CHEMICAL ENGINEERING TRANSACTIONS Volume 25, 2011
Editors Jiří Jaromír Klemeš, Petar Sabev Varbanov, Hon Loong Lam
Copyright © 2011, AIDIC Servizi S.r.l., ISBN 978-88-95608-16-7 ISSN 1974-9791
DOI: 10.3303/CET1125176

Optimal Design of Reverse Osmosis Based Desalination Process with Seasonal Variation of Feed Temperature

Kamal Sassi and Iqbal Mujtaba*

*School of Engineering Design & Technology, University of Bradford
West Yorkshire, Bradford, BD7 1DP, UK. Email: I.M.Mujtaba@bradford.ac.uk

The design of reverse osmosis (RO) networks is investigated here using a mixed-integer non-linear programming (MINLP) approach based on a superstructure. A flexible superstructure that contains all possible alternatives of a potential RO network was developed and was used in the synthesis of RO networks. The networks were designed by using DuPont's B10 Hollow Fiber module. For fixed freshwater demand and quality, the total annualized cost of the RO networks (capital and operating costs) is minimized in order to find the optimal operation and configuration of RO systems for three different feed concentrations and with seasonal variation of seawater temperature. It is found that seasonal variation in seawater temperature has a significant effect on the design and operation of RO systems. Also the results demonstrate that the variation in the number of modules required for the operation of RO process in high and low temperature seasons offers the possibility of flexible scheduling of cleaning and maintenance of membrane modules.

1. Introduction

Seawater desalination by RO has been the main source of drinking water supply in many regions in the world. RO membranes used in water desalination are capable of producing good water quality by removing salts and contaminants from seawater with lower cost compared to other desalination processes (Sassi and Mujtaba, 2010). During the last decade, tremendous advances were made in the research related to development of RO membranes, resulting in the development of new generation of membranes able to work within a wide pH ranges, higher temperatures and pressures, higher production with significantly low cost.

Designing a cost effective RO network depends mainly on the determination of optimal operational and structural schemes. It has been widely noted that temperature has significant effects on the design and operation of RO processes. RO system performance is affected by several factors, e.g. feed pressure, feed salinity, water flux, etc. Each of these parameters is influenced, under different conditions, by the feed temperature. The membrane's permeability to water and salt is proportional to the feed temperature. Therefore, operation at high temperature would result in increase of the salt passage and the permeate production. Substantial effort has been made by many researchers to study the influence of the feed temperature on RO performance (Nisan et al., 2005; Goosen et al., 2002). However, there are fewer studies investigating the impact of feed temperature on the problem of designing RO networks.

Please cite this article as: Sassi K. and Mujtaba I., 2011, Optimal design of reverse osmosis based desalination process with seasonal variation of feed temperature, Chemical Engineering Transactions, 25, 1055-1060
DOI: 10.3303/CET1125176

In this work, the total annualized cost of the RO network is minimized for a given water demand and quality in order to find the optimal design and operation of RO systems. The design of RO network for water desalination process is formulated as a non-convex MINLP problem. Several cases are solved for different feed concentrations and temperatures. It is to be noted that there are some work carried out for optimization of the design of various RO systems under different feed concentration using MINLP technique (Marcovecchio et al., 2005; Lu et al., 2007). However, their work was limited to determine the optimal design and operation of RO network for only one temperature.

2. Modeling of RO Process

2.1 RO Membrane Model

A steady state model of RO process that takes into account concentration polarization (CP) has been developed for DuPont's B10 Hollow Fibre module based on Kimura–Sourirajan model which describe transport phenomena through the membrane (Kimura and Sourirajan, 1967). According to Marcovecchio (2005), this model is the most used for this propose because it is able to provide an accurate prediction of the flow of water and salt through the membrane. The CP is characterized by using film theory approach (Michaels, 1968). Figure 1 summarizes the model equations for RO simulation.

2.2 RO Network Model

A superstructure of the RO network is developed based on two-stage RO system (as shown in Figure 2) to accommodate all possible connections between streams and unit operations so that the superstructure would include all possible system structures. However, it includes no prior knowledge about the optimum layout of the RO process within the superstructure since this issue is left to be determined by the optimization solver. The infeasible system structures were eliminated from the general superstructure by removing non-essential streams and mixing points from the superstructure. Note that the mixing of streams is only allowable for the streams with equal pressure.

Water flux $J_w(T) = A_w(T)(\Delta P - (\pi_m - \pi_p))$; Salt flux $J_s(T) = A_s(T)(C_m - C_p)$; Permeate conc. $C_p = J_s(T)/ J_w(T)$; Permeate flow $Q_P = A\, J_w(T)$; Volume balance $Q_f = Q_r + Q_p$; Material balance $Q_f C_f = Q_r C_r + Q_p C_p$; CP factor $CP = (C_m - C_p)/(C_b - C_p) = A\, J_w(T)$;

Sherwood number $sh = K\, 2r_o/D = 2.725 Re^{0.33}\, Sc^{0.33}$; Reynolds number $Re = \rho\, 2r_o U/\mu$; Schmidt number $Sc = \mu(T)/\rho D$; Inner velocity $U_i = Q_f / 2\pi R_i L$; Outer velocity $U_o = Q_r / 2\pi R_o L$; Velocity $U = (U_i - U_o) / \log(U_i/U_o)$; Water recovery $WR = Q_P/Q_f$;

Water permeability $A_w(T) = A_{w0}(T_0)\dfrac{\mu(T_0)}{\mu(T)}$; Salt permeability

$A_s(T) = A_{s0}(T_0)\dfrac{\mu(T_0)}{\mu(T)}\dfrac{T}{T_0}$; Diffusivity coefficient $D(T) = D(T_0)\dfrac{\mu(T_0)}{\mu(T)}\dfrac{T}{T_0}$

Figure 1: RO module model

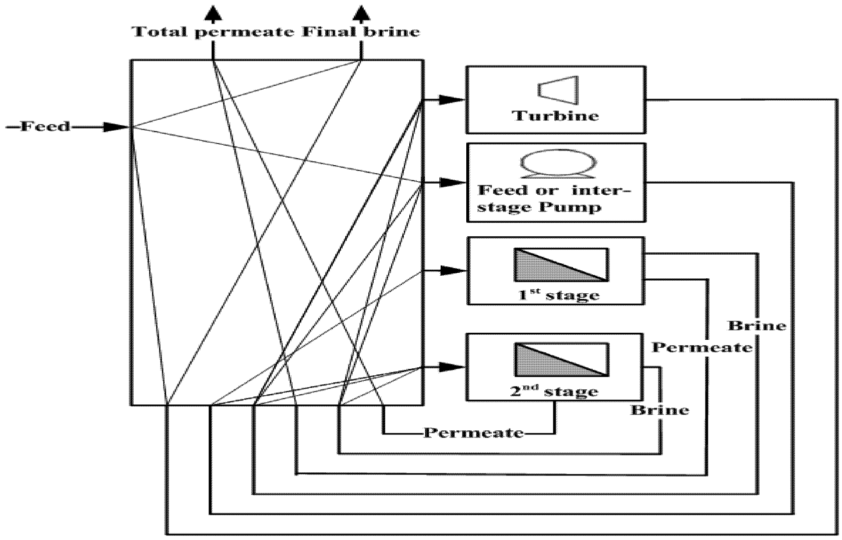

Figure 2: RO superstructure

3. MINLP Problem Formulation

The optimum design problem of RO network was formulated as a MINLP problem with reference to the superstructure given in Figure 2. Continuous variables are defined for the optimization of operating parameters and discrete variables are used to express discrete decisions as the existence of process units. The objective function is the total annualized cost (TAC) which is minimized for every candidate configuration subject to operation and design constraints. The cost function is a sum of capital and operating costs presented in Marcovecchio et al. (2005) and Lu et al., 2007). The MINLP problem was solved using outer approximation algorithm within gPROMS software. The formulation of the optimization problem enables the optimizer to identify the design with two stages or only one RO stage.

The MINLP problem investigated in this paper can be stated as follows. Given are single seawater feed source with different salt contents, design specifications of each membrane module, fixed water demand, maximum concentration of salts in the final permeate stream. The problem consists in determining the interconnections between different streams and equipments, optimum operating conditions (feed flow rate, feed pressure, pressure inlet to second stage, etc).

Mathematically the optimization problem can be described as:

Minimize TAC

$P_f, Q_f, S, N, N_{pu}, N_{tu}, BY, R$

Subject to: Equality constrains Model equations; Product demand and quality

Inequality constrains $P_f^L \le P_f \le P_f^U$; $Q_f^L \le Q_f \le Q_f^U$; $1 \le S \le S^U$;

$1 \le N \le N^U$; $1 \le N_{pu} \le N_{pu}^U$; $1 \le N_T \le N_T^U$;

$0 \le BY \le 1$; $0 \le R \le 1$.

Where S, N, N_{pu} and N_T are integer variables representing number of stages, number of membrane modules in each stage (in parallel), number of pumps and number of turbines respectively. The continuous variables P_f, Q_f, BY and R represent feed pressure, feed flow, brine bypass fraction and brine recycle fraction respectively. A set of binary variables which have a value of [0, 1] are used to express the existence or non-existence of different structural units and connections. L and U refer to lower and upper bounds.

4. Case Study

The optimization formulation presented in section 3 has been applied to optimize operational and structural characteristics of RO process based on a superstructure (Figure 2) and using DuPont B-10 hollow fiber RO module. The characteristics of the membrane module used here are taken from (See et al., 1999). It is assumed that the membrane module life is 5 years (Lu et al., 2006). The membrane module design parameters and the parameters used in optimization calculation are listed in Table 1.

The maximum allowable salt concentration in the desalinated product is maintained at 500 ppm and the total water demand is about 520 m^3/day.

Table 2 shows the optimal operation and configuration of RO systems for three different feed concentrations (25,000-45,000 ppm) and for a set of feed temperatures (ranging from 20°C to 35°C) representing the seasonal variation of seawater temperature. Based on the results, the following remarks may be drawn:

- There are no mixing between streams with different pressure was set as a condition in constructing the superstructure. Consequently, the recycle of brine should be done after passing through energy recovery device (turbine). This makes the brine recycle option unattractive for all cases. For most cases, with increasing feed temperature the required feed pressure decrease and the number of the elements decreases dramatically. Consequently, the unit cost of the product has decreased despite that the overall system recovery ratio decreased.
- For low and medium seawater concentrations (25,000–35,000 ppm), the unit product cost of the optimum RO design is fairly decreased as the feed temperature increases and is due to increase in the permeate production. And consequently, the required feed pressure is also lowered. Even though the salt passage is increased with increasing feed water temperature, the required product quality in this range of

Table 1: Input data for MINLP optimization

	Value	Ref.
Membrane unit cost ($)	800	Marcovecchio et al., (2005)
Maximum operating pressure (bar)	92	Lu et al., (2006)
Module Feed flow range (m^3/h)	1-2	Lu et al., (2006)
Feed pump efficiency (%)	75	Marcovecchio et al., (2005)
Turbine efficiency (%)	80	Marcovecchio et al., (2005)
Electricity unit cost ($/kWh)	0.08	Lu et al., (2006)
Pressure drop per module (bar)	0.2	Lu et al., (2006)
Load factor	0.9	Marcovecchio et al., (2005)

feed concentrations is achievable. Also, it can be seen that the optimization results are oriented to a section of the search region where the installing new pump is not favored because the added cost of installing new booster pump overcome the gain from the extra quantity of permeate produced. The dilution of feed stream by bypass part of the brine also is not desirable because brine bypass increases the operating cost without considerable enhancement in product quantity.

- In case 3, the optimal structure identified in the RO network design is strongly dependent on the seawater temperature, for lower temperature (20, 25°C), the two-stage RO systems without brine pressurizing or bypass are favored (Figure 3a).

  For higher temperatures (30, 35°C), in order to meet the product quality constraint it is necessary to pressurize the brine coming from stage 1 and bypass part of brine to reduce the effect of high amount of salts coming from stage 2. Also the second stage feed pressure hits the upper bound (92 bar) and this is to maintain the product quality within the allowable range (max. 500 ppm).

Table 2: MINLP optimization results

T (°C)	Optimum layout	Water recovery (%)	Feed pressure (bar)	Booster pump pressure (bar)	Product conc. (ppm)	Total Number of modules	Brine entering 2nd stage (%)	Product cost ($/m³)
Case 1: Feed conc. 25,000 ppm								
20	Figure 3a	70.91	75.08	-	267	43	100	0.555
25	Figure 3a	70.40	72.04	-	379	43	100	0.540
30	Figure 3a	71.85	71.85	-	421	39	100	0.536
35	Figure 3a	68.06	67.98	-	463	38	100	0.529
Case 2: Feed conc. 35,000 ppm								
20	Figure 3a	66.40	85.57	-	361	46	100	0.631
25	Figure 3a	66.01	84.00	-	479	44	100	0.625
30	Figure 3a	65.24	83.52	-	483	39	100	0.622
35	Figure 3a	66.63	86.17	-	500	34	100	0.635
Case 3: Feed conc. 45,000 ppm								
20	Figure 3a	57.57	87.53	-	364	51	100	0.722
25	Figure 3a	55.80	84.35	-	456	50	100	0.721
30	Figure 3b	50.40	74.66	92	500	43	77	0.735
35	Figure 3b	48.00	61.14	92	500	41	95	0.755

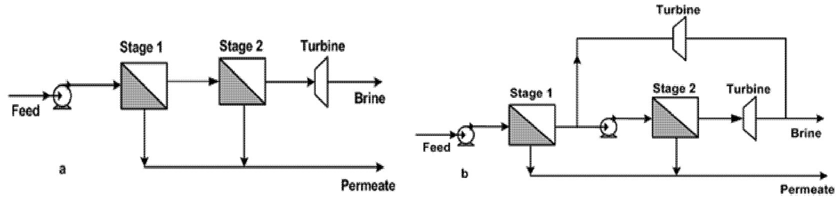

Figure 3: Optimum RO networks

5. Conclusion

The optimal design and operation of RO process has been addressed in this work. For different feed water concentrations and including seasonal variation of seawater temperature, an MINLP optimization framework based on a superstructure is developed for RO desalination process which identifies the optimal design parameters and operating policy of the RO network while minimizing the total annualized cost. It is found that the optimal design and operation of RO process are sensitive to the temperature variation as well as feed concentration. The RO layouts vary from two-stage with and without brine bypass and inter-stage pump. For low and medium feed concentration, the results indicate that the unit production cost of the optimum RO design is fairly decreased as feed temperature increased. For higher feed concentration, the production cost is increased as feed temperature increase due to difficulty of maintaining product quality in the required limit.

References

Goosen M. F. A., Sablani S. S., Al-Maskari S. S., Al-Belushi R. H. and Wilf M., 2002, Effect of feed temperature on permeate flux and mass transfer coefficient in spiral-wound reverse osmosis systems, Desalination, 144, 367-372.

Kimura S. and Sourirajan S., 1967, Analysis of data in reverse osmosis with porous cellulose acetate Membranes, AICE J., 13, 497-503.

Lu Y. Y., Hu Y. D., Xu D. M. and Wu L. Y., 2006, Optimum design of reverse osmosis seawater desalination system considering membrane cleaning and replacing, Journal of Membrane Science, 282, 7-13.

Lu Y. Y., Hu Y. D., Zhang X. L., Wu L. Y. and Liu Q. Z., 2007, Optimum design of reverse osmosis system under different feed concentration and product specification, Journal of Membrane Science, 287, 219-229.

Marcovecchio, M. G., Aguirre, P. A. and Scenna, N. J., 2005, Global optimal design of reverse osmosis networks for seawater desalination: modeling and algorithm, Desalination, 184, 259-271.

Michaels A. S., 1968, New separation technique for the chemical process industries, Chem. Eng. Prog. , 64, 31−43.

Nisan S., Commercon B. and Dardour S., 2005, A new method for the treatment of the reverse osmosis process, with preheating of the feedwater, Desalination, 182, 483-495.

Sassi, K. And Mujtaba, I.M., 2010, Simulation and optimization of full scale reverse osmosis desalination plant, 20th European Symposium on Computer Aided Process Engineering, 28, 895-900.

See H. J., Vassiliadis V. S. and Wilson D. I., 1999, Optimisation of membrane regeneration scheduling in reverse osmosis networks for seawater desalination, Desalination, 125, 37-54.