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Design of reverse osmosis networks for multiple freshwater production

Yanyue Lu*,†, Anping Liao*, and Yangdong Hu**

*Key Laboratory of Chemical and Biological Transforming Process, Guangxi Key Laboratory of Chemistry and Engineering of Forest Products, College of Chemistry and Chemical Engineering, Guangxi University for Nationalities, Nanning 530006, P. R. China
**College of Chemistry and Chemical Engineering, Ocean University of China, Qingdao 266003, China
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Abstract−Reverse osmosis (RO) desalination, which produces multiple freshwater from seawater, has been studied in this work. An optimization method based on process synthesis has been applied to design the RO system. First, a simplified superstructure that contains all the feasible design for this desalination problem has been presented. In this structural representation, the stream split ratios and the logical expressions of stream mixing were employed, which can make the mathematical model easy to handle. Then, the membrane separation units employing the spiral wound reverse osmosis elements were described by using a pressure vessel model, which takes into account the pressure drop and the concentration changes in the membrane channel. The optimum design problem can be formulated as a mixed-integer non-linear programming (MINLP) problem, which minimizes the total annualized cost of the RO system. The cost equation relating the capital and operating cost to the design variables, as well as the structural variables, has been introduced in the objective function. The problem solution includes the optimal streams distribution, the optimal system structure and the operating conditions. The design method could also be used for the optimal selection of membrane element type in each stage and the optimal number of membrane elements in each pressure vessel. The effectiveness of this design methodology has been demonstrated by solving a desalination case. The comparisons with common industrial approach indicated that the integrative RO system proposed in this work is more economical, which can lead to significant capital cost and energy saving and provide an economically attractive desalination scheme.

Key words: Reverse Osmosis, Seawater Desalination, Optimum Design, Superstructure, Mathematical Model

INTRODUCTION

Seawater desalination is commonly used to produce freshwater for drinking, domestic, agricultural, and industrial uses in water-short area. It is a main approach to solving the problem of scarcity of natural fresh water supplies. In the last few years, the reverse osmosis (RO) process has gained much popularity in the desalination field. The interest in RO is due to its low energy consumption compared to multistage flash distillation (MSF) process, high product recovery and quality [1-3]. Another attractive feature of the RO process is that its plant design and operation is simple and modular. Membrane plants are often more compact, can be scaled up easily and installed more quickly than the thermal separations plants. Also, it makes the maintenance of RO systems easier. The RO process is also able to meet the varying feed water concentration and the varying product water requirement in quantity and quality through the change of system construction and operating condition. RO membrane manufacturers have developed various membrane types to precisely meet the varying need of a wide range of industrial, municipal, commercial and drinking water applications, such as the high flux, high rejection membrane, the low pressure, high rejection membrane and fouling resistant membrane. All these advantages make the design of RO process more flexible [4-8,25].

Several research efforts have been directed to the design and optimization of reverse osmosis systems [9-12]. El-Halwagi [13] investigated the synthesis of RO networks which involve multiple feed streams for waste reduction. Based on the state-space approach, a structural representation of RO networks has been introduced. The mathematical model was formulated as a mixed integer nonlinear programming (MINLP). In the further work, Zhu et al. [14] used El-Halwagi's representation and included a factor for flux decline over time. Voros et al. [15,16] simplified El-Halwagi's representation by reducing the distribution boxes to junctions. Consequently, the model was formulated as a nonlinear programming (NLP) by using a variable split ratio. Maskan and Wiley [17] used a directed graph and connectivity matrix to represent the RO networks superstructure. In the mathematical model of the superstructure, a variable reduction technique is performed to accelerate the computational process. Nemeth [18] studied the behavior of the ultra-low pressure RO membranes in the full-scale system and presented recommendations to improve system design. Van der Meer [19,20], and Wessels [21] developed a simplified mathematical model to optimize the performance of NF and RO membrane filtration plants. The study showed that the productivity of nanofiltration plants can be significantly improved by installing a reduced number of membrane elements serially in pressure vessels (PV) and changing system configuration. Malek et al. [22] provided a realistic economic model that relates the various operational and capital cost elements to the design variable values.

We consider the RO-based desalination process for the production of multiple freshwater from seawater. An optimization method

†To whom correspondence should be addressed.
E-mail: luyanyue@163.com

based on process synthesis has been applied to design the RO system which can supply the various product water with different concentration. The adoption of this approach can provide an economically attractive desalination scheme. It can lead to the significant capital cost and energy saving and provide income from the multiple product water sales.

PROBLEM DESCRIPTION

A great number of discharging brine coming from RO desalination process has become an urgent problem. It is a feasible solution to design an RO system producing multiple freshwater productions. By using this RO system, the utilization of seawater would increase and the discharging brine would decrease; besides, the multiple freshwater with different concentration can meet varying requirement. The integrative design method is more effective than the common industrial approach to design this RO system. To achieve this aim, the RO unit model should be established firstly; then a system superstructure that contains all the feasible design for this desalination problem should also be set up. The mathematical expression of this superstructure and the solving approach are also important.

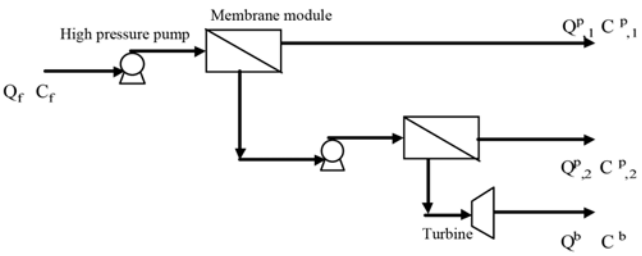

Fig. 1. RO process configuration with multiple-product requirement.

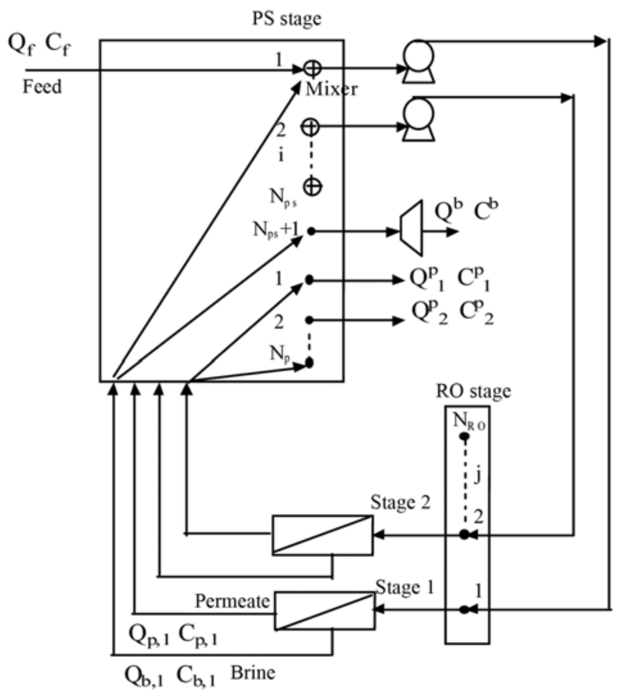

Fig. 2. Representation of the RO network via the superstructure.

For a seawater desalination RO system with multiple-product requirement, the design objective is to identify the most cost-effective RO network configuration, the optimal operating conditions, and the optimal arrangement of the membrane elements. Fig. 1 represents a potential process configuration for this desalination problem.

It is necessary to develop a structural representation that contains all the feasible designs for the problem of synthesizing an RO network. El-Halwagi [13,14] and Voros et al. [15,16] have presented a network representation based on the state space approach. Here we adopt and properly modify the approach, and present a simplified superstructure that incorporates all the feasible process flow for the seawater desalination RO system with multiple-product requirement. As shown in Fig. 2, an RO network consists of N_{ps} pressurization stages and N_{RO} reverse osmosis stages. In this configuration, there are three sets of stream nodes employed: N_{ps} mixing junctions, N_{RO} reverse osmosis junctions, N_p outlet junctions of product streams. The junction of $N_{ps}+1$ indicates the brine stream leaving the network. It is assumed that seawater only enters the RO system from stage 1. Each of the N_{ps} mixing junctions indicates that the brine and the permeate streams leaving all the reverse osmosis stages can mix at the node. The mixing streams pressurized by the high pressure (HP) pump are connected to the corresponding reverse osmosis stages. The RO stages consist of the multiple parallel reverse osmosis pressure vessels operating at the same conditions.

Based on the RO unit model listed in the appendix in detail and the simplified superstructure mentioned above, the optimal design of RO systems was formulated as a mixed integer nonlinear programming problem (MINLP) which is easily solved with less calculation time. The objective was to determine the optimal system structure, the stream distribution and the operating conditions. The solution to the problem also includes the most appropriate choice of the types of membrane elements in each stage and the optimal number of membrane elements in each PV.

RO NETWORK REPRESENTATION

The complete mathematical model that describes the superstructure is presented as follows by means of the appropriate relationships between the variables (material and energy balance equations, technical and operational constraints).

$$Q_{ps,1}=Q_f+\sum_{j=1}^{N_{RO}}Q_{ROb,j}\times x_{b,1,j}+\sum_{j=1}^{N_{RO}}Q_{ROp,j}\times x_{p,1,j} \tag{1}$$

$$Q_{ps,1}\times C_{ps,1}=Q_f\times C_f+\sum_{j=1}^{N_{RO}}Q_{ROb,j}\times x_{b,1,j}\times C_{ROb,j}+\sum_{j=1}^{N_{RO}}Q_{ROp,j}\times x_{p,1,j}\times C_{ROp,j} \tag{2}$$

$$Q_{ps,i}=\sum_{j=1}^{N_{RO}}Q_{ROb,j}\times x_{b,i,j}+\sum_{j=1}^{N_{RO}}Q_{ROp,j}\times x_{p,i,j} \qquad i=2, 3, \ldots, N_{ps} \tag{3}$$

$$Q_{ps,i}\times C_{ps,i}=\sum_{j=1}^{N_{RO}}Q_{ROb,j}\times x_{b,i,j}\times C_{ROb,j}+\sum_{j=1}^{N_{RO}}Q_{ROp,j}\times x_{p,i,j}\times C_{ROp,j} \qquad i=2, 3, \ldots, N_{ps} \tag{4}$$

$$Q_{ps,N_{ps}+1}=\sum_{j=1}^{N_{RO}}Q_{ROb,j}\times x_{b,N_{ps}+1,j} \tag{5}$$

$$Q_{ps,N_{ps}+1}\times C_{ps,N_{ps}+1}=\sum_{j=1}^{N_{RO}}Q_{ROb,j}\times x_{b,N_{ps}+1,j}\times C_{ROb,j} \tag{6}$$

$$\sum_{i=1}^{N_{ps}+1}x_{b,i,j}=1 \qquad j=1, 2, \ldots, N_{RO} \tag{7}$$

$$\sum_{i=1}^{N_{ps}+N_p}x_{p,i,j}=1 \qquad j=1, 2, \ldots, N_{RO} \tag{8}$$

where $Q_{ps,i}$, $C_{ps,i}$ denote the flow rate and the concentration of the i^{th} pressurization stage, respectively. $Q_{ROb,j}$, $C_{ROb,j}$ denote the brine flow rate and the concentration of the j^{th} RO stage, $Q_{ROp,j}$, $C_{ROp,j}$ denote the permeate flow rate and the concentration of the j^{th} RO stage, respectively. $x_{b,i,j}$, $x_{p,i,j}$ indicate the stream split ratios of the brine and permeate, respectively. Their values determine the flow rates of brine and permeate leaving the j^{th} RO stage and being linked to the i^{th} pressurization stage.

All the streams connected to the i^{th} pressurization stage first mix in the mixer. The outlet pressure from the mixer is the average feed pressure. The stream split ratios and the logical expression of stream mixing are employed in this paper; these techniques reduced the number of binary variables and the solving space; therefore, the mathematical model may be easily handled. The following are stream-mixing constraints.

$$L_1\times(1-y_{b,i,j})\le x_{b,i,j}-x_c\le U_1\times y_{b,i,j}-\varepsilon \qquad i=1, 2, \ldots, N_{ps}, j=1, 2, \ldots, N_{RO} \tag{9}$$

$$L_1\times(1-y_{p,i,j})\le x_{p,i,j}-x_c\le U_1\times y_{p,i,j}-\varepsilon \qquad i=1, 2, \ldots, N_{ps}, j=1, 2, \ldots, N_{RO} \tag{10}$$

$$(y_{b,i,j}+y_{p,i,j})\le 1 \qquad i=1, 2, \ldots, N_{ps}, j=1, 2, \ldots, N_{RO} \tag{11}$$

$$L_2\times(1-y_{b,i,j})\le(P_{b,j}-P_{b,i,j})\le U_2\times(1-y_{b,i,j}) \qquad i=1, 2, \ldots, N_{ps}, j=1, 2, \ldots, N_{RO} \tag{12}$$

$$P_{b,i,j}\le U_2\times y_{b,i,j} \qquad i=1, 2, \ldots, N_{ps}, j=1, 2, \ldots, N_{RO} \tag{13}$$

$$L_2\times(1-y_{b,i,j})\le(P_{p,j}-P_{p,i,j})\le U_2\times(1-y_{p,i,j}) \qquad i=1, 2, \ldots, N_{ps}, j=1, 2, \ldots, N_{RO} \tag{14}$$

$$P_{p,i,j}\le U_2\times y_{p,i,j} \qquad i=1, 2, \ldots, N_{ps}, j=1, 2, \ldots, N_{RO} \tag{15}$$

$$P_{ps,i}=\frac{\sum_{j}^{N_{RO}}(P_{b,i,j}+P_{p,i,j})}{\sum_{j}^{N_{RO}}(y_{b,i,j}+y_{p,i,j})} \qquad i=1, 2, \ldots, N_{ps} \tag{16}$$

where L_1 and L_2 are the arbitrary small numbers, U_1 and U_2 are the large enough numbers. y is binary variable. x_c and ε denote the small positive number. It is assumed that streams link to the i^{th} pressurization stage when the stream split ratios, x, is larger than x_c, hence y=1, whereas if x is smaller than x_c. $P_{b,j}$ and $P_{p,j}$ are the brine and permeate pressure of the j^{th} RO stage, respectively. $P_{b,i,j}$, $P_{p,i,j}$ denote the streams pressure which link to the i^{th} pressurization stage. $P_{ps,i}$ denotes the inlet pressure of the i^{th} pressurization stage.

The streams leaving the i^{th} pressurization stages are correspondingly connected to the j^{th} RO stages. Therefore the following equations can be obtained:

$$Q_{RO,j}=Q_{ps,i} \qquad j=i, j=1, 2, \ldots, N_{RO} \tag{17}$$

$$C_{RO,j}=C_{ps,i} \qquad j=i, j=1, 2, \ldots, N_{RO} \tag{18}$$

$$P_{RO,j}=P'_{ps,i} \qquad j=i, j=1, 2, \ldots, N_{RO} \tag{19}$$

where $Q_{RO,j}$, $C_{RO,j}$, $P_{RO,j}$ denote the feed flow rate, concentration, and operation pressure of the j^{th} RO stage, respectively. $P'_{ps,i}$ is the outlet pressure of the i^{th} pressurization stage.

The mathematical models that predict the performance of each RO stage have been presented in detail in the appendix. These model equations relate the flow rate and concentration of the brine and permeate leaving an RO stage to the flow rate, concentration, and pressure of the stream entering the stage.

The arrays of pressure vessels (PV) with one up to eight membrane elements per PV consist of an RO stage. In this paper, the optimal PV structure is also researched. Four different types of the spiral wound FilmTec reverse osmosis membrane elements are considered. According to its performance characteristics and requirements of a specific desalination application, the optimum selection of types of the membrane element employed in each PV can be determined by the following equations:

$$\sum_{k=1}^{4}Z_{j,k}\le 1 \qquad j=1, 2, \ldots, N_{RO} \tag{20}$$

$$L_3\times\left(1-\sum_{k=1}^{4}Z_{j,k}\right)\le Q_{ROf,j}-x_c\le U_3\times\sum_{k=1}^{4}Z_{j,k}-\varepsilon \qquad j=1, 2, \ldots, N_{RO} \tag{21}$$

$$Q_{p,j}=\sum_{k=1}^{4}Q_{p,j,k} \qquad j=1, 2, \ldots, N_{RO} \tag{22}$$

$$Q_{p,j,k}\le U_4\times Z_{j,k} \qquad j=1, 2, \ldots, N_{RO} \tag{23}$$

$$m_{j,k}\le U_5\times Z_{j,k} \qquad j=1, 2, \ldots, N_{RO} \tag{24}$$

where $Z_{j,k}$ is binary variable. It takes the value of 1 when the k^{th} element type is utilized in the PV in the j^{th} RO stage; otherwise, it takes the value of 0. Here, it is assumed that the same membrane element is employed in the same RO stage. L_3 and U_3, are the arbitrary small and large number, respectively. For Eq. (21), when $Q_{ROf,j}$ takes some value which is larger than x_c, it means the j^{th} RO stage is present and one element type should be chosen, otherwise if $Q_{ROf,j}=0$ it means the j^{th} RO stage is absent. $Q_{p,j}$ is the permeate flow rate of pressure vessel. While $Q_{p,j,k}$ denote the permeate flow rate of pressure vessel when the k^{th} element type is utilized in this PV, it can be calculated by Eq. (A13). $m_{j,k}$ is the number of the k^{th} membrane element. U_4 and U_5 are the large enough positive number so that $Q_{p,j,k}$ and $m_{j,k}$ are not restricted if $Z_{j,k}=1$. In terms of Eq. (20), (22) and (23), $Q_{p,j}$ is equal to one of $Q_{p,j,k}$ when $Z_{j,k}=1$, otherwise $Q_{p,j}=0$. By this way the module type and the number of stage are chosen simultaneously when the optimization design is performed.

Overall material balances for the RO network and a set of product quantity and quality constraints, concerning the minimum desirable product flow rate and the maximum allowable product concentration, are presented as follows:

$$Q_f=Q^b+\sum_{r=1}^{N_p}Q_r^p \tag{25}$$

$$Q_f\times C_f=Q^b\times C^b+\sum_{r=1}^{N_p}Q_r^p\times C_r^p \tag{26}$$

$$Q^b=Q_{ps,N_{ps}+1} \tag{27}$$

$$C^b=C_{ps,N_{ps}+1} \tag{28}$$

$$Q_r^p = \sum_{j=1}^{N_{RO}} Q_{ROp,j} \times x_{p,r,j} \qquad r=1, 2, \ldots, N_p \tag{29}$$

$$Q_r^p \times C_r^p = \sum_{j=1}^{N_{RO}} Q_{ROp,j} \times x_{p,r,j} \times C_{ROp,j} \qquad r=1, 2, \ldots, N_p \tag{30}$$

$$Q_r^p \geq Q_{r,min}^p \qquad r=1, 2, \ldots, N_p \tag{31}$$

$$C_r^p \geq C_{r,max}^p \qquad r=1, 2, \ldots, N_p \tag{32}$$

where Q^b, C^b are the flow rate and concentration of the brine leaving the RO network, respectively. Q_r^p, C_r^p are the flow rate and concentration of the r^{th} product water required, respectively. $x_{p,r,j}$ are the outlet stream split ratios. $Q_{r,min}^p$ refers to the minimum desirable flow rate of the r^{th} product required, $C_{r,max}^p$ refers to the maximum allowable concentration of the r^{th} product required.

SOLUTION METHODOLOGY

The optimization design problem is formulated as a mixed-integer nonlinear programming (MINLP) for minimizing the total annualized cost, which is subject to thermodynamic, technical, and flexibility constraints. The total annualized cost (TAC) of the system consists of two terms: the annual operating cost (OC) and the annualized capital cost (CC). The annual operating cost includes the energy cost required for pumps, the maintenance cost of membrane module (OC_m). The annualized capital cost is for the initial membrane module, pumps and energy recovery devices. The objective function is presented as follows:

$$\begin{aligned} TAC=&(CC_{in}+CC_{hpp}+CC_{Tb}+C_m)\times 1.411\times 0.08 \\ &+OC_{in}+OC_{hpp}-OC_{Tb}+OC_m \end{aligned} \tag{33}$$

$$CC_{hpp}=52\times(\Delta P\times Q_{hpp})^{0.96} \tag{34}$$

$$C_m = \sum_{j=1}^{N_{RO}} C_{pv} \times n_j + \sum_{j=1}^{N_{RO}}\sum_{k=1}^{4} C_k \times m_{j,k} \times n_j \tag{35}$$

$$OC_{hpp} = \frac{P \times Q \times C_e \times f_c}{3.6 \times \eta_{hpp} \times \eta_{motor}} \tag{36}$$

$$OC_{Tb} = \frac{P \times Q \times \eta_{Tb} \times C_e \times f_c}{3.6} \tag{37}$$

where CC_{in}, CC_{hpp} and CC_{Tb} are the capital cost of seawater intake pump, high pressure pump, and turbine, respectively. OC_{in}, OC_{hpp} and OC_{Tb} are the energy cost required for these pumps and saving cost generated by turbine. Their functions refer to the papers [2,6, 14,22]. C_m denotes the total membrane module cost. C_k is the price of the k^{th} membrane element and C_{pv} is the price of pressure vessel. n_j is the number of pressure vessel employed in the j^{th} RO stage. 1.411 is the coefficient that used to calculate the practical investment. 0.08 is the capital charge rate. C_e is the cost of electricity and f_c is the load factor. η_{hpp}, η_{motor}, η_{Tb} are the efficiency of HP pump, electric motor, and turbine, respectively.

The MINLP can be solved by using the software GAMS. It solves the problem by decomposing it into a series of nonlinear (NLP) subproblems and mixed integer (MIP) master problems. This procedure is carried out by introducing an excessive number of units as an initial guess, while at the optimum certain design variables, such as the stream split ratios, are either set to zero or to a value that indicate the absence or presence of the specific stage. Several starting points are used to obtain the best possible solution.

Good initial values are important for solving MINLP properly; it can reduce the work in finding a first feasible solution and likely return a desirable solution. In this paper, a simple system simulation has been made first, then based on the simulation results, the proper initial values and the value ranges are obtained for some key variables, e.g., the operating pressure, the stream split ratio and the membrane area, that from the context are known to be important. Thereafter, the values of other variables can be derived by using some of the equations of the model. The deriving procedure is based on a heuristic: as long as there is an equation with only one nonfixed variable (a singleton row) then a value should be assigned to the variable so the equation is satisfied or satisfied as closely as possible, and then the variable is fixed temporarily. When additional singleton rows emerge, the process is repeated until all variables have been fixed. The variables to be fixed at their initial value are selected by using a heuristic that both tries to create many row singletons and tries to select variables with "good values". Since the values of other variables will come to depend on the fixed variables, the procedure favors the assigned variables provided by modeler and among these it favors the variables that appear in many feasible constraints.

The result of the procedure will present a set of updated initial points in which usually a large number of equations will be feasible; it will often provide a good starting point for the following procedures that finds an initial feasible solution, and finally solver would likely return the desirable solution.

CASE STUDY

The proposed methodology for an RO system design has been applied to deal with seawater desalination. In this case, there are three kinds of product water requirement, which are subject to the different quantity and quality constraints on permeate. The minimum desirable product flow rate is 200 m^3/h, 100 m^3/h, and 50 m^3/h; while the corresponding maximum allowed salt concentration is 100 ppm, 300 ppm, and 500 ppm, respectively. Four different types of FilmTec reverse osmosis membrane elements from DOW are included in design studies of the current work: the low energy, high productivity element SW30XLE-400, the high rejection, high productivity element SW30HR-380, the high rejection, fouling resistant element SW30HR-320, and the high productivity, high rejection brackish RO element BW30-400. The geometrical properties and membrane characteristics (membrane pure water permeability, solute transport parameter) of these elements are given in Table 1 [7,8,25]. The necessary input data for this case study are summarized in Table 2 [6,14,22].

The optimal design results of the RO system are presented in Table 3. The two-stage RO configuration with brine re-processing was employed in the design (as shown in Fig. 3). This scheme supplies three kinds of product water. The first product water comes from the permeate of stage 1 ($x_{p,5,1}$=0.828) which concentration is lower, while the third product water comes from the permeate of stage 2 ($x_{p,7,2}$=0.46). The second product water consists of partial permeate coming from stage 1 ($x_{p,6,1}$=0.172) and stage 2 ($x_{p,6,2}$=0.54). The total annualized cost of the system is $1,397,600 per year. The prime cost items, i.e., the annualized capital cost, the pretreatment cost,

Table 1. Characteristics of FilmTec spiral wound reverse osmosis membrane elements

Element type	SW30XLE-400[a]	SW30HR-380[a]	SW30HR-320[a]	BW30-400[b]
Active area, ft^2 (m^2)	400(37.2)	380(35.3)	320(29.7)	400(37)
Length of the element, inch (mm)	40(1,016)	40(1,016)	40(1,016)	40(1,016)
Diameter of the element, inch (mm)	7.9(201)	7.9(201)	7.9(201)	7.9(201)
Feed space, mil*	28	28	34	34
Feed flow rate range, m^3/h	0.8-16	0.8-16	0.8-14	0.8-19
Permeate flow, gpd (m^3/d)	9000(34.1)	6000(22.7)	6000(22.7)	10,500(40)
Stabilized salt rejection, %	99.70	99.70	99.75	99.5
Maximum operating pressure, psig (Mpa)	1,200(8.3)	1,200(8.3)	1,200(8.3)	600(4.5)
[c]Pure water permeability constant A, ($kg/m^2 \cdot s \cdot Pa$)	3.5×10^{-9}	2.7×10^{-9}	3.1×10^{-9}	7.5×10^{-9}
[c]Salt permeability constant B, ($kg/m^2 \cdot s$)	3.2×10^{-5}	2.3×10^{-5}	2.2×10^{-5}	6.2×10^{-5}
[c]Membrane element cost, $ (estimation)	1200	1000	1400	800

*1 mil=0.0254 mm
[a]Refer to the Ref. [7], [b]Refer to the Ref. [8], [c]Refer to the Ref. [25]

Table 2. The parameters for calculation

Feed concentration of seawater, ppm	35,000
Feed water average temperature, °C	25
[d]Average brine density, ρ, kg/m^3	1,020
The average brine viscosity, μ, $kg/m \cdot s$	1.09×10^{-3}
Average diffusion coefficient, D_s, m^2/s	1.35×10^{-9}
[e]High pressure pump efficiency, η_{hpp}	75%
Turbine efficiency, η_{Tb}	80%
Electric motor efficiency, η_{motor}	98%
[f]The cost of electricity, C_e, $\$\cdot(kwh)^{-1}$	0.08
The pressure vessel cost, (estimation) $	1,000

[d]Refer to the Ref. [6], [e]Refer to the Ref. [14], [f]Refer to the Ref. [22]

the maintenance cost and the energy cost, are $296558, $179480, $137056, $784506, respectively. From the cost analysis it can be seen that the energy cost is the largest expense, and after then the capital cost. Therefore, if membrane technologies have improved and its operating pressure can be further decreased, the reverse osmosis method would be widely used in desalination field.

For the purpose of comparison with current industrial practices, the common RO system with only one product water outlet has been studied in this work. Corresponding to the three different product water requirements mentioned above, three different RO systems using common industrial approach were employed. When the required permeate concentration was 100 ppm, the employed RO configuration is shown in Fig. 4. While the RO configuration shown

Table 3. Design and optimization results for the study case

Process flow	Two-stage system, as shown in Fig. 3
Seawater feed flow, Q_f (m^3/h)	588
Flow rate of the first product water, Q_1^p (m^3/h)	200
Salt concentration of the first product water, C_1^p (ppm)	100
Flow rate of the second product water, Q_2^p (m^3/h)	100
Salt concentration of the second product water, C_2^p (ppm)	300
Flow rate of the third product water, Q_3^p (m^3/h)	50
Salt concentration of the third product water, C_3^p (ppm)	430
Membrane type in stage 1	SW30HR-320
Number of elements per PV in stage 1	3
Number of PV in stage 1	81
Operating pressure in stage1, P_1 (Mpa)	8.2
Membrane type in stage 2	SW30XLE-400
Number of elements per PV in stage 2	4
Number of PV in stage 2	53
Operating pressure in stage2, P_2 (Mpa)	8.3
The overall system recovery	59%
Annualized capital cost of pump and membrane unit, ($)	296,558
Pretreatment cost, ($)	179,480
Maintenance cost of membrane, ($)	137,056
Energy cost, ($)	784,506
The total annualized cost, ($)	1,397,600

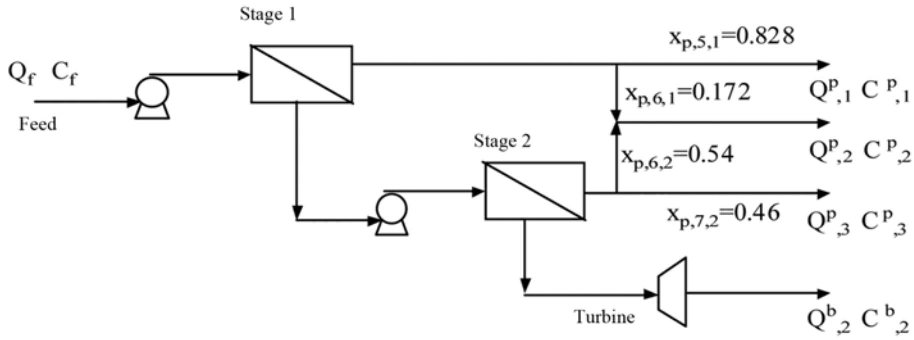

Fig. 3. Optimal RO configuration with multiple-product outlets.

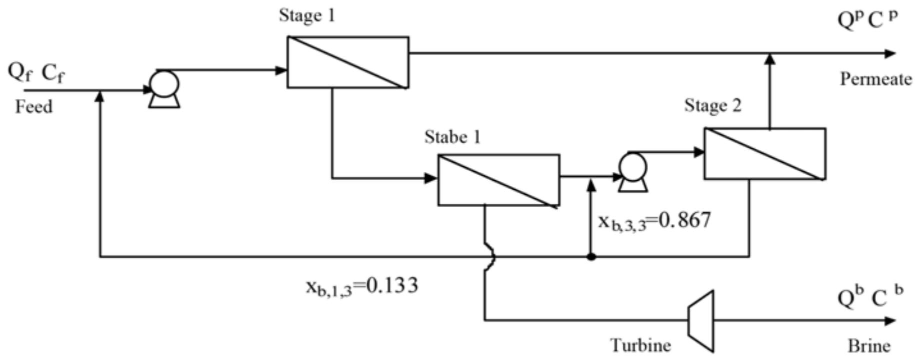

Fig. 4. Optimum RO system for permeate concentration 100 ppm.

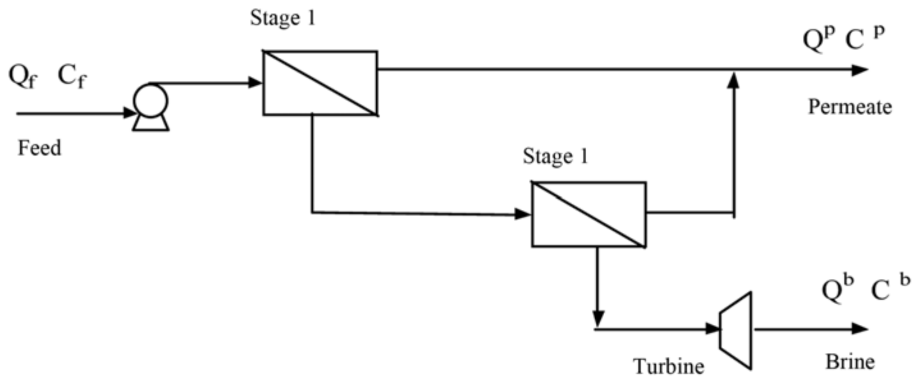

Fig. 5. Optimum RO system for permeate concentration 300 ppm and 430 ppm.

as Fig. 5 was employed when the required permeate concentration was 300 ppm and 430 ppm. With increasing concentration of the product, the structural schemes vary from two-stage arrangement with permeate re-processing to one-stage two-pass arrangement.

The detailed design results and economic analysis are listed in Table 4 for these common RO systems. For each of these cases, the rate of the annualized capital cost, the pretreatment cost, the maintenance cost and the energy cost is about 20%, 15%, 15% and 50% of the total annualized cost, respectively. To supply three kinds of permeate, the common desalination method needs totally $348,448 annualized capital cost, which is 17% higher than that of the integrated method mentioned above; as a result, the total maintenance cost of membrane increased by 40.5% to reach $192,600. The total pretreatment cost and the energy cost is $188,244 and $796,901, respectively. The design results show that all the prime cost items of the common desalination method are more than that of the integrated method. The total annualized cost of the three RO systems is $935,340, $404,020, and $186,930. Therefore, the sum of the three annualized cost is $1,526,290, which is 10% more expensive than that of the integrated RO system with multiple product outlet. The comparative results indicate that the integrated RO system proposed in this work is more economical than the common RO systems when product water with different concentration is simultaneously required. The presented synthesis procedure can lead to the significant capital cost and energy saving and provide an economically attractive desalination scheme.

CONCLUSIONS

A process synthesis method has been applied to the design of

Table 4. Design results for the common RO system with only one product water outlet

Product water concentration	100 ppm	300 ppm	430 ppm
Process flow	Two-stage system as shown in Fig. 5	One-stage system as shown in Fig. 6	One-stage system as shown in Fig. 6
Seawater feed flow, Q_f (m^3/h)	331	180	100
Flow rate of the product water, Q^p (m^3/h)	200	100	50
Membrane type in stage 1	SW30XLE-400	SW30HR-320	BW30-400
Number of membrane elements in stage 1	294	182	68
Number of PV in stage 1	86	47	26
Operating pressure in stage 1, P_1 (Mpa)	8.2	7.2	6.1
Membrane type in stage 2	SW30HR-320		
Number of membrane elements in stage 2	108		
Number of PV in stage 2	18		
Operating pressure in stage 2, P_2 (Mpa)	2.1		
The overall system recovery	60%	56%	50%
Annualized capital cost of pump and membrane unit, ($)	203,162	96,438	48,848
Pretreatment cost, ($)	107,650	51,936	28,658
Maintenance cost of membrane, ($)	128,400	47,800	16,400
Energy cost, ($)	496,114	207,844	92,943
The total annualized cost, ($)	935,340	404,020	186,930

RO seawater desalination system. The representation of RO networks via the superstructure incorporates all feasible arrangements for this desalination problem. This superstructure was used to develop a general mathematical model by means of appropriate relationships between variables. Finally, the design task has been formulated as an MINLP which minimizes the total annualized cost of RO system. The solution of the problem includes the optimal system structure and operating conditions, the optimal streams distribution, and the optimal output of the system. The design method could also be used for the optimal selection of type and number of membrane element in each stage.

SYMBOLS

A : water permeability [kg/m²·s·Pa]
B : solute transport parameter [kg/m²·s]
C_e : electricity cost [$/(kwh)]
C_m : membrane module cost [$]
C : concentration of solute [ppm]
C_k : the price of the k^{th} membrane element [$]
C_{pv} : the price of the pressure vessel [$]
C_w : concentration at the membrane wall [ppm]
CC_{in} : capital cost of the seawater intake pump [$]
CC_{hpp} : capital cost of the high pressure pump [$]
CC_{Tb} : capital cost of the turbine [$]
D_s : the solute diffusivity [m²/s]
d : the feed spacer thickness [m]
J_w : water flux [kg/m²·s]
J_s : salt flux [kg/m²·s]
K : the mass transfer coefficient [m/s]
L_{pv} : length of the pressure vessel [m]
L_m : the length of a element [m]
m : the number of membrane elements in each PV
n_j : the number of pressure vessel employed in the j^{th} RO stage
N_l : the number of leaves in a membrane element
N_p : outlet junctions of product streams
N_{ps} : mixing junctions
N_{RO} : reverse osmosis junctions
OC_{in} : energy cost of the intake pump [$]
OC_{hpp} : energy cost of the high pressure pump [$]
OC_{Tb} : the saving cost generated by turbine [$]
OC_m : the cost of membrane module maintenance [$]
P : operating pressure [Mpa]
ΔP_f : the pressure drop in the membrane channel
Q : flow rate [m³/h]
$Q_{p,n}$: the total permeate flow rate of the n^{th} pressure vessel [m³/h]
Q_r^p : the flow rate of the r^{th} product water required
C_r^p : the concentration of the r^{th} product water required
R_e : Reynolds number
S_c : Schmidt number
S_m : the membrane area per element [m²]
T : temperature [|C]
TAC : total annualized cost [$]
U : arbitrary large numbers
L : arbitrary small numbers
V_w : the permeate velocity [m/s]
W : membrane width [m]
$x_{b,i,j}$: the stream split ratio of the brine leaving the j^{th} RO stage and being linked to the i^{th} pressurization stage
$x_{p,i,j}$: the stream split ratio of the permeate leaving the j^{th} RO stage and being linked to the i^{th} pressurization stage
x_c : the small positive number
y, Z : binary integer

Greek

Π : osmosis pressure [Mpa]
Π_w : osmosis pressure of the brine at the membrane wall [Mpa]
μ : the water viscosity [kg/m·s]

ρ : density [kg/m^3]
η : pump efficiency
ε : the small positive number

Subscripts
f : feed stream
p : permeate stream
b : brine stream
in : intake seawater
ps, i : the ith pressurization stage
RO, j : the jth RO stage
ROf, j : the feed stream of the jth RO stage
ROb, j : the brine stream of the jth RO stage
ROp, j : the permeate stream of the jth RO stag
k : the kth element type
hpp : high pressure pump
Tb : turbine

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APPENDIX

1. Mass Transfer Model of RO Process

Numerous models to predict membrane performance have been introduced [23,24]. They are derived from different theories and all of them may be simplified to the solution diffusion model, as shown in Eqs. (A1) and (A2). The model is mainly based on two parameters: water permeability (A) and solute transport parameter (B). The values of these parameters are usually determined from the performance data supplied by membrane manufacturers. According to the model, the pure water flux, J_w (kg/m^2·s), and the salt flux, J_s (kg/m^2·s), are given as follows:

$$J_w = A\left[\left(P_f - P_p - \frac{\Delta P_f}{2}\right) - (\pi_w - \pi_p)\right]\times 10^6 \tag{A1}$$

$$J_s = B(C_w - C_p) \tag{A2}$$

$$\pi = \frac{0.2641\times C\times(T+273)}{10\times 10^6 - C} \tag{A3}$$

$$V_w = \frac{J_w + J_s}{\rho_p} \tag{A4}$$

$$C_p = \frac{J_s}{V_w}\times 1000 \tag{A5}$$

where P_f and P_p (Mpa) denote the feed and permeate pressure, respectively; ΔP_f is the pressure drop in membrane channel; Π_w (Mpa) is the osmotic pressure of the brine at the membrane wall concentration C_w (ppm), and Π_p and C_p are the corresponding variables for permeate; ρ_p denotes the density of the permeate. V_w (m/s) is the permeate velocity.

2. Model for RO Module

In a practical process, the multiple stages RO configuration would be used; one RO stage consists of multiple parallel RO pressure vessels operating at the same conditions. Each pressure vessel contains several membrane elements that are connected in series. The concentrate of the first element becomes the feed to the second, and so on. The product tube of all elements are coupled and connected to module permeate port [19-21]. For different application a suitable hydraulic design can be made (2, 3, 4, 5, 6, 7, 8 serial elements), based on the actual situation. Fig. A1 shows the schematic representation of an RO module. To simulate the performance of PV, a module model is presented in this work which will be used for the optimal selection of the membrane element type and number. Equations that describe the model are shown as follows, Eqs. (A6) to (A16).

$$C_w = C_p + \left(\frac{C_f + C_b}{2} - C_p\right)e^{\frac{V_w}{K}} \tag{A6}$$

K (m/s) is the mass transfer coefficient, which can be calculated

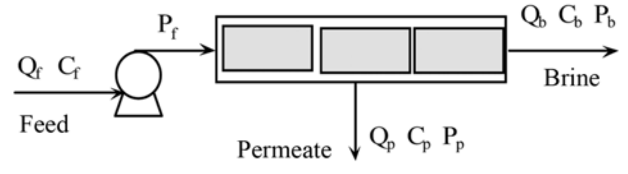

Fig. A1. Schematic diagram of an RO unit.

from empirical relations such as:

$$K = 0.04 \times R_e^{0.75} \times S_c^{0.33} \times \frac{D_s}{d} \tag{A7}$$

$$R_e = \frac{V \times \rho \times d}{\mu} \tag{A8}$$

where R_e and S_c are the Reynolds and the Schmidt numbers and D_s is the solute diffusivity. d is the feed spacer thickness, ρ is the feed side solution density and μ is water viscosity. V denotes the flow velocity that is calculated using the averaged values of the inlet and outlet flow rates in the membrane channel. For a spiral-wound membrane module, each of the permeate and feed side flows can be considered as a flow between two parallel plates with a length L, a width W and a spacing d. Hence the pressure drop on the feed side can be calculated as follows:

$$\Delta P_f = \left(\frac{0.0033 \times Q_a \times L_{pv} \times \mu}{W \times d^3}\right) \tag{A9}$$

$$L_{pv} = m \times L_m \tag{A10}$$

$$\Delta P_f \le 0.35 \tag{A11}$$

where Q_a (m^3/h) is the flow rate that is calculated using the averaged values of the inlet and outlet flow rates in the membrane channel; L_{pv} and L_m denote the length of the PV and the length of a membrane element, respectively; m is the number of membrane elements in each PV. To reduce the computation complexity, m is considered to be a continuous variable, and the approximate result will be obtained by rounding the variable. The maximum allowable pressure drop in pressure vessel is 0.35 Mpa. The technical constraint is usually specified by membrane manufacturers. For the spiral-wound membrane element, the membrane width (W), can be calculated by the membrane area (S_m) and the number of leaves (N_l) :

$$S_m = W \times L_m \times N_l \tag{A12}$$

For a pressure vessel, the feed flow rate, Q_f (m^3/h), the permeate flow rate, Q_p (m^3/h), the brine flow rate, Q_b (m^3/h), and the corresponding concentration, C_f, C_p, C_b (ppm), can be calculated from the mass and salt balance equations:

$$Q_p = 3600 \times V_w \times S_m \times m \tag{A13}$$

$$Q_f = Q_b + Q_p \tag{A14}$$

$$Q_f \times C_f = Q_b \times C_b + Q_p \times C_p \tag{A15}$$

$$Q_{rated}^{L} \le Q_f \le Q_{rated}^{U} \tag{A16}$$

where Q_{rated}^{L} and Q_{rated}^{U} are the lower bound and upper bound of rated flow rate of pressure vessel, respectively. When an RO stage consists of multiple parallel pressure vessels and operates at the same conditions, the flow rate of stream entering and leaving this RO stage can be calculated as the following:

$$Q_{ROf} = n \times Q_f \tag{A17}$$

$$Q_{ROp} = n \times Q_p \tag{A18}$$

$$Q_{ROf} = Q_{ROp} + Q_{ROb} \tag{A19}$$

where Q_{ROf}, Q_{ROp} and Q_{ROb} are the feed flow rate, permeate flow rate and brine flow rate entering and leaving an RO stage, respectively. n is the number of pressure vessels in an RO stage which is considered to be a continuous variable, and the approximate result would be obtained by rounding the variable.