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Modeling Approach to Estimate Energy Consumption of Reverse Osmosis and forward Osmosis Membrane Separation Processes for Seawater Desalination †

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Abstract: Due to growing industrialization and population increase, water scarcity is becoming a major global concern. Desalination is often regarded as a potential solution to the worldwide water crisis; however, due to rising prices and energy usage, desalination has remained a research focus. Traditionally, specific energy consumption (SEC) kWh/m^3 for seawater desalination has been calculated using a hybrid approach that ignores membrane design attributes and operational parameters. The current study constructed a mathematical framework based on well-established theory to quantify and compare the energy consumption of pressure-driven and osmotic-driven membrane separation processes by incorporating the necessary membrane design and operational parameters into the model framework. The model results were compared to the literature data and found to be in good agreement. The findings of this study show a non-linear relationship between the membrane flowrate factor and the energy needs of reverse osmosis RO, with the effect being more obvious at low values of K_f < 50 L/h.bar, where K_f is equal to the product of membrane permeability and membrane area. The results also showed that the lowest SEC was obtained at 60–65% recovery, and, from model testing, the energy consumption was 3.65 kWh/m^3 and 3.88 kWh/m^3 for the RO and FO–RO processes, respectively. Additionally, the hybrid process demands more membrane area, which further raises the cost of desalination. The mathematical framework developed in this work will act as a prediction design tool for membrane plant designers to check and compare the feasibility of these processes before experimental work to save money and time.

Keywords: pressure-driven membrane separation processes; osmotic-driven membrane separation processes; specific energy consumption; mathematical modeling; energy consumption comparison

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1. Introduction

Globally, there is an urgent demand for more water as a result of the recent rapid industrialization, growing population, and deterioration of sources of fresh water [1]. More than one third of the population is already suffering from a fresh water shortage; consequently, by 2025, this number is expected to rise to two thirds [2]. Desalination is widely thought of as a solution to provide drinkable water [3]. The most widely used processes are membrane-based, such as pressure-driven and osmotic-driven processes, and thermal desalination technologies like multistage flash distillation, and conventional evaporation methods [4–6].

Due to the absence of an energy-intensive phase transition step, membrane filtration procedures (RO and FO) utilize much less energy than traditional thermal desalination methods. Nevertheless, rising desalination costs as a result of surging oil prices make membrane desalination a potential water purification method [4,5,7]. Pressure-driven process PDM (RO) is the most energy-intensive membrane technology because it required 20 KWh/m^3 of power in 1970 and has now reduced to 2 KWh/m^3 at 50% recovery [8].

Osmotically driven membrane separation ODM is a fairly young separation process compared to traditional membrane technologies like reverse osmosis. It is being explored for potential use in desalination and water treatment, among other separation processes [9,10]. Forward osmosis has been proposed as an energy-saving process compared to PDM [8,11,12]; therefore, it is necessary to stand back and contrast the actual energy requirements for standalone RO, FO, and hybrid FO–RO, where RO is used to separate draw solute and drinkable water [13].

In this work, a mathematical framework has been developed to estimate the energy usage of PDM and ODMPs by incorporating most of the necessary membrane design parameters like membrane permeability, area, and operating parameters such as feed osmotic pressure and pressure loss in membrane elements into the design equations, and this approach acts as a foretelling tool for the designers to check the feasibility of these processes for a given set of conditions and choose an appropriate one among them (PDM or ODM).

2. Theory

2.1. Specific Energy Consumption

Energy is required in both the PDM and ODM processes, either thermal or electrical energy in the FO system to replenish and recycle the draw solute back to the FO module or electrical energy in the RO system to operate high-pressure pumps. Energy usage in these processes is expressed by the term SEC, which is "the amount of energy being used to produce a unit volume of permeate expressed as kWh/m^3". Until now, there has been no clear strategy available in the literature to estimate the SEC of these processes. In this research work, a novel strategy has been proposed to estimate energy usage of these systems for a particular set of operating conditions.

2.2. Modeling of PDM Processes (Standalone RO System)

Electrical energy being consumed in the reverse osmosis process is mostly by high-pressure pump (HPP), and a general relationship to estimate this energy usage has been obtained by applying mechanical energy balance over the HPP as shown [14]:

$$\mathrm{SEC} = \frac{P_f}{\eta_p R} \tag{1}$$

Here, P_f (bar) is the pressure at the pump outlet, η_p is the pump efficiency, and R is the recovery rate of the system, and this membrane recovery rate plays a vital role in determining both the capital and operating costs of the system and needed to be considered during the membrane designing procedures. Equation (1) contains only two parameters, feed pressure and recovery rate, to estimate energy usage of the RO process and overlook some of the design and operational parameters. By incorporating most of the necessary membrane design parameters like membrane permeability, area, and operating parameters such as feed osmotic pressure and pressure loss in membrane elements into the basic design Equation (1), a modified equation for estimating the energy consumption of PDMPs can be finally stated as [4]

$$\mathrm{SEC} = \frac{2}{36\eta_p R(1+\alpha)}\left[\frac{Q_p}{A_w A_p} + \left(\frac{2-R}{2-2R}\right)\sigma\varnothing\pi_f - \sigma\varnothing\pi_p\right] \tag{2}$$

This equation may be used to estimate SEC of any PDM process, in kWh/m^3, and, here, α is the pressure loss factor along membrane length, Q_p (m^3/h) is the permeate flowrate, A_w (m^2) is the membrane area, A_p (L/h·bar) is membrane permeability, σ is called membrane reflection coefficient, ∅ is concentration polarization factor, π_f (bar) is the feed osmotic pressure, and π_p (bar) is the permeate osmotic pressure.

2.3. Modeling of ODM Processes (FO and FO–RO System)

Drinkable water cannot be produced with the solitary FO procedure; instead, a diluted draw solution is formed, which must undergo a second stage of treatment; therefore, FO is coupled with the RO process for the regeneration of draw solute, and this regeneration is the main energy consuming step in the hybrid FO–RO process.

Energy usage in the ODMPs can be approximated by using the following formula [15]:

$$SEC_{FO} = \frac{Q_{fi} \times P_{fi} + Q_{di} \times P_{di}}{Q_p} \quad (3)$$

where Q_{fi} (m^3/h) is the feed flowrate to countercurrent FO module, P_{fi} (bar) is the inlet pressure required to pump the feed solution, Q_{di} (m^3/h) is the draw solution inlet flowrate, P_{di} (bar) is the inlet pump pressure to force the draw solution into the counter current FO system, and Q_p (m^3/h) is the rate of water permeated from the feed solution side to draw solution, and this is called dilution step in FO–RO system.

3. Results and Discussion

The theoretical models of PDMP and ODMP were validated using experimental data gleaned from the literature [10]. The results were produced for a sodium chloride solution with an estimated osmotic pressure of 27.5 bar and salinity of 35 g/L. Also, the values of η_p, φ, and σ were all assumed to be equal to 1, α = 0.96, while the osmotic pressure of the permeate was set equal to zero for simplicity of calculations.

The membrane flowrate factor is the product of membrane area and membrane permeability. Figure 1a shows the effect of K_f on the SEC of PDMPs at various values of Q_p by keeping feed osmotic pressure π_F = 27.5 bar and recovery R = 50% constant. It shows that increasing the value of K_f greatly reduces the energy usage of the system, while SEC decreases practically exponentially as K_f increases, and Figure 1b depicts the fluctuation of SEC of PDMPs with membrane permeate flowrate and using two different kinds of membranes with Kf = 30 L/h·bar and 60 L/h.bar. It demonstrates that, when membranes are operated with no throughput Q_p = 0, minimum SEC is obtained, and the minimum energy usage depends only on feed osmotic pressure. However, as the $Q_p > 0$, the SEC increases linearly, and the membrane with higher permeability and area requires less energy. Doubling the membrane flowrate factor can result in 30% of the energy savings of the overall system.

Figure 1c depicts the influence of changing feed hydraulic pressure on the energy requirements of PDMPs, and, as the pressure in HPP increases, SEC also increases, although the increase is non-linear. Initially, SEC increases slowly because less pressure is required at the start of operation; however, during the course of operation, solute builds up over the membrane surface and pressure requirements increase exponentially, so the slope of the curve also increases sharply (SEC increases). The core of the PDMPs is HPP, which consumes almost 70–80% of the total energy used in these processes.

Figure 1d shows the energy requirements and comparison for both PDMPs and ODMPs as a function of different permeate flowrates, keeping all the other parameters constant, such as feed osmotic pressure of 27.5 bar, K_f = 20 L/h·bar, and recovery at 50%, and it can be seen that SEC grows linearly with increasing Q_p. It also shows that less energy was required for solo RO and hybrid FO–RO processes at low permeate flowrates of roughly Q_p = 500 L/h. However, a low permeate flowrate will increase the capital cost of these facilities because a greater number of elements are required while operating at lower permeate flowrates. Initially, the energy needs of the hybrid process were only slightly higher than those of the standalone RO process, up to roughly 1500 L/h, and, beyond that, there are no obvious differences in the energy requirements of these processes. Figure 1d also provides information about the energy usage of the standalone FO process, which consumes only about 10–15% of the total hybrid system energy, and the remaining 80–85% of the energy was utilized in the draw solution regeneration stage. Moreover, SEC_{min} is the energy needed when Q_p = 0 m^3/h and increases linearly with osmotic pressure.

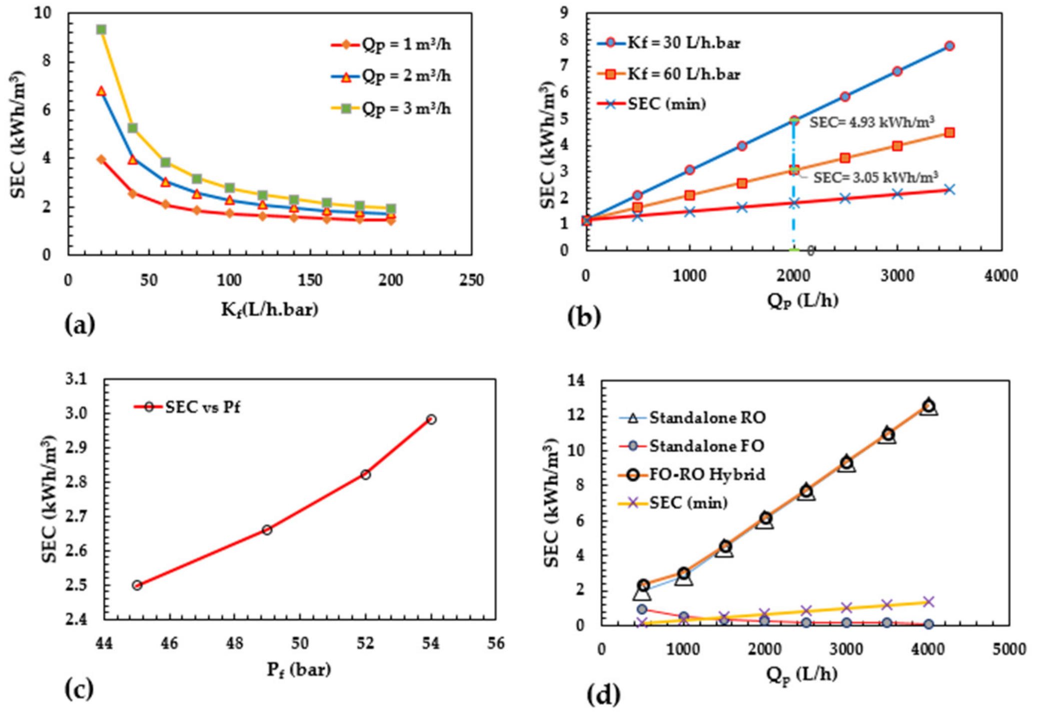

Figure 1. (**a**) Effect of membrane area and membrane permeability (K_f) on SEC of PDMPs at constant feed osmotic pressure and recovery; (**b**) change in SEC with membrane permeate flowrate at various K_f values; (**c**) influence of pump inlet hydraulic pressure on the SEC of PDMPs at constant π_p = 27 bar and K_f = 20 L/h·bar; (**d**) comparison of SEC (kWh/m^3) of both PDMPs and ODMPs as a function of permeate flowrate.

4. Conclusions

A novel mathematical framework has been developed to compute the energy requirements (kWh/m^3) of PDMPs and ODMPs. The results dictate that, for a particular value of feed osmotic pressure and permeate flowrate, the lowest SEC (kWh/m^3) was obtained at almost 65% recovery. In the FO–RO process, FO requires 10–15% of the total energy usage, whereas about 80–85% of the energy was utilized in the draw regeneration stage, and standalone RO was found to be more energy efficient than the hybrid FO–RO system. Also, using membranes with higher permeability and area (K_f) utilizes significantly less energy. The equations developed in this work can be generalized for any pressure-driven or osmotic-driven membrane separation process.

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