highly saline feeds, due to having higher osmotic pressures, increase the workload of pumps and, as a result, the system's energy consumption [41,42,44,45]. Figure 3 also shows that among the investigated designs, the first design consumes less energy than the second design. Based on Figure 3, the first design requires fewer PVs if the number of membranes does not change. Therefore, the first design is more economical than the second design.

Figure 4 demonstrates that as the TDS of the feedwater increases, the energy consumption of simple and hybrid single-stage BWRO systems increases. Additionally, hybrid single-stage systems consume less energy than simple ones due to the placement of mem-



Figure 2. Effects of feed's TDS on energy consumption in simple and hybrid single-stage SWRO systems.



Figure 3. Effects of feed's TDS on energy consumption in simple and hybrid two-stage BWRO systems.



Figure 4. Effects of feed's TDS on energy consumption in simple and single-stage hybrid BWRO systems.

branes with the highest removal percentage upstream of the PV and membranes with the highest Flux Percentage (FP) downstream of the PV [41,42]. Figure 4 shows that simple two-stage configurations consume less energy than hybrid two-stage configurations.

3.2. Effects of different designs of PVs on efficiency in simple and hybrid designs of RO systems

Figure 5 demonstrates that highly concentrated saline feeds diminish the effectiveness of simple and hybrid single-stage SWRO units [41,42,46]. Based on Figure 5, it is clear that the performance of single-stage hybrid SWRO systems is negligibly affected by the TDS of the feed. The efficiency of simple single-stage designs in SWRO systems is higher than in BWRO systems. The general deduction is that simple single-stage configuration of SWRO systems is more efficient than hybrid single-stage ones. Therefore, if the number of membranes used does not change, using a simple singlestage design not only increases the system's efficiency but also reduces the number of PVs required, lowering the construction costs of the SWRO plant.

Figure 6 demonstrates that in specific ranges, the TDS of feed does not majorly impact the efficiency of simple and hybrid two-stage BWRO units. Simple two-stage designs' efficiency is higher than hybrid two-stage ones. Consequently, simple two-stage designs are more economical regarding construction and operating costs in similar conditions than their hybrid two-stage counterparts.

Figure 7 displays how the feed's TDS affects the efficiency of both simple and hybrid configurations of single-stage BWRO plants. It is evident that, in specific ranges, increasing the TDS of the feedwater does not impact the efficiency of RO systems. Furthermore, simple single-stage configurations seem more efficient than hybrid single-stage ones.



Figure 5. Effects of feed's TDS on efficiency in simple and hybrid single-stage SWRO systems.



Figure 6. Effects of feed's TDS on efficiency in simple and hybrid two-stage BWRO systems.



Figure 7. Effects of feed's TDS on efficiency in simple and hybrid single-stage BWRO systems.

| Type of design | Minimum recovery | Maximum recover | |
|----------------------------|------------------|-----------------|--|
| Type of design | ratio | ratio | |
| Hybrid single-stage (BWRO) | 25 | 28 | |
| Simple single-stage (BWRO) | 24 | 25 | |
| Hybrid two-stage (BWRO) | 128 | 158 | |
| Simple two-stage (BWRO) | 64 | 76 | |
| Simple single-stage (SWRO) | 4 | 5 | |
| Hybrid single-stage (SWRO) | 3 | 4 | |

Table 4. Minimum and maximum recovery ratio in investigated RO systems.

The efficiency of different RO systems investigated in this study is summarized in Table 4. The highest efficiency is seen in two-stage hybrid BWRO systems. The least efficient systems were single-stage hybrid SWRO units.

4. Conclusion

Reverse Osmosis (RO) technology is an emerging method of water treatment. The effects of different designs of PVs on the efficiency and energy consumption in simple and hybrid designs of RO units were investigated in this paper. Simulation of simple and hybrid single-stage systems for seawater desalination showed that there was not much difference between the amount of consumed energy in such designs of Sea-Water RO (SWRO) systems. The results showed that in simple and hybrid two-stage and single-stage Brackish-Water RO (BWRO) plants, energy consumption in the first design was much less than in the second design. For seawater desalination, the first design of the simple single-stage system has higher efficiency than the second design. However, the first design of the hybrid single-stage system is no more efficient than the second design. For brackish water desalination, simulations showed that the RO system designs with a lower number of Pressure Vessels (PVs) and more membranes have higher efficiency and lower energy consumption than designs with a high number of PVs and a lower number of membranes. Furthermore, for seawater desalination, simple single-stage designs with fewer PVs and more membranes have higher efficiency than designs with a high number of PVs and a lower number of membranes.

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Biographies

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