

# 11

## Fundamentals of reverse osmosis

*Mark Wilf\**

Osmosis is a natural process of transport of solution constituents across a semipermeable membrane barrier. It is selective in the sense that the solvent passes through the membrane at a faster rate than the passage of dissolved solids. The difference of passage rate results in solvent–solids separation. The net direction of mass transport through the membrane is determined by the chemical potential of solution, at each side of the membrane. The chemical potential is a function of pressure, temperature, and concentration of dissolved species. Pure water in contact with both sides of an ideal semipermeable membrane at equal pressure and temperature has no net flow across the membrane because the chemical potential is equal on both sides. If a soluble salt is added to the water on one side of the membrane, the chemical potential of this salt solution is reduced. Osmotic flow, from the pure water side across the membrane to the salt solution side, will occur until the equilibrium of chemical potential is restored. In reverse osmosis process, pressure is applied to overcome the difference of chemical potential, due to salinity gradient, and to force water flow from a high salinity solution, through the membrane, to the low salinity solution.

### 11.1 Osmotic pressure of water solutions

The osmotic pressure,  $P_{\text{osm}}$ , of low salinity solutions can be determined indirectly by measuring the concentration of dissolved species in solution:

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$$P_{\text{osm}} = \text{UGC} \times (T + 273) \times \Sigma(m_i) \tag{11.1}$$

where  $P_{\text{osm}}$  is osmotic pressure (in bar), UGC is universal gas constant (0.082 l\*atm/mol × °K), T is the temperature (in °C), and  $\Sigma(m_i)$  is the sum of molar concentration of all constituents in a solution.

Eq. 11.1 is sufficiently accurate only for dilute salt solutions and temperatures close to 25°C. At significantly different conditions a more rigorous calculations that take into consideration ions activities rather than concentrations, have to be applied.

An approximate calculation of  $P_{\text{osm}}$  can be made by assuming that 1000 ppm concentration of Total Dissolved Solids (TDS) equals about 0.77 bar (11 psi) of osmotic pressure. For RO applications osmotic pressure is calculated, using computer programs. The calculations are based on concentration of individual ions and their contribution to osmotic pressure of solution. Approximate values of osmotic pressure for solutions of various salinities are listed in table 11.1.

### 11.2 Salt-water separation in reverse osmosis process

Under applied hydrostatic pressure, the semipermeable reverse osmosis membranes have the property of facilitating transport of solvent (water) through the membrane at a much higher rate than the parallel flow of solute (dissolved species). Preferential transport of solvent through the membrane could be the result of higher solubility of solvent in membrane polymer, membrane pore structure that hinders passage of solute molecules or repulsion of ionized species by membrane surface due to excess of membrane surface electrostatic charges.

TABLE 11.1  
Osmotic pressure of solutions with various concentration of dissolved solids.

Salinity, ppm TDS	1,000	2,000	5,000	10,000	35,000	70,000
p@ 30°C	0.8 bar (12 psi)	1.7 bar (24 psi)	3.3 bar (48 psi)	6.8 bar (99 psi)	25.7 bar (372 psi)	51.3 bar (744 psi)
p@ 15°C	0.7 bar (10 psi)	1.5 bar (22 psi)	3.2 bar (46 psi)	6.5 bar (94 psi)	24.5 bar (355 psi)	48.8 bar (708 psi)

### 11.2.1 Water transport

The rate of water passage through a semipermeable membrane is defined in Eq. 11.2:

$$Q_w = (DP - DP_{osm}) \times K_w \times S/d \quad (11.2)$$

where  $Q_w$  is the rate of water flow through the membrane,  $DP$  is the hydrostatic pressure differential across the membrane,  $DP_{osm}$  is the osmotic pressure differential across the membrane,  $K_w$  is the membrane permeability coefficient for water,  $S$  is the membrane area, and  $d$  is the membrane thickness.

This equation can be simplified to:

$$Q_w = A \times S \times NDP \quad (11.3)$$

where  $A$  is water transport coefficient and represents a unique constant for each membrane material type, and  $NDP$  is the net driving pressure or net driving force for the mass transfer of water across the membrane ( $NDP = DP - DP_{osm}$ ).

The units of water transport coefficient  $A$  are:  $g/cm^2/sec$  ( $gallon/ft^2/psi$ )

### 11.2.2 Salt transport

The rate of salt flow through the membrane is defined by Eq. 11.4:

$$Q_s = (C_f - C_p) \times K_s \times S/d \quad (11.4)$$

where  $Q_s$  is the flow rate of salt through the membrane,  $K_s$  is the membrane permeability coefficient for salt,  $(C_f - C_p)$  is the salt concentration differential of feed and permeate across the membrane,  $S$  is the membrane area, and  $d$  is the membrane thickness.

Eq. 11.4 can be simplified to:

$$Q_s = B \times S \times DC \quad (11.5)$$

where  $B$  is the salt transport coefficient and represents a unique constant for each membrane type, and  $DC$  is the concentration gradient which is the driving force for the transfer of dissolved ions through the membrane ( $DC = C_f - C_p$ ).

The units of salt transport coefficient  $B$  are  $cm/sec$  ( $ft/sec$ )

Eqs. 11.3 and 11.5 show that for a given membrane:

- a. Rate of water flow through a membrane is proportional to net driving pressure (NDP) differential across the membrane.
- b. Rate of salt flow is proportional to the concentration differential across the membrane and is independent of applied pressure.

Salinity of the permeate,  $C_p$ , depends on the relative rates of water and salt transport through reverse osmosis membrane:

$$C_p = Q_s/Q_w = (B \times S \times DC) / (A \times S \times NDP) \quad (11.6)$$

Applying the fundamental equations of water flow and salt flow illustrates some of the basic principles of RO membranes. For example, apparent salt passage is an inverse function of pressure; that is, the salt passage increases as applied pressure decreases. This is because with reduced feed pressure permeate flow rate decreases and hence dilution of salt, on the permeate side of the membrane, decreases as well (the salt flows through the membrane at a constant rate as the rate of flow is independent of pressure).

The fact that water and salt have different mass transfer rates through a semipermeable membrane creates the phenomena of water-salt separation and salt rejection. No membrane is ideal in the sense that it absolutely rejects salts; rather the different transport rates of water and dissolved ions create an apparent rejection. Eqs. 11.2–11.6 explain important design considerations in RO systems. For example, an increase in operating pressure will increase water flow without significantly affecting salt flow, thus resulting in lower permeate salinity. On the other hand, higher recovery rate will increase concentration gradient and result in higher permeate salinity. More rigorous derivation of transport relations can be found in references 1 and 2.

The direct relation of permeate salinity on salinity gradient and NDP, as expressed in Eq. 11.6 is based on a simple model that the effect of salt rejection is mainly result of difference of diffusion rates of water and solute through the membrane. A more realistic approach defines (3) solute transport mechanism as significant contributions of three processes: diffusion, convection and electrical migration. The convection contribution is the result of drag of dissolved species by the water permeating through the membrane. The practical effect of this contribution is that increase of water flux (due to increase of NDP through the increase of feed pressure) does not result in a proportional decrease of permeate

salinity. The decrease of permeate salinity gradually levels off at higher fluxes.

The effect of electrical migration on salt transport is a result of membrane surface charges and interaction between membrane surface charges and charged dissolved species in the feed water (3, 4). The surface of polyamide membrane is negatively charged due to presence of residual carboxylic groups. The presence of surface charges result in repulsion of co-ions and attraction of counter ions. The contribution of electric migration on salt passage is not constant but varies with feed water salinity as shown on Fig. 11.1.

At given operating parameters of RO membrane unit and for given membrane type, the permeate concentration is direct function of feed salinity. However, careful examination of experimental data for brackish composite polyamide membranes shows that there is anomaly of salt passage at very low and very high feed salinities (4). It is shown in Fig. 11.1 that for brackish RO membranes there is a minimum of salt passage at feed salinity of about 500 ppm. In the narrow range below this salinity, a steep increase of salt passage is observed.

There is also increase of salt passage at higher feed salinities, above about 500–800 ppm TDS range. However, in this salinity range the salt passage increase is at a lower rate as compared to increase at the very low salinity range. Eventually, at high feed salinities of about 5,500 TDS ppm the salt passage levels off. This effect of salt passage increase should be consider in calculations of permeate salinity.

The increase of salt passage in the low feed salinity range is quite important

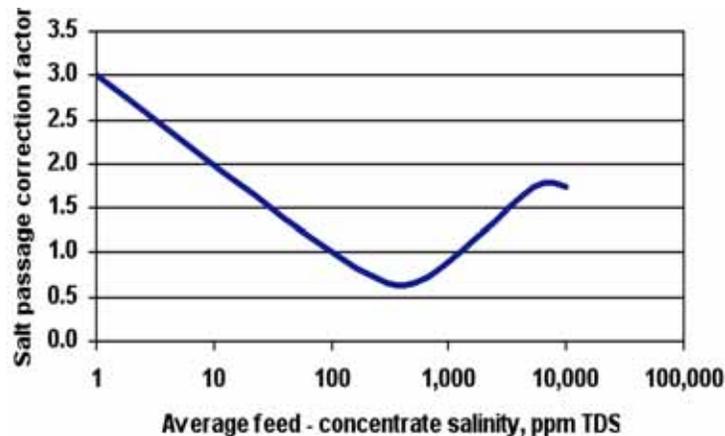


FIG. 11.1 Effect of feed salinity on salt passage using polyamide membrane.

in ultrapure water applications such as production of make up water for high pressure boilers and process water for semiconductor industry. Table 11.2 shows representative values of ion passage in RO systems treating low salinity and high salinity brackish feed and RO permeate.

The salt passage increase with increased salinity occurs in almost all RO brackish water systems. Even in systems operating with low feed salinity, due to the effect of water recovery–concentration gradient, the elements positioned close to the concentrate end, are exposed to high salinity water. In the process of membrane elements manufacturing, the nominal salt rejection is determined using single salt solution: NaCl. In field applications, feed water is composed of variety of ions, which diffuse through the membrane at different rates. In addition, membrane surface of polyamide membranes is negatively charged which contributes to salt rejection through repulsion of negatively charged ions.

When treating a solution of mixed ions composition the ion passage is affected by counter ions charge balance (Donnan effect). Therefore, presence in feed water

TABLE 11.2  
Illustration of potential reduction of feed concentration in an RO system.

Feed constituent	Low salinity brackish			High salinity brackish			Second pass RO		
	Feed ppm	Perm. ppm	Passage % <sup>1</sup>	Feed ppm	Perm. Ppm	Passage % <sup>1</sup>	Feed ppm	Perm. ppm	Passage % <sup>1</sup>
Ca	83	0.6	0.7	254	1.6	0.6	0.2	ND	
Mg	66	0.5	0.8	120	0.8	0.7	0.1	ND	
Na	350	11.5	3.3	1214	36.6	3.1	2.7	0.2	7.4
K	4	0.2	5.0	12	0.4	3.3	0.3	ND	
HCO <sub>3</sub>	340	10.6	3.2	100	5.0	5.0	11		
SO <sub>4</sub>	74	0.3	0.4	778	5.5	0.7			
Cl	600	10.5	1.8	2034	56.9	2.8	2.2	0.2	9.1
F	0.8	0.03	0.4	2.4	0.1	0.4			
NO <sub>3</sub>	46	5.6	12						
SiO <sub>2</sub>	29	0.5	1.7						
TDS	1564	39.8	2.5	4514	107	2.4	15.5	1.2	7.7

<sup>1</sup> For the purpose of illustration of potential concentration reduction, passage is being calculated relative to the concentration in the feed stream. These values of ions passage are higher than the usual values calculated relatively to the average feed (average of feed and concentrate)

of ions with high transport rate through the membrane (like  $\text{HCO}_3^-$ ) will increase passage of positively charged ions, contributing to increasing salt passage. Conversely, significant concentration of large, slowly diffusing ions (like  $\text{SO}_4^{2-}$ ) will retard passage of associated cations and result in lower permeate salinity. In addition, high concentration of ions with high positive charges, such as calcium and magnesium, will tend to neutralize negative membrane surface charge, reducing ions rejection that is due to surface-anions charge repulsion. Due to above effects, salt passage of brackish membranes in field conditions could differ significantly from the nominal values, obtained during factory testing.

In brackish and nanofiltration applications salt passage is affected by the ion composition of feed water. The effect of feed water composition on salt passage is most pronounced in softening (nanofiltration) membranes. The salt rejection of nanofiltration membranes is low and most of them have high surface charges. Therefore, exposure to mixed ion solution with high fraction of concentration of divalent cations will result in significant salt passage increase.

Another rejection phenomena, specifically related to reduction of concentration of dissolved organics is adsorption of organic feed constituents in the membrane material. Otherwise poorly rejected small organics, could show initially high rejection rate, due to adsorption in the RO membrane. After arriving at saturation level, a sharp passage increase of passage is observed. Usually, pilot unit operation is necessary to identify such process and determine rejection parameters for a given constituent.

### 11.3 Water salinity

Natural water sources contain dissolved ions at various concentrations, ranging from low salinity potable water of less than 0.05% concentration of dissolved ions to seawater of concentration of 3%–4.5% of dissolved salts.

The concentration of dissolved ions in water is expressed as parts per million (PPM), which, at low concentrations, is equivalent to milligrams per liter (mg/l) or grams per cubic meter ( $\text{g}/\text{m}^3$ ). Sometimes concentration is expressed as % of weight of dissolved ions in the total weight of solution. Approximately 10,000 ppm equals to 1% weight concentration. Concentrations can also be expressed as miliequivalents per liter (meqv/l). Miliequivalent concentration is calculated by dividing concentration, expressed as ppm, by ion weight valency. For example, calcium (Ca) ion concentration of 1000 ppm is equivalent to meqv concentration of  $1000/20 = 50$  meqv/l.

Direct determination of total dissolved solids concentration is quite cumbersome. It requires evaporation to dryness of accurately weighted volume of water solution and weight determination of the dry residue. The most common approach to measurement of concentration of total dissolved solids in solution is through analytical determination of concentration of dissolved ions and summation of individual ions concentrations.

Approximate determination of total concentration of dissolved ions can be accomplished by measurement of electrical conductivity of water solutions according to the equation:

$$\text{TDS} = K \times \text{EC} \quad (11.7)$$

where TDS is concentration in ppm, K is conversion factor and EC is electric conductivity in mS/cm (S = Simens).

For a single salt solution, the electrical conductivity of solution EC will be a sum of conductance of ions composing the dissolved salt.

$$\text{EC} = (\Lambda^+ + \Lambda^-) \times C \quad (11.8)$$

where  $\Lambda$  is molar conductance of a given ion expressed as  $\text{S} \times \text{cm}^2/\text{mol}$  and C is molar concentration of ion in solution expressed as mol/liter

The molar conductance of different ions covers quite a wide range of values. The reference values of molar conductances of highly mobile hydroxyl and hydrogen ions are about 200 and 350  $\text{S} \times \text{cm}^2/\text{mol}$  respectively. The reference value for chloride ion is significantly lower at 76  $\text{S} \times \text{cm}^2/\text{mol}$  and the conductance for bicarbonate ion it is only 45  $\text{S} \times \text{cm}^2/\text{mol}$ . Values of molar conductances of different ions are available in majority of handbooks of physics and chemistry.

It is obvious that electrical conductivity of solution will depend on its composition. Therefore, conductivity conversion to TDS has to be calibrated, using other means of TDS determination, for each site. In RO system the conversion factor, between electrical conductivity and TDS, will have different values for feed water, permeate water and concentrate stream. This is because relative concentration of ions changes in the RO process. RO permeate will have lower ratio of divalent to monovalent ions than the feed water and for concentrate this ratio will be higher. The common values of the conversion factor K, are in range of about 0.55 for RO permeate up to 0.75 for seawater concentrate (5).

The composite conductivity of ions in solution is easily measurable. It is customary to express it as micro Siemens per cm: mS/cm. Electrical conductivity of

solution is also affected by temperature. Conductivity varies about 2% per degree °C and is customary reported as corrected value at 25°C.

Determination of detailed composition of feed water is important proper design of RO system and determination of operating parameters.

### 11.4 Permeate recovery rate

Permeate recovery is one of more important parameters in the design and operation of RO systems. Recovery or conversion rate of feed water to product (permeate) is defined by Equation 11.9 and 11.10 and illustrated in Fig. 11.2:

$$R = 100\% \times Q_p / Q_f \tag{11.9}$$

$$R = 100\% \times Q_p / (Q_p + Q_c) \tag{11.10}$$

where R is recovery rate (in %),  $Q_p$  is the product water flow rate,  $Q_f$  is the feed water flow rate and  $Q_c$  is the concentrate flow rate.

The recovery rate affects salt passage and product flow. As the recovery rate increases, the salt concentration on the feed-brine side of the membrane increases. According to Eq. 11.5, higher concentration gradient, causes an increase of salt flow rate across the membrane. In parallel, a higher salt concentration of the feed-brine solution increases the osmotic pressure, reducing the net driving pressure available and consequently reducing the product water flow rate.

Using Eq. 11.10 and mass balance a relation can be developed between recovery and concentration of various streams in the RO unit:

$$R = Q_p / (Q_p + Q_c)$$

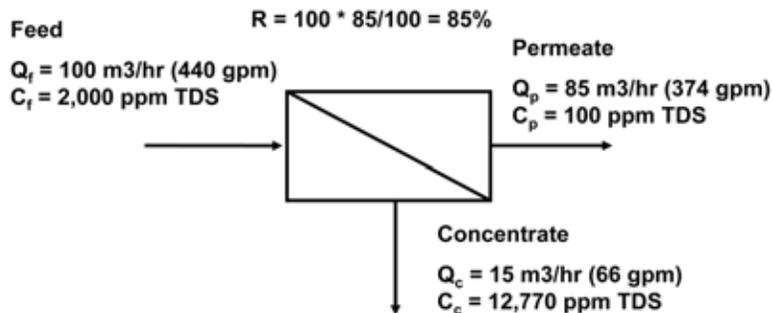


FIG. 11.2 Mass and flow balance in reverse osmosis unit. Recovery rate 85%.

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$$\begin{aligned}
 Q_f C_f &= Q_p C_p + Q_c C_c \\
 Q_f C_f &= Q_p C_p + (Q_f - Q_p) C_c \\
 Q_f (C_f - C_c) &= Q_p (C_p - C_c) \\
 R = Q_p / Q_f &= (C_c - C_f) / (C_c - C_p)
 \end{aligned}
 \tag{11.11}$$

where:  $C_f$  is the feed concentration,  $C_p$  is the permeate concentration and  $C_c$  is the concentrate concentration.

The above relations (Eq. 11.11) could be applied to determine recovery rate from concentration values of ions in the feed, permeate and concentrate stream. Usually, these calculations are based on concentrations of chloride or calcium ions, which can be determined easily and with high degree of accuracy.

*Example #11.1*

Designed recovery rate 75%

Concentrations, ppm of  $\text{Cl}^-$

Feed = 1000

Concentrate = 3800

Permeate = 200

Actual recovery rate,  $R = (3800 - 1000) / (3800 - 200) = 0.78$  (78%)

*Example #11.2*

Designed recovery rate 0.75 (75%)

Feed concentration, ppm  $\text{Cl}^-$  = 1000

Permeate concentration, ppm  $\text{Cl}^-$  = 200

Calculation of concentrate concentration:  $C_c = (C_f - R \times C_p) / (1 - R)$

$C_c = (1000 - 0.75 \times 200) / (1 - 0.75) = 3400$

In a multistage RO system recovery rate is defined for each stage and for combined system (Fig. 11.2).

Recovery rate calculations can be applied to a single reverse osmosis element, to a stage of an RO unit or as a single value characterizing multistage RO system.

Calculations of recovery rate for a two stage RO unit, shown on Fig. 11.2 are listed below:

Recovery rate of stage 1,  $R_1 = 65/100 = 0.65$  (65%)

Recovery rate of stage 2,  $R_2 = 20/35 = 0.57$  (57%)

Total recovery rate,  $R_t = R_1 + (1 - R_1) \times R_2 = 0.65 + (1 - 0.65) \times 0.57 = 0.85$  (85%)

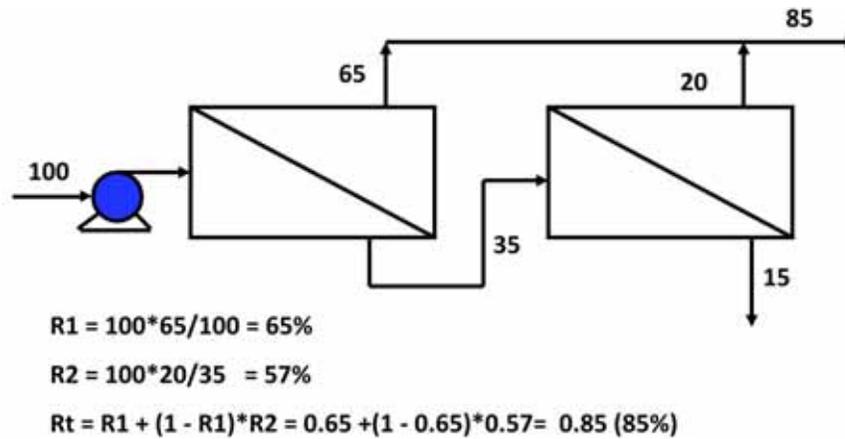


FIG. 11.3 Flow distribution in a two-stage reverse osmosis unit. Unit recovery rate = 85.0%.

RO units, treating low to medium salinity feed water, are usually designed to operate at high recovery rate in the range of 75% to 90%. Operation at high recovery rate results in better utilization of feed water source and reduction of volume of concentrate to be disposed. Higher recovery rate is usually associated with lower energy requirement of the RO process. The high values of recovery rate range correspond to low feed salinities. In most cases, the upper limit of recovery rate is determined by the risk of scale formation from precipitation of sparingly soluble salts at the concentrate end of the RO system.

In some cases it is possible to blend low salinity feed water with RO permeate and produce product water of acceptable salinity. Such configuration increases utilization of feed water as demonstrated in Fig. 11.4.

In the above configuration the size of RO unit could be reduced as part of the capacity of final product is provided by blending permeate with raw water.

### 11.5 Average feed salinity

Average feed salinity (AFS) is a representative value of feed concentration used for calculation of performance of membrane element or RO system. AFS accounts for the phenomena of salinity increase in the RO system from the salinity of feed water at the entrance to the RO device to the final salinity of concentrate leaving the system. Salinity of the feed stream increases in the RO

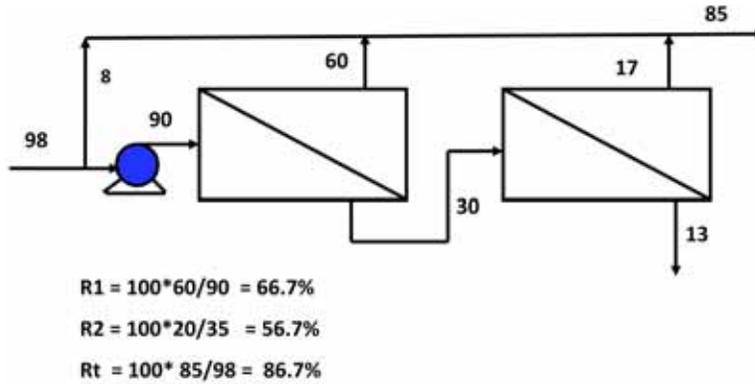


FIG. 11.4 Flow distribution in a two-stage reverse osmosis unit with blending. Total recovery rate = 86.7.0%.

process, due to conversion of part of the feed stream into low salinity permeate. Average feed salinity can be expressed as a function of recovery rate, assuming at the first approximation that dissolved species in the feed water are totally rejected by RO membranes. The AFS is calculated either as an arithmetic (Eq. 11.12) or logarithmic mean (equation 11.13):

$$AFS = C_f \times 0.5 \times (1 + 1/(1 - R)) \tag{11.12}$$

$$AFS = C_f \times \ln(1/(1 - R))/R \tag{11.13}$$

where  $C_f$  is feed salinity and  $R$  is recovery rate expressed as a decimal fraction.

Arithmetic mean is usually applied for calculations in cases of low recovery rate (single element calculations). In case of a high recovery rate a logarithmic mean is used for performance calculations. The ratio of salinity increase is represented by the concentration factor (CF).

$$AFS = C_f \times CF \tag{11.14}$$

The values of concentration factors for the arithmetic average, logarithmic average and for the RO concentrate are shown in Fig. 11.5.

### 11.6 Net driving pressure

The net driving pressure (NDP) is the driving force of the water transport through the semipermeable membrane. The value of NDP decreases along the

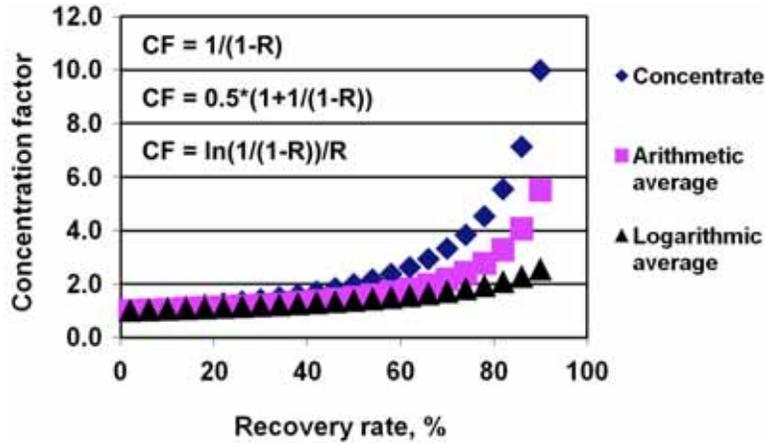


FIG. 11.5 Concentration increase vs. recovery rate.

RO unit. The decrease of NDP is result of feed salinity increase and increase of feed osmotic pressure as feed water is being converted to a permeate. Additional decrease of NDP is caused by reduction of feed pressure due to hydraulic friction losses. Therefore, for the purpose of membrane performance calculations it is defined as an average NDP. The NDP is defined as the fraction of the applied pressure in excess of average osmotic pressure of the feed and any pressure losses in the system according to the following equation:

$$NDP = P_f - P_{os} - P_p - 0.5 \times P_d (+ P_{osp}) \tag{11.15}$$

where:  $P_f$  = feed pressure  
 $P_{os}$  = average feed osmotic pressure  
 $P_p$  = permeate pressure  
 $P_d$  = pressure drop across RO elements  
 $P_{osp}$  = osmotic pressure of permeate.

In regular RO applications osmotic pressure of permeate is negligible. Therefore, the last term in Eq. 11.15 can be neglected:

$$NDP = P_f - P_{os} - P_p - 0.5 \times P_d \tag{11.16}$$

However, in nanofiltration applications, where salt rejection of membranes is relatively low, permeate salinity could be significant compared to the feed

concentration. Therefore, osmotic pressure of permeate has to be accounted for in calculation of NDP in nanofiltration systems.

*Example #11.3*

Brackish RO system operates at recovery rate of 85% (0.85)

Feed salinity: 2000 ppm TDS

Permeate salinity = 80 ppm TDS

Concentrate salinity =  $(2000 - 0.85 \times 80)/(1 - 0.85) = 12880$  ppm

Feed pressure: 14.9 bar (216 psi)

Pressure drop across the system: 2.7 bar (39) psi

Permeate pressure: 1.0 bar (14.5 psi)

Average feed salinity =  $0.5 \times (2000 + 12880) = 7444$  ppm

Average feed osmotic pressure =  $0.77 \times (7444/1000) = 5.7$  bar (83 psi)

Permeate osmotic pressure =  $0.77 \times (80/1000) = 0.06$  bar (0.9 psi)

Average net driving pressure: NDP =  $14.9 - 5.7 - 1.0 - 0.5 \times 2.7 = 6.9$  bar (100 psi)

*Example #11.4*

Nanofiltration RO system operates at recovery rate of 85% (0.85)

Feed salinity: 1000 ppm TDS

Permeate salinity = 350 ppm TDS

Concentrate salinity =  $(1000 - 0.85 \times 350)/(1 - 0.85) = 4683$  ppm

Feed pressure: 7 bar (101 psi)

Pressure drop across the system: 3.0 bar (45) psi

Permeate pressure: 1.0 bar (14.5 psi)

Average feed salinity =  $0.5 \times (1000 + 4683) = 2842$  ppm

Average feed osmotic pressure =  $0.77 \times (2842/1000) = 2.2$  bar (32 psi)

Permeate osmotic pressure =  $0.77 \times (350/1000) = 0.3$  bar (4 psi)

Average net driving pressure: NDP =  $7 - 2.2 - 1.0 - 0.5 \times 3.0 + 0.3 = 2.6$  bar (38 psi)

Fig. 11.6 corresponds to system that is configured as a two stage membrane unit, with fourteen membrane elements connected in series: seven in the first stage and seven in the second stage. The changes of feed pressure and osmotic pressure are depicted schematically in Fig. 11.6 as straight lines. This is not the case in the actual system as the changes of salinity and pressures are not linear along the membrane unit.

However, the values corresponding to the entrance (feed end) and exit (concentrate end) points are easily determined by measurements of corresponding salinities and pressures.

The change of NDP along the RO system is shown schematically in Fig. 11.6.

### 11.7 Salt passage and salt rejection

Salt passage is defined as the ratio of concentration of salt on the permeate side of the membrane relative to the average feed concentration. Mathematically, it is expressed in Eq. 11.17:

$$SP = 100\% (C_p / C_{fm}) \tag{11.17}$$

where SP is the salt passage (in %),  $C_p$  is the salt concentration in the permeate, and  $C_{fm}$  is the mean salt concentration in feed stream.

Salt rejection is the opposite of the salt passage, and is defined by Equation 11.18:

$$SR = 100\% - SP \tag{11.18}$$

where SR is the salt rejection (expressed as %), and SP is the salt passage as defined in Eq. 11.18.

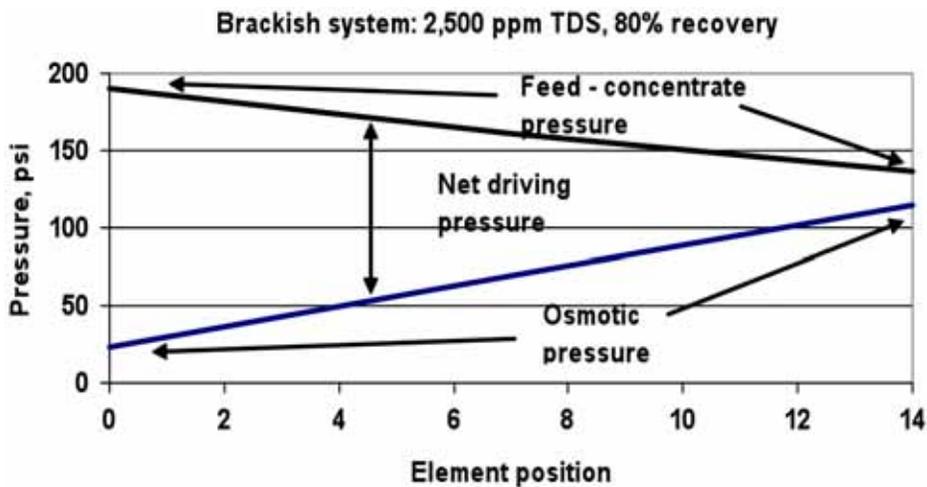


FIG. 11.6 Change of NDP along the RO system operating at 85% recovery rate, feed salinity 2000 ppm TDS.

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Calculation of salt passage and salt rejection for a single RO element is shown in Example 11.5, and for a membrane unit in Example 11.6. As illustrated by the examples below, usually there is a difference between apparent results of salt rejection for a single element and membrane unit, even when employing the same membrane elements and treating similar feed salinity. Salinity of permeate, produced by an RO device, is function of number of process parameters (recovery rate, permeate flux, feed composition and temperature), in addition to salt rejection property of the membrane elements. Effect of operating parameters on membrane and RO unit performance is provided in Chapters 14 and 15.

*Example #11.5*

RO element is tested at 15% recovery rate,  $R = 0.15$

Feed salinity: 1500 ppm NaCl

Permeate salinity: 4.5 ppm NaCl

Average feed salinity (equation 11.12)  $= 0.5 C_f \times (1 + 1/(1 - R)) =$

$$0.5 \times 1500 \times (1 + 1/(1 - 0.15)) = 1632 \text{ ppm}$$

Salt passage  $= 100\% \times (4.5/1632) = 0.3\%$

Salt rejection  $= 100\% - 0.3\% = 99.7\%$

*Example #11.6*

RO unit operates at 80% recovery rate,  $R = 0.80$

Feed salinity: 1500 ppm TDS

Permeate salinity: 38 ppm TDS

Average feed salinity (equation 11.13)  $= C_f \times \ln(1/(1 - R))/R =$

$$1500 \times \ln(1/(1 - 0.80))/0.80 = 1500 \times 2.01 = 3015 \text{ ppm}$$

Salt passage  $= 100\% \times (38/3015) = 1.3\%$

Salt rejection  $= 100\% - 1.3\% = 98.7\%$

**11.8 Temperature effect on transport rate**

Feed water temperature effect rate of water and salt permeability through the membrane. According to early investigations of RO process parameters (6) and later additional work on this subject (7, 8), the variation of water and salt transport rates can be described by Arrhenius equation:

$$J = C \exp(-E/RT) \quad (11.19)$$

where  $J$  is the flux,  $E$  is activation energy of the transport process,  $R$  is the universal gas constant and  $T$  is temperature ( $^{\circ}\text{K}$ ).

The reported results indicated that activation energy for salt transport process was usually higher than the corresponding activation energy for water transport. In RO applications the following equation is being used to calculate temperature correction factor (TCF), applied for calculation of water permeability:

$$\text{TCF} = 1/\exp(C \times (1/(273 + t) - 1/298)) \tag{11.20}$$

where  $t$  is temperature  $^{\circ}\text{C}$ ,  $C$  is constant, characteristic of membrane barrier material. For polyamide membranes a  $C$  values of 2500–3000 are being used.

It is customary for RO applications to use temperature of  $25^{\circ}\text{C}$  ( $77^{\circ}\text{F}$ ) as the reference temperature, for which  $\text{TCF} = 1.0$ . The water and salt transport increases about 3% per degree C. Fig. 11.7 shows value of TCF in the temperature range of 15– $40^{\circ}\text{C}$ . By comparison, relative values of water viscosity are also included. There is striking similarity of both curves, suggesting that changes of water permeability with temperature are result of changes of water viscosity.

Due to design considerations of stability of membranes performance and logistic of operation of desalination systems, the output capacity and permeate flux is maintained constant in RO plants. The fluctuations of water permeability with temperature are compensated by adjustment of feed pressure to the membrane

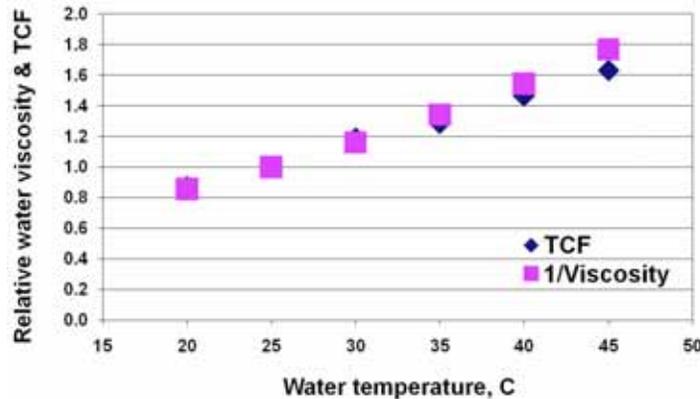


FIG. 11.7 Temperature effect on water permeability through the membrane as expressed by the value of temperature correction factor (TCF). Inverse of water viscosity for the same temperature range is provided for comparison.

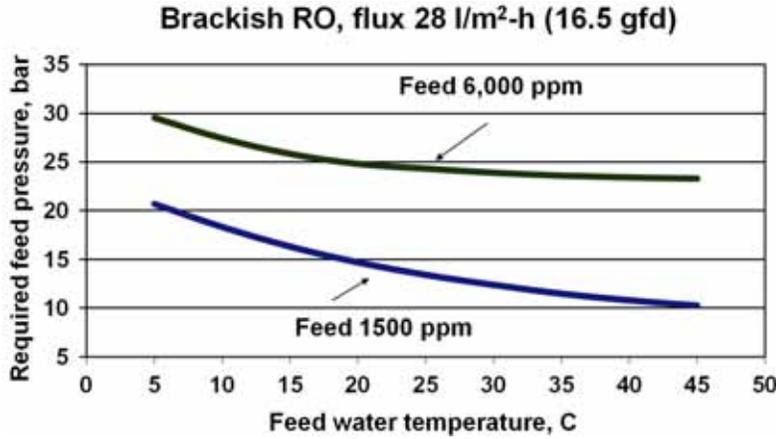


FIG. 11.8 Example of feed pressure vs. temperature relations in an RO unit operating at recovery rate of 80% and treating feed salinity of 1500 and 6000 ppm TDS at average permeate flux of .28 l/m<sup>2</sup>/hr (16.5 gfd).

unit. The results in Fig. 11.7 suggest that due to increased water permeability with temperature increase, the operating feed pressure should be lower at higher temperature. This is indeed the situation in case of processing of low salinity feed (brackish applications). In RO systems desalting very high salinity feed (seawater applications), the increase of permeability with temperature is offset to some extent by an increase of the osmotic pressure of feed-concentrate solution.

Changes of required feed pressure to maintain constant permeate flux in RO unit are shown in Fig. 11.8. The calculation of feed pressure were conducted for operating conditions of feed salinities of 1500 and 6000 ppm, operating at recovery rate of 80% and average permeate flux rate of 28 l/m<sup>2</sup>/hr (16.5 gfd)

The following example demonstrates effect of temperature on NDP required to maintain design permeate flux. The required feed pressure at each temperature can be derived in a similar way using Eq. 11.5 as shown in Example 11.3.

*Example #11.7*

RO system operates in temperature range of 15–28°C. At feed water temperature of 28°C the NDP<sub>1</sub> required for the design capacity is 7.5 bar (108.9 psi). What NDP will be required at 15°C to maintain the design permeate capacity?

Value of constant C (Eq. 11.20) for the membrane used is 2700.

For 28°C the  $TCF_1 = 1/(\exp(2700 \times (1/(273 + 28) - 1/298)) = 0.914$   
 For 15°C the  $TCF_2 = 1/(\exp(2700 \times (1/(273 + 15) - 1/298)) = 1.370$   
 $NDP_2 = NDP_1 TFC_2/TFC_1 = 7.5 \text{ bar} \times 1.370/0.914$   
 $NDP_2 = 11.2 \text{ bar (162.4 psi)}$

Similar relations, as for water permeability, apply to changes of salt transport with temperature. As mentioned above, RO systems are designed to operate at constant permeate output (constant average permeate flux) and to compensate fluctuations of feed water temperature with adjustment of feed pressure. For this reason, increase of feed water temperature results in increase of permeate salinity, as shown in Fig. 11.9

### 11.9 Average permeate flux

Average permeate flux (APF) is another important design parameter of the RO process. The APF is the combined permeate flow divided by the total membrane area installed in the RO unit. Units: l/m<sup>2</sup>-hr or gfd (gallon/ft<sup>2</sup>-day)

$$APF = Q_p / (EN \times MA) \tag{11.21}$$

where  $Q_p$  is permeate flow rate, EN is number of elements in the system and MA is membrane area per element

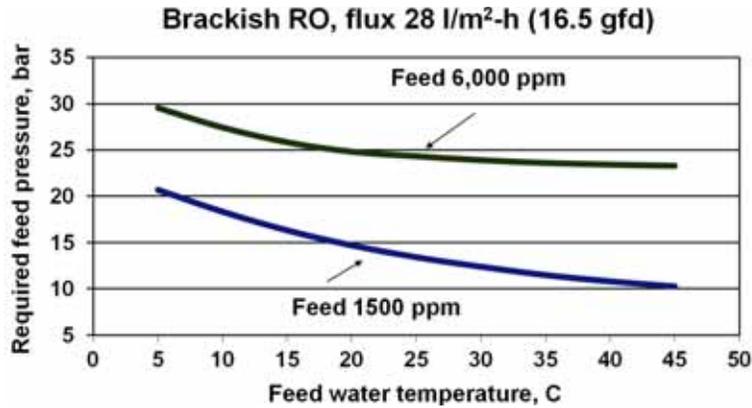


FIG. 11.9 Example of permeate salinity vs. temperature relations in an RO unit operating at recovery rate of 80% and treating feed salinity of 1500 and 6000 ppm TDS at average permeate flux of .28 l/m<sup>2</sup>/hr (16.5 gfd).

*Example #11.8*

RO system produces 400 m<sup>3</sup>/day (105,700 gallons/day). Membrane array consists of 3 pressure vessels, each housing 6 membrane elements.

Each element has 37 m<sup>2</sup> of membrane area (400 ft<sup>2</sup>). APF is calculated as follows:

$$\text{APF} = 400,000 \text{ l/day} / (3 \times 6 \times 37 \text{ m}^2 \times 24) = 25.0 \text{ l/m}^2\text{-hr}$$

$$\text{APF} = 105,700 \text{ gal/day} / (3 \times 6 \times 400 \text{ ft}^2) = 14.6 \text{ gfd}$$

Conversely, the design APF is used to determine required number of membrane elements in RO system for required permeate capacity.

*Example #11.9*

RO system will produce 400 m<sup>3</sup>/hour (1,760 gallons/min). The design average flux rate is 25 l/m<sup>2</sup>-hour (14.7 gfd). The membrane element type selected for this system has 37 m<sup>2</sup> of membrane area (400 ft<sup>2</sup>) per element.

Number of membrane elements required (NEPV):

$$\text{NEPV} = 400,000 \text{ l/hr} / (25 \text{ l/m}^2\text{-hr} \times 37 \text{ m}^2) = 432 \text{ elements}$$

NEPV = 1,760 gal/min  $\times$  1440 min/day / (14.7 gallons/ft<sup>2</sup>/day  $\times$  400 ft<sup>2</sup>) = 431 elements. The number of elements required will be rounded up according to number of elements per vessel. Assuming seven elements per vessel:

$$431/7 = 61.6 \text{ pressure vessels}$$

Number of elements required:

$$62 \times 7 = 434 \text{ elements}$$

Recommended values of average permeate flux are provided as recommendation by membrane manufacturers. The upper limits of APF values are related to sources of feed water and expected feed water quality. Representative values of APF, recommended by membrane manufacturers and their relation to number of membrane elements required is illustrated in Table 11.3

It is evident from Fig. 11.6 that the net driving pressure changes along the RO system. Correspondingly, the permeate flux rate follows in parallel. The permeate flux rate from membrane elements positioned at the feed end of the membrane unit will be much higher than the average flux value. However, body of experience from field operation of membrane systems strongly indicates that system design based on average flux rate, in the range recommended by membrane manufacturers, results in stable membrane performance.

TABLE 11.3

Relation between water source, average permeate flux and number of membrane elements required for an RO unit of 10,000 m<sup>3</sup>/day (2.6 mgd) permeate capacity using membrane elements with 37 m<sup>2</sup> (400 ft<sup>2</sup>) membrane area per element.

Feed water type or water source	Recommended range of average permeate flux, l/m <sup>2</sup> /hr (gfd)	Number of membrane elements required for 10,000 m <sup>3</sup> /d (2.6 mgd)
Secondary municipal effluent treated with membrane filtration (MF/UF)	17–20 (10–12)	590
Brackish wells	26–29 (15–17)	406
RO permeate	30–37 (18–22)	325
Seawater intake	12–15 (7–9)	812

### 11.10 Specific water permeability

Specific permeability, or specific flux–SF, characterizes the membrane material in terms of water flux rate driven by the gradient of applied net driving pressure.

$$SF = APF/NDP \quad (11.22)$$

Specific permeability depends on resistance of membrane to water flow. This resistance is composite of flow resistance of membrane barrier, support layers and any foulant layer on the membrane surface. It is usually calculated for the feed water temperature of 25°C. Specific flux units are: l/m<sup>2</sup>/hr/bar (gfd/psi)

#### Example #11.10

RO membrane element has been tested at the following test conditions:

Feed water temperature = 21°C

Temperature correction constant = 2700

Feed salinity = 1500 ppm NaCl

Recovery rate = 15% (0.15)

Feed pressure = 10.3 bar (150 psi)

Pressure drop = 0.2 bar (2.9 psi)

Permeate pressure: 0.1 bar (1.5 psi)

Permeate flow: 41.6 m<sup>3</sup>/day (11,000 gpd)

Membrane area: 39.5 m<sup>2</sup> (430 ft<sup>2</sup>)

Average permeate flux =  $41.6 \times 1000 / (24 \times 39.5) = 43.9$  l/m<sup>2</sup>/hr (25.8 gfd)

Average feed salinity =  $1500 \times 0.5 \times (1 + 1/(1 - 0.15)) = 1632$  ppm NaCl

Average osmotic pressure =  $1632/1000 \times 0.77 = 1.3$  bar (19 psi)

Net driving pressure =  $10.3 - 1.3 - 0.1 - 0.5 \times 0.2 = 8.8$  bar (128.0 psi)

Specific flux, SF =  $43.9/8.8 = 4.99$  l/m<sup>2</sup>/hr/bar (0.20 gfd/psi)

Temperature correction factor TCF =  $1/(\exp(2700 \times (1/(273 + 21) - 1/298)))$

TCF = 1.13

Specific flux, corrected to 25°C =  $4.99 \times 1.13 = 5.64$  l/m<sup>2</sup>/hr/bar

(0.23 gfd/psi)

#### *Example #11.11*

RO system utilizes RO membranes elements with specific flux of 3.8 l/m<sup>2</sup>/hr/bar (0.15 gfd/psi) and operates at following parameters:

Feed salinity: 2000 ppm TDS

Permeate salinity: 80 ppm TDS

Recovery rate 85%

Feed pressure: 14.9 bar (188.5 psi)

Permeate pressure 1 bar (14.5 psi)

Pressure drop across the system 2.7 bar (39 psi)

Calculate average permeate flux rate, permeate flux at the feed and concentrate ends of the RO unit.

According to calculations in Example 11.3, the average NDP and the NDP's at the unit entrance and exit are 6.9 bar (100 psi), 12.4 bar (180 psi) and 1.3 bar (19 psi) respectively. Accordingly, the permeate fluxes are 26.2 l/m<sup>2</sup>/hr (15.4 gfd), 47.1 l/m<sup>2</sup>/hr (27.7 gfd) and 4.9 l/m<sup>2</sup>/hr (2.8 gfd).

### **11.11 Concentration polarization**

As water passes through the membrane and dissolved species are rejected by the membrane, a boundary layer is formed near the membrane surface. In this boundary layer, the salt concentration exceeds the salt concentration in the bulk solution. This increase of salt concentration at the membrane surface is called concentration polarization. As shown on Fig. 11.10 during the RO process there is a convective flow of water and ions toward the membrane surface. Ions rejected by the membrane, diffuse back to the bulk due to the concentration gradient. The observed effect of concentration polarization on membrane

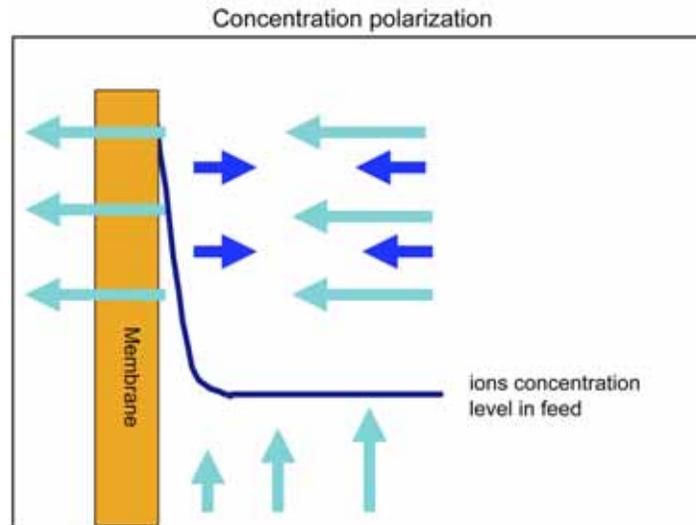


FIG. 11.10 Formation of the concentration gradient at the surface of a semipermeable membrane.

performance is reduction of actual product water flow rate and increase of salt passage versus the theoretical estimates.

The increase of concentration near the membrane surface follows the relation (8):

$$J_w = k \times \ln[(C_m - C_p)/(C_b - C_p)] \tag{11.23}$$

where  $J_w$  is water flux through the membrane,  $C_m$  is concentration at the membrane surface,  $C_p$  is concentration of permeate and  $C_b$  is bulk (feed) concentration.  $k$  is related to solute diffusion coefficient  $D$  and the boundary layer thickness  $d$  according to equation 11.24

$$k = D/d \tag{11.24}$$

Eq. 11.23 illustrates that at the given bulk concentration  $C_b$ , the excess membrane concentration  $C_m$  will increase with increase of permeate flux rate  $J_w$ .

Concentration polarization has the following effect on the RO process:

1. Increased osmotic pressure at the membrane surface than in the bulk feed solution,  $DP_{osm}$ , and reduced net driving pressure differential across the membrane ( $DP - DP_{osm}$ ).

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2. Reduced water flow across membrane ( $Q_w$ ).
3. Increased salt flow across membrane ( $Q_s$ ) due to increase concentration gradient ( $C_m - C_p$ ) across the membrane.
4. Increased probability of exceeding solubility of sparingly soluble salts at the membrane surface, and the distinct possibility of precipitation causing membrane scaling.

The Concentration Polarization Factor (CPF) is defined as a ratio of salt concentration at the membrane surface ( $C_m$ ) to bulk concentration ( $C_b$ ):

$$\text{CPF} = C_m / C_b \quad (11.25)$$

As illustrated by Eq. 11.23, increase in permeate flux will increase the delivery rate of ions to the membrane surface and increase  $C_m$ . An increase of feed flow, parallel to the membrane surface, increases turbulence and reduces the thickness of the high concentration layer near the membrane surface  $d$ . Therefore, the CPF will increase with increase of permeate flow ( $Q_p$ ), due to increase of permeate flux, and will decrease with increase of the average feed flow ( $Q_{\text{avg}}$ ).

$$\text{CPF} = K_p \exp(Q_p / Q_{\text{avg}}) \quad (11.26)$$

Where  $K_p$  is a constant depending on membrane element geometry, namely configuration and dimensions of feed channel and of the feed spacer.

Using the arithmetic average of feed and concentrate flows as an average feed flow:

$$Q_{\text{avg}} = (Q_f + Q_c) / 2 = (2Q_f - Q_p) / 2 \quad (11.27)$$

Therefore, the CPF can be expressed as a function of the permeate recovery rate of a membrane element ( $R_i$ ).

$$\text{CPF} = K_p \exp(2R_i / (2 - R_i)) \quad (11.28)$$

The value of the concentration polarization factor of 1.2, which is the recommended limit by some of the membrane manufacturers, corresponds to about 18% permeate recovery for a 1 m (40") long membrane element, as shown in Fig. 11.11.

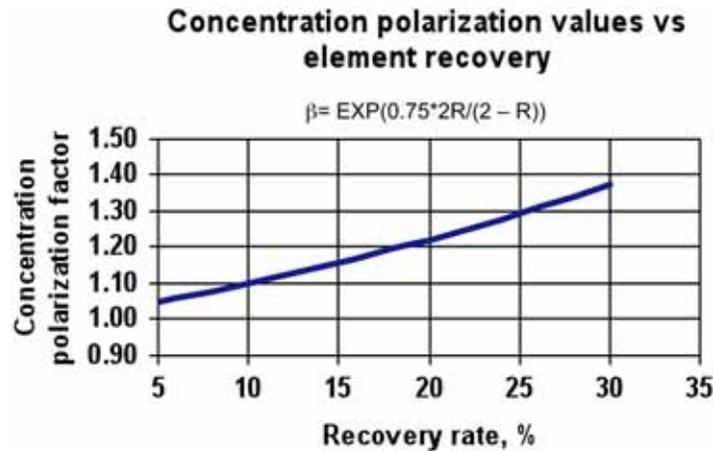


FIG. 11.11 Relation of concentration polarization factor (CPF) to membrane element recovery rate ( $R_1$ ).

The value of CPF is applied in computerized calculations of RO elements performance (as an internal parameter of membrane manufacturer computer programs) to account for excess feed water concentration adjacent to the membrane surface, according to recovery rate of individual elements.

In most instances the calculations of CPF do not account for potential effect of membrane fouling on excess surface concentration. Laboratory tests (9) indicate that under conditions of membrane fouling, the surface concentration could exceed bulk concentration by over 75%. However, for projection of membrane performance and conditions of clean membrane surface are assumed.

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