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A study on optimal schedule of membrane cleaning and replacement for spiral-wound SWRO system

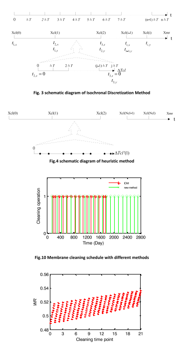
Aipeng Jiang *, Haokun Wang, Yinghui Lin, Wen Cheng, Jian Wang

School of Automation, Hangzhou Dianzi University, Hangzhou, Zhejiang 310018, China

HIGHLIGHTS

- Optimal schedule of membrane cleaning and replacement of SWRO system was studied.
- The optimization problem was formulated with detailed RO model considering membrane.
- A new solution method was proposed and compared with traditional method.
- Better optimal schedule and computing performance were demonstrated by case study.
- Influence of feed temperature and feed concentration was analyzed.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work, the optimal schedule of membrane cleaning and replacement of spiral-wound SWRO (seawater reverse osmosis) system was studied and analyzed under different feed conditions. Firstly, the spiral-wound RO process model described by differential and algebraic equations was established with the consideration of membrane fouling. Then the optimization problem was formulated to minimize the daily cost of the SWRO system, and a new method by which the optimization problem was transformed as an NLP problem was proposed to solve the problem effectively and quickly. The method was used for SWRO case study and was compared with the traditional method in the form of MINLP. Computing results demonstrate that the proposed method has the advantages of efficiency and stability. Moreover, it can get schedule of membrane cleaning and replacement with lower operational cost as well as give more detailed information of membrane channel. Lastly, influence of feed temperature and feed concentration of seawater was analyzed with the new method. Computing results show the stability of the new method and lead to new profiles of optimal operational variables and performance when feed temperature and salt concentration change, which are quite different from those in designed conditions.

1. Introduction

The world is suffering the serious freshwater shortage crisis because of the growth in the world's population, the development of industrialization and climate change [1–2]. Desalination is one of the most feasible ways to obtain freshwater, especially in the coastal regions and islands. And as one of the most promising desalination technology, seawater reverse osmosis (SWRO) increased its market shares recently [3–6]. In the past decades, Researchers made great efforts to reduce the energy cost through many kinds of approach, such as improving the

* Corresponding author.

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performance of membranes, building more accurate models, designing more economical flow sheet and optimizing the operation of the system [7–12]. The new high rejection and high flow membranes were permitted operating at high pressures (up to 80–90 bar), and a higher efficient energy recovery device PX (pressure exchanger) was used to reduce the *SEC* (specific energy consumption). All these advances have made the RO process achieve higher water recovery with lower capital and operational cost.

But as a technique of high energy consumption, optimizing the operation of RO desalination for further energy saving is still very attractive. As the key part of SWRO desalination, the performance of membrane modules has major influence on the energy cost and production quality. Membrane fouling and scaling are major factors affecting the performance of membrane modules. Thus the membrane should be cleaned for regeneration frequently to recover the performance and be replaced when it is not good enough for reuse.

Modeling of membrane fouling process and suitable schedule of membrane cleaning and replacing is quite important to SWRO process. Lee et al. [13] discovered that the gel layer over the membrane surface is the primary cause of the pollution. Then Wu et al. [14] established a mathematical model to simulate the membrane pollution, and verified its accuracy with real data. Peiris et al. [15] realized real-time prediction of the critical parameters in the model with the Extended Kalman Filter. Based on the reverse osmosis non-equilibrium thermodynamic character, Ma et al. [16] discussed and improved the common membrane flux model from the pollution layer resistance and concentration polarization. See and Vassiliadis [17] mainly researched the cleaning timing of the two stage RO system based on El-Halwagi et al.'s [18] studies on system design of RO system. Hoek et al. [19–20] build up a new model to describe the fouling behavior of full-scale RO process according to the combined effects of incomplete membrane cleaning and physical membrane compaction which lead to irreversible fouling. Considering the significant effect of membrane fouling on the performance of RO system, Zhu and See et al. [21–22] studied optimal configuration and schedule of RO process with the decay of membrane permeability caused by membrane fouling. And Lu et al. [23–24] proposed a new membrane cleaning and replacement strategy considering both the optimal design and the optimal operation to reduce the total cost, and formulated the cleaning problem as a mixed-integer nonlinear programming (MINLP) problem. But in his method the membrane replacing time is fixed, what could be obtained is the optimal membrane cleaning time. And with so many binary variables, solution of the MINLP problem often causes time-consuming and even solving failure.

In this paper, following the research efforts mentioned above, and based on accurate founded model of RO process considering membrane fouling equations, the optimal scheduling of membrane cleaning and replacement was studied. A new strategy with continuous variables to denote membrane cleaning and replacing interval and with NLP (nonlinear programming) problem formulated by simultaneous method was proposed. And then the optimal scheduling of membrane cleaning and replacement changes along operational parameters such as feed temperature and feed salinity were discussed.

2. Optimization problem formulation considering membrane fouling

2.1. Modeling of the RO process

The full-scale flow chart of one stage SWRO system can be seen in Fig. 1 [25]. As can be seen, after pre-treatment of intake, flocculation and filtration, the seawater was driven into RO membrane modules with high pressure. After the reverse osmosis process, the seawater was separated into freshwater with low salinity and brine. Then the freshwater goes into the product pool for further treatment before it gets to the terminal users. Meanwhile, the brine with high pressure is sent to energy recovery device to recycle pressure before discharged into oceans.

Based on solution–diffusion model and film theory, and according to the scheme of feed channel in RO membrane module shown in Fig. 2, more accurate membrane transport equations of steady-state in the form of distributed parameters can be derived.

For the RO membrane, the overall fluid and solute mass balance equations are:

$$Q_p = Q_f - Q_r \tag{1}$$

$$Q_f C_f = Q_r C_r + Q_p C_p \tag{2}$$

$$Q_p = n_l W \int_0^L Jv dz \tag{3}$$

Here subscripts *f*, *r*, and *p* refer to the feed, reject (brine) and permeate (product) streams. *Q* and *C* refer to the flowrate and salt concentration, respectively. The local water flux and salt flux can be calculated from the Kimura–Sourirajan solution-diffusion mass transport relations. n_l, *W* and *L* denote the number of leaf, the width and length of the RO module, respectively. The solution–diffusion model is assumed to be valid for the transport of solvent and solute through the membrane. According to this model, solvent flux *Jv* and solute flux *Js* through membrane are expressed by the following equations

$$Jv = A_w (P_f - P_d - P_p - \Delta\pi) \tag{4}$$

$$Js = B_s (C_m - C_b) \tag{5}$$

Let

$$P_b = P_f - P_d \tag{6}$$

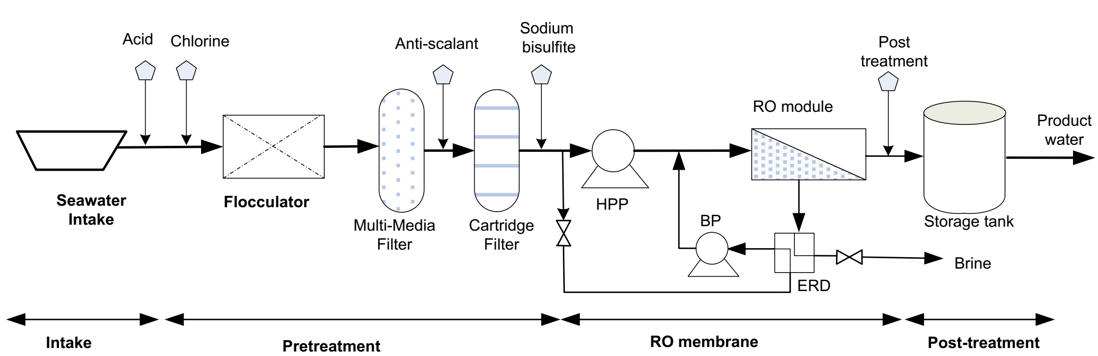

Fig. 1. Flow sheet of full-scale SWRO process.

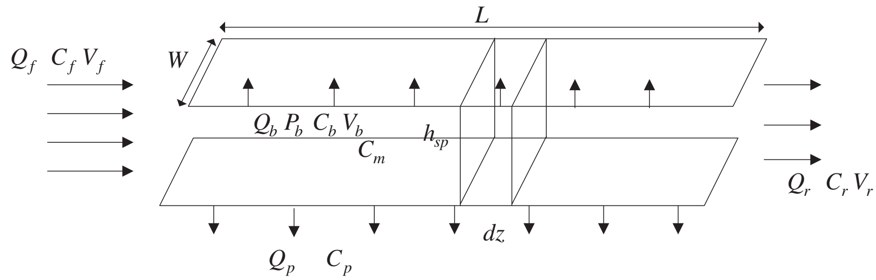

Fig. 2. Scheme of the feed channel in spiral wound module.

And

$$\Delta P = (P_b - P_p), \tag{7}$$

Then

$$Jv = A_w(\Delta P - \Delta\pi) \tag{8}$$

where A_w is the solvent transport parameter, P_f is the feed pressure and P_d is the pressure drop along feed channel, P_b is the pressure along the feed channel of spiral-wound module, P_p is the pressure of permeate side, which general assumed as environment pressure. $\Delta\pi$ is the pressure loss of osmosis pressure. B_s is the solute transport parameter, C_m and C_{sp} are solute concentration at the membrane surface on the feed side and solute concentration on the permeate side, respectively. And C_r is the value of C_b at the end of channel, which means $C_r = C_b(L)$.

The osmotic pressure is nearly linearly related to concentration by the equation

$$\Delta\pi = RT(C_m - C_p) \tag{9}$$

Here R is the gas law constant. Solution of the above equations requires knowledge of the RO process specification and parameters as well as the solute concentration of C_m at the membrane wall, which is quite different from the bulk concentration C_b due to the CP (concentration polarization) phenomenon. Through steady-state material balance around the boundary layer and CP theory, the following simple expression is developed:

$$\phi = \frac{C_m - C_p}{C_b - C_p} = \exp\left(\frac{Jv}{k_c}\right) \tag{10}$$

The bulk concentration C_b and solvent transports Jv vary along the membrane channel. The computation of the mass transfer coefficient k_c is as follows [26]:

$$Sh = \frac{k_c d_e}{D_{AB}} = 0.065 Re^{0.875} Sc^{0.25} \tag{11}$$

According to Fig. 2, the pressure loss along the RO channel can be formulated as [27]:

$$\frac{dP_d}{dz} = -\lambda \frac{\rho}{d_e}\frac{V^2}{2} \tag{12}$$

$$\lambda = 6.23 K_\lambda Re^{-0.3} \tag{13}$$

K_λ is the empirical parameter. Since the pressure along the RO P_b = -$P_f - P_d$, so

$$\frac{dP_b}{dz} = -\frac{dP_d}{dz} = \lambda \frac{\rho}{de}\frac{V^2}{2} \qquad z=0,\ P_b = P_f\ ;\quad z=L,\ P_b = P_r \tag{14}$$

V is axial velocity in feed channel, and satisfies

$$\frac{dV}{dz} = -\frac{2Jv}{h_{sp}} \qquad z=0,\ \ V = V_f = \frac{Q_f}{n_e W h_{sp}};\ z=L,\ \ V = V_r = \frac{Q_r}{n_e W h_{sp}} \tag{15}$$

h_{sp} is height of the feed spacer channel.

The bulk concentration C_b varies along the membrane channel, and can be given as:

$$\frac{dC_b}{dz} = \frac{2Jv}{h_{sp}V}(C_b - C_p), \qquad z=0,\ \ C_b = C_f;\ \ z=L,\ \ C_b = C_r. \tag{16}$$

From the solution of above equations, Q_p and C_p at given operational conditions and specification of membrane can be obtained, and from which the water recovery rate WR and specific energy consumption SEC can be calculated by the equations:

$$WR = Q_p/Q_f \tag{17}$$

$$SEC = (P_f Q_f/\varepsilon_p - P_r Q_r \varepsilon_{pf})/Q_p. \tag{18}$$

Salt rejection coefficient can also be obtained by the follow equation:

$$SR = (C_f - C_p)/C_f \times 100\% \tag{19}$$

Here ε_p and ε_{pf} denote the mechanical efficiency and energy recovery efficiency, respectively.

Parameters A_w and B_s are two very important performance factors of membrane module, which are quite sensitive with operational temperature, membrane fouling and related factors. Based on experimental and semi-mechanism research, membrane solvent and solute transport performance equations considering fouling can be expressed as [23]:

$$A_w = A_{w0} \times FA \times MFA \times e^{\left(\alpha_1 \frac{T-273}{273} - \alpha_2 (P_f - P_d)\right)} \tag{20}$$

$$B_s = B_{s0} \times FB \times MFB \times e^{\left(\beta_1 \frac{T-273}{273}\right)} \tag{21}$$

where A_{w0} and B_{s0} are intrinsic transport parameter in standard condition, α_1, α_2 and β_1 are constant parameters for transport. T represents operational temperature with unit of kelvin degree. MFA and MFB are membrane performance coefficient, which can be calculated by the follow equations:

$$MFA = e^{(-t_q/\Gamma_1)} \tag{22}$$

$$MFB = e^{(t_q/\Gamma_2)} \tag{23}$$

$$F_A = 1 - at \tag{24}$$

$$F_B = 1 + bt \tag{25}$$

Here FA and FB stand for irreversible degradation coefficient of membrane performance owning to the incomplete cleaning. Γ_1 and Γ_2 represent time constants of performance degradation. a and b are the decay coefficient of A_w and B_s, t is the operational time, and t_q means membrane operation time during each cleaning interval.

2.2. Formulation of the optimization problem

Based on flowsheet of SWRO process, the operational cost of the SWRO system mainly consists of: 1) the operating energy cost of the RO process (OC_{EN}). 2) The energy cost of seawater intake and pre-treatment (OC_{IP}). 3) The cost of chemicals (OC_{CH}) including acid, scale inhibitor, flocculants and other additives. 4) The cost of membrane replacing (OC_{ME}), which can be evaluated according to the design and operating conditions. 5) Maintenance cost (OC_{MN}), which comprises the maintenance fee of conventional equipment (OC_{MNCON}) and membrane module cleaning fee (OC_{MNCL}). 6) Labor cost (OC_{LB}). Generally, labor cost can be calculated as constant value with fixed SWRO plant, and the maintenance fee of conventional equipment is the same. Other costs can be calculated as follows [27]:

$$OC_{CH} = F_{UCH} Q_f = 0.0225 Q_f \tag{26}$$

$$OC_{IP} = P_{in} \cdot Q_f \cdot P_{elc} / \eta_{hp} \cdot PLF \tag{27}$$

$$OC_{ME} = Pri_{ME} \cdot MOD \cdot \zeta_{re} / 365 \tag{28}$$

$$OC_{EN} = P_f Q_f / \eta_{hp} - P_r Q_r \eta_{pX} \tag{29}$$

$$OC_{MNCL} = Ncl \cdot (OC_{OT} + OC_{PC}) / Xmr \tag{30}$$

$$OC_{MN} = OC_{MNCON} + OC_{MNCL} \tag{31}$$

Here Ncl and Xmr denote the number of membrane cleaning time before replacement and the membrane replacement time, respectively. And OC_{OT} OC_{PC} denotes membrane cleaning fees.

The operational cost of the system is as follows:

$$OC = OC_{IP} + OC_{EN} + OC_{ME} + OC_{MN} + OC_{LB} + OC_{CH} \tag{32}$$

To minimize the total cost of SWRO process when considering the membrane cleaning and replacement cost, we take the daily cost of the system within a membrane replacement period as the objective function, and take the RO process model and operational cost equations as constraints. The formulated optimization problem is shown in the following equation:

$$\underset{Q_f, P_f, T, Ncl, Xmr}{\mathrm{Min}} \frac{1}{Xmr} \int_0^{Xmr} OC \ \mathrm{d}t \tag{33}$$

2.2.1. Constraints

RO process Eqs. (1)–(25)

Operational cost Eqs. (26)–(32)

2.2.2. Initial value and boundaries

$$z = 0, \quad V = V_f = \frac{Q_f}{n_e W h_{sp}}; C_b = C_f; P_b = P_f$$

$$z = L, \quad V = V_r = \frac{Q_r}{n_e W h_{sp}}; C_b = C_r; P_b = P_r$$

$$P_f \le P_{f,\max}, V_f \le V_{f,\max}, C_{sp} \le C_{\max}$$

3. Solution of the optimization problem

The optimization problem includes differential equations and strongly nonlinear algebraic equations, and the time for membrane cleaning and replacement schedule is quite long, it is of great difficulty to get the accurate solution in direct way. To simplify the problem, researchers intend to use simplified lumped-parameter method to replace the differential equations of Eqs. (14)–(16) and used average values to express Q_b, C_b, P_b and so on [23,28]. This method would lose the detailed state information of RO feed channel and sometime would cause violation of the "thermodynamic restriction" [29]. This can bring wrong solution results and gives us wrong guidance in practice.

Since Ncl and Xmr are variables to obtain, and the integration Eq. (33) need to be discretized for numerical computing. Lu assumes that the time horizon t of membrane replacing is fixed as five years, and then it is partitioned into n equal time periods of ΔT. At the end of each ΔT, membrane cleaning condition was checked. This method can be called as Isochronal Discretization Method (IDM), and more details can be seen in Fig. 3. Here t_1, t_2, t_3..., t_i, signify each time period after membrane cleaning, respectively. The subscripts x and y denote the start and the end of each membrane cleaning time, respectively. Membrane cleaning is assumed to be performed at the beginning of each period, and can be described by the decision variable Z_m. When no cleaning is required, the binary

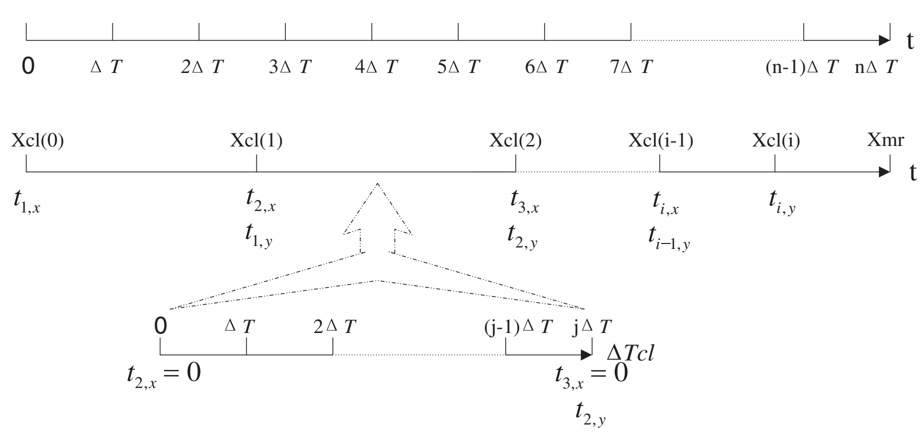

Fig. 3. Schematic diagram of Isochronal Discretization Method.

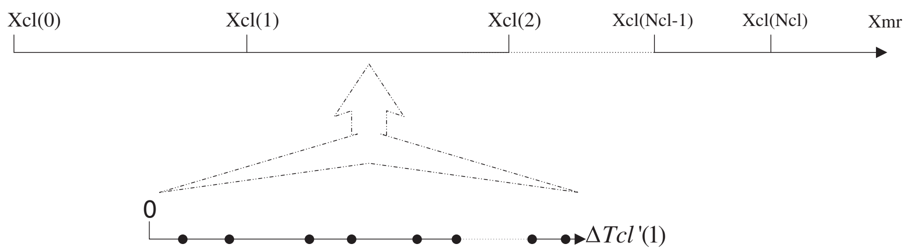

Fig. 4. Schematic diagram of our new method.

variable Z_m takes the value of 0, otherwise, it takes 1. Since the duration of cleaning action is a few hours, the downtime can be neglected compared to the time interval of ΔT. The operation day can be described by the following equations [17]:

$$\sum_i \sum_j \Delta T = n\Delta T = t \tag{34}$$

$$t_{i,x} = (1-Z_m)t_{i-1,y} \tag{35}$$

$$t_{i,y} = t_{i,x} + j \cdot \Delta T \tag{36}$$

In fact, the above method can only get the membrane cleaning intervals, which are integer variables, and with those binary variables of Z_m, the optimization problem was formulated as Mixed Integer Nonlinear Programming (MINLP), which is quite hard to solve and is of low computing efficiency.

In our method, we assume that the optimal life span of membrane module is a continuous variable named *Xmr*, and the optimal membrane cleaning number is *Ncl* during the time. Then during the time horizon of *Xmr*, the cleaning time points along time zone are $Xcl(1), Xcl(2), \ldots Xcl(Ncl)$, as shown in Fig. 4. They are continuous variables satisfying:

$$Xcl(i+1) > Xcl(i) \quad i = 1, 2, \ldots, (Ncl-1) \tag{37}$$

$$\Delta Tcl(i) = Xcl(\mathrm{i}+1) - Xcl(\mathrm{i}) i = 1, 2, \ldots (Ncl-1) \tag{38}$$

$$\Delta Tcl(Ncl) = Xmr - Xcl(Ncl) \tag{39}$$

Based on the above method, the objective function to minimize the operational cost considering the membrane cleaning and replacing can be formulated as the following form:

$$\begin{aligned} &\underset{P_f, Q_f, Xcl, Xmr, Ncl}{\mathrm{Min}} F_{obj} = \frac{1}{Xmr} \int_0^{Xmr} OC \ \mathrm{d}t = \\ &\frac{1}{Xmr} \left[\int_0^{Xcl(1)} OC \ \mathrm{d}t + \sum_{i=1}^{Ncl-1} \int_{Xcl(i)}^{Xcl(i+1)} OC \ \mathrm{d}t + \int_{Xcl(Ncl)}^{Xmr} OC \ \mathrm{d}t \right] \end{aligned} \tag{40}$$

Table 1
Default conditions of feed flow.

Feed condition	
C_f (kg/m^3)	30
T (K)	298
Feed PH	5–8
Density ρ (kg/m^3)	1000
μ viscosity (kg/m/s)	1.02e^{-6}

Table 2
Process parameters of the SWRO system.

Property	Value
Effective membrane area	35 m^2
Effective membrane leaf length	0.88 m
Effective membrane leaf width	0.69 m
Number of membrane leafs	29
Feed cross-section area	0.0147 m^2
Feed spacer	
Height	0.737 mm
Porosity	0.90
Mesh length	2.7 mm
Equivalent diameter	0.935 mm
Operation limits	
Maximum feed velocity	0.7 m/s
Minimum feed velocity	0.068 m/s
Maximum permeate salinity	1.2 kg/m^3
Maximum feed pressure	82 bar

Table 3
Number of variables with IDM.

ΔT	*Ngrid*					
	5	10	15	20	25	30
60	6612	13,062	19,512	25,962	32,412	38,862
30	13,212	26,112	39,012	51,912	64,812	77,712
24	16,512	32,637	48,762	66,887	81,012	97,137
20	19,812	39,162	58,512	77,862	97,212	116,562

Table 4
Iteration number of IDM.

ΔT	*Ngrid*					
	5	10	15	20	25	30
60	23,173	46,344	70,799	90,747	116,822	142,826
30	35,046	144,024	176,776	Overrun	Overrun	Overrun
24	60,316	126,614	171,138	Overrun	Overrun	Overrun
20	43,322	148,365	Overrun	Overrun	Overrun	Overrun

Table 5
Optimal objective value with IDM.

ΔT	*Ngrid*					
	5	10	15	20	25	30
60	3.376	3.3669	3.364	3.362	3.364	3.3643
30	Invalid	3.3658	3.3624	Invalid	Invalid	Invalid
24	3.3656	3.3654	3.3578	Invalid	Invalid	Invalid
20	3.3576	3.3568	Invalid	Invalid	Invalid	Invalid

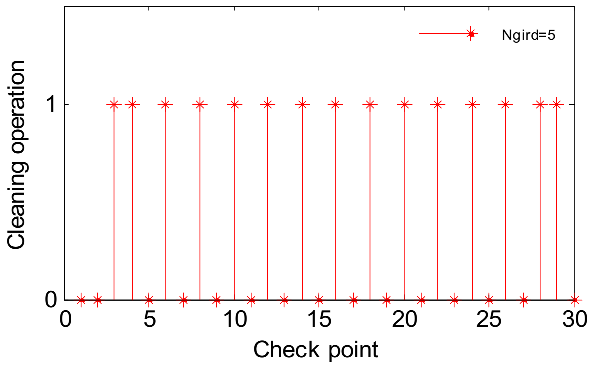

Fig. 5. Optimal cleaning schedule obtained by IDM.

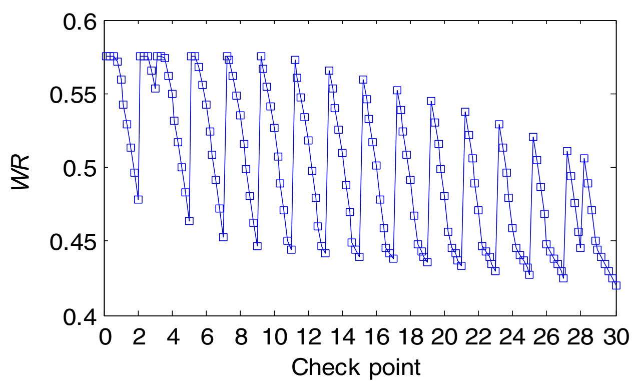

Fig. 6. Water recovery of IDM.

To compute all the integral items, each membrane cleaning interval was divided into *Ngrid* parts, and was calculated as follow form:

$$\int_{Xcl(i)}^{Xcl(i+1)} OC \ \mathrm{d}t = \frac{Xcl(i+1) - Xcl(i)}{Ngrid} \sum_{k=1}^{Ngrid} OC_k \tag{41}$$

To avoid the difficulty of the differential Eqs. (12)–(15), simultaneous method with finite element collocation was used to discretize all the state variables and control variables. Monomial basis representation for the differential profiles was used, which is popular for the Runge–Kutta discretization [30]:

$$w(z) = w_{i-1} + h_i \sum_{q=1}^{K} \Omega_q \left(\frac{z - z_{i-1}}{h_i} \right) \frac{\mathrm{d}w}{\mathrm{d}z_{i,q}} \tag{42}$$

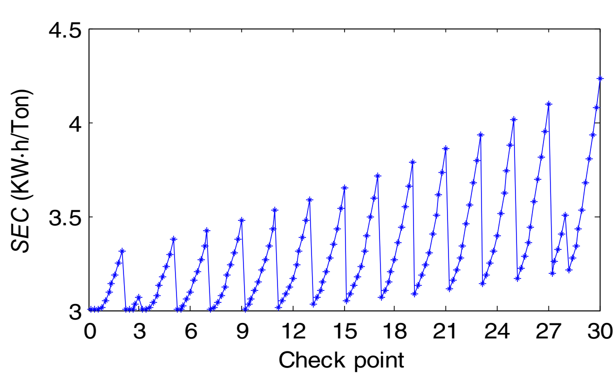

Fig. 7. *SEC* of IDM.

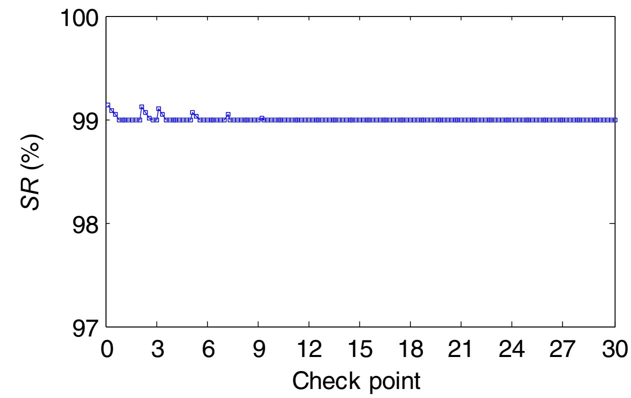

Fig. 8. Salt rejection ratio of IDM.

Here, w_{i-1} is the value of the differential variable at the beginning of element i, h_i is the length of element i, $dw/dz_{i,q}$ denotes the value of its first derivative in element i at the collocation point q, and Ω_q is a polynomial of order K, which satisfies:

$$\Omega_q(0) = 0 \quad q = 1 \ldots, K \tag{43}$$

$$\Omega_q^{'}(\sigma^r) = \delta_{q,r} \quad q = 1 \ldots, K \tag{44}$$

where σ_r is the rth collocation point in each element. The continuity of the differential profile is enforced by:

$$w_i = w_{i-1} + h_i \sum_{q=1}^{K} \Omega_q(1) \frac{\mathrm{d}w}{\mathrm{d}z_{i,q}} \tag{45}$$

Table 6
Number of variables with the proposed method.

Ncl	*Ngrid*					
	5	10	15	20	25	30
5	1082	2132	3182	4232	5282	6332
16	3436	6796	10,156	13,516	16,876	20,236
30	6432	12,732	19,032	25,332	32,686	37,932
50	10,712	21,212	31,712	42,212	52,712	63,212

Table 7
Iterations with the proposed method.

Ncl	*Ngrid*					
	5	10	15	20	25	30
5	69	66	65	54	51	60
16	55	53	63	56	67	52
30	82	71	66	101	82	85
50	84	87	87	120	90	77

Table 8
Optimal objective value with the proposed method.

Ncl	*Ngrid*					
	5	10	15	20	25	30
5	3.3012	3.1930	3.2825	3.2802	3.2789	3.2780
16	3.1584	3.1443	3.1396	3.1371	3.1357	3.1347
30	3.2079	3.1967	3.1930	3.1911	3.1948	3.1892
50	3.3111	3.3033	3.3008	3.2995	3.2987	3.2982

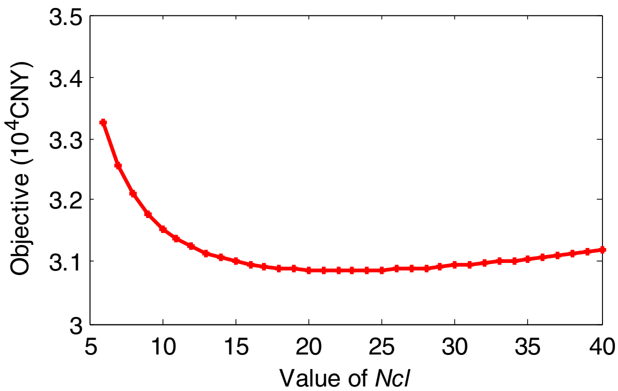

Fig. 9. Optimal objective value along with *Ncl*.

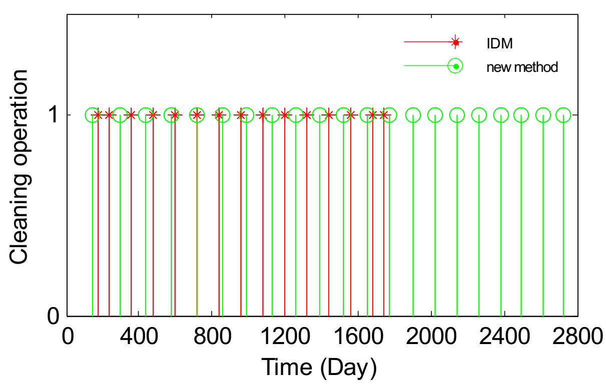

Fig. 10. Membrane cleaning schedule with different methods.

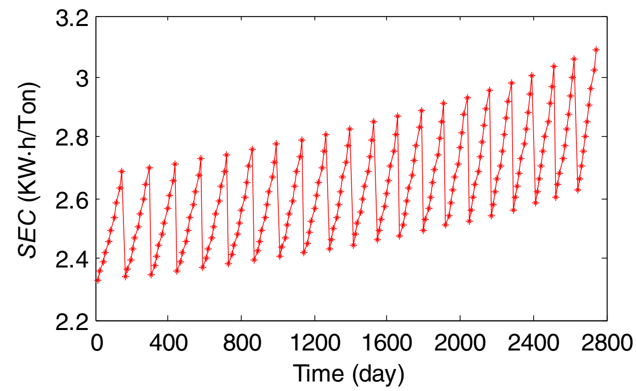

Fig. 12. *SEC* value with the new method.

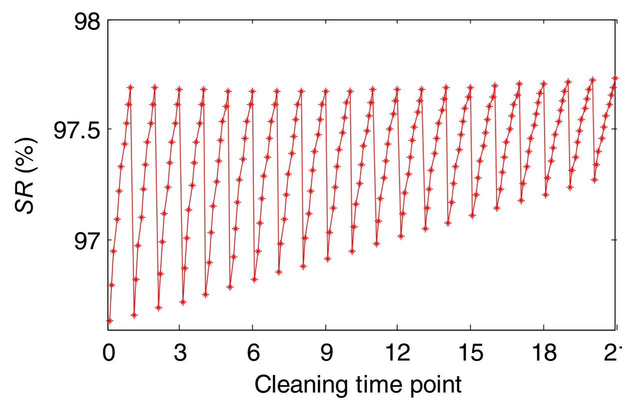

Fig. 13. Salt rejection ratio with the new method.

In addition the algebraic profiles are approximated using a Lagrange basis representation, which takes the form:

$$y(z) = \sum_{q=1}^{K} \psi_q \left(\frac{z - z_{i-1}}{h_i} \right) y_{i,q} \tag{46}$$

where $y_{i,q}$ represent the values of the algebraic variables in element i at collocation point q, z is the value that satisfies $z_{i-1} \le z \le z_i$, and Ψ_q is the Lagrange polynomial of degree K.

Since $Xcl(1), Xcl(2), \ldots Xcl(Ncl)$ and Xmr are the continuous variables to be optimized, and all the variables of RO process are continuous algebraic variables with above transform, the optimization problem was transformed into NLP problem with fixed value of the integer variable *Ncl*. Since the optimal value of *Ncl* is generally in the range of 10 to 40, we can solve the NLP problem with several different *Ncl* values and get the last value with Lagrange interpolation.

4. Case study

A single-stage SWRO system, identical to the flow chart in Fig. 1 was studied to demonstrate the new method and the influence of temperature and feed concentration on the optimal schedule. The SWRO system is located in Zhejiang province of China and is a part of LiuHeng desalination plant with the daily production capacity of 10^4 t of permeate

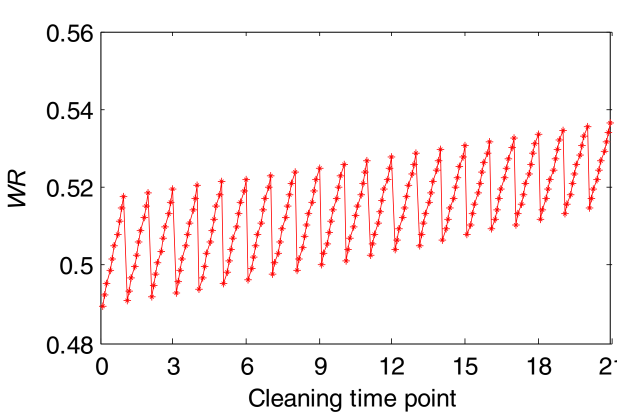

Fig. 11. Water recovery with the new method.

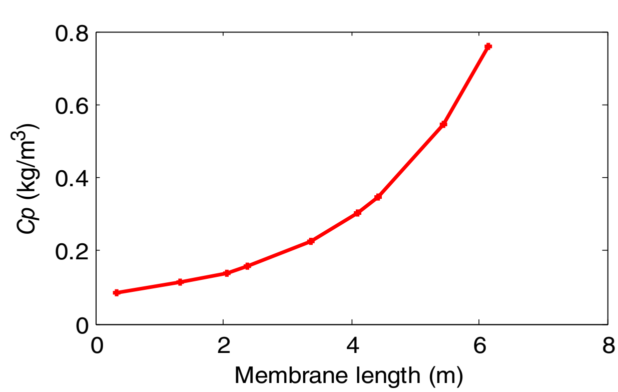

Fig. 14. Profile of *Cp* along the membrane channel.

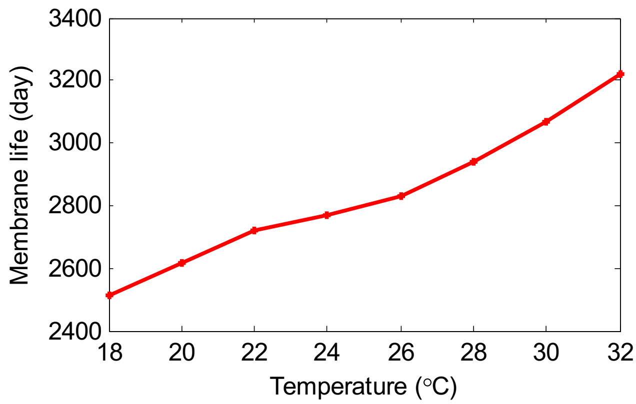

Fig. 15. Profile of membrane replacing time vs. temperature.

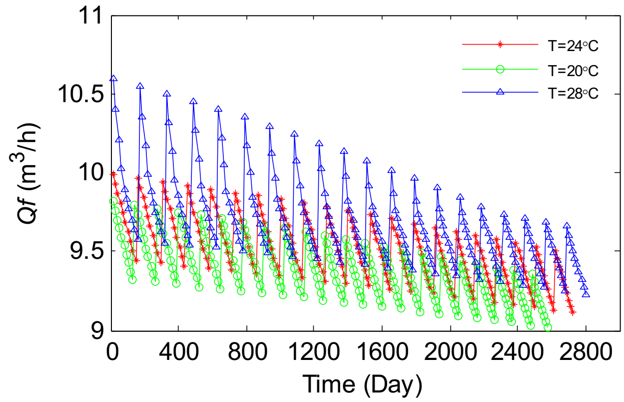

Fig. 18. Profile of Q_f along with time.

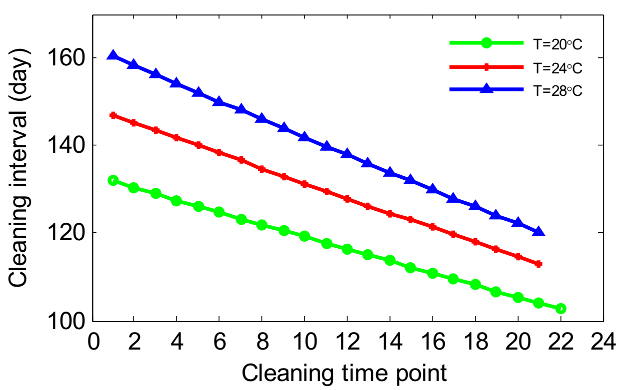

Fig. 16. Profile of feed temperature vs cleaning time point.

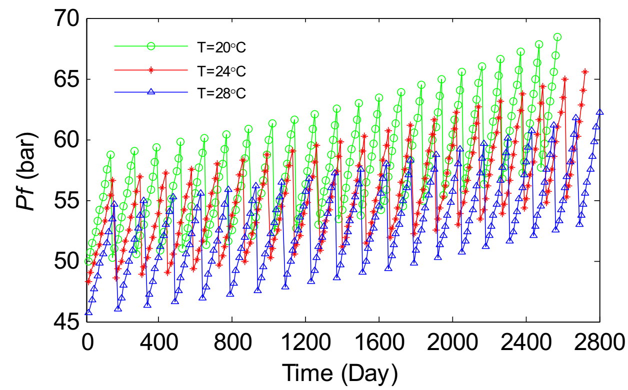

Fig. 19. Profile of P_f along with time.

water. The temperature of seawater for desalination generally ranges from 15 to 32 °C. SW30HR-3XX membrane modules are used for salt removal.

The finally formulated NLP problem was programmed in the GAMS24.0 [31] modeling environment which runs on an Inter(R) Pentium(R) CPU G2030 3 GHz with 4 GB Memory. IPOPT [32] were used for the solution, and the computing results were compared with the Isochronal Discretization Method.

Table 1 gives the default conditions of the feed flow. Table 2 shows the process parameters and the operational conditions of the SWRO system.

4.1. Comparison of different solution methods

The proposed method was compared with the IDM which can be shown in literature [23], and in IDM the membrane replacement time was set as 5 years. ΔT was taken as 60, 30, 24 and 20 days, and there will be 30, 60, 75 and 90 points to check the membrane fouling conditions and to determine whether it is necessary to execute cleaning operation at the beginning of each period. *Ngrid* was also set as 5, 10, …, 30.

Since BARRON and LINGO were not as effective as DICOPT to solve the problem, DICOPT was selected as solver. Solution information under different ΔT and *Ngrid* can be seen from Tables 3–5. They give

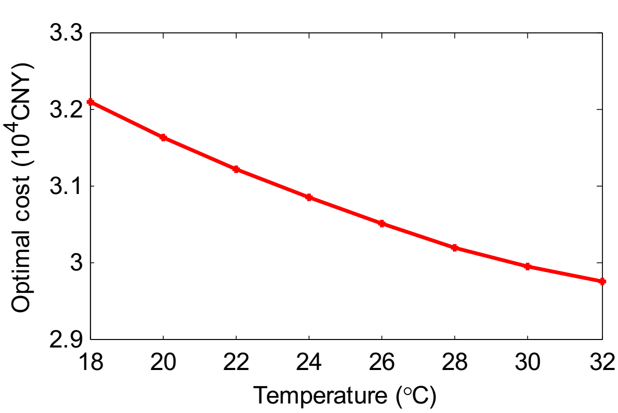

Fig. 17. Profile of optimal cost vs feed temperature.

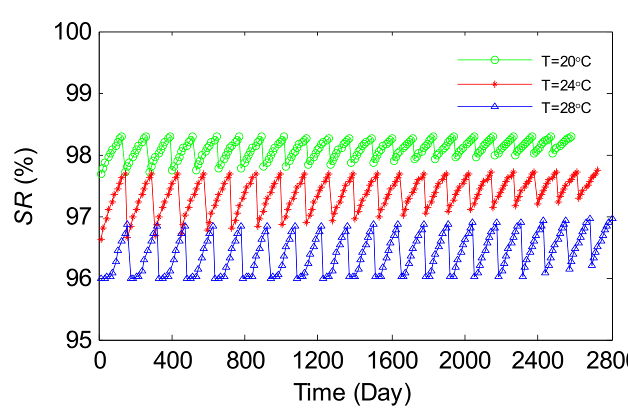

Fig. 20. Profile of *SR* along with membrane life time.

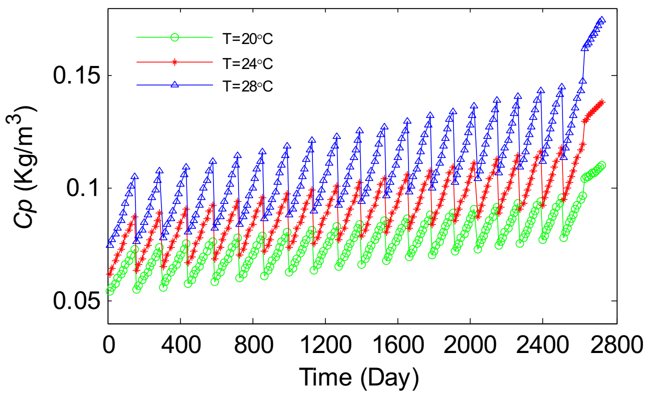

Fig. 21. Profile of *Cp* along with time.

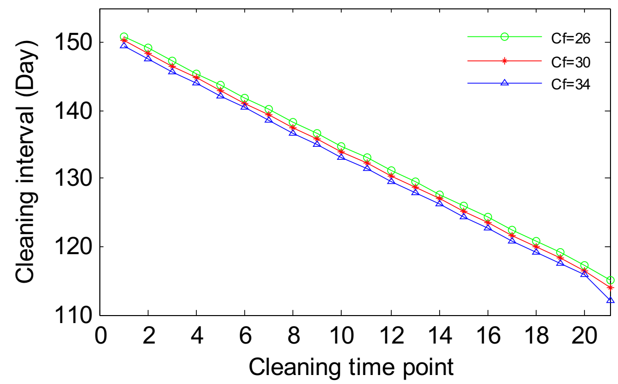

Fig. 23. Profile of cleaning interval vs cleaning time point.

the number of variables, iterations and objective values with IDM method (Table 4).

As can be seen, when ΔT is set as 60 days, the optimal solution of the system can be found whatever *Ngrid* is. But if it is set as 30, 24 or 20, only quite few cases the problem can be successfully solved. Too many iterations and too much time needed for the solution caused the solution failure. It also can be seen from Table 5 that, different value of ΔT and *Ngrid* will also cause minor differences. When ΔT is set as 60 days and membrane cleaning conditions would be checked 30 times, computing results give the optimal cleaning schedule and key performance index, which can be seen from Fig. 5, Fig. 6, Fig. 7 and Fig. 8. Fig. 5 shows whether to cleaning the membrane modules at different check point with different *Ngrid* values. Fig. 6 to Fig. 8 shows the water recovery ratio (*WR*), *SEC* and Salt rejection (*SR*) along the time. From these figures we can see the performance decreases along the time before the next membrane cleaning, resulting energy cost increase. Once the membrane is cleaned, the water recovery improves and the *SEC* decreases correspondingly. As to the salt rejection ratio, it has a slight variation during the periods, but keeps higher than 99%.

In our proposed method, membrane replacement time *Xmr* and membrane cleaning time are continuous variables. With the *Ngrid* is also set as 5, 10, …, 30, and membrane cleaning number *Ncl* is fixed with different values. The optimization problem can be solved efficiently in each case. Computing results and information were listed in Tables 6–8.

From Table 6 it can be found, with the increase of *Ncl* and *Ngrid*, the scale of the formulated problem with proposed method increase greatly. But in all the listed cases, the problem was quickly and successfully solved in decade's iterations. With different values of *Ncl*, the value of objective function changes, this means that there exists the optimal number of membrane cleaning times. If we increase the value of *Ncl* one by one to solve the optimization problem, we can get the profile of the objective value shown in Fig. 9. From which we can get the optimal value of *Ncl* and the minimized objective value. Compared with Table 5, we also can found that the objective value of our proposed method is quite lower than that of IDM. This shows that our method is better than IDM in optimal schedule results as well as in solution difficulty.

Fig. 10 gives the optimal membrane cleaning schedule with the two methods. Figs. 11–13 shows the profiles of water recovery, *SEC* and salt rejection along time or membrane cleaning time point. From which we can find that before the next membrane cleaning, the water recovery, *SEC* and salt rejection increase gradually, they are quite different from those obtained with IDM. Since with our method, more detailed state information can be obtained, we can get the change of C_b, C_p, V_b, P_b and etc. along the membrane feed channel, this will be helpful to understand the RO process. Fig. 14 shows the salt concentration of permeate water along the membrane channel.

4.2. Influence of temperature on the optimal results

Lu and Hu [23] studied membrane cleaning strategy under the default design conditions, but since the operational conditions frequently deviate from default conditions and have important impact on optimal schedule results. So these influences were analyzed here.

Figs. 15–18 shows the optimal membrane cleaning and replacement schedule, and the optimal operational cost change along with feed temperature from 18 °C to 32 °C. As can be seen from the Fig. 15 and Fig. 16, membrane replacement time and membrane cleaning time point increase significantly when feed temperature increases, and the number of membrane cleaning is different. These results show that with

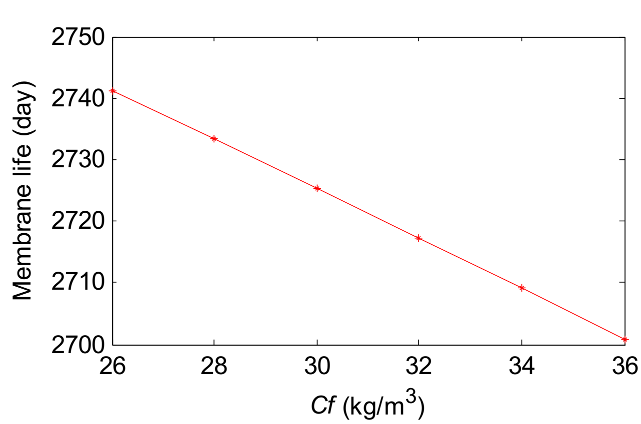

Fig. 22. Profile of membrane life vs feed concentration.

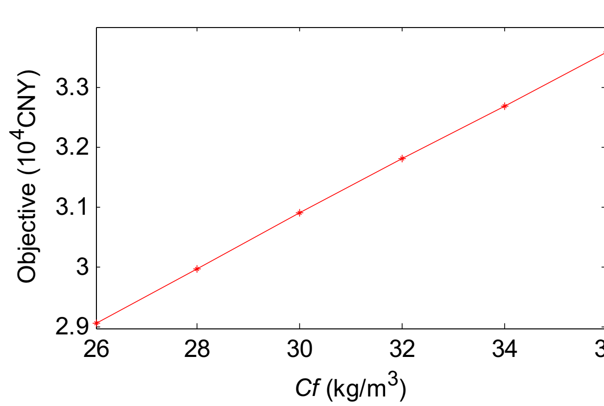

Fig. 24. Profile of optimal objective with different C_f.

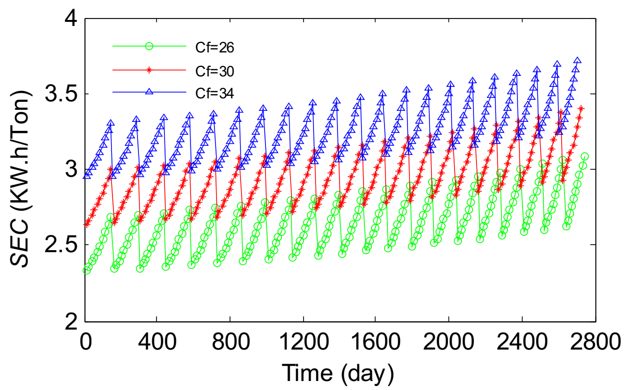

Fig. 25. Profile of *SEC* along the time with different C_f.

different feed temperature, membrane cleaning and replacement should be scheduled differently to reduce the total operational cost. The change of operational cost along with the feed temperature can be seen from Fig. 17. It can be found that the optimal operational cost reduces significantly as the feed temperature increase. This because that osmosis pressure is lower when feed temperature is higher, and to fulfill the output permeate requirement the feed pressure and feed flowrate is higher. Fig. 18 and Fig. 19 are the results with optimal objective value in different feed temperature, and they are consistent with the above explanation. Since state variables can be obtained through the solution of the optimization problem, we also can get the profile of salt rejection and so on. Fig. 20 and Fig. 21 show the optimal profile of C_p and *SR* along the time with different feed temperature.

4.3. Influence of feed salinity on the optimal results

If the feed seawater has different concentration of salinity, the optimal schedule of membrane cleaning and replacement as well as the operational cost will also change. Solution of the optimization problem with different feed salinity leads to the profiles of Figs. 2222–25.

From Fig. 22 and Fig. 23, it can be seen that the change of membrane replacement time and membrane cleaning time points is relatively small. When feed concentration increases from 26 kg/m^3 to 36 kg/m^3, the total membrane cleaning number is the same, and the time interval of two cleaning time point reduces slightly. But since the osmosis pressure increase quickly as the feed concentration increase from 26 kg/m^3 to 36 kg/m^3, much higher driven pressure would be needed, which will cause the *SEC* and operational cost increase significantly. Fig. 24 and Fig. 25 show the increase of daily operational cost and energy cost per cubic meter permeate water, which is consistent with the theoretical analysis.

With the established SWRO process model considering membrane fouling and the proposed solution method, other factors such as membrane transport parameter, membrane fouling parameter and the fares for membrane maintenance can also be analyzed and can give more meaningful results.

5. Conclusion

Since membrane fouling affects the operational cost and the quality of freshwater, it is quite important to optimize the schedule of membrane cleaning and replacement, especially when the SWRO system isn't operated in the default design conditions.

In this work, optimal schedule of membrane cleaning and replacement to minimize the daily operational cost was studied. With the consideration of membrane fouling, the detailed RO process model described by differential and algebraic equations was established, and with operational cost equations the optimization problem was formulated. To solve the problem effectively, a new method which can transform the problem into NLP was proposed. The new method was also compared through SWRO case study with traditional strategy called Isochronal Discretization Method, which was formulated as MINLP problem and the membrane replacement time was set as constant value. Computing results demonstrate that: the new proposed method can solve the problem more effective and efficiently. Moreover, the new method can get better optimal schedule of membrane cleaning and replacement, and can give more detailed information of RO process in membrane channel.

With the new solution method, influence of feed temperature and feed concentration of seawater was analyzed. Computing results show that: feed temperature has significant influence on optimal schedule of membrane cleaning and replacement as well as on the optimal operational cost. So under different feed temperature, different schedule should be obtained to reduce the operational cost. Feed concentration has quite small influence on optimal schedule of membrane cleaning and replacement, but has quite big influence on the optimal operational cost. Other factors such as membrane price and membrane fouling parameters can also be analyzed with the established optimization problem.

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Appendix A. *Nomenclature*

a	decay level of water permeability
A_w	membrane water permeability (m·s^{-1}·Pa^{-1})
A_{w0}	intrinsic membrane water permeability (m·s^{-1}·Pa^{-1})
b	decay level of TDS permeability
B_s	membrane TDS permeability (m/s)
B_{s0}	intrinsic membrane TDS permeability (m/s)
C_b	bulk concentration along feed channel (kg/m^3)
C_f	feed salt concentration (kg/m^3)
C_m	salt concentration of membrane surface (kg/m^3)
C_p	permeate concentration of RO unit (kg/m^3)
C_r	brine concentration (kg/m^3)
C_{sp}	permeate concentration of permeate side (kg/m^3)
FA	irreversible degradation coefficient of A_w
FB	irreversible degradation coefficient of B_s
Jv	solvent flux (kg/m^2·s)
Js	solute flux (kg/m^2·s)
L	length of the RO channel (m)
MFA	membrane performance coefficient of A_w
MFB	membrane performance coefficient of B_s
MOD	number of membrane module
Ncl	cleaning frequency
n_l	number of leaf in RO module
n_{pv}	number of pressure vessel
OC	operational cost of whole process
OC_{EN}	energy cost of RO process
OC_{BP}	energy cost of boost pump
OC_{CH}	cost for chemicals
OC_{IP}	energy cost for intake and pretreatment
OC_{ME}	cost for membrane replacement
OC_{MN}	cost for system maintenance
OC_{MNCON}	cost for conventional equ maintenance
OC_{MNCL}	cost for membrane module cleaning
OC_{OT}	membrane cleaning cost for chemicals
OC_{PC}	membrane cleaning cost for other
P_b	pressure along feed channel (bar)
P_{elc}	electricity price
P_d	pressure drop along RO spiral wound module (bar)
P_f	feed pressure (bar)

P_p	pressure in permeate side (bar)
P_r	brine pressure (bar)
P_{ri}	membrane price
PLF	load coefficient
Q_f	feed flowrate (m^3/h)
Q_p	permeate flowrate (m^3/h)
Q_r	brine flowrate (m^3/h)
WR	water recovery ratio
SR	salt rejection coefficient (%)
SEC	specific energy consumption (kw·h/m^3)
t	operation time of membrane module (day)
t_q	membrane operation time after last cleaning
T	feed(operational) temperature (K)
V_b	axial velocity of bulk flow (m/s)
V_f	axial velocity of feed flow (m/s)
V_r	axial velocity of brine flow (m/s)
W	width of the RO module (m)
Xcl	membrane cleaning time
Xmr	membrane replacing time

Greek symbols

$\alpha_1, \alpha_2, \beta_1$	constant parameters
$\Delta\pi$	pressure loss of osmosis pressure (bar)
ΔT	time of each schedule period
ΔTcl	membrane use time since last cleaning
ρ	density of permeate water (kg/m^3)
λ	friction factor
Γ_1, Γ_2	membrane performance decay constants
ζ_{re}	membrane replacing rate
ε_p	mechanical efficiency of high pressure pump
ε_{pf}	energy recovery efficiency

Subscripts

b	bulk
f	module feed channel
m	membrane surface
p	permeate side
r	brine side

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