SYSTEM

DESIGN

Guidelines for the Design of Reverse Osmosis Membrane Systems

Lewabrane®

LANXESS

Energizing Chemistry

Index

1. System Design

1.1 Introduction of RO System

1.1.1 Material Balance of RO System

The RO system includes a set of RO membrane elements, housed in pressure vessels that are arranged in a design manner. A high-pressure pump is used to feed the pressure vessels. The RO system is operated in crossflow filtration mode, not in dead end mode, because of the osmotic pressure of rejected solute.

The RO system is usually designed for continuous operation and the operating parameters (permeate flow rate and recovery rate) are constant with time. Figure 1.1 illustrates the material balance of a typical RO system. The feed flow is devided to permeate and concentrate flow.

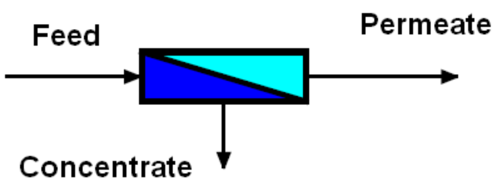

Figure 1.1: Material balance of RO system

1.1.2 Single-Module System

An RO membrane system consists of RO elements arranged in pressure vessels. The arrangement of the RO system can be single or double Pass with the specific geometry of the pressure vessel arrangement described in Stages, and with pressure vessels inside a Stage arranged in what is called an Array. Inside the pressure vessel, the elements are connected sequentially in series format with up to eight elements per pressure vessel.

The concentrate of first element becomes the feed to the second, and so on. The product water tubes (center pipe) of all elements are coupled, and connected to the module permeate port. In a single-module RO system, the system recovery rate is approx 50%. This value is applicable to standard single Pass seawater desalination systems.

To achieve the recovery rate higher than 50%, concentrate recirculation is applied. In this system configuration, part of concentrate is recycled and added to the suction side of the high-pressure pump, thus increasing the feed flow rate (shown in Figure 1.2). A high fraction of the concentrate being recycled helps reduce single hydraulic element recovery, and thus, reducing the risk of membrane fouling or scaling. On the other hand, concentrate recirculation has disadvantages of larger high-pressure feed pump, higher energy consumption and permeate quality decrease.

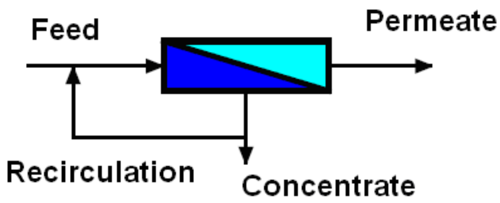

Figure 1.2: Single module system with concentrate recirculation

1.1.3 Single-Stage System

In a single-stage system, two or more vessels are arranged in parallel. Feed, concentrate and permeate lines from the parallel pressure vessels are connected to the corresponding manifolds. The single-stage system operates in the same way as a single-module system. Single-stage system is typically used where the recovery rate does not exceed 50% to 60%, e.g., in seawater desalination.

1.1.4 Multi-Stage System

Systems with more than one stage are used for higher system recovery rates without exceeding the single element recovery limit. Usually two stages will be applied for recovery rate up to 75-80%. To compensate for the permeate which is removed and to maintain a uniform feed cross flow rate in each stage, the number of pressure vessels per stage decreases in the flow direction. In a typical two-stage system (shown in Figure 1.3), the ratio of vessel number is 2:1 (upstream: downstream).

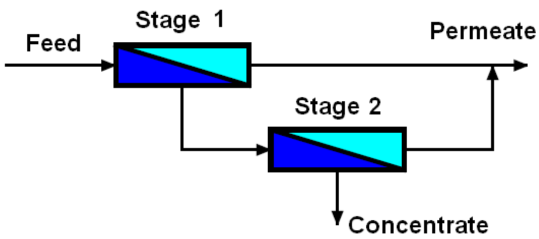

Figure 1.3: Example of 2nd stage system

The relation between recovery rate and the stage number is as follows:

1 stage : < 50-60%;

2 stage : < 75-80%;

3 stage : < 85-90%

1.1.5 2-Pass RO System

A 2 pass RO system is used if a very high permeate quality is required. In this system configuration, the permeate of the 1st pass RO is the feed to the 2nd pass RO. Figure 1.4 shows a schematic flow diagram of the 2 pass RO system. The concentrate of the 2nd pass RO is recycled back to the feed of 1st RO because its quality is usually better than the system feed water. Because the feed to the 2nd RO is of high quality, the recovery of the 2nd pass RO can be very high, usually in the range of 85-95%.

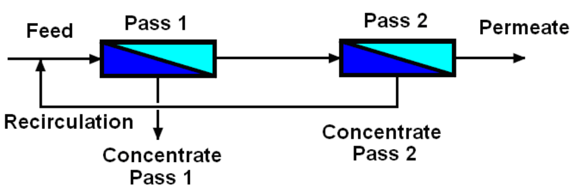

Figure 1.4: 2 pass RO system

1.1.6 Permeate Blending with Feed Water

Permeate blending is utilized whenever possible without exceeding required salinity of product water. This is usually the case of brackish RO system. In this case, some additional system feed water (blending flow) is taken and added to the permeate (shown in Figure 1.5). By utilizing permeate blending with the feed water, the number of RO elements in the RO unit can be reduced.

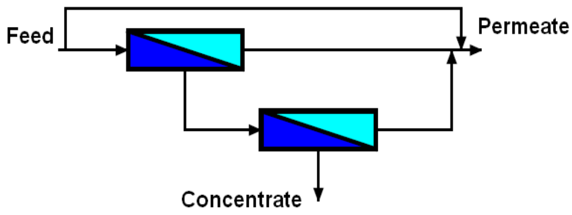

Figure 1.5: Permeate blending system of a two stage system

1.1.7 Permeate Recirculation

In the case that the feed temperature greatly differs (e.g. summer and winter), the feed pressure should be changed to keep the permeate constant. This change in feed pressure may cause permeate quality instability. To prevent the instability, a part of the permeate is recycled and added to the suction side of the high-pressure pump (shown in Figure 1.6), when the permeate flow is higher than the estimated value. By keeping the feed pressure constant, the permeate quality is kept constant.

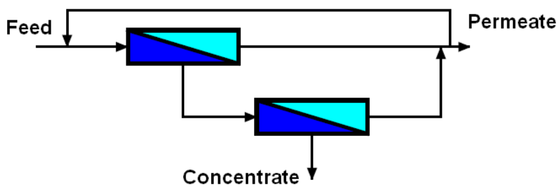

Figure 1.6: Permeate recirculation of a two stage system

1.2 Items of Water Analysis

The major water types treated by RO membrane are roughly divided into seawater, brackish water, wastewater, municipal water and RO permeate. In addition, these water types are finely classified by the type of pretreatment (natural or artificial).

In case of seawater, TDS concentration, 35,000 mg/l is considered to be the standard. However, the actual TDS concentration may vary from 7,000 mg/l up to 45,000 mg/l. The composition may be proportionally estimated from the standard seawater composition (shown in Table 1.1).

Whereas the composition of brackish water and wastewater may be extremely wide in variation, and accordingly, feed water analysis is very important for a good process design. Because in brackish water desalination, calcium carbonate and silica scale are frequent occurrences, at least concentrate of TDS, calcium ion, bicarbonate ion (alkalinity), silica, temperature and pH value are needed to design RO process. If the water analysis is not balanced, the addition of either sodium ion or chloride ion to achieve electroneutrality is recommended.

Ion	Concentration (mg/l)
Calcium	420
Magnesium	1,320
Sodium	10,880
Potassium	400
Barium	0.03
Strontium	10
Iron	< 0.02
Manganese	< 0.01
Silica	2.0
Chloride	19,800
Sulfate	2,660
Fluoride	1.3
Bromide	65
Nitrate	< 0.7
Bicarbonate	150
Boron	4-5
TDS (Total Dissolved Solid)	35,000
pH	8.1 – 8.2 (-)

Table 1.1: Standard seawater composition

1.3 Basic Equations for RO Calculations

1.3.1 Water Transport

Water transport through the membrane is expressed as a permeate flux. The flux is generally defined as the volumetric flow rate of water through a given membrane area. In the case of RO, the unit of flux is expressed as liters of water per square meter of membrane area per hour (lmh) or gallons per square foot per day (gfd). The permeate flux is proportional to the net driving pressure (NDP).

$$Jv = A \times NDP \qquad (1.1)$$

$$NDP = \Delta P - \Delta\pi - 0.5 \times dp \qquad (1.2)$$

In which: $\Delta P = P_f - P_p$, pressure differential

$\Delta\pi = \pi(C_{fave}) - \pi(C_p)$, average osmotic pressure differential

J_V, permeate flux, A, water permeability (specific flux), NDP, net driving pressure

P_f, feed pressure, P_p, permeate pressure, P_c, concentrate pressure, dp, pressure drop

π (C_{ave}), average feed osmotic pressure, π (C_p), permeate osmotic pressure

C_f, feed concentration, C_p, permeate concentration, Cc, concentrate concentration

$C_{fave} = (C_f + C_c)/2$, average feed concentration

NDP is calculated by pressure difference, osmotic pressure difference and pressure drop. The average feed concentration (feed and concentrate) is used to calculate osmotic pressure.

The product flow rate can be obtained by multiplying the permeate flux by total membrane area.

$$Q_p = M_A \times J_V \qquad (1.3)$$

In which: Qp, product flow rate, M_A, total membrane area

The pressure drop is calculated by the average flow rate (feed and concentrate) as follows:

$$dp = a \times \{(Q_f + Q_c)/2\}^b \qquad (1.4)$$

In which a and b are coefficients, specific for element and feed spacer configuration. The values for these coefficients are obtained experimentally.

1.3.2 Solute Transport

Solute transport through an RO membrane is expressed as a solute flux. This solute flux is proportional to the concentration difference across the membrane. The average feed concentration (feed and concentrate) is used in the feed side to calculate solute transport. And the rate of solute transport is defined by rejection or salt passage as follows:

$$J_S = B \times (C_{fave} - C_p) \qquad (1.5)$$

$$R = 1 - (C_p / C_{fave}) \qquad (1.6)$$

$$SP = 1 - R = C_p / C_{fave} \qquad (1.7)$$

In which:

J_S, solute flux, B, solute permeability, R, rejection, SP, salt passage

Rejection and salt passage are usually expressed as percent.

1.3.3 Correlation of Operating Conditions

RO membrane system performance (flux and rejection or salt passage) is influenced by operating conditions such as operating pressure, temperature, feed concentration etc. So the parameters of RO performance (specific flux and salt passage) are revised by the operating conditions influencing the RO performances as follows:

$$A_S = A_n \times TCF_1 \times SCF_1 \times FF \qquad (1.8)$$

$$SP_s = SP_n \times \{(J_V)_n / (J_V)_s\} \times TCF_2 \times SCF_2 \qquad (1.9)$$

In which:

A_S, specific flux at operating conditions, A_n, specific flux at nominal conditions

SP_S, salt passage at operating conditions, SP_n, salt passage at nominal conditions

$(J_V)_n$, permeate flux at operating conditions, $(J_V)_n$, permeate flux at nominal conditions

TCF, correlation factor of temperature (1; on specific flux, 2; on salt passage)

SCF, correlation factor of feed concentration (1; on specific flux, 2; on salt passage)

FF, fouling factor

In computer programming, estimated performance based on the nominal value is automatically calculated by using above equations.

1.4 RO System Design Guidelines

1.4.1 Fouling Tendency with Operating Conditions

The factor which has the greatest influence on the RO system design guideline is the fouling tendency of the feed water. Membrane fouling is caused by particles and colloidal materials which are present in the feed water and become concentrated at the membrane surface. The Silt Density Index (SDI) of pretreated feed water is an index of the fouling potential of particle or colloidal materials in the RO system. The concentration of the fouling materials at the membrane surface increases with increasing permeate flux, increasing element recovery and decreasing concentrate flow rate. Therefore the average permeate flux of the RO system (total product flow rate divided by total membrane area) should be low if a strong fouling environment is anticipated.

1.4.2 Recommended Range of Element Operating Conditions (Design Guideline)

The RO membrane system should be designed such that each element of the system operates within the recommended operating conditions to minimize the fouling possibility, and to exclude mechanical damage. The limiting conditions are the maximum recovery (system and element), the maximum average permeate flux, the minimum concentrate flow rate, the maximum feed flow rate, the maximum lead element permeate flux, and so on. The higher the fouling tendency of the feed water, the limits of the parameters become stricter.

Table 1.2 shows the range of these parameters according to the type of the feed water and the type of pretreatment. The membrane pretreatment improves the feed water quality in view of the fouling. In the table the parameter of membrane performance changes with time is added (flux decline rate and salt passage increase).

The range of parameters shown in the table is recommended value to minimize the fouling possibility, but it does not mean that the system design out of the parameter range is impossible. It means that the possibility of the fouling becomes higher.

Feed Water Type	Average Permeate Flux (range) [l/m²·hr]	Lead Element Permeate Flux [l/m²·hr]	Concen-trate Flow Rate per Vessel [m³/hr]	Feed Flow Rate per Vessel [m³/hr]	Pressure Drop per Vessel [bar]	Element Recovery Rate [%]	Salt Passage Increase [%]
Municipal Supply	23 (20-26)	< 31	8-inch: > 3.6 4-inch: > 0.7	8-inch: < 15 4-inch: < 2.8	< 2.0	< 15	> 10
Brackish Wells	27 (23-29)	< 34	8-inch: > 3.0 4-inch: > 0.6	8-inch: < 16 4-inch: < 3.2	< 3.0	< 20	> 10
Surface Water Media Filtration	23 (20-26)	< 31	8-inch: > 3.6 4-inch: > 0.7	8-inch: < 15 4-inch: < 2.8	< 2.0	< 15	> 10
Surface Water MF/UF Filtration	27 (23-29)	< 34	8-inch: > 3.0 4-inch: > 0.6	8-inch: < 16 4-inch: < 3.2	< 3.0	< 20	> 10
Secondary Waste Media Filtration	17 (14-20)	< 24	8-inch: > 4.1 4-inch: > 0.8	8-inch: < 14 4-inch: < 2.6	< 2.0	< 12	> 15
Secondary Waste MF/UF Filtration	20 (17-23)	< 28	8-inch: > 3.6 4-inch: > 0.7	8-inch: < 14 4-inch: < 2.8	< 2.0	< 17	> 10
Seawater Intake Media Filtration	14 (11-17)	< 30	8-inch: > 3.6 4-inch: > 0.7	8-inch: < 14 4-inch: < 2.8	< 2.0	< 13	> 10
Seawater Intake MF/UF Filtration	17 (14-20)	< 35	8-inch: > 3.4 4-inch: > 0.7	8-inch: < 16 4-inch: < 3.0	< 3.0	< 15	> 10
Seawater Beach Wells	17 (14-20)	< 35	8-inch: > 3.4 4-inch: > 0.7	8-inch: < 16 4-inch: < 3.0	< 3.0	< 15	> 10
RO Permeate	37 (32-42)	< 48	8-inch: > 2.4 4-inch: > 0.5	8-inch: < 17 4-inch: < 3.6	< 3.0	< 30	> 5

Table 1.2: Example of RO system design guideline

1.5 Steps to RO membrane system design

1.5.1 System Design Information and Feed Water

The RO membrane system highly depends on the available feed water. Therefore, the system design information (customer/OEM, required product flow rate, expected recovery rate, annual water temperature, water source, application, pretreatment, required product water quality, operating pressure limit, etc.) and the feed water analysis should be thoroughly studied and considered in selection of the RO system design. If the required permeate water quality is so high that the quality cannot be achieved by 1pass RO system, and then a 2 pass RO system should be considered. As an alternative to the 2 pass RO, an ion exchange resin system may also be a viable design option.

1.5.2 Selection of Element Type and Average Permeate Flux

According to the feed water source, pretreatment and feed water salinity, the type of RO membrane element is selected. The relationship between the feed salinity and general selection of RO element is shown in Table 1.3. In the case that the RO feed water is a wastewater, the low fouling RO element may be also be considered.

Low conc. Brackish water (up to 500mg/l)	: BWRO (Low energy)
Brackish water (up to 5,000 mg/l)	: BWRO (Standard)
Brackish water (more than 5,000 mg/l), Seawater	: SWRO

Table 1.3: Selection of RO element according to the feed salinity

Once the water source, pretreatment and RO element type are fixed by the designer, the recommended value of the average permeate flux (also called "design flux") is given. The LANXESS recommended design flux values for Lewabrane® RO membrane elements are listed in Table 1.2. In some cases, the design flux value is determined by pilot experiment data or customer's experience.

1.5.3 Calculation of Number of Total RO Elements

The relationship between the number of total elements, the product flow rate and the average permeate flux is expressed as follow equation:

$$N_E = Q_p / \{ J_{V,ave} \times (M_A)_E \} \quad (3.10)$$

In which:

N_E = total element numbers

Q_p = product flow rate

$J_{V,\,ave}$ = average permeate flux

$(M_A)_E$ = membrane area of element (as shown in data sheet)

The calculated number of RO elements may be a slightly changed based on the decision of element arrangement, that is, the number of pressure vessels and RO elements per pressure vessel.

1.5.4 Decision of Recovery Rate

In an RO membrane system, a recovery rate as high as possible is desirable, but a high recovery rate can also cause some problems as follows:

- Possibility of scale formation increase because of the increase of concentration factor
- Osmotic pressure increase because of the increase of concentration factor
- Concentrate flow rate decrease
- Permeate water quality deterioration because of average feed concentration increase

Recovery Rate	Concentration Factor
50%	2
75%	4
80%	5
90%	10

Table 1.4: Relationship between Recovery Rate and Concentration Factor

The relationship between recovery rate and concentration factor is shown in Table 1.4.

Usually in brackish water desalination, the recovery rate is decided by scale formation, and in seawater desalination, by feed pressure limit. Some customers often require the highest possible recovery rate, but in that case, the value of the recovery rate should be decided by considering the potential for the above problems.

1.5.5 Decision of Number of Stages

The number of RO stages defines how many pressure vessels are in series in the RO membrane system. Every stage consists of a certain number of pressure vessels in parallel. The number of stages is a function of the system recovery rate, the number of elements per vessel, and the feed water quality shown in Table 1.5.

1 stage system: < 50%
• Usual recovery SWRO (< 50%)
2 stage system: < 75-80%
• Usual recovery BWRO (< 80%)
• High recovery SWRO (< 60%)
• High recovery 2nd pass (< 90%)
3 stage system: < 85-90%
• High recovery BWRO (< 90%)
• High recovery 2nd pass (< 95%) (special case)
SWRO: seawater desalination, BWRO: brackish water desalination

Table 1.5: Relationship between recovery rate and number of RO stage

1.5.6 Decision of Number of RO Elements per Pressure Vessel

RO membrane elements can be coupled together in series in the pressure vessel, typically 1-8 elements per one pressure vessel. In decision of the number of RO elements per pressure vessel, plant size is usually considered first. In a large-scale plant (> 40 m3/h), 6-8 elements per pressure vessel are usually adopted, and in a smaller plant, 3-5 elements per pressure vessel. In all cases, the space required to install or remove the RO elements should be considered in the plant design.

By increasing the number of RO elements per pressure vessel, almost all RO design parameters will change. RO design parameters are average permeate flux, lead element permeate flux, concentrate flow rate per vessel, feed flow rate per vessel, individual element recovery rate, and pressure drop per vessel, etc.. Some factors improve (become desirable) and some factors become worse (undesirable). Table 1.6 shows RO system design parameters and the correlation between an increase in number of RO element per pressure vessel, and change in RO system design parameters. It is recommended that these parameters are in accordance with the design guideline (Table 1.6).

RO System Design Parameters	Effect of increasing number of Elements/Vessel	Judgement of the effect
Average Permeate Flux	Same	No change
Lead Element Flux	Larger	Undesirable
Concentrate Flow Rate per Vessel	Larger	Desirable
Feed Flow Rate per Vessel	Larger	Undesirable
Pressure Drop per Vessel	Larger	Undesirable
Pressure Drop per Element	Larger	Undesirable
Recovery Rate of Element	Smaller	Desirable
Recovery Rate of System	Same	No change
Number of Vessel	Smaller	Desirable

Table 1.6: Effects of changing the RO design

1.5.7 Decision of Element Arrangement

The RO element arrangement (array) means element numbers per vessel, vessel numbers per stage and stage numbers per pass. For the decision of element arrangement, the system design parameters should be consistent with the design flux guideline. However, not all the parameters are suitable to the guideline. In the case that not every parameter is in accordance with the design guideline, it is necessary to make a priority in the parameters. Usually average permeate flux, concentrate flow rate per vessel and pressure drop per vessel should be of higher priority.

To decide the array, several calculations for case study should be done by computer program and these results should be compared. Some case studies should be done with the consideration of different operating conditions (feed concentration, temperature, etc.) or performance changes with time. For each typical case, a comparison should be done in consideration of value of design parameter, the numbers of RO elements or pressure vessel, and satisfying the customers demand (product water quality, limit of feed pressure etc.).

1.5.8 Relations between Nominal Performances and Field Results

The relationship between nominal performances (data sheet values) and actual field results are as follows:

a) With same membrane area and at the same nominal test conditions, a higher nominal flow rate element will require lower feed pressure.

b) At different test conditions and / or different membrane area, feed pressure will be defined by water permeability (specific flux).

c) With the same membrane area, the same nominal test conditions, and the same permeate flow rate, a higher salt rejection element will produce a permeate of lower salinity.

d) At different membrane area and / or nominal test conditions, a lower relative salt passage element (multiplier of nominal permeate flux by nominal salt passage) will produce a permeate of lower salinity.

e) The nominal permeate flux (catalogue value) is usually quite large (large enough that it will not cause membrane fouling), therefore the average permeate flux in actual field becomes smaller than the nominal permeate flux.

1.5.9 Comparing Actual Performance of Lewabrane® Elements to Projection Program

The LewaPlus™ projection program is a tool used to estimate stabilized performance for a specific RO membrane system under design or actual conditions. The projected RO membrane system performance is based on a nominal performance specification for the Lewabrane® elements used in the given system. A fouling factor of 1 in the projection program is used to calculate the performance of new elements based on the nominal flow rate (data sheet value). A fouling factor of < 1 should be used when making a design for long-term operation.

In the actual RO membrane system, the RO elements may have a flow rate variation of +/-15% of the nominal value, or whatever variation is specified for a given element type. Also, the salt rejection of an individual element may be higher or lower than the nominal salt rejection (but more than the minimum value). Therefore, the measured stabilized performance is unlikely to be exactly the same as the computer projected performance, but as a rule of thumb, the computer projection for RO systems with more than 36 new elements should come close to the computer design projection.

The actual fouling factor of a stabilized new RO system with at least 36 elements should range between 0.95 and 1.05. The actual measured TDS value of permeate should be no higher than about 1.5 times the calculated TDS value. For RO membrane systems with only one, or a few elements, the deviation of the measured actual performance from the projected performance may become as large as the specified performance variation.

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