14

Calculation of RO unit performance

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Reverse osmosis membrane unit is divided into subsequent stages, each one consisting of array of parallel connected pressure vessels (Fig. 13.9). Each pressure vessel in a stage operates at very similar hydraulic conditions (feed flow and pressure). Inside pressure vessel, membrane elements operate in series, connected together through permeate tubes. Each subsequent element in pressure vessel operates at increasing feed salinity and decreasing feed pressure; i.e., producing lower quantity of RO permeate of increasing salinity due to decreasing NDP. There is symmetry of operating conditions and performance across the membrane unit and gradual change of parameters along the unit. For the calculation purpose, each stage can be represented by a single pressure vessel. Performance of membrane elements in subsequent positions have to be calculated in a stepwise manner, where concentrate conditions of leading element becoming feed conditions to the next element in line, along the feed–concentrate flow path.

14.1 Manual method of membrane system performance calculations

Manual calculation of RO system feed pressure and permeate salinity, provides results that are only rough approximation of actual performance in field conditions. However, manual calculations helps understand relations that are

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applicable to important operational procedure: normalization of system performance.

The common approach to manual projection of performance of RO system is to calculate permeate flow according to the net driving pressure model and base calculations of permeate salinity on salinity gradient between feed and permeate as a driving force of the salt transport. The reference conditions are the nominal element performance, as tested at standard test conditions, defined by membrane manufactures. Single point calculations for basic system configuration can be conducted manually (as shown below). However, repeated calculations, required for optimization of process design, are conducted using computer programs available from all major membrane manufacturers.

The manual calculations process is conducted through to the following steps:

1. According to the type of feed water source, select membrane element model for the application and select value of system average permeate flux (APF). Recommended ranges of APF are listed in Table 11.3
2. Using nominal test conditions and nominal element performance calculate specific permeability (specific flux) of the selected membrane element (Example 11.10).
3. Using the above values of APF and SP calculate the required net driving pressure (Equation. 11.22).
4. Based on feed water composition, feed water type or project specifications select system recovery ratio and calculate average feed salinity (Equations 11.12 or 11.13).
5. Calculate corresponding average feed osmotic pressure (Equation 11.1 or salinity–osmotic pressure relations).
6. Make assumptions regarding system array, pressure drop per stage and permeate back pressure.
7. Using calculated values of required NDP, average osmotic pressure of feed water and system pressure drop calculate required feed pressure (Equation 11.16).
8. Calculate permeate salinity based on average feed salinity, average system permeate flux, nominal element salt passage and element permeate flux at nominal test conditions.

Example #14.1

Brackish two stage RO system.
Feed salinity, FS = 1500 ppm TDS.
Recovery rate: R = 85%.
Average flux rate, AFR = 27.2 l/m^2/hr (16 gfd).
Feed water temperature, t = 25°C.

Calculations of specific element performance
Element type: ESPA2+, membrane area: 39.5 m^2 (430 ft^2)
Nominal element performance: 41.6 m^3/d @ pressure 10.3 bar (11,000 gpd @ 150 psi)
Nominal salt rejection, NSR = 99.6%
Nominal flux, NF = 41.6 × 1000/(24 × 39.5) = 43.9 l/m^2/hr (25.8 gfd)
Nominal test conditions: feed salinity 1500 ppm NaCl, recovery rate 15%
Average feed salinity during nominal test: 1500 × 0.5 (1 + 1/(1 – 0.15)) = 1632 ppm NaCl
Average feed osmotic pressure: 1.25 bar (18.1 psi)
Nominal NDP: 10.3 – 1.25 = 9.05 bar (131.2 psi)
Specific permeability: 43.9/9.05 = 4.85 l/m^2/hr/bar (0.20 gfd/psi)

Calculation of system feed pressure
$P_f = NDP + P_{os} + P_p + 0.5 \times P_d$ (11.16)
Required system NDP: 27.2/4.85 = 5.6 bar (81 psi)
Pressure drop per stage 2 bar (29 psi), total for system, P_d = 4 bar (58 psi).
Permeate back pressure, P_p = 0.5 bar (7.2 psi).
Feed salinity 1500 ppm TDS, osmotic pressure 1.1 bar (16 psi)
Average feed osmotic pressure, P_{osm} = 1.1 × 0.5(1 + 1/(1–0.85)) = 4.2 bar (61 psi)
Required system feed pressure, P_f = 5.6 + 4.2 + 0.5 × 4 + 0.5 = 12.3 bar (178 psi)

Calculation of permeate salinity, C_p
Permeate salinity is function of average feed salinity and operating permeate flux rate as compared to the nominal flux.
$C_p = AFS \times (1 - NSR/100) \times (NF/AFR)$ (15.1)
Average feed salinity, AFS = 0.5 × (1500 + 1500/(1 – 0.85)) = 5750 PPM
Permeate salinity: 5750(1 – 99.6/100) × (43.9/27.2) = 37 PPM

For feed water temperatures different than 25°C, temperature correction factor TCF, should be applied to calculations of feed pressure and permeate salinity.

Example #14.2

For the design conditions of example 14.1 calculate feed pressure and permeate salinity for feed water temperatures of 12°C and 32°C.
Utilize equation 11.20
Assume C = 2700, both for water and salt transport

For feed temperature t = 12°C
TFC = 1.51
Required $NDP_2 = NDP_1 \times TCF = 5.6 \times 1.51 = 8.5$
Feed pressure = $P_f + NDP_2 – NDP_1 = 12.3 + 2.9 = 15.2$ bar (220 psi)
Permeate salinity, $C_{p2} = C_{p1}/TCF = 37/1.51 = 25$ ppm

For feed temperature t = 30°C
TFC = 0.71
Required $NDP_2 = NDP_1 \times TCF = 5.6 \times 0.71 = 4.0$
Feed pressure = $P_f + NDP_2 – NDP_1 = 12.3–1.6 = 10.7$ bar (155 psi)
Permeate salinity, $C_{p2} = C_{p1}/TCF = 37/0.71 = 52$ ppm

14.2 Use of computer programs for projections of membrane performance

Applying manual calculations, it is possible to calculate small number of required feed pressure and permeate salinities in the operating range. For repeated calculations and optimization of operating parameters, application of specialized computer programs for calculations is necessary. Information on membrane products and computer programs for projection of membrane unit performance are available, free of charge, form all commercial RO membrane manufacturers [1–5]. Various performance projection programs are quite similar in functionality, design of user interface, input values required and output format.

Prior to computer calculation, the engineer should calculate approximate number of membrane elements required for a given permeate output from the membrane unit (membrane train) and the initial pressure vessels array. The calculation of number elements (EN) is based on rearranged Eq. 11.21

$$EN = Qp/(MA \times APF) \quad (14.1)$$

where Qp is permeate flow from membrane unit, MA is membrane area per element and APF is the average permeate flux.

The average permeate flux used in wastewater application is usually in the range of 17–21 l/m^2/hr (10–12 gfd). Membrane area of standard, 200 mm diameter (8") elements is 37–41 m^2 (400–440 ft^2). The recovery rate in wastewater reclamation systems, treating low salinity feed water, is in the range of 80–85%. Therefore, membrane units are configured in 2 or 3 concentrate stages array.

Example #14.3

Membrane unit will produces 10,000 m^3/day (2.64 mgd). The design average flux rate is 20.4 l/m^2-hour (12.0 gfd). The membrane element type selected for this system has 40 m^2 of membrane area (430 ft^2) per element.

Number of membrane elements required (NE):

NE = 10,000 $\times$ 1000 l/hr/(20.4 l/m^2-hr $\times$ 24 hr $\times$ 40 m^2) = 510 elements

The number of elements required will be rounded up according to number of elements per vessel. Assuming seven elements per vessel:

510/7 = 72.8 pressure vessels

Assuming a two stage system

72.8/3 = 24.2

According to above result, the array of pressure vessels will be: 48:24, total of 72 pressure vessels.

Number of elements required:

72 $\times$ 7 = 504 elements

The computerized calculation procedure usually starts with input of feed water analysis (Fig. 14.1).

After completing input to the water analysis screen the next screen includes entry of design process parameters and system configuration parameters (Fig. 14.2).These include:

- Feed temperature
- Feed water pH
- Membrane age
- Permeate flow
- Recovery rate
- Membrane model
- Membrane array (number of stages, number of pressure vessels per stage, number of elements per vessel)

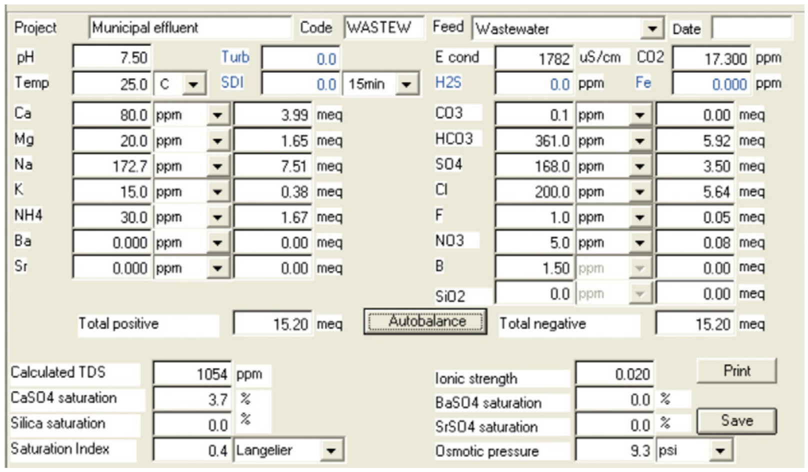

FIG. 14.1 Computer projection program—feed water analysis entry screen.

- Salt passage increase factor
- Flux decline coefficient (or fouling factor)

The element type is selected from elements look up table (Fig. 14.3). The membrane array (number of pressure vessels in each stage) is adjusted to arrive to the design permeate average flux rate.

After calculations are completed, the display shows relevant operating parameters (Fig. 14.4). If the design or calculated operating parameters exceed recommended values then program generated warnings are display. In this particular case, program display warning related to high concentration polarization factor (Beta) in the last element and high saturation level $CaCO_3$ (langelier index > 1.8). The warnings could be addressed by changing the design parameters (recovery rate, feed pH). If the deviations are small, a waiver can be requested from membrane manufacturer to accept these operating conditions in the framework of membrane performance warranty.

The standard features of performance projection programs include provision for feed pH adjustment, calculation of feed pressure, composition of feed, permeate and concentrate and projecting values of saturation indexes. Additional features may include calculation of energy requirements, determination of selected components of operating cost and quantities of chemicals required for permeate treatment. Computer projection programs enable optimization of design based on selected criteria of performance or operating cost.

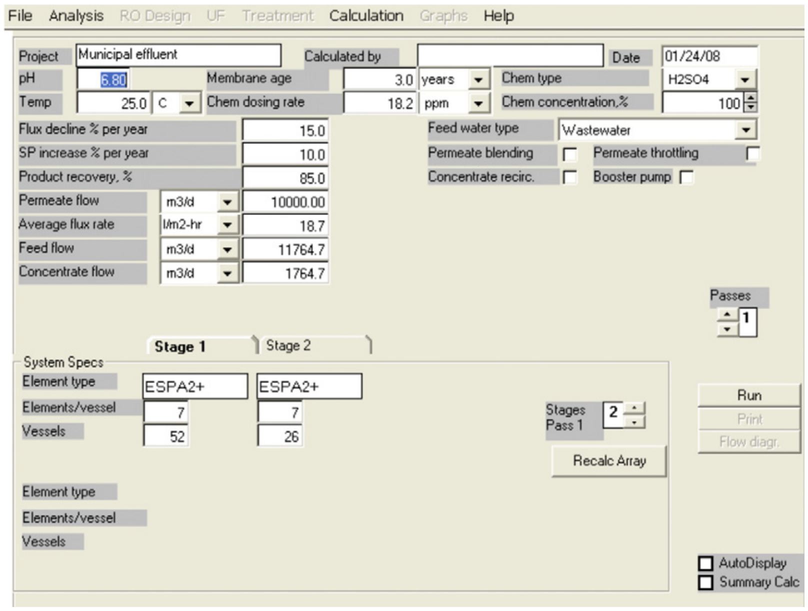

FIG. 14.2 Computer projection program—process parameters and membrane array entry screen.

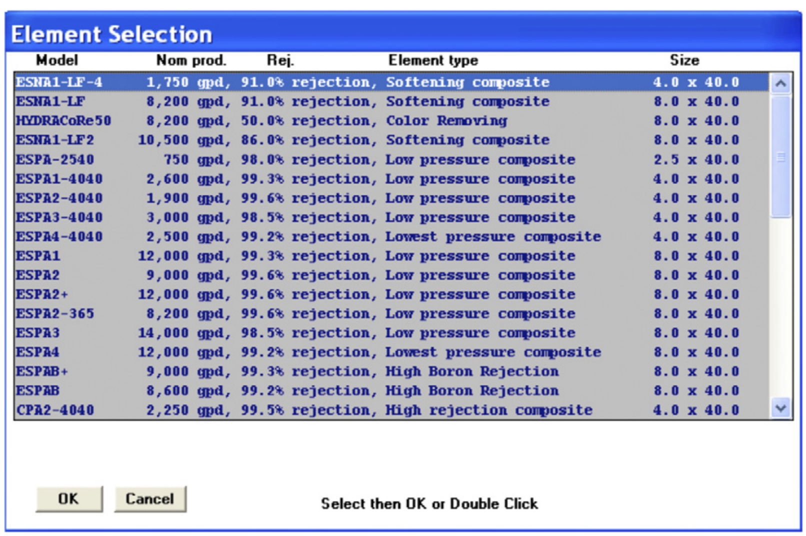

FIG. 14.3 Computer projection program—membrane elements look up table.

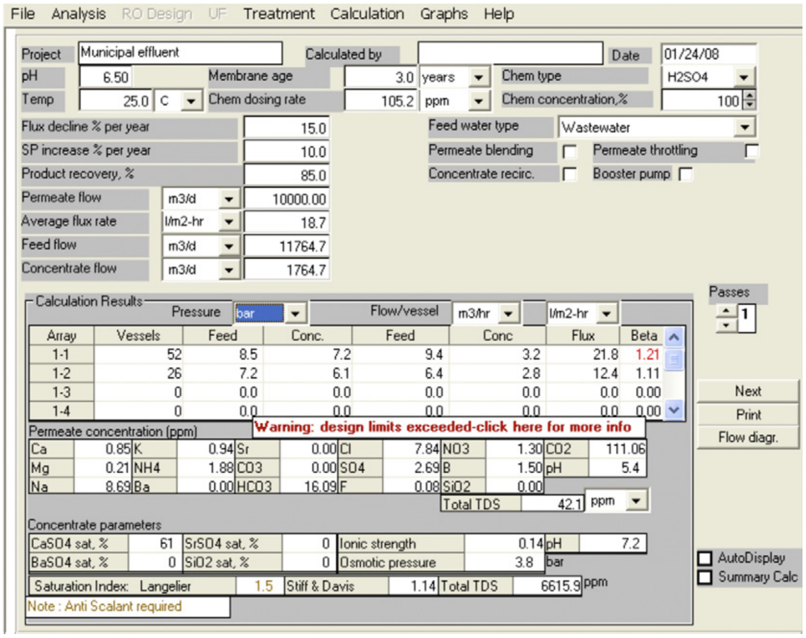

FIG. 14.4 Computer projection program—display of calculation results.

Examples of determination of membrane unit configuration and calculation of operating parameters are included in Appendix C

Results of computer calculations are basis for RO system design and terms of membrane performance warranty. It is customary for membrane manufacturers to provide system performance warranty with some safety margins, applied to the results calculated by their programs. The usual range is 10–20% below calculated permeate salinity and 5–10% above calculated feed pressure.

Treatment of municipal wastewater represents a unique application where permeate salinity observed in field operation is usually significantly lower than calculated by computer membrane performance projection programs. This is probably a result of presence of relatively high concentration of organic matter in the feed water and fouling of membrane surface. It is likely that organic foulants cover pinholes and other surface defects. Correspondingly, high rate of water permeability decline is common phenomena in this type of application. An example of actual and projected water quality data recorded at wastewater reclamation system at Orange County Water District, CA is shown in Table 14.1.

TABLE 14.1
Water quality data from OCWD wastewater reclamation plant.

Constituent	OCWD–RO feed	RO permeate actual	RO permeate projected
Calcium	72.8	<0.1	0.6
Magnesium	29.1	<0.1	0.2
Sodium	240	6.7	9.1
Bicarbonate	93.7	13.6	9.1
Chloride	212	4.4	9.9
Ammonia	35.5	1.5	1.7
Nitrate	2.0	0.4	0.6
Sulfate	459	1.1	5.4
Silica	18.3	<1.0	0.6
TOC	13.3	0.9	—
TDS	1040	22.3	38.4

References

1. Hydranautics web page: http://www.membranes.com/
2. Dow web page: http://www.dow.com/liquidseps/prod/prd_film.htm
3. Toray web page: http://www.toray-membrane.com/
4. Koch web page: http://www.kochmembrane.com/
5. Trisep web page: http://www.trisep.com/