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A new theoretical approach to estimate the specific energy consumption of reverse osmosis and other pressure-driven liquid-phase membrane processes

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ABSTRACT

The specific energy consumption (SEC) of pressure-driven liquid-phase membrane processes, in particular the reverse osmosis (RO) process, has usually been estimated using a phenomenological approach, which does not explicitly consider the membrane properties and operating parameters. This paper presents a new analytical approach that has been derived, from a well-established theory, to estimate the SEC and to quantify the effect of membrane properties; namely, membrane permeability and surface area as well as the effect of process parameters such as feed pressure, recovery rate, membrane element permeate rate, and feed osmotic pressure. The SEC is also presented in terms of a dimensionless parameter, namely, the specific energy indicator (SEI), which can be used as a membrane property to indicate the SEC of the membrane element for a given process recovery rate and feed osmotic pressure. The SEC calculations are presented for desalting a NaCl solution with a salinity of 35,000 mg/L over a wide range of recovery rates and membrane element permeate flow rates. The calculations showed that for a membrane element with a permeate flow rate of 2 m^3/h operating at 50% system recovery rate, the SEC of the RO process can be reduced by more than 35% if the membrane element flow rate factor is doubled, for example, from a value of 20 to 40 L/h·bar.

Keywords: Specific energy consumption; Reverse osmosis; Pressure-driven membrane separation; Desalination

1. Introduction

The provision of drinkable water supplies through the desalination of sea and ground water and through the treatment of industrial and domestic wastewater is one of the most significant challenges that the world faces [1]. The most widely used membrane and thermal desalination processes are respectively reverse osmosis (RO) and multistage-flash (MSF) distillation. Despite significant reductions in their capital and operating costs over the last 40 years, due to technological innovations and advancement, these technologies still face major operational constraints resulting in relatively high operating and capital costs, restricting their deployment to countries that can afford them [2].

RO uses significantly less energy than thermal methods because the RO process does not involve phase change. As oil prices increase, the cost of desalinated water is likely to increase too, making RO the most promising desalination technique. Yet, the breakdown of the plant total operating cost shows that approximately 50% is energy cost [3] making the process's economic viability still strongly dependent on oil prices. The RO process is the most energy-intensive pressure-driven

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membrane process with operating pressures in the range 50–80 bar for seawater desalination and 20–40 bar for brackish water applications. The high applied pressure is required to overcome the osmotic pressure of the salty water, which is a function of feed solute concentration and temperature. For example, the osmotic pressure is approximately 7.9 bars for every 1% of NaCl concentration [4]. The main aim of RO process designers and practitioners is to achieve a maximum throughput and maximum salt rejection (i.e. lower salinity of permeate, normally less than 500 ppm for drinking water applications), at minimal capital and operating costs.

In RO desalination, product capacity and quality depend on feed salinity, temperature, salt rejection, and membrane permeability. The first two parameters are imposed by the process environment and requirements. The third and fourth ones, namely salt rejection and membrane permeability, are design and technology parameters. It is important to be able to predict how variation in membrane permeability and other process parameters affect the energy consumption of the RO process.

As mentioned earlier, energy consumption is the major contributor to the operating cost of a RO unit, while high pressure pumps, pipes and valves are the most expensive parts and the main determinants of the capital cost [5]. The energy consumption is mainly at the high pressure pumps to overcome the osmotic pressure barrier. Other parts of the RO plant including the pre-treatment units and accessories, usually require less energy to operate which is normally up to 10% of the total energy consumption, unless feed water is pumped over a long distance or to a high location, in which case the energy consumption exceeds the 10% level [6]. In RO desalination, power usage effectiveness is usually represented by the specific energy consumption (SEC), which is generally the amount of energy being used to produce a unit volume of permeate (J/m^3), or commonly expressed in kWh/m^3 or kJ/kg.

In this paper a new analytical formula is derived from a well-established theory to estimate the SEC of the RO process, or any pressure-driven liquid-phase membrane process, for different process conditions. The new model allows the estimation of the SEC based on predefined design parameters and membrane properties. For the RO process, it quantifies the effect of membrane properties (e.g. membrane permeability and surface area), feed osmotic pressure and system recovery rate on the SEC. The present analyses have also included an estimation of the recovered energy, using the energy recovery system (ERS), over a wide range of process parameters. For generality, a new dimensionless parameter; namely a specific energy indicator (SEI) is defined which can be used as a membrane property to indicate the SEC of a given membrane for a given feed salinity and temperature (osmotic pressure) and process recovery rate.

This new formula can be of significant importance to RO plant designers to optimise the process in terms of the operation and design parameters, such as: recovery rate, membrane production rate, feed osmotic pressure; as well as membrane properties, namely; membrane permeability and membrane surface area. Additionally, the new approach provides a predictive tool which allows the process designer to optimise the design and performance of the membrane before doing any expensive and time consuming physical testing.

2. Specific energy consumption (SEC)

Energy is consumed in the RO process, as illustrated in Fig. 1, mainly by the high pressure pump (HPP). The specific energy consumed, E_s, can be estimated practically by using the following relation between the power delivered to the high pressure pump, HP, and the volumetric flow rate of the permeate, Q_p:

$$E_s = \frac{HP}{Q_p} \tag{1}$$

Pumping power, HP, can be estimated using the following relation [7]:

$$HP = \frac{HQ_f \rho g_c}{\eta_p} = \frac{Q_f\left(P_f - P_i\right)}{\eta_p} \tag{2}$$

where H is the actual head developed by the pump, Q_f is the volumetric feed flow rate, ρ is the fluid density, g_c is the gravity acceleration, P_f is the hydraulic pressure of the pump output, P_i is the hydraulic pressure of the pump input (intake pressure) and η_p is the pump conversion efficiency ($\eta = \eta_{pump} \bullet \eta_{motor}$).

The specific energy consumption, E_s, of the HPP can be rewritten by substituting Eq. (2) in Eq. (1):

$$E_s = \frac{Q_f\left(P_f - P_i\right)}{\eta_p Q_p} \tag{3}$$

The pump efficiency is variable and depends on the type of the pump; positive displacement pumps have overall efficiency of 85 to 95%, while centrifugal pumps are less than 60% efficient.

For generality, Eq. (3) can be expressed in terms of the process recovery rate, R, which is defined as the volu-

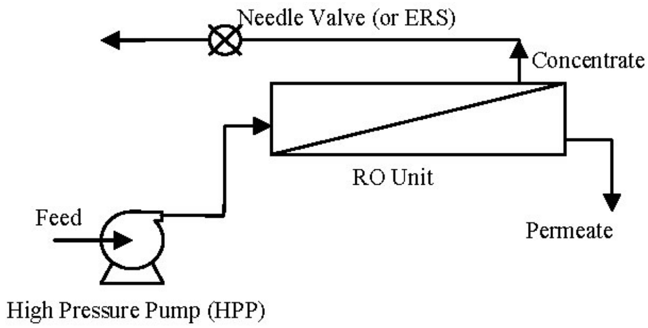

Fig. 1. Schematic diagram of a reverse osmosis unit.

metric ratio of the permeate flow rate to the feed flow rate (i.e. $R = Q_p/Q_f$):

$$E_s = \frac{P_f - P_i}{\eta_p R} \quad (4)$$

The process recovery rate plays a primary role in determining both capital and operating costs of RO systems. The recovery rate specifies the costs of pre-treatment and pumps. The operating cost is also influenced by the recovery rate dependency of the SEC [8].

Eq. (4) can be rewritten by neglecting the value of P_i as follows:

$$E_s = \frac{P_f}{\eta_p R} \quad (5)$$

Eq. (5) requires only two process parameters, namely; P_f and R, to estimate the SEC of the RO process or any pressure-driven liquid-phase membrane process.

However, while these two parameters implicitly account for the effect on the SEC of other process parameters such as feed salinity and temperature (i.e. feed osmotic pressure); hydraulic pressure losses along and across the membrane element, salinity of the concentrate (brine) and the permeate, they do not explicitly quantify the effect of other process parameters, such as membrane permeability, membrane surface area and feed osmotic pressure. This presents a limitation for the RO system designer to be able to estimate the SEC of the process in terms of the process design parameters such as the production capacity of the membrane element, process recovery rate, feed osmotic pressure and membrane permeability.

3. Energy recovery systems (ERSs)

ERSs are widely used in water treatment plants. The recovered specific energy by the ERS, $E_{s\text{-}ERS}$, is usually deducted from the total consumed energy. The net SEC, $E_{s\text{-}net}$, in such plants is calculated by:

$$E_{s\text{-}net} = E_s + E_{s\text{-}pt} + E_{s\text{-}ac} - E_{s\text{-}ERS} \quad (6)$$

where E_s, $E_{s\text{-}pt}$, and $E_{s\text{-}ac}$ are the SEC of the high pressure pump, pre-treatment units, and the accessory units, respectively. As mentioned earlier, the main component of the energy consumption in a RO plant is the HPP. This high energy consumption is due to the high operating pressure required to overcome the osmotic barrier as well as the membrane resistance, for example, the operating pressure for seawater desalination is in the range of 50–80 bar, and for brackish water treatment is in the range of 20–40 bar.

In Eq. (6), the saving in SEC due to the implementation of an ERS could be up to 50% of the total energy consumption of the RO plants, depending on the system recovery rate and the ERS conversion efficiency. But the ERS comes with a high price and normally adds up to 30% to the capital cost of the RO plant [9]. However, the ERS is only efficient for low to intermediate process recovery rates (e.g., up to 50%) and becomes less viable at higher recovery rates. This is because the recovered energy is reduced due to the smaller volume of the concentrate associated with higher recoveries (e.g., higher than 50%). Typically, most current RO plants operate with recovery rates in the range of 35–50% for seawater desalination and up to 75% for brackish water applications.

The recovered specific energy from the concentrate stream using ERS can be estimated using an equation similar to Eq. (3):

$$E_{s-ERS} = \frac{P_c Q_c \eta_{ERS}}{Q_p} \quad (7)$$

where P_c and Q_c are the hydraulic pressure and the volumetric flow rate of the concentrate stream, respectively, and η_{ERS} is the conversion efficiency of the ERS, which in some systems reaches more than 95%. Eq. (7) can be rewritten in terms of R, P_f, and E_s as:

$$E_{s-ERS} = \alpha\,\eta_{ERS}\left(\frac{1-R}{R}\right)P_f \quad (8)$$

or

$$E_{s-ERS} = \alpha\,\eta_{ERS}\eta_p(1-R)E_s \quad (9)$$

where α is the hydraulic pressure loss factor on the feed side along the membrane length, and it is defined here as the ratio of the hydraulic pressure of the concentrate stream to that of the feed stream, i.e. ($\alpha = P_c/P_f$). α normally has a value of less than 1, as the hydraulic pressure of the concentrate stream is always less than the feed pressure, due to pressure losses along the membrane element length. One of the aims of membrane designers is to minimise these pressure losses and bring the value of α closer to unity. Typical values of α are in the range 0.96–0.98 [6,10].

4. Modelling the specific energy consumption of the reverse osmosis process

The permeate volumetric flow rate through a control element of RO process, Q_p, as a function of the net applied cross-membrane pressure is given by the combined Spiegler–Kedem model [11] and concentration polarization (film theory) model as [12]:

$$Q_p = K_f(\Delta P - \sigma\phi\Delta\Pi) \tag{10}$$

where σ is the Staverman membrane reflection coefficient, ϕ is the concentration polarization (CP) factor, K_f is the membrane flow rate factor (L/h.bar) expressed here as the product of the membrane permeability (A_w in L/m^2.h.bar) and the active surface area (A_m in m^2), i.e., $K_f = A_w.\ A_m$. The pressure driving force is defined by the following relations:

$$\Delta P = \overline{P}_b - P_p\ ;\ \overline{P}_b = \frac{1}{2}\left(P_f + P_c\right) \tag{11}$$

and

$$\Delta\Pi = \overline{\Pi}_b - \Pi_p\ ;\ \overline{\Pi}_b = \frac{1}{2}\left(\Pi_f + \Pi_c\right) \tag{12}$$

where P and Π are the hydraulic and the osmotic pressure, respectively; and the subscripts f, p, c and b refer to the feed, permeate, concentrate and bulk (feed-concentrate side), respectively. The dash on the top of some variables refers to average values, and the symbol Δ refers to the difference between values across the membrane. For the product (permeate) stream, the hydraulic pressure (P_p) in Eq. (11) is assumed to be low and can be neglected. For most RO applications, Π_p is small and is normally neglected, unless the salt rejection of the membrane is low. However, in Eq. (12), Π_p is retained for completeness. $\overline{\Pi}_b$ in Eq. (12) has been evaluated as the arithmetic mean for the feed-concentrate side of the membrane and used instead of the logarithmic mean, which is more applicable, for simplicity of calculations.

It should be noted that the osmotic pressure at the membrane surface on the feed side is higher than the bulk value due to the CP effect [13]. Therefore, when calculating the design hydraulic pressure, the CP effect must be considered. This phenomenon increases the designed hydraulic pressure to overcome the osmotic pressure near the membrane surface by a factor, ϕ, ranging from 1.25 up to 1.5 depending on the; membrane geometry, system recovery rate, concentrate TDS level, membrane life, feed temperature, and fouling on the membrane's surface [6]. This factor is placed in the negative sign term of the osmotic pressure difference in Eq. (10).

In general, it is convenient to express Eq. (12) in terms of the feed osmotic pressure (Π_f). The relation between Π_c and Π_f in terms of R at a constant temperature, assuming high solute rejection rate by the membrane, can be expressed as:

$$\Pi_c = \frac{\Pi_f}{1-R} \tag{13}$$

Accordingly, Eq. (12) can be presented as:

$$\Delta\Pi = \frac{(2-R)}{(2-2R)}\Pi_f - \Pi_p \tag{14}$$

Here, we have taken the osmotic pressure on the feed side of the membrane as the average bulk osmotic pressure of the concentrate for a given recovery rate. In the present analysis, and as mentioned above, P_p is assumed to be small and can be neglected. Eq. (11) can be expressed in terms of P_f as follows:

$$\Delta P = \frac{1+\alpha}{2}P_f \tag{15}$$

By substituting Eqs. (14) and (15) in Eq. (10) and by assuming $P_p = 0$, Eq. (10) can be rewritten as:

$$Q_p = K_f\left[\frac{1+\alpha}{2}P_f - \left(\frac{2-R}{2-2R}\right)\sigma\phi\Pi_f + \sigma\phi\Pi_p\right] \tag{16}$$

Rearranging and writing Eq. (16) in terms of P_f yields:

$$P_f = \frac{2}{1+\alpha}\left[\frac{Q_p}{K_f} + \left(\frac{2-R}{2-2R}\right)\sigma\phi\Pi_f - \sigma\phi\Pi_p\right] \tag{17}$$

By combining Eq. (17) with Eq. (5), E_s can be expressed in terms of Q_p, R, K_f, Π_f, and other parameters:

$$E_s = \frac{2}{\eta_p R(1+\alpha)}\left[\frac{Q_p}{K_f} + \left(\frac{2-R}{2-2R}\right)\sigma\phi\Pi_f - \sigma\phi\Pi_p\right] \quad 18)$$

where Π_f is in bars, Q_p in L/s, K_f in L/s.bar, and E_s in J/m^3

(W.s/m^3). Eq. (18) can be derived by using the mechanical energy balance around the HPP [14]:

$$E_s = \frac{1}{\eta_p R}\left[\frac{2}{(1+\alpha)}\left(\frac{Q_p}{k_f} + \frac{2-R}{2-2R}\Pi_f - \Pi_p + P_p\right) - P_i + \rho\left(h_f - h_i\right)\right] \quad (19)$$

Eq. (19) is consistent with Eq. (18) if the values of P_i and heights difference are negligible, where h is the height and the subscripts i and f refer to the pump and the module inlets, respectively.

However, for E_s in kW.h/m^3, Π_f in bar, Q_p in m^3/h, and K_f in m^3/h.bar, which are the commonly used units in membranes applications, Eq. (18) can be re-expressed as:

$$E_s = \frac{2}{36\eta_p R(1+\alpha)}\left[\frac{Q_p}{K_f} + \left(\frac{2-R}{2-2R}\right)\sigma\phi\Pi_f - \sigma\phi\Pi_p\right] \quad (20)$$

Eq. (20) quantifies the effect of Q_p, R, K_f, and Π_f including the effect of reflection coefficient, polarization factor, and pressure losses along the membrane element on the SEC of the pressure-driven process. The first part in the square bracket of Eq. (20) accounts for the hydraulic resistance due to the membrane and fluid viscosity, while the second part accounts for the osmotic pressure barrier. Eq. (20) can also be used to calculate the SEC of any pressure-driven liquid-phase membrane process.

For the RO process, Eq. (20) shows that for particular values of Q_p, R, and Π_f, the SEC decreases as K_f increases (K_f is the reciprocal of the membrane resistance). Since the membrane flow rate factor is directly related to the membrane permeability and area ($K_f = A_w \cdot A_m$), membranes with higher permeability and/or larger area, therefore, have higher K_f values than less permeable membranes for similar membrane active areas, or less surface area for similar permeability. The actual value of K_f depends on the specific properties of the membrane as well as on the operating conditions. Membrane properties include porosity, tortuosity, active skin layer thickness, surface roughness, mean pore size, in addition to the membrane's surface active area.

Expressing K_f in terms of membrane permeability and membrane area, Eq. (20) can be rewritten as:

$$E_s = \frac{2}{36\eta_p R(1+\alpha)}\left[\frac{Q_p}{A_w.A_m} + \left(\frac{2-R}{2-2R}\right)\sigma\phi\Pi_f - \sigma\phi\Pi_p\right] \quad (21)$$

Eq. (21) can also be expressed in terms of the flux through the membrane, J, and membrane permeability, A_w, as follows:

$$E_s = \frac{2}{36\eta_p R(1+\alpha)}\left[\frac{J}{A_w} + \left(\frac{2-R}{2-2R}\right)\sigma\phi\Pi_f - \sigma\phi\Pi_p\right] \quad (22)$$

Eqs. (18)–(22) can be applied to any liquid-phase pressure-driven membrane process. These equations are derived from a well established theory and can serve as basic design equations for estimating the SEC of the RO process with reasonable assumptions and accuracy. A more rigorous analysis would involve solving a set of differential equations for the process variables; namely permeate rate, hydraulic pressure and osmotic pressure, which vary along the membrane element. Then it would be possible to integrate an equivalent set of differential equations to Eqs. (18)–(22) along the length of the membrane element for a more accurate estimate of the SEC of the process.

It is worth noting that to reduce the SEC; new membranes with higher permeability should be developed. Membrane permeability could be increased by increasing mean pore diameter, increasing membrane porosity, reducing the active layer's thickness or minimizing the micropore tortuosity. A proper value of mean pore diameter should be maintained when developing new membranes to obtain suitable salt rejection rate. For a specific membrane type, RO modules can be developed to reduce their SEC by increasing membrane element surface area to obtain higher flow rate factor. Present RO plants can reduce their SEC by increasing the number of elements but on the expense of increasing the capital cost. Additionally, increasing of the operating hydraulic feed pressure reduces the SEC by increasing process recovery rate providing keeping the permeate quality.

5. Specific energy indicator (SEI)

Eq. (20) can be used to calculate the minimum SEC of the HPP of the RO process for a given recovery rate and feed osmotic pressure. The minimum SEC is defined as the minimum specific mechanical energy required to overcome the osmotic pressure of the feed, and it is referred to as $E_{s\text{-}min}$. It is worth noting that $E_{s\text{-}min}$ of the RO process is independent of membrane properties. This may have led to the common inaccurate perception that membrane properties have little or no effect on the SEC of the RO process. This may be true for the case of the RO process operating with no throughput (i.e. Q_p= 0) or at very low throughputs. However, as will be shown later, when Q_p>0, then the impact of membrane properties on the SEC of the RO process becomes pronounced.

$E_{s\text{-}min}$ can be obtained by considering the first term in the square bracket of Eq. (20) to be zero. This gives:

$$E_{s-\min} = \frac{2}{36\eta_p R(1+\alpha)}\left[\left(\frac{2-R}{2-2R}\right)\sigma\phi\Pi_f - \sigma\phi\Pi_p\right] \quad (23)$$

Eq. (23) can be expressed by substitution from equation (14) as

$$E_{s-\min} = \frac{2\sigma\phi\Delta\Pi}{36\eta_p R(1+\alpha)} \quad (24)$$

Eq. (24) can be simplified to an ideal state by setting: σ, ϕ, α and η_p to one. Then by eliminating the conversion factor, to be written as follows:

$$E_{s-\min} = \frac{\Delta\Pi}{R} = \frac{Q_f.\Delta\Pi}{Q_p} \quad (25)$$

Eq. (25) is consistent with the analysis of Spiegler and Al-Sayed [15] for the theoretical (ideal) minimum work per unit product of a reverse osmosis process, W_{th0}:

$$W_{th0} = V_f.\Pi_f \quad (26)$$

where V_f and P_f are the volume and the osmotic pressure of the feed solution, respectively.

In general, it is more convenient to express SEC in dimensionless form. For that we introduced a dimensionless parameter, namely, an SEI, which is defined as the ratio of the SEC (E_s) to the minimum SEC ($E_{s\text{-}min}$) of the RO process, i.e., dividing Eq. (20) by Eq. (23). The SEI of the RO process for a given Q_p, R, K_f, and Π_f, is given by:

$$SEI = \frac{Q_p}{K_f}\left[=\left(\frac{2-R}{2-2R}\right)\sigma\phi\Pi_f - \sigma\phi\Pi_p\right]^{-1} + 1 \quad (27)$$

Eq. (27) shows that for a given Q_p, R, and Π_f, the SEI decreases, as K_f increases, to approach a value of unity, which represents the minimum SEC of the process.

For seawater desalination, it may be reasonable to assume the feed osmotic pressure to be the same as that of NaCl solution with 35,000 mg/L concentration. This would allow the SEI to be estimated for each RO membrane and used as a membrane property to indicate the SEC of that membrane for seawater desalination applications. However, care should be taken as a lower permeate flow rate element would give lower SEI but this could be done at the expense of increasing the number of membrane elements for a given plant capacity, i.e. increasing plant footprint size and hence increasing capital cost. An optimal value of SEI would have to be obtained in combination with optimal membrane permeate rate and process operation conditions.

6. Results and discussion

A number of illustrative examples are presented here to investigate and quantify the effect of the main design parameters Q_p and R as well as the membrane property K_f (consequently A_w and A_m) on the SEC of the HPP (E_s), which, as has been mentioned earlier, is the main energy consumer in the RO seawater desalination process. These illustrative examples are summarized in Table 1.

For the generation of these results, the feed osmotic pressure (Π_f) was set to that of an NaCl solution having 35,000 mg/L concentration, which is equivalent to seawater salinity having an osmotic pressure of approximately 27 bar, and the values of η_p, ϕ and σ were all assumed to be equal to 1, α= 0.97, while Π_p was considered zero to simplify the calculations.

Fig. 2 shows the effect of the variation of K_f on E_s for different values of Q_p (e.g., 1, 2, and 3 m^3/h) where R and Π_f are fixed at 50% and 27 bar, respectively. The results show that as K_f increases (i.e. increasing A_w or A_m or both), E_s of the RO process is reduced. However, the reduction in E_s with increasing K_f is nonlinear. It is more pronounced at values of K_f below 40 L/h.bar, and becomes less noticeable as the K_f value increases beyond 100 L/h.bar. It should be noted that most commercial RO membranes have values of K_f in the range of 15–30 L/h.bar [16].

Fig. 2 also shows that E_s increases with Q_p. However, at lower values of K_f (e.g. K_f<40 *l*/h·bar) increasing the Q_p has more impact on E_s than at large values of K_f (e.g. K_f >40 L/h·bar). In other words, by using membranes which have higher values of K_f, the SEC of the process becomes less dependent on Q_p. Furthermore, based on Eq. (20), Fig. 2 shows that E_s of an RO process approaches its minimum value if the membrane K_f value exceeded 180 L/h·bar regardless of membrane product rate.

The results obtained are also consistent with the general understanding that low SEC values are obtained when operating membrane elements with low permeate flow rate (Q_p <0.5 m^3/h). This, as mentioned previously, could increase capital cost significantly as the number of

Table 1
Description of the illustrative examples

Figure no.	Description
2	Variation of E_s with K_f for various values of Q_p at Π_f=27 bar and R =50%.
3	Variation of E_s with Q_p for various values of K_f at Π_f = 27 bar and R =50%.
4	Variation of E_s with Q_p for various values of R at Π_f = 27 bar and K_f = 25 L/h.bar.
5	Variation of E_s with R for various values of Q_p at Π_f = 27 bar and K_f = 25 L/h.bar.

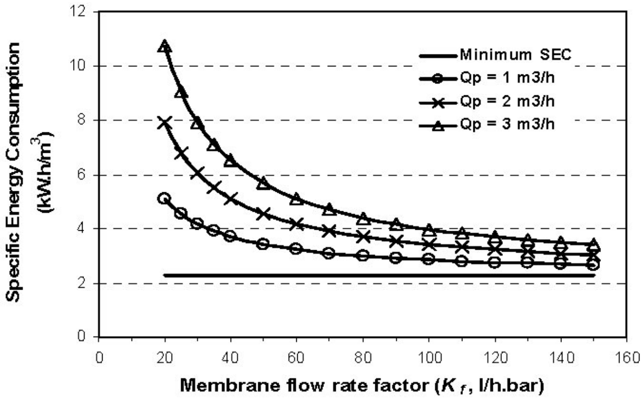

Fig. 2. Variation of E_s with K_f for various values of Q_p at Π_f = 27 bar and R = 50%.

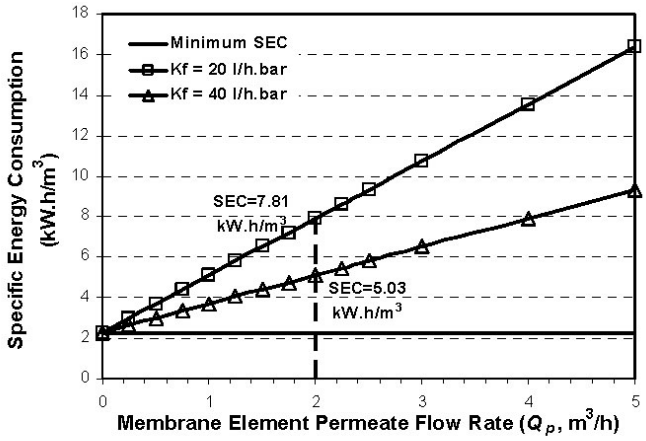

Fig. 3. Variation of E_s with Q_p for various values of K_f at R = 50% and Π_f = 27 bar.

the membrane elements is increased for a given plant capacity.

In order to explain the above results, for a fixed feed osmotic pressure (Π_f) and Π_p= 0, Eq. (20) is expressed in the following form:

$$E_s\left(Q_p,R,K_f\right)=\frac{a(R)Q_p}{K_f}+b(R) \tag{28}$$

where

$$a(R)=\frac{2}{36\eta_p(1+\alpha)R} \tag{29}$$

$$b(R)=\frac{2}{36\eta_p(1+\alpha)R}\left(\frac{2-R}{2-2R}\right)\sigma\phi\Pi_f \tag{30}$$

In Eq. (28), the first and the second terms account for membrane hydraulic resistance and osmotic pressure barrier respectively. It is clear from Equation (28) that for a fixed value of R and feed osmotic pressure, the SEC becomes a function of membrane hydraulic resistance only. The hydraulic pressure and consequently the SEC of the high pressure pump are directly proportional to the volumetric flow rate (Q_p) and inversely proportional to the membrane flow rate factor (K_f), as evidenced in Fig. 2.

Now, for certain design parameters (e.g., $R = R_0$, $Q_p = Q_{p0}$), we can derive an equation that can be used to select an optimum membrane property (K_f) and provide the minimum specific energy consumption. It is clear that taking the first derivative (dE_s/dK_f) of Eq. (28), equating it to zero, and solving for K_f, yields no solution with $K_f \rightarrow \infty$. Therefore, instead of equating the first derivative to zero, we can equate it to a certain small value (G) that represents the change in SEC (E_s) with respect to K_f. Then the value of K_f obtained is:

$$K_f=\sqrt{\frac{-a(R_o)Q_{p0}}{G}} \tag{31}$$

The negative sign in Eq. (31) is due the fact that as K_f increases, E_s decreases (i.e., G is a negative value). The value of G in design application can be set to a small value as, e.g., –100 kW.h^2.bar/m^6.

Fig. 3 shows the effect of Q_p on E_s for the RO process at fixed process recovery rate (R = 50%) and feed salinity (Π_f = 27 bar) for two types of membranes, as characterised by the two flow rate factors of 20 and 40 L/h.bar. The results show that operation of both membranes with no throughput (i.e. Q_p = 0) yields the same $E_{s\text{-}min}$, since $E_{s\text{-}min}$ is dependent on the osmotic pressure only, which has been left constant in this case, and is independent of either the membrane type or its properties. However, with a pronounced throughput (Q_p >0), the membrane with the higher K_f requires less energy, with this difference in energy consumption between the two membranes increasing as Q_p increases.

As mentioned before, most of the commercial RO membranes have a production capacity of around 2 m^3/h. Fig. 3 shows that for a given RO process more than 35% saving in the E_s can be achieved by increasing the K_f from 20 to 40 L/h.bar. Increasing of K_f can be achieved by increasing the membrane area and/or membrane permeability. A similar plot to Fig. 3 can be obtained for the SEC vs. membrane flux at different membrane permeabilities, i.e. at constant membrane area. The SEC decreases as the membrane permeability increases at certain value of membrane flux.

Fig. 4 shows the variation of E_s with Q_p for a number of values of R at Π_f = 27 bar and K_f = 25 L/h.bar. It shows that

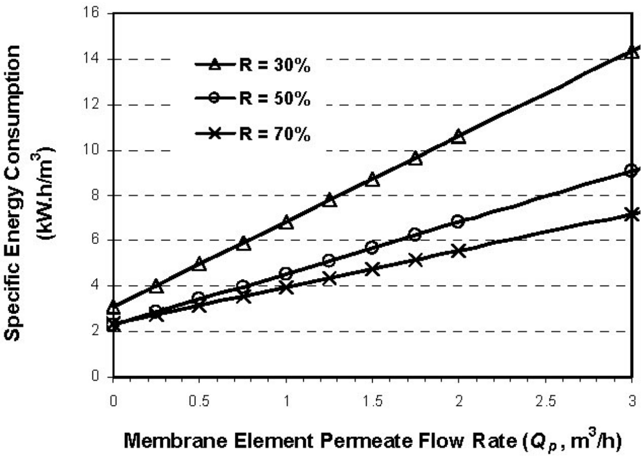

Fig. 4. Variation of E_s with Q_p for various values of R and constant values of K_f = 25 l/h.bar and Π_f = 27 bar.

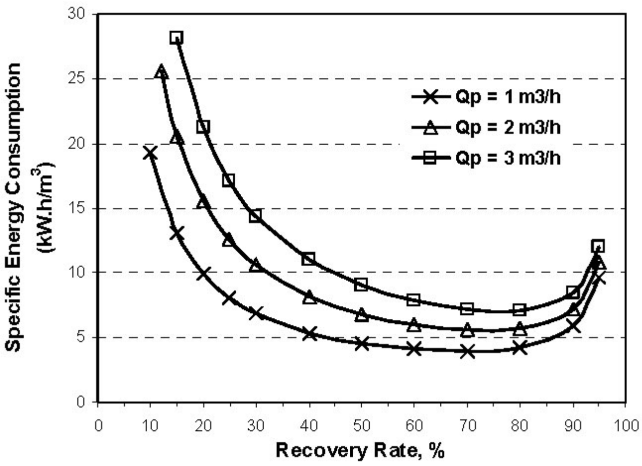

Fig. 5. Variation of E_s with the membrane recovery rate for different values of Q_p and constant values of K_f = 25 L/h.bar and Π_f =27 bar.

for a particular R value, E_s varies linearly with Q_p but the rate of this variation (slope of the line) decreases as R increases.

Fig. 5 shows the effect of increasing R on E_s for different values of Q_p and constant values of K_f = 25 L/h.bar and Π_f =27 bar. It shows that E_s decreases as R increases due to an increase in membrane utilisation up to a certain value of R, above which E_s starts to increase. This is because the feed hydraulic pressure and bulk side osmotic pressure increase with the increase in recovery rate. The value of R at which E_s is at the minimum, R_0, can be derived by setting the derivative of Eq. (20) with respect to R to zero. For certain values of Q_p, K_f, α, σ, ϕ, and Π_f, R_0 is:

$$R_0 = \frac{1-\sqrt{1-k}}{k} \tag{32}$$

where

$$k = \frac{2C_0 + C_1}{2(C_0 + C_1)},\ C_0 = \frac{2Q_p}{36\eta_p(1+\alpha)K_f},\ C_1 = \frac{2\sigma\phi\Pi_f}{36\eta_p(1+\alpha)} \tag{33}$$

7. Conclusions

A new theoretical model has been derived from a well-established theory to estimate the SEC of the RO process and any other pressure-driven liquid-phase membrane process. The new model allows quantifying the effect of membrane properties; namely, membrane permeability and membrane surface area as well as the effects of process parameters such as recovery rate, permeate flow rate, applied pressure and feed salinity (osmotic pressure).

The results of the present study have shown that the relationship between the SEC of the RO process and the membrane flow rate factor is nonlinear where the effect is much higher at small values of the membrane flow rate factor (K_f <40 L/h.bar). The results also show that for a given feed osmotic pressure and membrane element permeate rate, minimal specific energy consumption is obtained at a recovery rate of 70% for membrane permeate rate of less than 2 m^3/h. Therefore, for a membrane module with higher permeate rate, the minimum SEC can be achieved at high recovery rates.

A dimensionless parameter, namely, the specific energy indicator, can be used as a membrane property to indicate the SEC of that membrane. SEI is defined as the ratio of the SEC at given operating conditions to the minimum SEC which is equivalent to the osmotic barrier of the RO process for a given feed osmotic pressure and process recovery rate. An optimal value of SEI would have to be obtained in combination with optimal membrane permeate rate and process operation conditions.

The present results suggest that in the RO process lower specific energy consumption can also be achieved by using membranes with a higher flow rate factor (i.e., higher permeability and surface area).

The present model can be implemented into an algorithm for defining optimum process operating parameters for RO systems or any pressure-driven membrane process where recovery rate, permeate flow rate, membrane area and SEC are to be optimised.

8. Symbols

A_m — Membrane surface area, m^2

A_w — Membrane permeability, L/m^2.h.bar

E_s — Specific energy consumption of the high pressure pump, kWh/m^3

$E_{s\text{-}ac}$	—	Specific energy consumption of the accessory units, kWh/m^3
$E_{s\text{-}ERS}$	—	Recovered specific energy by the energy recovery system, kWh/m^3.
$E_{s\text{-}min}$	—	Minimum specific energy consumption, kWh/m^3
$E_{\text{s-net}}$	—	Net specific energy consumption, kWh/m^3
$E_{\text{s-pt}}$	—	Specific energy consumption of the pre-treatment units, kWh/m^3
g_c	—	Gravity acceleration
J	—	Permeate flux through the membrane, L/m^2.h.
K_f	—	Membrane flow rate factor, L/h.bar
P	—	Hydraulic pressure, bar
$\overline{P}$	—	Average hydraulic pressure, bar
Q	—	Permeate volumetric flow rate, m^3/h
R	—	System recovery rate ($R = Q_p/Q_f$)

Greek

α	—	Hydraulic pressure losses factor ($\alpha = P_c/P_f$)
Δ	—	Difference across the membrane
ϕ	—	Concentration polarization (CP) factor
Π	—	Osmotic pressure, bar
$\overline{\Pi}$	—	Average osmotic pressure, bar
η_{ERS}	—	Energy recovery system conversion efficiency
η_p	—	High pressure pump conversion efficiency
ρ	—	Fluid density, kg/m^3
σ	—	Membrane reflection coefficient

Subscripts

c	—	Concentrate stream
f	—	Feed stream
p	—	Permeate stream
b	—	Bulk side (feed–concentrate) of membranes

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