

Process design of reverse osmosis systems

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The learning objectives of this chapter are the following:

- To apply the principles of membrane filtration in the process design of a seawater reverse osmosis system
- Calculate the number of RO elements, number of pressure vessels, capacity of the high-pressure pump, membrane permeability coefficients for salt and water, permeate flow, feed flow, concentrate flow, permeate of the quality with and without the flux effect, verify the concentration polarization factor, cross-flow velocity of the water inside the membranes, and energy consumption with and without an energy recovery device

9.1 INTRODUCTION

The purpose of the manual calculations described in this chapter is to apply the basic equations governing reverse osmosis (RO) systems described in chapter 2. This process design considers the total dissolved solids (TDS) concentration of the seawater. The focus of this process design is the design of the RO system and not the need for or the type of pre-treatment. The steps described in this chapter are such that they can easily be converted in a calculation sheet with the help of software such as MS Excel. By following a step-wise procedure, the design of RO units does not remain a black box and can help to further understand the design methodology applied by commercial software.

The reader could at the end of the manual design followed in this chapter, compare the results with the ones of computer software for the same design parameters.

Most manufacturers of RO membranes, like Hydranautics (IMS Design), DOW (Wave), Toray, Suez (Winflows) and several others have available design software, enabling to make design projections for their membranes and systems in a quick manner. Figure 1 shows some examples of the available commercial software which in general are free to use.

9.1.1 Basic data

Before we can start with the design of the RO units, we need to know the design capacity of the plant, the type and TDS of the feedwater, and the water temperature. For seawater RO, the recovery ranges in practice between 40 to 50 %. The design information is presented in Table 1.

Table 1 Information for the design of the RO units

Source water	Seawater
Capacity of the plant	$Q_{p \text{ plant}} = 45 \text{ m}^3/\text{h}$
Salt concentration (feed)	$C_f = 35,030 \text{ mg/L}$
Total recovery (plant)	$R = 40 \%$
Temperature of the water	$T = 25 \text{ }^\circ\text{C}$



Figure 1 Examples of computer programmes for the design of RO membrane systems

Pre-treatment: Considering that we will make the process design of the RO, there is no need to indicate the type of pretreatment. Pre-treatment is discussed in chapter 3.

Ion composition: Note that we do not specify the ion composition in the feedwater but only the salinity of the seawater, expressed as TDS of the feed water. Commercial softwares allow the input of anions and cations present in the water and they use this information for calculating specific rejections per ion type by the RO membranes.

Recovery: In brackish water RO (BWRO), the scaling potential determines the maximum recovery. In seawater RO (SWRO), the osmotic pressure determines the maximum recovery.

In BWRO, the maximum allowable conversion (in brackish water) in one bank (group of parallel vessels) equipped with spiral wound elements is in practice not more than about 50 %. Reason is that higher conversions result in too low ratio's concentrate to permeate flow per element. As a result too high concentration polarization factor (CPF or β). When the ratio concentrate flow/permeate flow, drops below 5:1 (recovery higher than 18 %, then CPF exceeds 1.2 according the formula 2.57 in chapter 2.

In the last elements in a bank/stage, of BWRO plant, this ratio goes down since:

- concentrate flow drops substantially, at 50 % conversion, this flow drops with a factor 2.
- permeate flow drops as well, but much less than the concentrate flow.

9.1.2 Membrane type

We can select any of the options suggested by the RO manufacturer (Hydranautics). The options for seawater RO desalination are presented in Table 2. Some of the information for selection is the nominal production, the salt rejection, available filtration area, height feed spacer.

Table 2 Seawater reverse osmosis elements recommended by Hydranautics in the IMSDesign software

Model	Nominal production		Salt rejection, %	Element type	Size (DxL) (in x in)	Area		Spacer	
	gpd	m ³ /d				(ft ²)	(m ²)	(mil)	(mm)
SWC4 MAX	7,200	27.3	99.8	SWRO Highest rejection	8x40	440	40.9	28	0.71
SWC4-LD	6,500	24.6	99.8	SWRO High rejection	8x40	400	37.2	34	0.86
SWC5 MAX	9,900	37.5	99.8	SWRO High rejection	8x40	440	40.9	28	0.71
SWC5-LD	9,000	34.1	99.8	SWRO High rejection, Low Dp	8x40	400	37.2	34	0.86
SWC6 MAX	6,600	25	99.6	SWRO Highest flow	8x40	440	40.9	28	0.71
SWC6-LD	6,000	22.7	99.6	SWRO High flow Low Dp	8x40	400	37.2	34	0.86

NB 1: The specified test pressure for the first 4 elements is 55 bar and for the last two elements is 41.4 bar.

NB 2: 1 mil = 1/1000 inch.

For elements with similar salt rejection, an element with higher nominal production will produce permeate water with higher salt concentration than an element with lower nominal production. On the other hand, if we consider the same permeate production, then the feed pressure requirement will be lower for the RO element with higher nominal production than for an element with lower nominal production.

Table 3 Basic properties of the selected RO element and selected number of elements per pressure vessel

Manufacturer	Hydranautics
Type	SWC4 MAX
Membrane area per element	$A_e = 40.9 \text{ m}^2$
Salt rejection	SR = 99.8%
Elements per vessel	$\#_{\text{elem}} / \text{PV} = 6 [-]$

Each RO element manufacturer provides an element specification sheet (ESS) for each type of membranes they have available. The information in the ESS will be later used to verify maximum flows per element, calculate the permeability coefficient for water and for salt, etc.

The information from the EES that will be used in the following steps is marked by an arrow. The standard testing conditions reported in the EES will be later used to calculate the permeability coefficients for salt and water.

Spiral wound elements are placed in pressure vessels (1 m to 8 m in length). In large plants 6 to 8 elements of 1 m length are placed in one vessel. In small units 1 to 4 elements of 1 m length are placed in vessel, in one vessel.

Total number of elements in one stage follows from: $N_e = A/A_e$, where $A = Q_p / J$.

Where: N_e = number of elements; A = total required membrane area; A_e = membrane area per element (35 m^2); Q_p = permeate flow/capacity; J = Average flux in the stage.

Example 1– Number of membrane elements

A sea water plant is producing $1,000 \text{ m}^3/\text{h}$. Spiral wound elements of 1 m length are placed in vessels of 6 m in length. Surface membrane is 35 m^2 . Average flux of the membranes is about $14 \text{ L}/\text{m}^2\text{h}$

Questions: How many elements are in the plant? How many vessels are installed?

Answers:

Number of elements, $N_e = \text{Plant capacity} / (\text{Surface area per element} \cdot \text{flux})$

$N_e = 1,000 / (35 \cdot 14 \cdot 10^{-3}) = 2040 \text{ elements}$

Number of vessels = number of elements / number of elements per vessel

$N_{\text{vessels}} = 2040 / 6 = 340 \text{ vessels}$

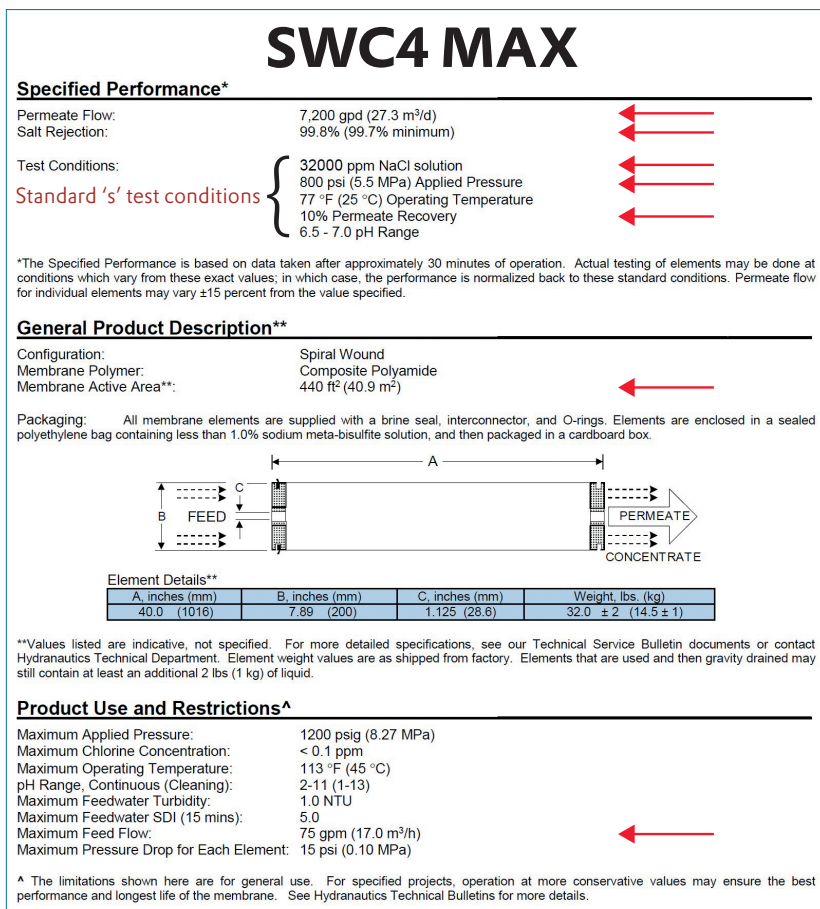


Figure 3 Element specification sheet of the SWC4 MAX RO element selected for the design (www.membranes.com [accessed 05 Dec 2018])

9.2 DESIGN GUIDELINES

Most of the RO manufacturers have their own design guidelines considering the many years of experience, the properties of their membranes, etc. In Table 4 a summary of the design recommendations is presented for three membrane manufacturers, namely: DuPont, Toray and Hydranautics.

Table 4 Design guidelines as recommended by DuPont, Hydranautics and Toray (DuPont, 2020, Nitto Hydranautics, 2020, Toray Industries Inc, 2020)

		Dupont			Toray		Hydranautics		
Raw water source		Sea	Sea	Sea	Sea	Sea	Sea	Sea	Sea
Intake type		Well or MF	Open	Open	Well	Open	Well	Surface	Surface
Pre-treatment type		UF	MF/Conv.	Conv.	Conv.	Conv.	MF/UF		
SDI @15 minutes		2.5	3	5	3	4	3	4	4
System average flux	L/m ² /h	15-19	14-17	12-17	15-19	12-16	17-20	13.6-17	17-20.4
Lead element flux	L/m ² /h	36	34	32	35	28	42.4	34	42.4
Maximum element recovery	%	15	14	13	13	13			
Flux decline	% year					5	7	5	
Salt passage increase	%/year			7	7	7	10	7	
Beta standard element				1.2	1.2	1.2	1.2	1.2	
Feed flow 8" (maximum per vessel)	m ³ /h	16	15	14	15	13	17	17	17
Reject flow 8" (min per vessel)	m ³ /h	3	3.2	3.4	3.6	3.6	2.7	2.7	2.7
Pressure drop (bar)									
6 m vessel typical	bar			3	2	1.72	1.72	1.72	
6 m vessel max	bar	3.5	3.5	3.5	4	4	3.45	3.45	3.45
Element max	bar	1	1	1	1	1	1.03	1.03	1.03

The maximum feed flow per element (from the data sheet) is 17 m³/h. The concentration polarization factor $\beta < 1.2$ (β is the concentration polarization factor) or the minimum ratio of concentrate to permeate flow for any element 5:1.

9.3 PROCESS DESIGN STEPS

9.3.1 Step 1 - Simplified calculation of permeate concentration

In the following sections, the subscripts f, c, and p are used for feed, concentrate and permeate, respectively.

Feed flow of the plant	$Q_f \text{ plant} = 112.5 \text{ m}^3/\text{h}$	$R = Q_p / Q_f$
Concentrate flow of the plant	$Q_c \text{ plant} = 67.5 \text{ m}^3/\text{h}$	$Q_c = Q_{fc} - Q_p$
Concentrate concentration	$C_c = 58,336 \text{ mg/L}$	$C_c = C_f [1 - R (1 - SR)] / (1 - R)$
Avg feed-conc. concentration	$C_{fc} = 46,683 \text{ mg/L}$	$C_{fc} = (C_{fc} + C_c) / 2$
Permeate concentrationw	$C_p = 93.37 \text{ mg/L}$	$C_p = C_{fc} (1 - SR)$

NB. The formula: $C_c = C_f / (1 - R)$ assumes $SR = 100 \%$. Not used in this design. Differences in the final results are not significant.

Summarising the calculations for the whole plant, we have:

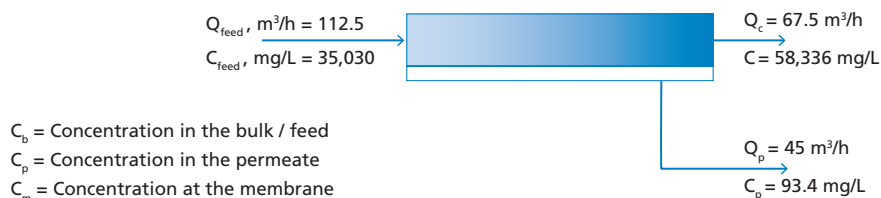


Figure 4 Flows and preliminary calculated concentrations in the RO plant

9.3.2 Step 2 - Calculation number of elements and pressure vessels

We need to select an average design flux. The selection can be based from practice or from design limits suggested by RO membrane manufacturers as presented in Table 4 and Table 5.

The flux which can be achieved in a RO plant is governed by the fouling potential of the feed water. The higher the flux the higher the rate of fouling of the membranes. A high fouling rate results in the need for frequent cleaning of the membranes with chemical cleaning solutions.

Table 5 Recommended RO operating flux ranges as function of water type (Nitro Hydranautics, 2020)

Feed water	$J, \text{L}/\text{m}^2.\text{h}$
Sea/ Surface water	14 – 24
Well water	24 – 31
RO permeate	34 – 51

Flux has to be chosen, based on the expected fouling potential feed water. RO plant operators are not in favour of frequent cleaning because:

- cleaning takes time. Long down time e.g., at least 8 hours.
- risk of damaging membranes
- requires careful acting and a lot of attention

Assuming average design flux	$J_{avg} = 15 \text{ L/m}^2\cdot\text{h}$	
Flow per element	$Q_e = 0.61 \text{ m}^3/\text{h}$	$Q_e = J_{avg} / A_e$
Nr of elements required in the plant	$N_e = 73.5$	$\#_{\text{elements}} = Q_{\text{plant}} / Q_e$
Nr of pressure vessels in the plant	$N_{pv} = 12.25$	$\#_{PV} = \#_{\text{elem}} / \#_{\text{elem/PV}}$
	12	Round up digits
Total number of elements	$N_e = 72$	$\#_{\text{elements}} = \#_{PV} \cdot \#_{\text{elem/PV}}$
Flux check:	$J_{avg} = 15.3 \text{ L/m}^2\cdot\text{h}$	$J_{avg} = Q_{\text{plant}} / (\#_{\text{elements}} \cdot A_e)$
	OK	$(J_{\text{calc}} - J_{\text{assumed}}) < 0.5$; "OK"; "not OK"
Flow per element check:	$Q_e = 0.63 \text{ m}^3/\text{h}$	$Q_e = J_{avg} / A_e$ (NB. Considers the new total # of elements, i.e., 72)

Feed, permeate, and concentrate flow per pressure vessel

Feed flow per pressure vessel	$Q_{\text{feed PV}} = 9.38 \text{ m}^3/\text{h}$	$Q_{\text{feed PV}} = Q_{\text{feed plant}} / \#_{PV}$
Permeate flow per pressure vessel	$Q_{\text{perm PV}} = 3.75 \text{ m}^3/\text{h}$	$Q_{\text{perm PV}} = R \cdot Q_{\text{feed PV}}$
Concentrate flow per pressure vessel	$Q_{\text{conc PV}} = 5.63 \text{ m}^3/\text{h}$	$Q_{\text{conc PV}} = Q_{\text{feed PV}} - Q_{\text{perm PV}}$

Check maximum feed flow in first element

Max. feed flow per element	$Q_{\text{max}} = 17 \text{ m}^3/\text{h}$	(from element specification sheet, application data)
	then, OK	$Q_{\text{feed PV}} < Q_{\text{max}}$; "OK"; "not OK"

NB. This is to avoid membrane damage

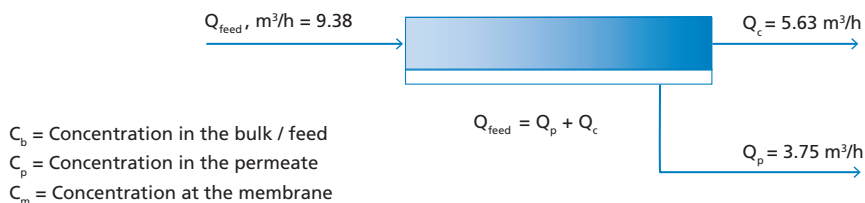


Figure 5 Flows per pressure vessel

9.3.3 Step 3 - Membrane permeability coefficients for water and salt

9.3.3.1 Calculation of membrane permeability coefficient for water (K_w)

K_w is not directly available from manufacturers information. So, K_w has to be calculated from test results under standard conditions.

Results at standard conditions (subscript "s" below) are usually made available by membrane manufacturers (see element specification sheet).

We will follow the following steps for the calculation of K_w :

1. $Q = NDP \times K_w \times A$
2. $NDP = P_{\text{feed}} - \Delta P/2 - \Delta \pi_{\text{avg}} - P_{\text{perm}}$

3. P_{feed} from element specification sheet (P_{fs})
4. Pressure loss per element, $\Delta P_e = 0.2$ bar
5. $R_e = 10 \%$
6. $\Delta\pi_{\text{avg}} = (\Delta\pi_{\text{feed}} + \Delta\pi_{\text{conc}}) / 2$
7. Standard conditions “s”
8. $C_{\text{conc s}} = C_{\text{feed s}} / (1 - R_e)$
9. Osmotic pressure: 1,000 mg/L ~ 0.8 bar
10. Nominal capacity (permeate flow) of element = Q_s (element specification sheet)
11. $J_s = Q_s / A_e$
12. Membrane permeability: $K_w = Q_s / (\text{NDP} \times A_e)$
13. Membrane productivity = $K_w \cdot A_e$

$T_s =$	25	°C	(from element specification sheet, test conditions)
$P_{\text{fs}} =$	5.5	MPa	(from element specification sheet, test conditions)
$P_{\text{fs}} =$	55	bar	
$\Delta p_e =$	0.2	bar	Assumed head loss per element
$C_{\text{fs}} =$	32,000	mg/L	(from element specification sheet, test conditions)
$R_e =$	10 %		(from element specification sheet, test conditions)
$C_{\text{cs}} =$	35,548	mg/L	$C_{\text{cs}} = C_{\text{fs}} \cdot [1 - R_e (1 - \text{SR})] / (1 - R_e)$
1,000 mg/L =	0.8	bar	Equivalence for osmotic pressure, rule of thumb
$\pi_{\text{fs}} =$	25.6	bar	$\pi_{\text{fs}} = C_{\text{fs}} \cdot (0.8/1000)$
$\pi_{\text{cs}} =$	28.4	bar	$\pi_{\text{cs}} = C_{\text{cs}} \cdot (0.8/1000)$
$\pi_{\text{fcs}} =$	27.0	bar	$\pi_{\text{fcs}} = (\pi_{\text{fs}} + \pi_{\text{cs}}) / 2$
$\pi_{\text{ps}} =$	0.270	bar	$\pi_{\text{ps}} = 0.01 \pi_{\text{fcs}}$ [For Brackish water: $0.05 \pi_{\text{fc}}$]
$\Delta\pi_{\text{avg s}} =$	26.7	bar	$\Delta\pi_{\text{avg s}} = (\pi_{\text{fcs}} - \pi_{\text{ps}})$
$P_{\text{ps}} =$	0	bar	
$\text{NDP}_s =$	28.2	bar	$\text{NDP}_s = P_{\text{fs}} - \Delta P_e / 2 - \Delta\pi_{\text{avg s}} - P_{\text{ps}}$

Nominal capacity:

$Q_{\text{ws}} =$	27.3	m ³ /d	(from element specification sheet, performance)
	1.14	m ³ /h	

Flux under standard conditions:

$J_{\text{ws}} =$	27.9	L/m ² · h	$J_{\text{ws}} = Q_{\text{ws}} / A_e$
$K_{w \text{ 25}^\circ\text{C}} =$	0.00099	m ³ /m ² · bar · h	$K_w = J_{\text{ws}} / \text{NDP}_s$
	0.99	L/m ² · bar · h	

Membrane productivity:

$K_{w25} A_e =$	0.040	m ³ /ba · h	
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Remark: Temperature has an effect on K_w . The higher the temperature the higher the permeability (It is about 3 % per C).

K_w is linked with the viscosity of water; as a consequence, the higher the temperature, the lower the required pressure to maintain a certain flux (and capacity).

9.3.3.2 Calculation of membrane permeability coefficient for salt (K_s)

We will use the following formula: $C_p = (C_{fc} \cdot K_s) / J$

Steps for calculating the membrane permeability for salt K_s :

1. Standard conditions “s”
2. J_s from step 2
3. from element specification sheet: C_{fs} , R_e , SR
4. $C_{concS} = C_{feedS} / (1 - R_e)$
5. $C_{fc} = (C_{feed} + C_{conc}) / 2$
6. $C_p = C_{fc} \cdot (1 - SR)$
7. $C_p = (C_{fc} \cdot K_s) / J$
8. $K_s = C_p \times J / C_{fc}$

Remarks:

- Water can pass a membrane; salts as well, however, at a much lower rate. Transport of salts through RO membranes is due to diffusion ($J_s = (C_f - C_p) \cdot K_s$).
- We need K_s to calculate the permeate concentration as function of flux (Step 6b).
($C_p = J_s / J_w = [(C_f - C_p) \cdot K_s] / J_w$, but $C_p \ll C_f$, then: $C_p \approx (C_f \cdot K_s) / J_w$)
- K_s is not directly available from manufacturers' information. So, K_s has to be calculated from test results under standard conditions.

$T_s =$	25	°C	(from element specification sheet, test conditions)
$C_{fs} =$	32,000	mg/L	(from element specification sheet, test conditions)
$R_e =$	10%		(from element specification sheet, test conditions)
$C_{cs} =$	35,548	mg/L	$C_{cs} = C_{fs} \cdot [1 - R_e(1 - SR)] / (1 - R_e)$
$C_{fcs} =$	33,774	mg/L	$C_{fcs} = (C_{fs} + C_{cs}) / 2$
SR =	99.8%		(from element specification sheet, performance)
$C_{ps} =$	67.5	mg/L	$C_{ps} = C_{fcs} \cdot (1 - SR)$

Nominal flow:

$Q_{ws} =$	27.3	m ³ /d	(from element specification sheet, performance)
	1.14	m ³ /h	

Flux under standard conditions:

$J_s =$	27.9	L/m ² ·h	$J_s = Q_{ws} / A_e$
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Now, we can calculate, $K_s = J_s (C_{ps} / C_{fcs})$

$K_{s, 25^\circ C} =$	0.056	L/m ² ·h	
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Comments:

- K_s is independent of applied pressure.
- K_s is dependent of water temperature; the higher the temperature the higher the salt passage.
- Different ions have different K_s values, so, the rejection (SR) is different.
- In general, SR: $Mg^{2+} > Ca^{2+} > Na_+$ and $SO_4^{2-} > Cl^-$. So, calculations should be done for different ions, which makes the whole set of calculations very complicated. Moreover, K_s values for other ions are hardly available.
- High salt rejection (low K_s) combines with low K_w value (due to smaller pores) e.g., Seawater: $K_s = 0.08 \text{ L/m}^2 \cdot \text{h}$ and $K_w = 1 \text{ L/m}^2 \cdot \text{h}$, while for brackish water, $K_s = 1.1 \text{ L/m}^2 \cdot \text{h}$ and $K_w = 5 \text{ L/m}^2 \cdot \text{h}$.
- The larger the pores, the larger the permeability for salt and water.

9.3.4 Step 4 - Preliminary calculation of feed pressure

The required feed pressure (P_f) depends on the average (chosen) flux (J_w), the permeability (K_w) of the RO membrane (selected), the osmotic pressure (π); the pressure loss in the feed/concentrate channel ΔP .

$$J_w = (P_f - \pi) \cdot K_w = \text{net driving pressure} \cdot \text{permeability}$$

or

$$P_f = J_w / K_w + \pi = \text{flux} / \text{permeability} + \text{osmotic pressure}$$

Salinity, governs together with recovery, the osmotic pressure.

$$C = C_f / (1 - R)$$

The feed pressure, P_f , should overcome all the resistances present in the system to diffuse salts and overcome the osmotic pressure. The net driving pressure, is the effective pressure to push water only.

The chosen flux dictates the required Net driving pressure (NDP) according to the formula:

$$J = \text{NDP} \times K_w$$

However, the flux in the RO elements in a system depends on the position of the element inside the pressure vessel, because the NDP depends on pressure losses and osmotic pressure. Even in one element the NDP is not constant, which is clearly shown in the following formula.

$$\text{NDP} = P_f - \Delta P - \Delta\pi - P_p$$

Where: NDP = average net driving pressure; P_f = feed pressure; ΔP = head loss across one element ($\sim 0.2 \text{ bar}$); $\Delta\pi_{\text{avg}}$ = average difference osmotic pressure: feed – permeate; P_p = product pressure.

The step to estimate the feed pressure in the RO system, are the following:

1. $J = Q_{\text{perm plant}} / A_{\text{mem plant}}$
2. $Q_e = Q_{\text{perm plant}} / N_{\text{elements}}$
3. $NDP = J / K_w$
4. For a pressure vessel:
5. $C_{\text{conc}} = C_{\text{feed}} / (1 - R)$
6. Osmotic pressure: 1,000 mg/L ~ 0.8 bar
7. $\Delta P = 0.2$ bar
8. $P_{\text{feed}} = NDP + \Delta P / 2 + \Delta_{\text{avg}} + P_{\text{perm}}$

Average flux per element	$J_{\text{avg}} =$	15.3	L/m ² .h	$J_{\text{avg}} = Q_{\text{plant}} / (\#_{\text{elements}} \cdot A_e)$
Flow per element	$Q_e =$	0.625	m ³ /h	$Q_e = Q_{\text{plant}} / \#_{\text{elements}}$ (or: $Q_e = J_{\text{avg}} \cdot A_e$)
	NDP =	15.5	bar	$NDP = J_{\text{avg}} / K_w$
For a pressure vessel	$C_f =$	5,030	mg/L	TDS of feed water (data)
	R =	40 %		Plant design recovery
	$C_c =$	58,336	mg/L	$C_c = C_f \cdot [1 - R \cdot (1 - SR)] / (1 - R)$
		0.8	bar	1,000 mg/L = 0.8 bar. Equivalence for osmotic pressure, rule of thumb.
	$\pi_f =$	28.0	bar	$\pi_f = C_f (0.8 / 1000)$
	$\pi_c =$	46.7	bar	$\pi_c = C_c (0.8 / 1000)$
	$\pi_{fc} =$	37.3	bar	$\pi_{fc} = (\pi_f + \pi_c) / 2$
	$\pi_p =$	0.373	bar	$\pi_p = 0.01 \pi_{fc}$
	$\Delta\pi_{\text{avg}} =$	37.0	bar	$\Delta\pi_{\text{avg}} = (\pi_{fc} - \pi_p)$
Head loss per element	$\Delta p_e =$	0.2	bar	Assumed head loss per element
Head loss per pressure vessel	$\Delta p_{\text{PV}} =$	1.2	bar	$\Delta p_{\text{PV}} = \Delta p_e \cdot \#_{\text{elements}}$
Pressure in permeate	$P_p =$	0.0	bar	Negligible
Estimated feed pressure	$P_f =$	53.0	bar	$P_f = NDP + \Delta p_{\text{PV}} / 2 + \Delta\pi_{\text{avg}} + P_p$
	say:	54	bar	round up

9.3.5 Step 5 - Calculations of flows, recovery, and concentration polarization factor for each element

We will calculate the flow and recovery for each element in a pressure vessel, as illustrated in Figure 6.

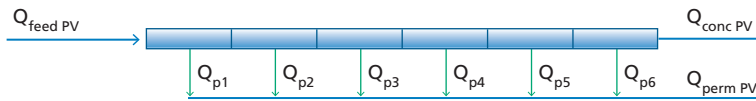


Figure 6 Schematic of the flow streams inside a RO pressure vessel with 6 elements in series

This is to verify: the feed pressure, the recovery, and check the concentration polarization factor β for each element (and/or the ratio of concentrate to permeate flow per element and the permeate quality per element).

$$NDP_i = P_{fi} - \Delta P_{ei}/2 - \Delta \pi_{avg i} - P_{pi}$$

Where: P_{fi} = feed pressure for element “i”, ΔP_{ei} = pressure headloss for element “i”, $\Delta \pi_{avg i}$ = average osmotic pressure for element “i”, $P_{perm i}$ = pressure in the permeate side of element “i”.

The pressure headloss per pressure vessel is in the range 1.2 – 2 bar. In our design we will consider that the headloss is the same per element and equal to 0.2 bar.

Another consideration is that we will calculate the values at the middle of the element, thus we will take the feed-concentrate concentration [$C_{fc} = (C_f + C_c)/2$].

The procedure to follow will be the following:

1. We start with the *Element 1*. (From feed to rear in the pressure vessel)
2. P_{f1} = Feed pressure calculated in Step 4.
3. $Q_{f1} = Q_{Perm plant} / N_{PV}$ (This value was already calculated in Step 2)
4. C_{f1} (From initial data for the design)
5. Assume R_{e1} to calculate osmotic pressure. (We will assume a value and later on verify if the assumption was correct).
6. $C_{c1} = C_{f1} / (1 - R_{e1 \text{ assumed}})$
7. Osmotic pressure: 1,000 mg/L ~ 0.8 bar (Rule of thumb)
8. $NDP_1 = P_{f1} - \Delta P/2 - \Delta \pi_{avg} - P_{perm}$
9. $Q_{p1} = NDP_1 \cdot K_w \cdot A_e$ (This is the main formula)
10. $R = Q_{p1} / Q_{f1}$
11. Is $R_{e1 \text{ assumed}} = R_{e1 \text{ calculated}}$?
No? Then repeat procedure
Yes? Then continue to next element
12. $Q_{c1} = Q_{f1} - Q_{p1}$

For step 5 and 6 we can calculate:

1. $C_{fc1} = (C_{f1} + C_{c1}) / 2$
2. $Q_{fc1} = (Q_{f1} + Q_{c1}) / 2$

And then we can proceed for *Element 2*, considering the information from element 1.

1. Element 2
2. $P_{f2} = P_{f1} - \Delta P$
3. $Q_{f2} = Q_{c1}$
4. $C_{f2} = C_{c1}$
5. Assume R_{e2} to calculate osmotic pressure

We can repeat the procedure for the following elements in the pressure vessel.

	1	2	3	4	5	6	Unit	
$P_{fi} = 54$	53.8	53.6	53.4	53.2	53.0	bar		
$\Delta p_{ei} = 0.2$	0.2	0.2	0.2	0.2	0.2	bar		headloss per element
$Q_{fi} = 9.38$	8.38	7.54	6.84	6.29	5.87	m ³ /h		$Q_{f1} = Q_{fPV}, Q_{f2} = Q_{c1}, \text{ etc}$
$C_{fi} = 35,030$	39,163	43,556	47,982	52,181	55,868	mg/L		$C_{f1} = C_{fPV}, C_{fi+1} = C_{ci}$
Iter. 1 $R_{ei} = 10.5$	10.0	9.3	8.0	6.7	5.2	%		Assume R_{ei} to start iteration
$C_{ci} = 39,131$	43,506	48,013	52,146	55,921	58,926	mg/L		$C_{ci} = C_{fi} \cdot [1 - R_{ei} \cdot (1 - SR)] / (1 - R_{ei})$
$\pi_{fi} = 28.02$	31.33	34.84	38.39	41.74	44.69	bar		$\pi_{fi} = C_{fi} \cdot (0.8/1000)$
$\pi_{ci} = 31.30$	34.80	38.41	41.72	44.74	47.14	bar		$\pi_{ci} = C_{ci} \cdot (0.8/1000)$
$\pi_{fci} = 29.66$	33.07	36.63	40.05	43.24	45.92	bar		$\pi_{fci} = (\pi_{fi} + \pi_{ci}) / 2$
$\pi_{pi} = 0.297$	0.331	0.366	0.401	0.432	0.459	bar		$\pi_{pi} = 0.01 \cdot \pi_{fci}$
$\Delta \pi_{avg i} = 29.37$	32.74	36.26	39.65	42.81	45.46	bar		$\Delta \pi_{avg i} = (\pi_{fci} - \pi_{pi})$
$NDP_i = 24.53$	20.96	17.24	13.65	10.29	7.44	bar		$NDP_i = P_{fi} - \Delta p_{ei} / 2 - \Delta \pi_{avg i} - P_{pi}$
$Q_{pi} = 0.99$	0.85	0.70	0.55	0.42	0.30	m ³ /h		$Q_{pi} = NDP_i \cdot K_w \cdot A_e$
$R_{ei} = 10.57$	10.10	9.24	8.06	6.61	5.12	%		$R_{ei} = Q_{pi} / Q_{fi}$
Iter. 2 $R_{ei} = 10.57$	10.10	9.24	8.06	6.61	5.12	%		
$C_{ci} = 39,163$	43,556	47,982	52,181	55,868	58,876	mg/L		$C_{ci} = C_{fi} [1 - R_{ei} \cdot (1 - SR)] / (1 - R_{ei})$
OK	OK	OK	OK	OK	OK			$(C_{ci \text{ iter2}} - C_{ci \text{ iter1}}) < 100 ?$; "OK" ; "not OK"
$\pi_{fi} = 28.02$	31.33	34.84	38.39	41.74	44.69	bar		$\pi_{fi} = C_{fi} \cdot 0.8 / 1000$
$\pi_{ci} = 31.33$	34.84	38.39	41.74	44.69	47.10	bar		$\pi_{ci} = C_{ci} \cdot 0.8 / 1000$
OK	OK	OK	OK	OK	OK			$(\pi_{ci \text{ iter2}} - \pi_{ci \text{ iter1}}) < 0.5 ?$; "OK" ; "not OK"
$\pi_{fci} = 29.68$	33.09	36.62	40.07	43.22	45.90	bar		$\pi_{fci} = (\pi_{fi} + \pi_{ci}) / 2$
$\pi_{pi} = 0.297$	0.331	0.366	0.401	0.432	0.459	bar		$\pi_{pi} = 0.01 \cdot \pi_{fci}$
$\Delta \pi_{avg i} = 29.38$	32.76	36.25	39.66	42.79	45.44	bar		$\Delta \pi_{avg i} = (\pi_{fci} - \pi_{pi})$
$NDP_i = 24.52$	20.94	17.25	13.64	10.31	7.46	bar		$NDP_i = P_{fi} - \Delta p_{ei} / 2 - \Delta \pi_{avg i} - P_{pi}$
$Q_{pi} = 0.99$	0.85	0.70	0.55	0.42	0.30	m ³ /h		$Q_{pi} = NDP_i \cdot K_w \cdot A_e$
OK	OK	OK	OK	OK	OK			$(Q_{pi \text{ iter2}} - Q_{pi \text{ iter1}}) < 0.25 ?$; "OK" ; "not OK"
$R_{ei} = 10.57$	10.09	9.25	8.05	6.62	5.13	%		$R_{ei} = Q_{pi} / Q_{fi}$
$Q_{ci} = 8.38$	7.54	6.84	6.29	5.87	5.57	m ³ /h		$Q_{ci} = (Q_{fi} - Q_{pi})$
$C_{fci} = 37,097$	41,360	45,769	50,081	54,024	57,372	mg/L		$C_{fci} = (C_{fi} + C_{ci}) / 2$
$P_{ci} = 53.8$	53.6	53.4	53.2	53.0	52.8	bar		$P_{ci} = P_{fi} - \Delta p_{ei}$

The results so far of the previous design steps can be displayed as follow:

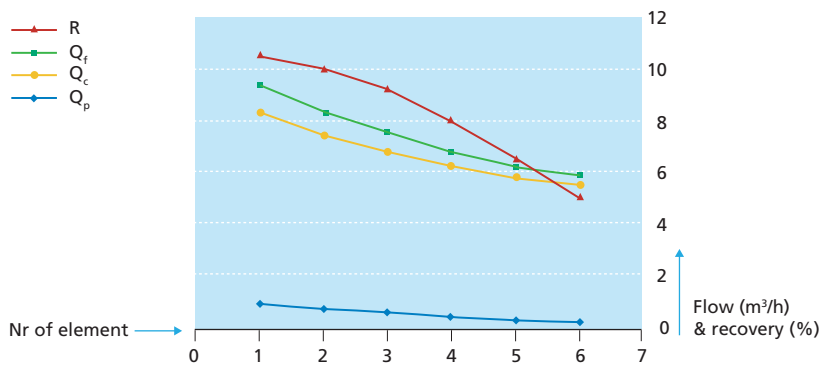


Figure 7 Flow and recovery per element along the pressure vessel

As can be observed in Figure 7, the recovery per element and permeate flow per element are not uniform in a pressure vessel. The front element produces more than three times that the last element in the pressure vessel. The recovery of the first element is 10.6 % while the last element has a recovery of 5.6 %.

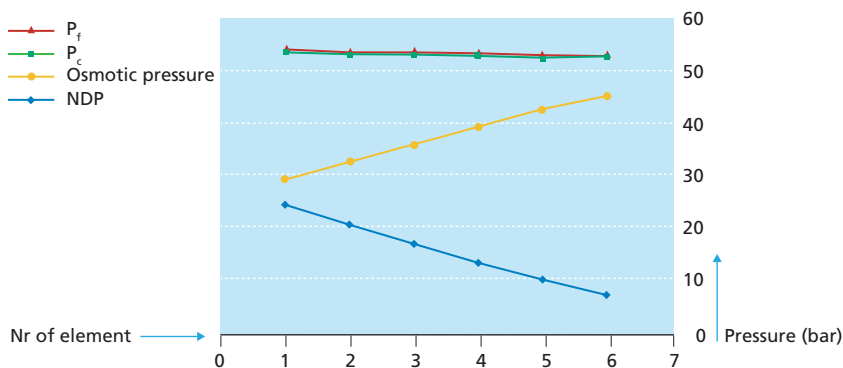


Figure 8 Pressure and osmotic pressure per element along the pressure vessel

The net driving pressure decreases along the pressure vessel as illustrated in Figure 8. The net driving pressure is calculated from the feed pressure, minus the head losses per element, minus the increasing osmotic pressure (due to the salt rejection by the RO membranes). The first element has an NDP of 24.5 bar while the last element has an NDP of 7.5 bar which results in a flux of 24.3 L/m²/h for the first element and 7.4 L/m²/h for the last element (see Figure 9).

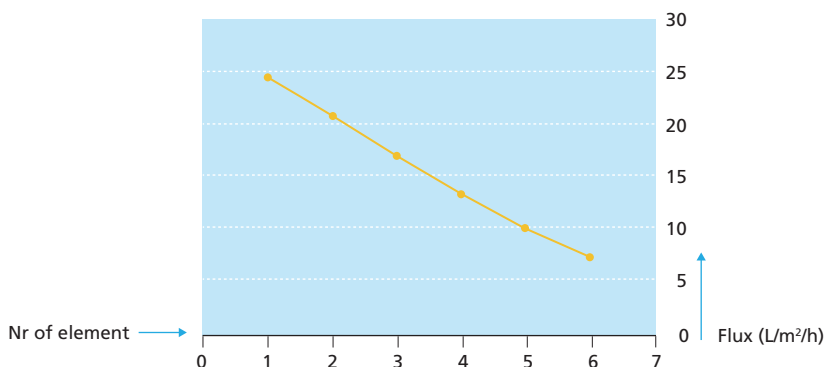


Figure 9 Flux per element along the pressure vessel

9.3.5.1 Calculation of the concentration polarization factor

With the results obtained per element, we can calculate the concentration polarization factor (CPF or β) for each element, with the following formula:

$$\beta_i = K_p \cdot e^{\left(\frac{Q_{p1}}{Q_{fc1}}\right)}$$

Where:

Q_{p1} = Permeate flow of element 1

$Q_{fc1} = (Q_{f1} + Q_{c1}) / 2$ (Average feed-concentrate flow for element 1)

$K_p = 0.99$ (Hydranautics)

repeat for other elements and verify that $\beta < 1.2$.

	1	2	3	4	5	6	Unit	
$\beta_i =$	1.107	1.101	1.091	1.077	1.060	1.044	-	$\beta_i = K_p \cdot \text{Exp}(Q_{pi} / Q_{fci})$
	OK	OK	OK	OK	OK	OK		$\beta < 1.2 ?$
$Q_{ci} / Q_{pi} =$	8.5	8.9	9.8	11.4	14.1	18.5	-	
	OK	OK	OK	OK	OK	OK		$Q_{ci} / Q_{pi} > 5 ?$

NB. We have used the formula applied by Hydranautics. DOW has a different formula.

Dupont Filmtec applies for their elements the formula: $\text{CPF} = \exp^{(0.7R)}$. Where: CPF = Concentration Polarization Factor, R = Recovery.

The recommended recovery (by Dow) varies with the quality of the feed water e.g. Seawater (10-12 %); filtered treated domestic waste water 10-12 %; pre-treated surface water 15-18 %; Softened well water 19-25 %.

Remark: In practice commonly $\beta < 1.2$ is used as a guideline (Hydranautics) as a maximum for CPF, to avoid operational problems e.g., scaling and fouling. When the ratio concentrate flow/permeate flow, drops below 5:1 (recovery higher than 18 %), then β exceeds 1.2 according the formula.

In sea water RO systems, the concentration polarization will decrease with increasing recovery. Reason is that the flux is dropping dramatically with increasing recovery.

9.3.6 Step 6 - Calculations of permeate quality

9.3.6.1 Assuming a constant salt rejection (no flux effect)

We will calculate the permeate quality for each element and per pressure vessel.

To simplify the calculations, it is assumed that salt rejection is constant, namely 99.7 % (standard conditions).

The step will be the following:

1. $C_{fc1} = (C_{f1} + C_{c1}) / 2$ (calculated in step 5, iteration 2)
2. $C_{p1} = CF_{fc1} \times (1 - SR)$
3. Repeat same procedure for elements 2, 3, 4, 5 and 6.
4. $Q_{p1}, Q_{p2}, Q_{p3}, Q_{p4}, Q_{p5}, Q_{p6}$ from step 5.
- 5.

$$C_{\text{product}} = \frac{C_{p1} \cdot Q_{p1} + C_{p2} \cdot Q_{p2} + C_{p3} \cdot Q_{p3} + C_{p4} \cdot Q_{p4} + C_{p5} \cdot Q_{p5} + C_{p6} \cdot Q_{p6}}{Q_{p1} + Q_{p2} + Q_{p3} + Q_{p4} + Q_{p5} + Q_{p6}}$$

6. Compare with Step 2.

	1	2	3	4	5	6	Unit	
$C_{fc1} =$	37,097	41,360	45,769	50,081	54,024	57,372	mg/L	from step 5, iteration 2
$C_{pi} =$	74.2	82.7	91.5	100.2	108.0	114.7	mg/L	$C_{pi} = C_{fc1} (1 - SR)$

Now, we can calculate the permeate concentration per pressure vessel with the mentioned formula:

$$C_{\text{product}} = \frac{74.2 \cdot 0.99 + 82.7 \cdot 0.85 + 91.5 \cdot 0.70 + 100.2 \cdot 0.55 + 108.0 \cdot 0.42 + 114.7 \cdot 0.30}{0.99 + 0.85 + 0.70 + 0.55 + 0.42 + 0.30}$$

$$C_{\text{product}} = 89.96 \text{ mg/L}$$

9.3.6.2 Salt rejection depends on the flux

We will calculate the salt rejection and permeate quality per element, taking into account the effect of flux.

Salinity of the feed water determines the permeate salinity, together with membrane performance (K_s), flux and recovery.

The steps to calculate the permeate quality with effect of flux are the following:

1. $C_{fc1} = (C_{f1} + C_{c1}) / 2$
2. $J_1 = Q_{p1} / A_e$
3. $C_{p1} = (C_{fc1} \times K_s) / J_1$
4. Repeat same procedure for elements 2, 3, 4, 5, and 6.

5.

$$C_{\text{product}} = \frac{C_{p1} \cdot J_1 + C_{p2} \cdot J_2 + C_{p3} \cdot J_3 + C_{p4} \cdot J_4 + C_{p5} \cdot J_5 + C_{p6} \cdot J_6}{J_1 + J_2 + J_3 + J_4 + J_5 + J_6}$$

6. Compare with Step 2 and with calculation without the flux effect.

	1	2	3	4	5	6	Unit	
$C_{fci} =$	37,097	41,360	45,769	50,081	54,024	57,372	mg/L	from step 5, iteration 2
$J_i =$	24.28	20.74	17.09	13.50	10.21	7.39	L/m ² .h	$J_i = Q_{pi} / A_e$
$C_{pi} =$	85.2	111.2	149.4	206.8	294.9	433	mg/L	$C_{pi} = C_{fci} \cdot K_s / J_i$

Now, we can calculate the permeate concentration per pressure vessel with the mentioned formula:

$$C_{\text{product}} = \frac{85.2 \cdot 24.28 + 111.2 \cdot 20.74 + 149.4 \cdot 17.09 + 206.8 \cdot 13.50 + 294.9 \cdot 10.21 + 433 \cdot 7.39}{24.28 + 20.74 + 17.09 + 13.50 + 10.21 + 7.39}$$

$$C_{\text{product}} = 170.9 \text{ mg/L}$$

What is the effect of temperature on salinity of product water? The higher the temperature, the higher the K_s [$K_s = J \cdot (C_p / C_{fc})$ and $J = \Delta P / (\eta \cdot R)$]. As a consequence the salinity in the product will increase (~3 % increase per °C).

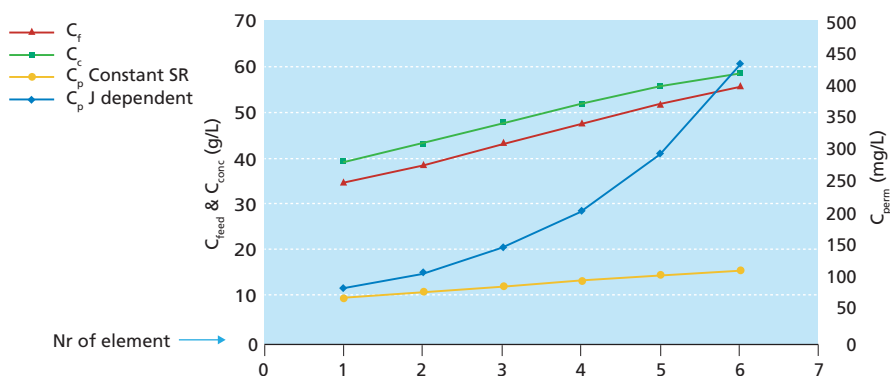


Figure 10 Feed concentration, concentrate concentration, and permeate concentration (considering salt rejection is constant & considering the effect of flux on permeate concentration) per element along the pressure vessel

Why is the salinity of the product water (permeate) of the elements increasing with the position (1, 2, 3, ...6)? This is due to two reasons: *i*) the salinity in the feed/concentrate stream is increasing with increasing recovery (element 1 to element 6); *ii*) the flux is decreasing with increasing recovery.

9.3.7 Step 7 - Cross-flow velocity calculation

SWC4 MAX	Type of membrane element	
$A_e = 40.8 \text{ m}^2$	Area of the membrane element	
$L_e = 1.0 \text{ m}$	Length of the membrane element	
$h = 0.00071 \text{ m}$	Height of the feed space	
$\varepsilon = 085$	Porosity of the feed spacer	0.8-0.85 (Vrouwenvelder, 2009)

The steps to follow are the next ones:
 Q_{fc} = flow in the feed-concentrate stream
 w = total spacer width

	1	2	3	4	5	6	Unit	
$Q_{fci} =$	8.88	7.96	7.19	6.57	6.08	5.72	m^3/h	$Q_{fci} = (Q_{fi} + Q_{ci}) / 2$
$w =$	20.4	20.4	20.4	20.4	20.4	20.4	m	$w = (A_e / L_e) / 2$
$A_{eff} =$	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123	m^2	$A_{effective} = \varepsilon \cdot h \cdot w$
$v_{fci} =$	0.20	0.18	0.16	0.15	0.14	0.13	m/s	$v_{fci} = Q_{fci} / A_{effective}$

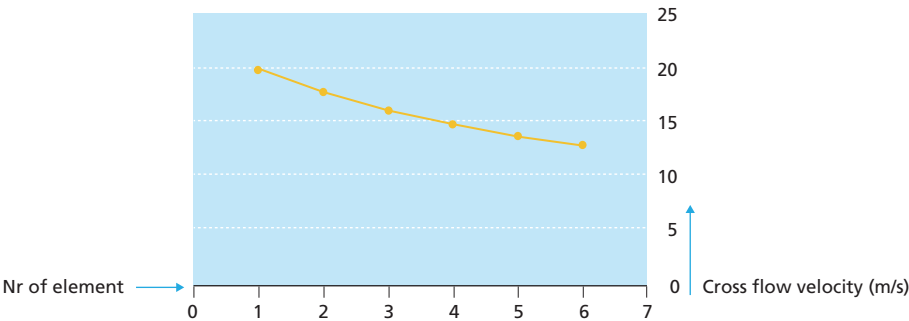


Figure 11 Cross flow velocity per element along the pressure vessel

9.3.8 Step 8 - Energy consumption

9.3.8.1 Energy to raise the pressure of 1 m³ to 1 bar

By definition: Work = Energy = force $\times$ displacement = $N \times m$ = Joule
1 Joule = 1 N $\times$ m = 1 kg·m/s² $\times$ m = 1 kg·m²/s²

To bring water at a higher level of e.g., h metres (1 bar = 10 m), the work will be per m³:

$\text{Force} = F = m \cdot g = (\rho \cdot V) \cdot g$ or $\text{force per m}^3 = (\rho \cdot g)$
 $\text{Work} = \text{Energy} = \text{force} \times \text{distance}$ $= (\rho \cdot g) \cdot h$
 $= (1,000 \text{ kg/m}^3 \cdot 9.8 \text{ m/s}^2) \cdot 10 \text{ m} = 98,000 \text{ Joule}$
 Note: Joule / s = Watt or Joule = W·s = Ws
 Then, we have:
 $= 98,000 \text{ W} \cdot \text{s} = 98,000 / 3,600 \text{ W} \cdot \text{h}$
 $= 0.0275 \text{ kW} \cdot \text{h per m}^3$.

9.3.8.2 Without energy recovery device (ERD)

$$E = (0.0275 \cdot P_{\text{feed}}) / (N_{\text{pump}} \cdot R)$$

	0.0275	kWh/m ³	Energy required to raise the pressure of 1 m ³ water to 1 bar
$P_{\text{feed}} =$	54	bar	Feed pressure in the system
$N_{\text{pump}} =$	0.77		Efficiency of pump with driver
	5,030	mg/L	TDS of feed water (data)
$R =$	40%		Recovery
$E =$	4.82	kWh/m ³	without energy recovery device

9.3.8.3 With energy recovery device (ERD)

$$E = [(0.0275 \cdot P_{\text{feed}}) / (N_{\text{pump}} \cdot R)] - [0.0275 \cdot (1 - R) \cdot P_{\text{conc}} \cdot N_{\text{turbine}}] / R$$

	0.0275	kWh/m ³	Energy required to raise the pressure of 1 m ³ water to 1 bar
$P_{\text{feed}} =$	54	bar	Feed pressure in the system
$P_{\text{conc}} =$	52.8	bar	Pressure in concentrate stream at the end of pressure vessel
$N_{\text{pump}} =$	0.77		Efficiency of pump with driver
$N_{\text{turbine}} =$	0.8		Efficiency of turbine with driver
$R =$	40%		Recovery
$E =$	3.08	kWh/m ³	without energy recovery device

9.3.9 Step 9 – Summary

Nr of pressure vessels in the plant =	12		#PV
Total number of elements =	72		#elements
$R =$	40.6	%	$R = Q_{p \text{ PV}} / Q_{f \text{ PV}}, \text{ where } Q_{p \text{ PV}} = \sum Q_{p i}$
$J_{\text{avg}} =$	15.5	L/m ² .h	$J_{\text{avg}} = \sum J_i / \# \text{ elements}$

$Q_{P \text{ Plant}} =$	45.6	m^3/h	$Q_{P \text{ Plant}} = \#_{PV} \times Q_{P \text{ PV}}$
$E =$	4.8	kWh/m^3	without energy recovery device
$E =$	3.1	kWh/m^3	with energy recovery device

Summary of the process design per RO pressure vessel:

Element	R, %	$Q_p, \text{m}^3/\text{h}$	$Q_c, \text{m}^3/\text{h}$	$Q_{p'}, \text{m}^3/\text{h}$	$C_p, \text{mg/L}$	$C_c, \text{mg/L}$	$C_p, \text{mg/L}$	Const SR	J dependent
1	10.6	9.38	8.38	0.99	35,030	39,163	74	85	
2	10.1	8.38	7.54	0.85	39,163	43,556	83	111	
3	9.2	7.54	6.84	0.70	43,556	47,982	92	149	
4	8.1	6.84	6.29	0.55	47,982	52,181	100	207	
5	6.6	6.29	5.87	0.42	52,181	55,868	108	295	
6	5.1	5.87	5.57	0.30	55,868	58,876	115	433	
Total			$Q_{p \text{ PV}} =$	3.80				90	171

The total recovery of the designed RO unit can be calculated by dividing the permeate flow over the feed flow. This is $3.8 \text{ m}^3/\text{h} / 9.38 \text{ m}^3/\text{h}$ equals 0.405 or 40.5 % which corresponds with our initial target for the RO recovery.

The total flow of the plant is equal to $3.8 \text{ m}^3/\text{h}$ multiplied by the number of pressure vessels, equal to 45.6 m^3/h which also matches our designed capacity. Note that the pre-treatment units need to be designed for the RO feed flow ($45.6 \text{ m}^3/\text{h}$ divided by 40 % recovery equals to $112 \text{ m}^3/\text{h}$).

Element	P_f, bar	P_c, bar	NDP, bar	$J, \text{L}/\text{m}^2 \cdot \text{h}$	$Q_{fc}, \text{m}^3/\text{h}$	Beta	$Q_c:Q_p$	$v_{fc}, \text{m/s}$
1	54	53.8	24.52	24.3	8.88	1.107	8.5	0.20
2	53.8	53.6	20.94	20.7	7.96	1.101	8.9	0.18
3	53.6	53.4	17.25	17.1	7.19	1.091	9.8	0.16
4	53.4	53.2	13.64	13.5	6.57	1.077	11.4	0.15
5	53.2	53.0	10.31	10.2	6.08	1.060	14.1	0.14
6	53.0	52.8	7.46	7.4	5.72	1.044	18.5	0.13
Total			$J_{\text{avg}} =$	15.5				

The average flux also matches our initially selected design flux of $15 \text{ L}/\text{m}^2/\text{h}$. The front elements in the RO unit operate at higher flux rate than the rear elements. In our design, the rear element operated at 3.5 times less flux than the front element.

In all the elements, the concentration polarization factor was below 1.2, as required by the RO membrane manufacturers.

The cross flow velocity ranged between 0.1 and 0.2 m/s which is considered normal in RO installations. In order to keep the production constant, the feed pressure will increase to overcome the extra resistance due to membrane fouling.

Comment:

- For drinking water, 500 mg/L is usually the guideline for TDS (WHO, 2011).
- For industrial waters much lower guidelines are often adopted, e.g., 10 to 50 mg/L.
- Usually a second pass is installed when lower salinity is required.

9.4 REFERENCES

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