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Calculation of energy consumption for crossflow RO desalination processes

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ABSTRACT

Reverse osmosis (RO) is an energy-intensive technology and consistent efforts have been made to reduce energy requirement of the technology in order to make it a more affordable means of water supply. There is an urgent need for a more accurate quantification of energy consumption in the crossflow RO process because it is the predominant configuration used in water desalination and purification. The energy required in the crossflow RO desalination processes is affected by a complex set of parameters or variables, including raw water quality, membrane property, operating requirements such as permeate flux and water recovery, as well as option of energy recovery device in the concentrate stream. The crossflow RO process is fundamentally a heterogeneous system that can only be well defined with the localized variables for the salt concentration, cross flow velocity, and permeate flux along the membrane channel. A theoretical framework was developed in this study for a more accurate quantification of energy consumption in the crossflow RO process by rigorously treating the process as a heterogeneous system as it is. An inverse problem was first solved to determine the driving pressure for a RO process of given set of conditions. The resulted pressure was then used to calculate energy consumption in the RO systems either with fully energy recovery from the concentrate stream or without energy recovery at all. It was demonstrated that the energy consumptions in both RO systems were limited by mass transfer mechanism at low water recoveries but was controlled by thermodynamic restriction at high recoveries. The specific energy (energy consumption for per unit volume of permeate) was calculated for seawater and brackish RO processes for wide ranges of water recovery while the permeate flux was maintained constant at different levels. The specific energy for the RO system with concentrate energy recovery was observed to increase with both increasing permeate flux and increasing recovery. However, there was a minimum at a particular recovery in the specific energy for RO system without concentrate energy recovery and the minimum specific energy shifted to the high recovery end with increasing permeate flux.

Keywords: Specific energy; Reverse osmosis; Desalination; Crossflow; Recovery

1. Introduction

Reverse osmosis (RO) is one of the most promising technologies to meet the ever increasing worldwide demand for water supply of adequate quality in a foreseeable future because of its ability to produce high purity potable water readily from the unconventional water sources, such as seawater, brackish water, and treated wastewater [1,2]. As an energy intensive process, energy cost is usually one of the major cost components of RO processes [3,4], which can easily be counted for over 50% of the total cost in seawater desalination.

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Since the emergence of the technology in 1960s, there have been consistent efforts to reduce energy consumption in RO desalination to make it a more affordable means of water supply [5–8]. Indeed, the continuous improvement on RO membrane permeability and the recent installations of energy recovery devices in the concentrate stream have substantially reduced energy consumption in RO seawater desalination [8–10]. However, energy consumption still remains as the largest cost component in RO seawater desalination.

The current RO systems commonly used in seawater and brackish water desalination predominantly employ the so-called crossflow configuration. The crossflow RO processes are characterized with long pressure vessels, in which several membrane elements are connected in series to form long membrane channels. Raw water is fed at high pressure to one end of the membrane channels and permeate is produced as raw water flows along the membrane channel. The remaining raw water comes out of the other end of the membrane channel as concentrate, which contains the majority of the impurities originally in raw water and subject to disposal [11,12]. Energy consumption in a crossflow RO desalination process is a very complex problem that is affected by many factors, such as raw water salinity, membrane resistance, and performance requirements (e.g., permeate flux and water recovery). Although many case studies on energy consumption in crossflow RO systems have been reported in the literature, a general theoretical method for the calculation of energy consumption from the basic parameters of the RO systems is still not available [3,13–15]. It appears that the challenge to theoretically quantify energy consumption in crossflow RO processes manifest itself as the difficulty to accurately determine the driving pressure for a particular crossflow RO system [16,17] because of the heterogeneous nature of crossflow RO process.

A theoretical framework was developed in this study for a more accurate quantification of energy consumption in the crossflow RO process by rigorously treating the process as a heterogeneous system as it is. An inverse problem was first solved to determine the driving pressure for a RO process of given set of conditions. Then the specific energies of crossflow RO systems with fully concentrate energy recovery and without concentrate energy recovery were calculated. The mechanisms to determine energy consumption in crossflow RO under various water recoveries were analyzed and discussed. The control mechanisms for the energy consumption in crossflow RO systems are useful for the understanding of the ultimate energy requirements in extreme cases of the systems. Finally, The energy consumptions for RO systems in which fixed permeate fluxes are maintained were simulated and discussed.

2. Theory

2.1. Energy requirements in reversible and ideal RO processes

The energy efficiency of RO desalination processes is usually expressed in terms of the specific energy that is defined as the energy required for the production of one unit volume of permeate. One convenient energy unit commonly used in desalination applications is the kilo-watt-hour (kWh), which is equal to 3.6×10^6 Joules. Before the discussion of energy calculations in the crossflow RO processes, two important specific energies for the reversible and ideal RO desalination processes will be introduced first. In a recent paper [17], we developed concise equations for specific energy requirements in these two processes that are of fundamental importance to RO desalination. A reversible RO process is a process in which the driving pressure is always equal to the osmotic pressure [4,17,18]. The specific energy of the reversible RO process is given by:

$$W_1 = 2.78 \times 10^{-7} \pi_0 \frac{1}{R} \ln \frac{1}{1-R} \tag{1}$$

where W_1 is the specific energy for desalination in the reversible RO processes, π_0 is the osmotic pressure of feed water, and R is the water recovery that is defined as the ratio of the permeate flow rate to the feed flow rate in an RO process. The specific energy for the reversible RO process represents the theoretical (thermodynamic) minimum energy requirement for desalination. Because the RO membranes have finite resistance, a revisable RO process means that permeate flux is practically zero in the process. But nonzero permeate flux is always required for any practical RO processes and it can be demonstrated that permeate flux of a finite value actually minimize the combined cost of membrane and energy [16].

The ideal RO process that we first introduced in the recent paper [17] is defined as the most energy efficient RO process with a required nonzero permeate flux, in which the energy above the thermodynamic minimum energy is entirely used for maintaining permeate flux. The specific energy for the ideal RO process is determined as:

$$W_2 = 2.78 \times 10^{-7} \left(\pi_0 \frac{1}{R} \ln \frac{1}{1-R} + \Delta P_{\text{net}} \right) \tag{2}$$

where W_2 is the specific energy for the ideal RO process, ΔP_{net} is the net driving pressure for the required permeate flux. The ideal RO is considered to provide a more appropriate baseline than the reversible RO for the assessment of the energy efficiency of practical RO desalination processes.

The osmotic pressure of the feed water can be linearly related to its salt concentration, that is:

$$\pi_0 = f_{os}C_0 \tag{3}$$

where C_0 is the salt concentration of the feed water in the unit of mg l^{-1}, and f_{os} is the osmotic pressure coefficient. The osmotic pressure coefficient has a value of 73.9 Pa (mg $l^{-1})^{-1}$ for the average seawater at 25°C [18,19]. This value will be used indiscriminately for both seawater and brackish water in the paper.

2.2. Energy consumption in crossflow RO processes

The practical RO desalination processes are dominantly employing a cross flow configuration with pressure vessels 6–8 m long, in which 6–8 membrane elements are connected in series. Feed water is supplied by a high pressure pump into one end of the pressure vessels, and retentate exits the pressure vessels through the other end. Permeate comes out of the pressure vessels through the third outlet usually placed along the central line.

The specific energy requirements for permeate production in the cross flow RO process with and without energy recovery from the concentrate stream are determined as, respectively [17]:

$$W_3 = 2.78 \times 10^{-7}\,\Delta P \tag{4}$$

$$W_3' = 2.78 \times 10^{-7}\,\frac{\Delta P}{R} \tag{5}$$

where W_3 and W_3' are the specific energies in the common cross flow RO process with and without energy recovery from concentrate stream respectively, and ΔP is the driving pressure. A full recovery of the energy remaining in the concentrate stream is assumed when the energy recovery devices are applied.

A significant recovery (40% or greater) is usually required for a membrane channel in the practical RO desalination processes. As a result, the salt concentration and crossflow velocity inside of the membrane channel change significantly along the channel. Because of the increase in the osmotic pressure, the net driving pressure, as well as the permeate flux, decreases substantially along channel. As schematically shown in Fig. 1, the crossflow membrane channel is therefore a heterogeneous separation system. Localized variables are required to accurately describe or characterize the properties and behaviors of such a heterogeneous system [20,21]. In the figure, the increasing salt concentration from the entrance to the exit of the membrane channel is indicated by the intensifying color of the fluid. The decreasing crossflow velocity is indicated by the shortening solid arrows in the channel. The decreasing permeate flux along the channel is indicated by the reducing length of the hollow arrows.

A differential equation was rigorously derived by Song and Tay [22] to describe the variations of salt concentration in the heterogeneous RO channel, which is:

$$\frac{dC}{dx} - \frac{\Delta P}{HR_m C_0 u_0}\left(1 - \frac{f_{os}C}{\Delta P}\right)C^2 = 0 \tag{6}$$

where x is the coordinate along the flow direction, C is the variable of salt concentration, H is the height of the membrane channel, R_m is the membrane resistance, and C_0 and u_0 are the feed salt concentration and the feed velocity, respectively.

In their original work, Song and Tay [22] were able to develop an analytical solution to Eq. (6) as follows:

$$R = \left(1 - \frac{\pi_0}{\Delta P}\right)\left[1 - e^{-\frac{\Delta P}{\pi_0}\left(\frac{\Delta P}{\Delta P^*} - R\right)}\right] \tag{7}$$

where ΔP^* is the characteristic pressure of the RO channel that was originally defined as:

$$\Delta P^* = \frac{u_0 H R_m}{L} \tag{8}$$

where L is the length of the membrane channel. In the formulation of Eq. (6), the salt concentration C is treated as one-dimensional variable along flow direction. Concentration polarization transversal to membrane surface

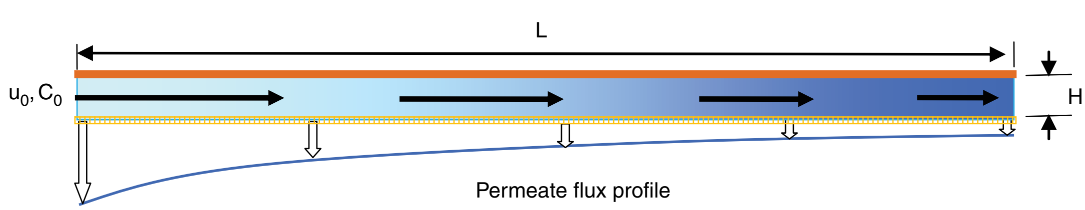

Fig. 1. A schematic presentation of the RO channel as a heterogeneous separation system.

was not considered. Therefore, in the following analysis, the effect of concentration polarization on the energy consumption was not included.

A minor modification to Eq. (7) will be made below so that it will serve our current purpose more conveniently.

By multiplying the width of the channel W simultaneously to the numerator and denominator of the right hand side of Eq. (8), and noting that feed flow rate $Q_f = u_0HW$ and total membrane area $S_m = LW$, one has:

$$\Delta P^* = \frac{Q_f R_m}{S_m} = \frac{Q_p R_m}{R S_m} = \frac{J R_m}{R} \tag{9}$$

where Q_p is the permeate flow rate and J is the average permeate flux. Substituting Eq. (9) into Eq. (7) results in:

$$R = \left(1 - \frac{\pi_0}{\Delta P}\right)\left[1 - e^{-\frac{\Delta P}{\pi_0}\left(\frac{\Delta P}{J R_m} - 1\right) R}\right] \tag{10}$$

Now the average permeate flux J is explicitly involved in Eq. (10) and the characteristic pressure ΔP^* is eliminated from the equation. When the osmotic pressure of the feed water π_0, the required permeate flux J, and the membrane resistance R_m are known, a quantitative relationship between the water recovery R and the driving pressure ΔP is established with Eq. (10). Because water recovery R appears on both sides of Eq. (10), a simple iteration scheme can be employed to find the value of R. A detailed description of the iteration scheme can be found in the original work for the derivation of the equation [22].

Eq. (10) was originally developed to determine the water recovery for a given driving pressure. However, the pressure for any given recovery can be inversely determined from the equation by the method of trial-and-error or by solving the inverse problem of Eq. (10) rigorously with a nonlinear mathematical programming method. Then the specific energies for the crossflow RO systems with and without energy recovery from the concentrate stream can be calculated with Eqs. (4) and (5), respectively.

2.3. Two extreme cases

A crossflow RO under operating conditions can be well described by Eq. (10). It can be shown that there are two extreme cases of RO operations for which much simpler equations can be used. One is the mass transfer limited case in which the recovery is linearly related to the driving pressure. Another is the thermodynamic restriction case in which the recovery is solely determined by the thermodynamic parameters of the RO process [22]. Similarly, energy consumptions in the two extreme cases can also be determined with relatively simpler equations. When a RO channel is working in the mass transfer limited regime in which the osmotic pressure of the retentate by the exit end of the channel is much smaller than the driving pressure ΔP, the required pressure can be estimated by homogenizing the RO system as:

$$\Delta P = \overline{\Delta\pi} + \bar{v} R_m = \pi_0 \frac{2 - R}{2(1 - R)} + \Delta P_{net} \tag{11}$$

where $\overline{\Delta\pi}$ is the arithmetic mean osmotic pressure in the RO membrane channel, $\bar{v}$ is the required average permeate flux, R_m is the membrane resistance, and ΔP_{net} (= $\Delta P - \overline{\Delta\pi}$) is the net driving pressure. Substituting Eq. (11) for the ΔP in Eqs. (4) and (5) results in:

$$W_4 = 2.78 \times 10^{-7} \left(\pi_0 \frac{2 - R}{2(1 - R)} + \Delta P_{net}\right) \tag{12}$$

$$W_4' = 2.78 \times 10^{-7} \frac{1}{R}\left(\pi_0 \frac{2 - R}{2(1 - R)} + \Delta P_{net}\right) \tag{13}$$

where W_4 and W_4' are the specific energies in the cross flow RO process with and without energy recovery from concentrate stream respectively, controlled by mass transfer mechanism.

When thermodynamic restriction occurs in cross flow RO, the driving pressure for the RO process with a given recovery is equal to the osmotic pressure at the exit end of the membrane channel, which can be easily determined from the initial feed salt concentration and the required recovery as:

$$\pi_c = \frac{f_{os} C_0}{1 - R} \tag{14}$$

The specific energy requirement in the cross flow RO process under thermodynamic restriction is determined by substituting Eq. (14) for ΔP in Eqs. (4) and (5):

$$W_5 = 2.78 \times 10^{-7} \frac{\pi_0}{1 - R} \tag{15}$$

$$W_5' = 2.78 \times 10^{-7} \frac{\pi_0}{R(1 - R)} \tag{16}$$

where W_5 and W_5' are the specific energies in the cross flow RO process with and without energy recovery from concentrate stream, respectively, controlled by thermodynamic restriction. The occurrence of thermodynamic restriction in the full-scale RO processes was detailed discussed by Song et al. [23] when the concept was initially proposed. However, the energy consumption was not touched that time.

3. Discussions

In this section, the values listed in Table 1 were used for parameters in all simulations unless other specified.

A trial calculation was first conducted to determine the pressure for a given recovery inversely with Eq. (10) in an MS Excel spreadsheet by the method of trial-and-error. Experience demonstrated that the task is straightforward and can be easily done. The pressures for varies feed salt concentrations determined this way were presented in Fig. 2. A net pressure of 6.89×10^5 Pa (100 psi)

Table 1
Default values of parameters used in simulations

Parameter	Value
Seawater RO membrane resistance	3×10^{11} Pa·s m^{-1}
Brackish RO membrane resistance	1×10^{11} Pa·s m^{-1}
Seawater feed salt concentration	34,500 mg l^{-1}
Brackish feed salt concentration	5000 mg l^{-1}
Osmotic pressure coefficient	73.9 Pa (mg l^{-1})$^{-1}$

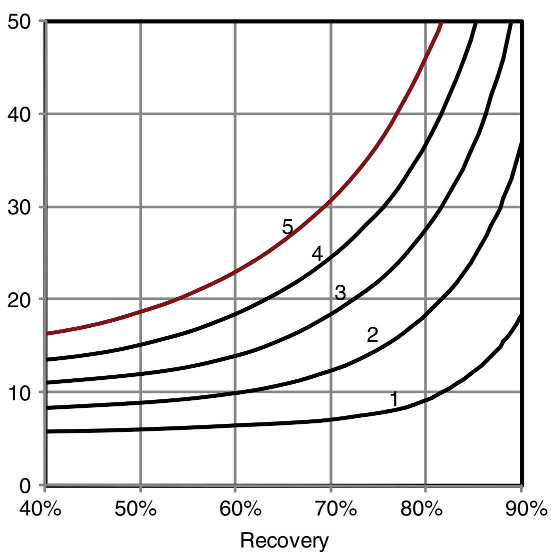

Fig. 2. The pressures determined inversely from Eq. (10) for a constant average permeate flux of 6.89×10^{-6} m s^{-1} in a RO with feed salt concentrations of: (1). 2500 mg l^{-1}, (2). 5000 mg l^{-1}, (3). 7500 mg l^{-1}, (4). 10,000 mg l^{-1}, and (5). 12,500 mg l^{-1}.

was used in the calculation, which corresponds to a constant average permeate flux of 6.89×10^{-6} m s^{-1} (14.62 gfd) in the RO channel regardless feed salt concentration and water recovery. It can be seen from Fig. 2 that the pressure increases with feed salt concentration and water recovery when a constant permeate flux is maintained. Pressure increases relatively slowly and remains below 10 bar for the feed salt concentration of 2500 mg l^{-1} for recoveries up to 82%. The increasing rate of pressure with water recovery becomes greater for higher feed salt concentrations.

3.1. Seawater desalination

Specific energy for seawater RO desalination was calculated for recoveries from 20% to 70% with a fixed permeate flux of 4.6×10^{-6} m s^{-1} (9.75 gfd). The net driving pressure for such an average permeate flux was 13.8 bar (200 psi). The results were plotted in Fig. 3 with the hypothetical specific energies for mass transfer limited and thermodynamic restricted cases. The specific energy for the ideal RO system was also plotted in Fig. 3(a) as a long dash line, which can be used as a baseline to assess the energy efficiency of the crossflow RO processes. Fig. 3(a) was for the RO system with the assumption that the energy remaining in the concentrate stream was fully recovered. Fig. 3(a) showed that the specific energy was controlled by mass transfer mechanism at low recovery end but restricted by thermodynamic equilibrium at high recovery end. Both mechanisms jointly govern the specific energy in the range of intermediate recoveries. It can be seen from Fig. 3(a) that specific energy increases with recovery when energy in the concentrate stream of the RO process is fully recovered. It makes sense because higher pressure or energy is required to squeeze water out of the membrane channel due to the higher salt concentration at higher recovery. Fig. 3(a) also showed the specific energy in crossflow RO system approaching to that of ideal RO for decreasing water recovery but deviating significantly from it with increasing water recovery. It can be seen that the thermodynamic restriction only manifests itself as the controlling mechanism at high recoveries.

The specific energy for the RO system without energy recovery was presented in Fig. 3(b), also companied by the hypothetical mass transfer limited and thermodynamic cases. Similarly, the graphs in Fig. 3(b) showed that mass transfer and thermodynamic restriction were separately the major controlling mechanisms at low and high recovery ends, respectively, and jointly for the intermediate recoveries. On the other side, the specific energy for the RO system without energy recovery is greater than that with complete energy recovery. For instance, the specific energy in the RO without energy

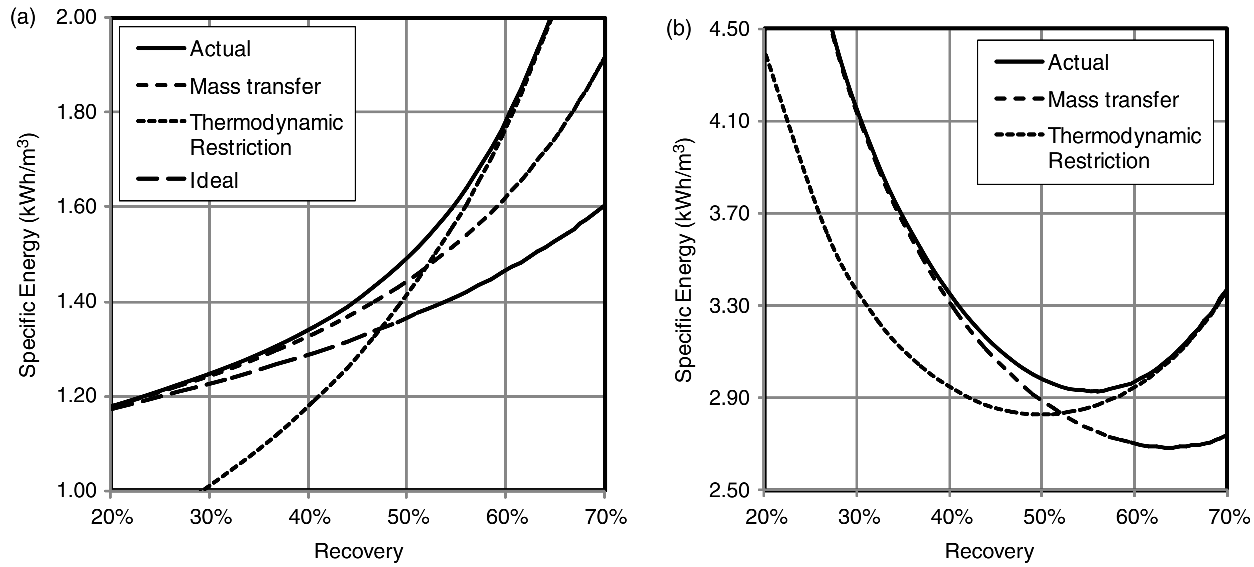

Fig. 3. Specific energies for the mass transfer limited, thermodynamic restricted, and actual cases as functions of water recovery in (a) a seawater RO system with full energy recovery from the concentrate stream and (b) a seawater RO system without energy recovery from the concentrate stream.

recovery doubles that with complete energy recovery at a water recovery of 50%. The specific energy in the RO system without energy recovery increases astonishingly as water recovery decreases from 50%. Obviously, there is a minimum in the specific energy for the RO system without energy recovery. It is interesting to note that the minimum specific energy occurs at different recoveries for the mass transfer limited, thermodynamic restricted, and the actual cases. The minimum occurs at 50% water recovery for the thermodynamic restricted case but slightly beyond 60% for the mass transfer case. The minimum specific energy of the actual RO occurs in a place that compromises with the two controlling mechanisms.

Permeate flux is an important performance indicator of RO desalination process. For a fixed RO membrane resistance, the permeate flux is directly translated to the net driving pressure ΔP_{net}. The specific energy for seawater desalination at different net driving pressures (i.e., different permeate fluxes) were calculated. The results were presented in Figs. 4(a) and 4(b), respectively, for RO systems with and without energy recovery from the concentrate stream.

The specific energies in the RO with full energy recovery from the concentrate stream increase with water recovery as shown in Fig. 4(a) while there were minimum specific energies for RO without energy recovery from the concentrate stream as shown in Fig. 4(b). Both Figs. 4(a) and 4(b) demonstrated that the magnitude of the net driving pressure (or the permeate flux level) has more profound impact on the specific energy at lower water recoveries. The reason is that when the RO system is working in the mass transfer regime, the total pressure is dominantly controlled by the net driving pressure. It can be also seen in both Figs. 4(a) and (b) that all the lines representing different net driving pressure converge together as recovery increases to 70%. The behavior indicates that the total pressure in the RO system is determined by the thermodynamic state rather than by the net driving pressure when it is working in the regime of thermodynamic restriction. Fig. 4(b) also showed that the minimum specific energy shifted to the higher recovery end with increasing net driving pressure. Overall, the most energy efficient RO systems without energy recovery from the concentrate stream should be operated at a recovery in the range of 50–60%.

3.2. Brackish desalination

Although brackish RO shares the same principles with the seawater RO, the behaviors of brackish RO can be quite different from those of seawater RO due to the significant difference in salinity and driving pressure. For this reason, the specific energy for brackish RO desalination was calculated for recoveries from 40% to 90% for a fixed permeate flux of 4.83×10^{-6} m s^{-1} (10.23 gfd). The corresponding net driving pressure for such a average permeate flux is 4.8 bar (70 psi). The results were plotted in Fig. 5 with specific energies for the hypothetical mass transfer limited and thermodynamic restricted cases, as well as the ideal RO. Similar to

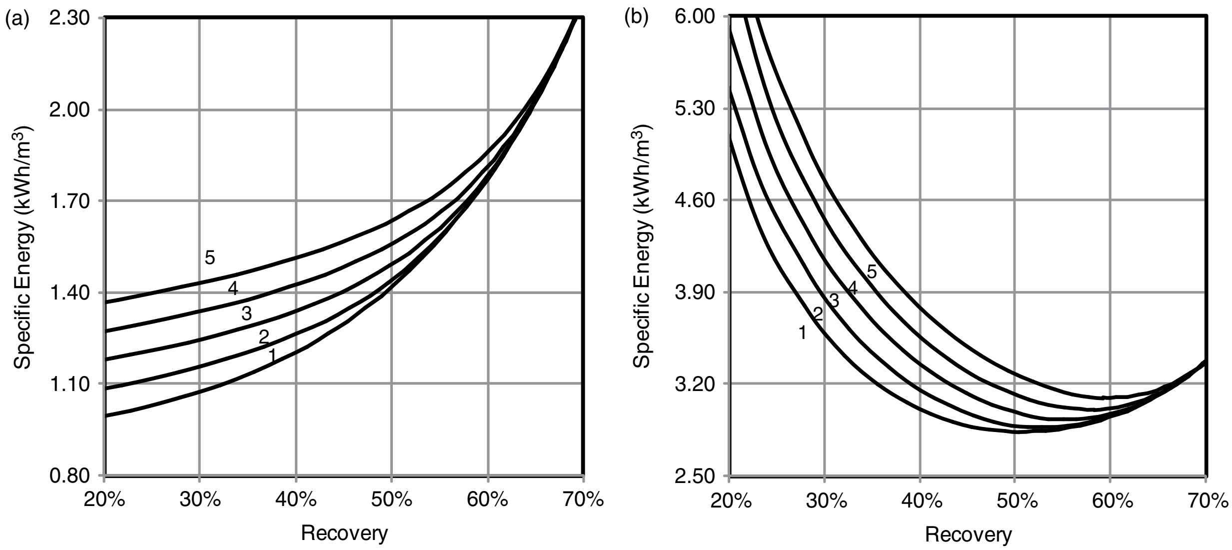

Fig. 4. Specific energies for seawater desalination were plotted as functions of water recovery in (a) an RO system with full energy recovery from the concentrate stream and (b) an RO system without energy recovery from the concentrate stream. The net driving pressures are: (1) 6.89 bar (100 psi), (2) 10.3 bar (150 pis), (3) 13.8 bar (200 psi), (4) 17.2 bar (250 psi), and (5) 20.7 bar (300 psi).

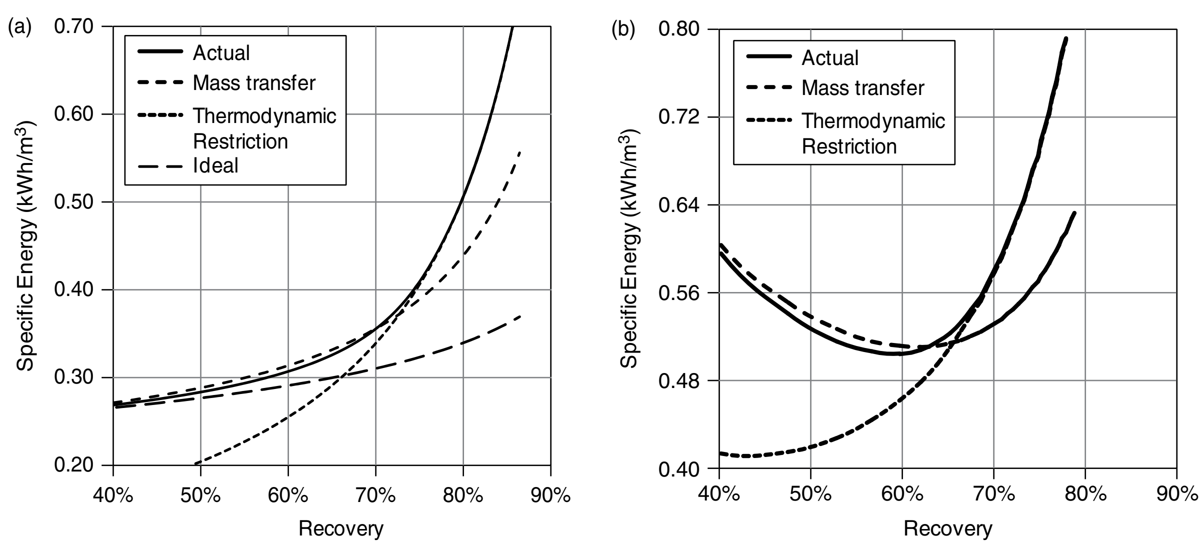

Fig. 5. Specific energies for the mass transfer limited, thermodynamic restricted, and actual cases as functions of water recovery in (a) a brackish RO system with full energy recovery from the concentrate stream and (b) a brackish RO system without energy recovery from the concentrate stream.

the situation in seawater desalination, Figs. 5(a) and 5(b) showed that the specific energy for brackish desalination in principle is also governed jointly by the mass transfer and thermodynamic restriction mechanisms. However, the actual specific energy for brackish desalination is slightly smaller than that of the hypothetical mass transfer case. The difference between the actual and mass transfer cases indicates that the mass transfer controlled case is not a good approximation to the brackish RO processes even for small recoveries. Rigorous solution to the inverse problem of Eq. (10) has to be used for a more accurate calculation of the specific energy in the brackish RO desalination systems.

The impact of the net driving pressure (average permeate flux) on the specific energy was also investigated for brackish RO systems and the results were presented

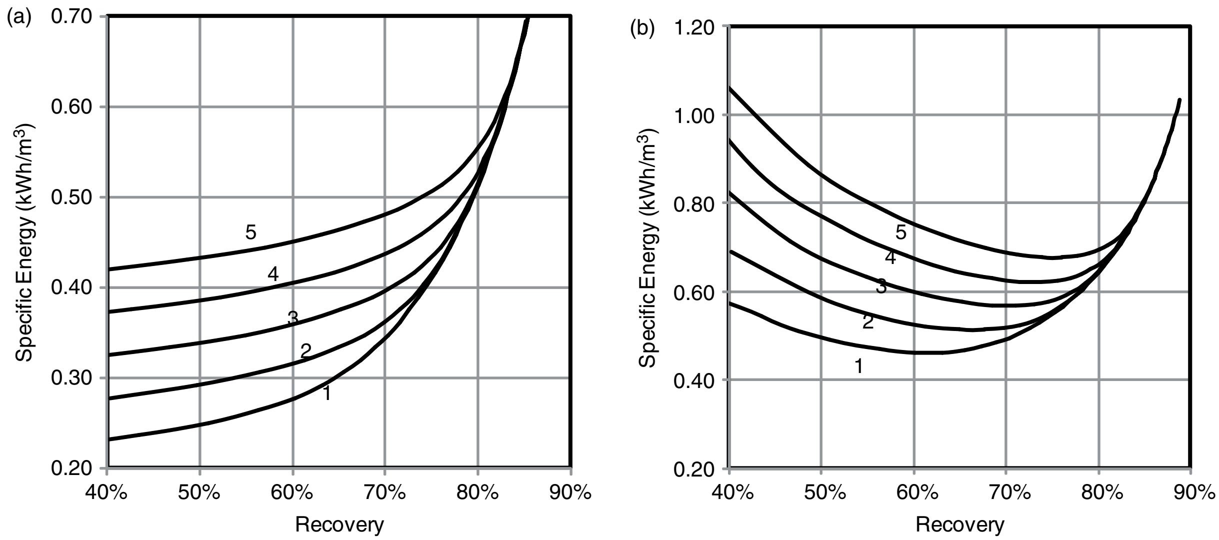

Fig. 6. Specific energies for brackish desalination were plotted as functions of water recovery in (a) a RO system with full energy recovery from the concentrate stream and (b) a RO system without energy recovery from the concentrate stream. The net driving pressures are: (1) 3.45 bar (50 psi), (2) 5.17 bar (75 psi), (3) 6.90 bar (100 psi), (4) 8.62 bar (125 psi), and (5) 10.3 bar (150 psi).

in Figs. 6(a) and 6(b) for the RO systems with and without energy recovery from the concentrate stream, respectively. It was observed again in the brackish RO systems that the net driving pressure had a strong impact on the specific energy in a wide range of water recovery. The significance of the net driving pressure on the specific energy diminished as water recovery approached to the region where thermodynamic restriction takes control. Fig. 6(b) also showed that the recovery where minimum specific energy occurs shifted from about 60% for the net driving pressure of 3.45 bar (50 psi) to about 75% for the net driving pressure of 10.3 bar (150 psi).

4. Conclusions

One of the key steps in quantifying energy consumption in crossflow RO desalination process is to determine the driving pressure that is required for a given water recovery. It has been demonstrated in this work that the driving pressure in a crossflow RO channel can be determined by solving the inverse problem of the equation that was used originally to calculate water recovery from a given driving pressure. This task can be completed straightforward with the method of trial-and-error.

The specific energy in the RO systems with concentrate energy recovery increases monotonically with the increasing recovery. It is almost equal to the specific energy in the ideal RO system at low water recoveries but departs substantially from the ideal RO as water recovery increases. The RO system without concentrate energy recovery usually has much higher specific energy at low water recoveries than the RO system with energy recovery under the same conditions. There is a minimum specific energy at a particular recovery in a RO system without concentrate stream energy recovery.

The specific energy in both RO systems with or without concentrate energy recovery were controlled mainly by mass transfer mechanism at low water recoveries and limited by thermodynamic restriction at high recoveries. The net pressure to maintain a required permeate flux is a major contributor to the total energy consumption at low recoveries when a RO process is obviously controlled by mass transfer mechanism. Its contribution to the total energy consumption reduces with increasing recovery and become insignificant when thermodynamic restriction takes over the control of the RO system.

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