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Process modeling and simulation of an SWRO desalination plant: case study of Gijang SWRO desalination plant in Korea

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ABSTRACT

An operator training simulator (OTS) provides the identical operating system environment with a real plant as well as the systematic accumulation of operation and maintenance (O&M) know-how in a seawater reverse osmosis (SWRO) desalination plant. Those properties could significantly increase a plant O&M efficiency. OTS system consists of a distributed control system server, a virtual controller, and a simulator reflecting an actual plant. This study describes the development of the plant simulator and the results from its application to Gijang SWRO desalination plant in Korea. The process models of the simulator were developed based on the previously established mathematical equations, and the process models simulate all of the unit process in the SWRO plant such as a dissolved air flotation, a dual-media filtration (DMF), an ultrafiltration (UF), and a reverse osmosis (RO) with an energy recovery device, respectively. They are the main components of the plant. All the parameters of each unit process were based on the actual design values from the plant. As a result, there was good agreement between the simulated values from the developed process models and the designed performance values of the plant. In addition, the results from the dynamic simulations like the increase of different pressure and the performance recovery by the cleaning activities at DMF, UF, and RO unit processes were well simulated with a typical decay rate according to the process time. The process models developed in this study could be the basis to develop the OTS system of Gijang SWRO desalination plant, and furthermore, it can be used for a platform in developing a digital SWRO plant after improving it more in detail.

Keywords: Seawater reverse osmosis (SWRO) plant; Process modeling; Operator training simulator (OTS); Operation and maintenance (O&M)

1. Introduction

As an effort to reduce the operation cost of seawater reverse osmosis (SWRO) plant, several multidiscipline approaches have been suggested in the operation and maintenance (O&M). Especially, the advanced O&M technology combined with Information Communication Technology has been focused and applied for a cost-effective O&M. There are several examples of the developments such as remote monitoring system, energy management system, computerized maintenance management system, reliability ability maintainability, and membrane maintenance optimizer. However, the development of the operator training simulator (OTS) in SWRO desalination plants is limited although OTS system is well established in the different fields like coal power plant and oil refinery. As SWRO desalination plants have been more complex due to their scale-up and the application of advanced technologies,

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the importance of OTS system has been increased for the purpose of effective management of the plant operators and site-specific O&M know-how.

An OTS system is defined as a device for simulation training with a process simulator based on mathematical equations, which enables operators to be accustomed with actual operation in a plant. It has the following benefits: (1) increased safety and productivity, (2) improved trouble-shooting response, (3) realistic test bed for control system changes, and (4) fast start-up and shutdown. It mainly consists of a distributed control system (DCS) server, a virtual controller (VC), and a simulator reflecting an actual plant, which is shown in Fig. 1. Also, it is classified as a high fidelity with dynamic process model and low fidelity with simplified feedback. Recently, a high-fidelity OTS system is preferred for a realistic performance simulation and feedback. Until now, most of OTS systems have been developed in the power plant, refinery, and oil and gas industries, and there are only a few cases in the desalination plant.

There are several unit processes in SWRO desalination plants such as a dissolved air flotation (DAF), a dual-media filtration (DMF), an ultrafiltration (UF), and a reverse osmosis (RO) with an energy recovery device (ERD). Beside these, the other unit models for common parts such as pipe, valve, pump, and tank in a plant can be easily developed using commercial OTS S/W such as TRAX (TRAX Energy Solutions, USA), GSE (GSE SYSTEMS, USA), DYNSIM (Schneider Electric, France), and UniSim (Honeywell, USA) by applying the design values of a plant. However, the major unit process models mentioned above in SWRO desalination plant are needed to be developed for simulating the performance of the plant. Several researches have been studied for a mathematical modeling of each unit process (i.e., DAF, DMF, UF, RO, and ERD) separately [1–7], but the unit process models should be integrated as an entire process model of SWRO desalination plant.

In this study, the process model replicating the Gijang SWRO desalination plant in Korea is developed based on the mathematical equation with the actual design values used in the plant. The process model includes a DAF, a DMF, an UF, and an RO with an ERD, which are unit processes of the plant. The objectives of this study are (1) to develop the process model including all the above unit processes based on actual design values of the plant, (2) to simulate the performance of plant according to raw water temperature seasonal variation, and (3) to estimate the energy consumption of the plant.

2. Materials and methods

2.1. Experimental system description

The Gijang SWRO desalination plant which has the capacity of 45,460 m^3/day [10 million gallons per day (MIGD)] was selected as a target plant for the development of OTS system. Fig. 2 shows a schematic diagram of Gijang SWRO desalination plant which is divided into two process lines (i.e., 2 MIGD line and 8 MIGD line) to consider all commercially available pretreatment processes in an SWRO desalination plant: DAF with ball filter, UF, pressure type DMF, and cartridge filter (CF) as pretreatment processes and RO process as the two-pass system with high-pressure (HP) pump and ERD [1]. In the case of ERD, a pressure exchange type, DWEER (Flowserve, USA), for the 8 MIGD and a turbo charger type (FEDCO, USA) for the 2 MIGD are employed. Sixteen-inch diameter membranes are used in the RO units. The 8 MIGD of RO unit is the largest capacity among those employing 16 inches of membrane.

2.2. Model development

In this study, SWRO plant unit process models such as DAF, DMF, UF, and RO with ERD are developed based on the mathematical equations based on several references [1–7], which are described as follows (Fig. 3).

2.2.1. DAF unit process

A DAF process separates the floc which are floated by microbubbles (10–100 μm in diameter) from the top of the liquid by a skimmer or a weir. A 10% of the effluent is recycled into the saturator for generating microbubble with pressurized air (around 5 bar). The effluent total suspended solid (TSS) concentration (C_n) is calculated as the below equation [2] with coagulation and flocculation.

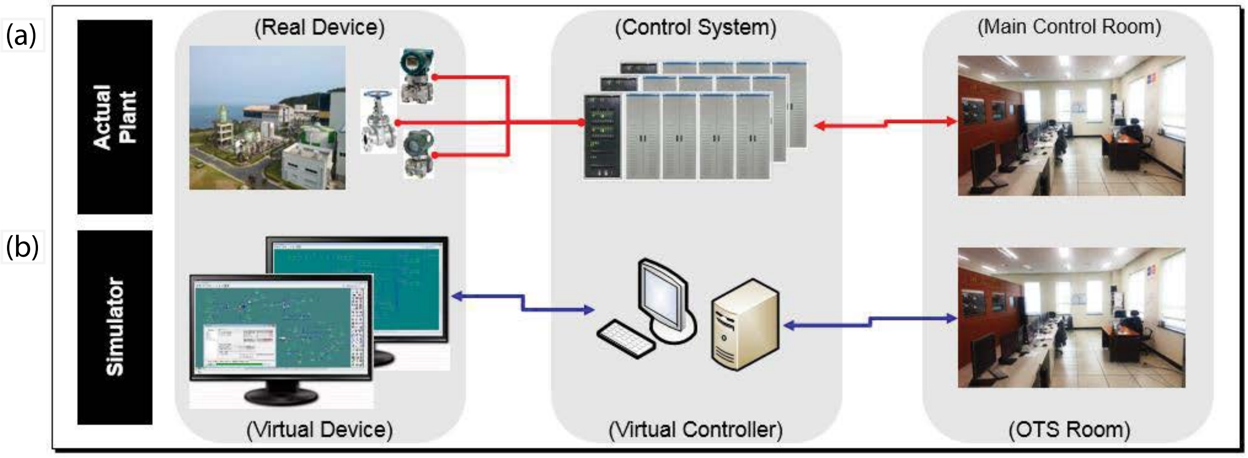

Fig. 1. OTS system configuration: (a) Actual plant and (b) OTS system.

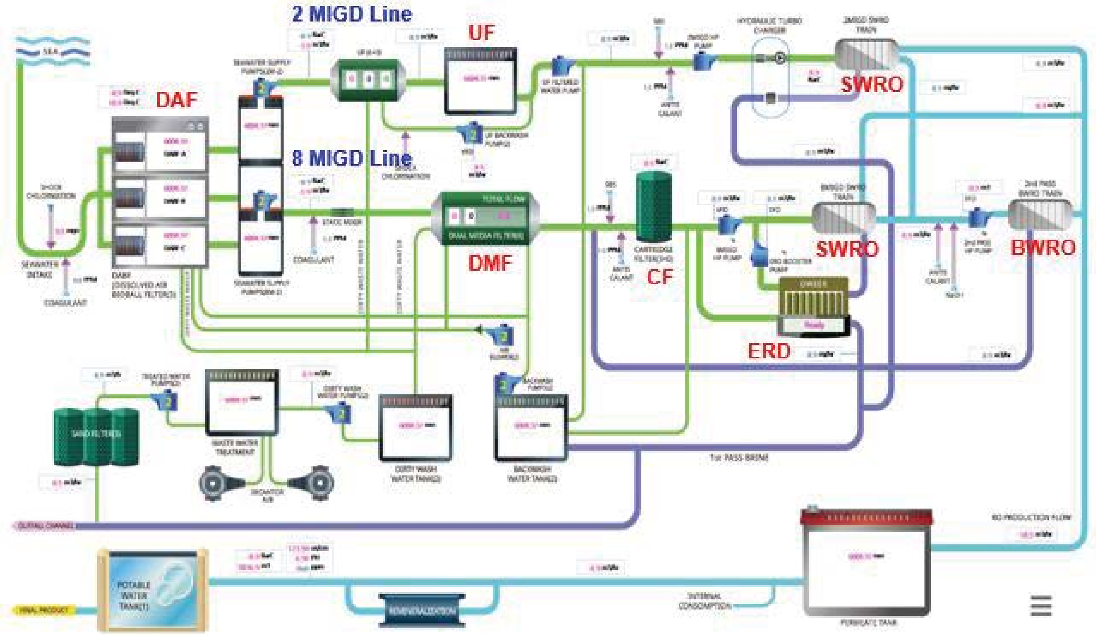

Fig. 2. Schematic diagram of Gijang SWRO desalination plant.

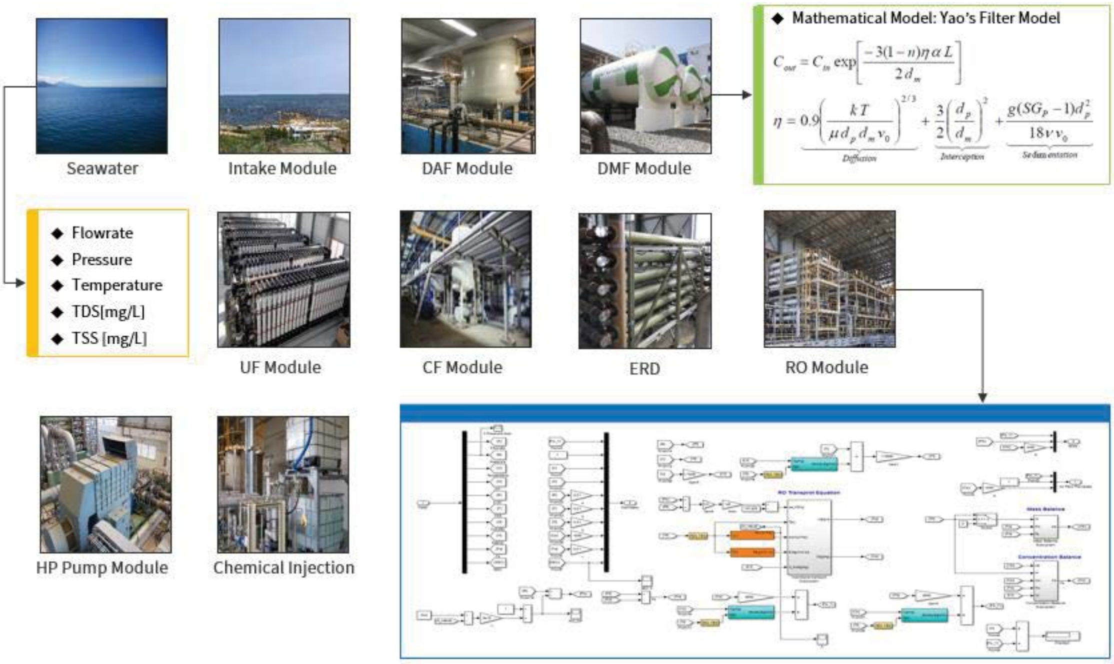

Fig. 3. Unit processes in Gijang SWRO desalination plant.

$$C_n = \frac{K_b C_0 G}{K_a} \tag{1}$$

$$G = \sqrt{\frac{P}{\mu V}} \tag{2}$$

where C_0 is the influent TSS concentration, K_a is the collision constant, K_b is the breakup constant, G is the velocity gradient, P is the power dissipation, μ is the fluid viscosity, and V is the basin volume.

2.2.2. DMF unit process

A DMF process is the conventional pretreatment of an SWRO desalination plant, which mainly removes particles from water through dual granular media (i.e., sand and anthracite coal). The main removal mechanism is the straining process by a size difference between pores and particles but rather depth filtration or an adsorption-like effect using attraction between particles and the filter media due to van der Waals molecular forces. The effluent concentration of DMF can be physically calculated by the Yao filtration model [3].

$$C = C_0 \exp\left[-\frac{3}{2}\left(\frac{(1-\varepsilon)}{d_c}\right)\alpha\eta L\right] \tag{3}$$

where C_0 and C are the influent and effluent particle concentration, respectively, ε is the bed porosity, d_c is the diameter of the spherical collector, α is the sticking coefficient of particles to a collector, η is the single-collector collision efficiency, and L is the length of the column.

Single-collector collision efficiency consists of diffusion, interception, and gravitational sedimentation which are expressed as a function of three dimensionless numbers such as the Peclet number (N_{Pe}), the interception number (N_R), and the gravitation number (N_G).

$$\eta = 4N_{\mathrm{Pe}}^{-2/3} + \frac{3}{2}N_R^2 + N_G \tag{4}$$

$$N_{\mathrm{Pe}} = u^* \times \frac{d_c}{D_p} \tag{5}$$

$$N_R = \frac{d_p}{d_c} \tag{6}$$

$$N_G = \frac{U_p}{u^*} \tag{7}$$

where D_p is the particle diffusion coefficient, d_p is the particle diameter, u^* is the upstream (approach) velocity to the collector, and U_p is the particle settling velocity.

$$D_p = \frac{k_B T}{3\pi\mu d_p} \tag{8}$$

$$U_p = g\left(\rho_p - \rho_f\right)\frac{d_p^2}{18\mu} \tag{9}$$

where g is the gravitational constant, ρ_p is the particle density, ρ_f is the fluid density, and μ is the fluid viscosity.

2.2.3. CF unit process

A CF model is simply developed in the view of pressure drop (different pressure (DP)). There are two types of DP such as an initial DP due to the CF module itself and increased DP due to fouling according to the filtration time.

$$P_{\mathrm{out}} = P_{in} - P_{\mathrm{loss\_i}} - P_{\mathrm{loss\_f}} \tag{10}$$

where P_{out} is the pressure at the outlet of CF, P_{in} is the pressure at the inlet of CF, $P_{\mathrm{loss\_i}}$ is the initial pressure loss, and $P_{\mathrm{loss\_f}}$ is the increased pressure loss.

$$P_{\mathrm{loss\_f}} = \frac{1}{2}\rho\left[\left(\frac{Q}{A_i}\right)^2 - \left(\frac{Q}{A_f}\right)^2\right] \tag{11}$$

$$A_f = A_i e^{-\gamma_c t} \tag{12}$$

where ρ is the density, Q is the flow rate, A_i is the initial filter area, A_f is the fouled filter area, and γ_c is the CF degradation factor.

2.2.4. UF unit process

An UF model is based on the Darcy equation which describes a general flow through a porous medium as a size exclusion. It can be extended to membrane resistance model considering both overall resistance and filtration efficiency. The flux J_v can be described by ref. [4]:

$$J_v = \frac{\Delta P}{\mu\left(R_m + R_f\right)} \tag{13}$$

where ΔP is the transmembrane pressure ($P_f - P_p$), μ is the dynamic viscosity, R_m is the membrane resistance, and R_f is the resistance for cake layer.

The cake layer builds on the membrane surface, and a simple mass balance can be considered in non-steady state indicating the accumulation of particles around the membrane.

$$\frac{dm}{dt} = J_v A_m C_{\mathrm{bulk}} \tag{14}$$

where A_m is the membrane area and C_{bulk} is the TSS concentration.

2.2.5. RO unit process

Balance equations for overall mass, solute mass, and momentum of the process are derived for developing the dynamic process model for spiral wound membrane as the following:

$$\frac{dm_b}{dt} = F_f - F_b - F_m \tag{15}$$

$$\frac{dm_p}{dt} = F_m - F_p \tag{16}$$

where m_b and m_p are the mass in brine and permeate channels, respectively, and t is time. F_f, F_b, F_m, and F_p are the flow rates of feed, brine, membrane, and permeate, respectively.

$$\frac{dC_b}{dt} = \frac{1}{m_b}\left[F_f\left(C_f - C_b\right) - F_m\left(C_m - C_b\right)\right] \tag{17}$$

$$\frac{dC_p}{dt} = \frac{1}{m_p}\left[F_m C_m - F_p C_p\right] \tag{18}$$

where C_f, C_b, C_m, and C_p are the TDS concentrations of feed, brine, membrane, and permeate, respectively.

As an irreversible thermodynamic model, Spiegler Kedem model is used to calculate water (J_w) and solute (J_s) flux as follows [5,6]:

$$J_v = A_t\left(\Delta P - \sigma\Delta\pi\right) \tag{19}$$

$$J_s = B_t\Delta C + \left(1-\sigma\right)\bar{C}J_v \tag{20}$$

where A and B denote water and salt transport coefficients, respectively, ΔP is the transmembrane pressure, $\Delta\pi$ is the transmembrane osmotic pressure, ΔC is the transmembrane concentration, $\bar{C}$ is the arithmetic average of TDS concentration across the membrane, and s is the reflection coefficient determining the degree of coupling between water and solute fluxes.

The osmotic pressure can be determined by the Van't Hoff formula.

$$\Delta\pi = \frac{N_{\text{ion}}}{M_W} R_g T_a C_W \tag{21}$$

where N_{ion} is the number of ion, M_w is the molecular weight, R_g is the universal gas constant, and T_a is the absolute temperature. C_w is assumed 1.6 times of C_{bulk} concentration considering the effect of concentration polarization.

In addition, membrane degradation is modeled using first-order differential equations, where water transport coefficient (A) and salt transport coefficient (B) are the corresponding solutions [7]. The water and salt transport coefficients are dependent on not only temperature but also time variant fouling.

$$A_t = A\left(t\right) = A_1\left(t\right)\exp\left(a_{T_1}\frac{T-T_{\text{ref}}}{T}\right) \tag{22}$$

$$B_t = B\left(t\right) = B_1\left(t\right)\exp\left(a_{T_2}\frac{T-T_{\text{ref}}}{T}\right) \tag{23}$$

where $A_1(t)$ and $B_1(t)$ satisfy the differential equations.

$$A_1\left(t\right) = A_0 e^{-\psi t + \left(\psi-\gamma\right)t_c + \gamma t_r} \tag{24}$$

$$B_1\left(t\right) = B_0 e^{-\psi t + \left(\psi-\gamma\right)t_c + \gamma t_r} \tag{25}$$

where γ and ψ are the membrane performance decay factor and the membrane degradation factor, respectively.

2.2.6. ERD Unit Process

An ERD process is used for recovering HP energy from an RO brine, which reduces a substantial amount of energy consumption of SWRO desalination process [8].

$$F_{\text{isw}} + F_{\text{osw}} = F_{\text{ibr}} + F_{\text{obr}} \tag{26}$$

$$F_{\text{osw}} = F_p\left(\frac{1}{R_m} - 1\right) - \left(F_{\text{ibr}} - F_{\text{osw}}\right) \tag{27}$$

$$C_{\text{osw}} = C_{\text{isw}}\left(1 - R_{\text{mix}}\right) + C_{\text{ibr}}R_{\text{mix}} \tag{28}$$

$$R_{\text{mix}} = \frac{\left(C_{\text{osw}} - C_{\text{isw}}\right)}{\left(C_{\text{ibr}} - C_{\text{isw}}\right)} \tag{29}$$

where F_{isw}, F_{osw}, F_{ibr}, and F_{obr} are the flow rates of seawater-in, seawater-out, brine-in, and brine-out, respectively. F_p is the permeate flow rate, R_m is the recovery rate, and R_{mix} is the mixing rate. C_{isw}, C_{osw}, and C_{ibr} are the ion concentrations of sweater-in, seawater-out, and brine-in, respectively.

Collectively, the entire process model of Gijang SWRO desalination plant was developed through MATLAB & SIMULINK softwares (MathWorks, USA) by combining the individual unit process models constructed in this study. As shown in Fig. 4, the process model is composed of two different process lines: 2 MIGD line (DAF-UF-RO) and 8 MIGD line (DAF-DMF-CF-RO). In addition, DAF system consists of 3 identical units with one saturator, DMF system has 6 identical units, UF system includes 6 trains, and RO system is configured as 2 pass. In this study, individual unit processes are simply connected to an input/output port without considering pipeline, valve, tank, and so on, which cause pressure drop in the process. Then, the design values of the plant are practically applied to the model for simulating performance of the plant.

3. Results and discussions

The raw seawater conditions in Gijang are as follows: total dissolved solids (TDS) of 34,458 mg/L and temperature of 25°C (Table 1). The results of the input parameters of feed flow rate, TDS, and temperature applied into the simulation model are summarized in Table 1. The results obtained from the simulation were highly similar to those of each unit process in Gijang SWRO desalination plant. In the case of permeate production, there was 0.5% difference between the simulated value (1,905 m^3/h) and the design value (1,914 m^3/h) when seawater feed was 4,213 m^3/h. The permeate TDS is simulated as 149.0 mg/L, which is almost identical value with the design value of 149.1 mg//L. It shows the rejection rate of 99.6% from raw seawater of 34,458 mg/L. The minor differences on the performance parameters suggested that the model could be applied to simulate the SWRO plant performance.

The increase of DP in both UF and DMF according to the filtration time (minutes) is shown in Fig. 5. Filtration time of the UF system is normally 30 min, and DP is increased during the operation time. Therefore, it needs periodic backwash (BW) and/or chemically enhanced backwash (CEB) to recover its performance. The reduction of the filtration performance could be due to a membrane fouling caused by the accumulation of foulants on the membrane surface and in the membrane pores. In Fig. 5a, the BW was performed in the simulation when DP approaches the criteria of its DP limit (here, around 1.0 bar) and CEB is applied with chemical when the recovery of DP is not sufficient after BW. Here, CEB is performed after 30 cycles of BW as an operation

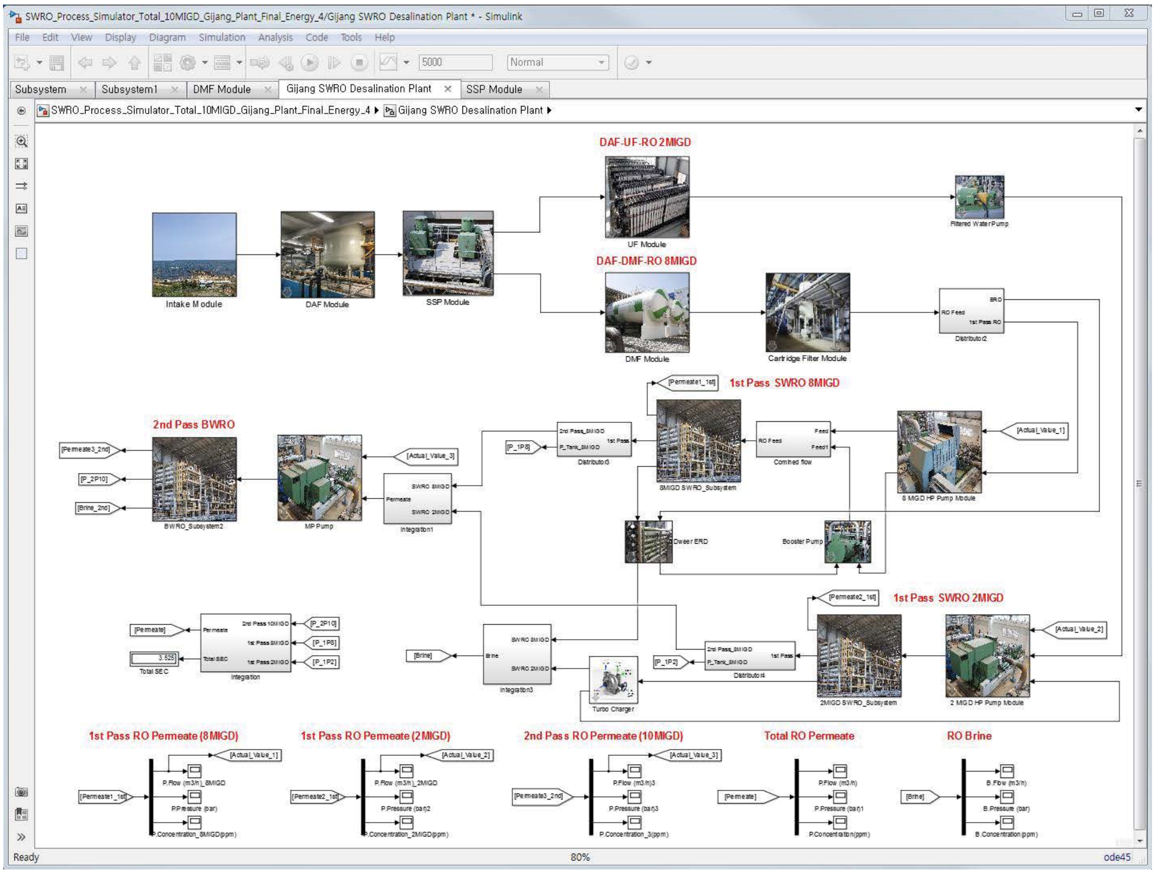

Fig. 4. Gijang SWRO plant process modeling.

Table 1
Simulated results of each position in Gijang SWRO desalination plant

Process position	Flow rate (m^3/h)		Pressure (bar)		TDS (mg/L)	
	Design	Model	Design	Model	Design	Model
Raw seawater	4,213	4,213	0.4	0.4	34,458	34,458
DAF outlet	4,130	4,129	0.4	0.4	34,458	34,458
SSP outlet	4,130	4,129	6.5	6.5	34,458	34,458
UF inlet	890	890	4	4	34,458	34,458
DMF inlet	3,240	3,239	6.2	6.2	34,458	34,458
CF inlet	3,337	3,239	3.5	3.5	34,458	34,458
8 MIGD line 1st RO feed	3,337	3,203	55.1	55.3	34,458	34,458
8 MIGD line 1st RO permeate	1,608	1,600	1.0	1.0	301.2	301.8
2 MIGD line 1st RO feed	835	835	55.1	55.0	34,458	34,458
2 MIGD line 1st RO permeate	402	402	1.0	1.0	302.7	306.1
2nd RO feed	1,070	1,062	13.1	13.7	301.5	302.6
Total permeate	1,914	1,905	1.0	1.0	149.1	149.0

logic. Similar to a UF, a DP in DMF increases according to the operation time and BW is carried out after around 24 hours operation (1,440 min.) to avoid an overlapped BW time of several DMF units as shown in Fig. 5b. Generally, BW based on operation time setting is used in actual plants as an operation control logic.

DP increases of both CF and RO are shown in Fig. 6 with respect to filtration time (hours). Although the lifetime of CF

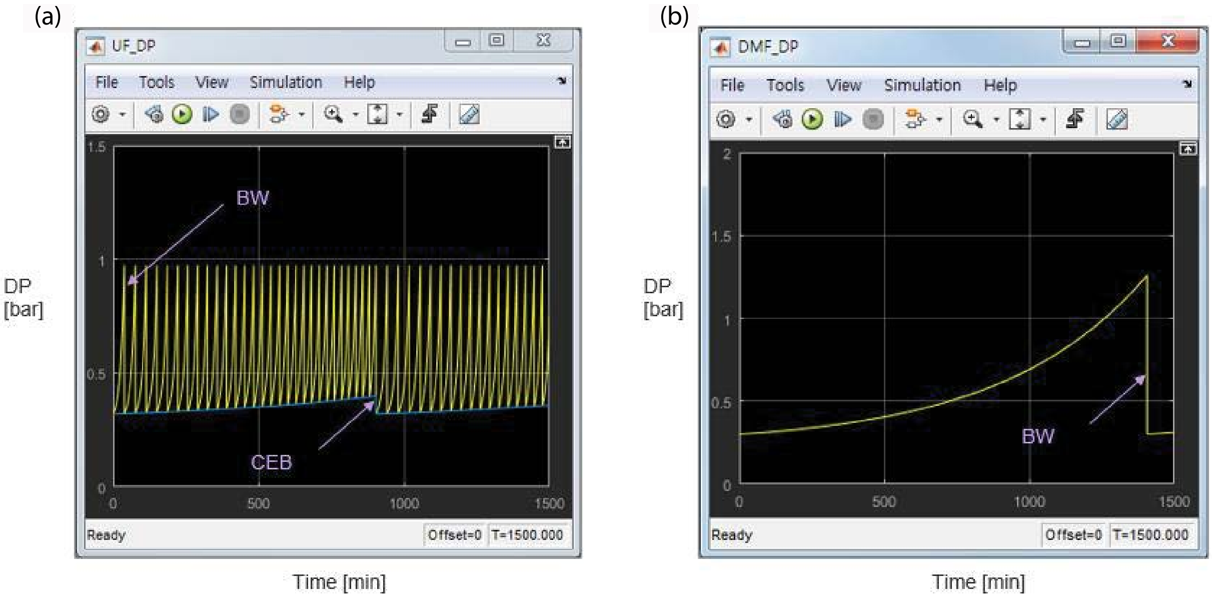

Fig. 5. Simulation results according to filtration time (minutes): (a) UF DP and (b) DMF DP.

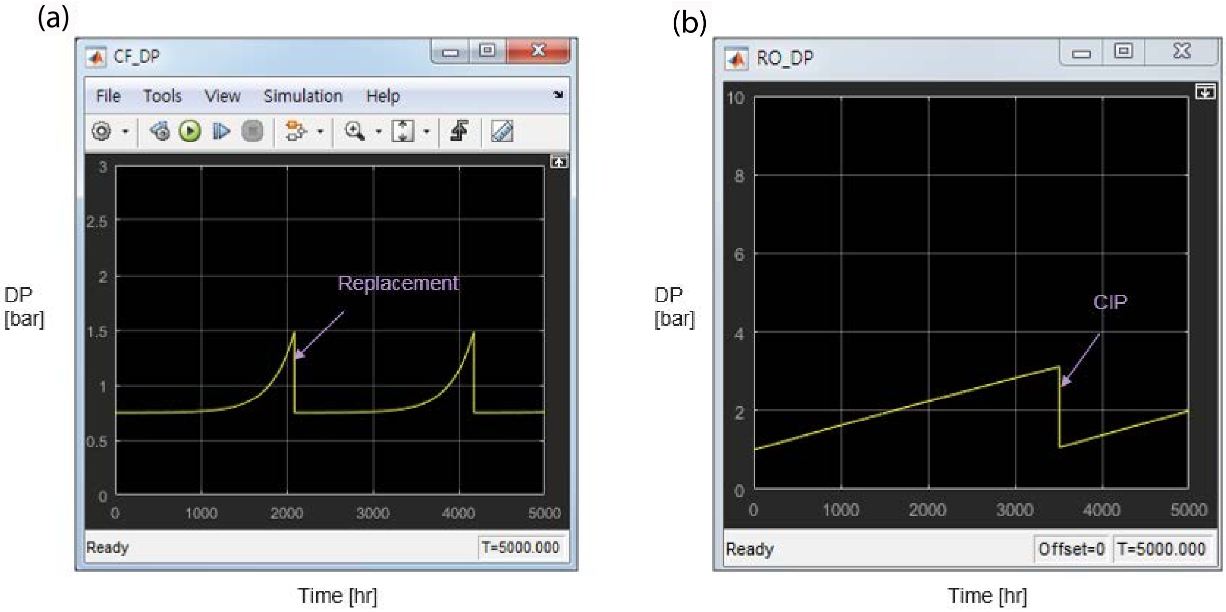

Fig. 6. Simulation results according to filtration time (hours): (a) CF DP and (b) RO DP.

is varied according to the seawater qualities such as TSS and turbidity, it is generally replaced after 3 months operation or when DP of CF reaches 1.5 bar during the filtration (Fig. 6a). On the other hand, DP in RO increases according to the operation time due to membrane fouling such as colloidal, organic, and biofouling. The operating feed pressure should be increased in accordance with the increased DP to produce the same amount of permeate flow rate. Such correlations were successfully demonstrated in the developed model (Fig. 6b). Similar to those of UF, when DP in RO approaches certain criteria (i.e., DP of 3 bar), cleaning in place (CIP) will be performed. However, as CIP is no longer effective to recover performance of RO membrane, a certain portion of RO membranes will be replaced with new membranes.

In addition, Fig. 7 shows the simulation results when the seasonal temperature is varied from 15°C to 25°C for a year. Two times of RO CIP was assumed during the period. As the feed temperature increases, the production will be increased because of the decrease of water viscosity. Therefore, feed pressure can be decreased in order to produce the same amount of permeate. The permeate TDS increases with the increased temperature due to the decrease of salt rejection of membranes. The results are well correlated to the general performance alternation of SWRO

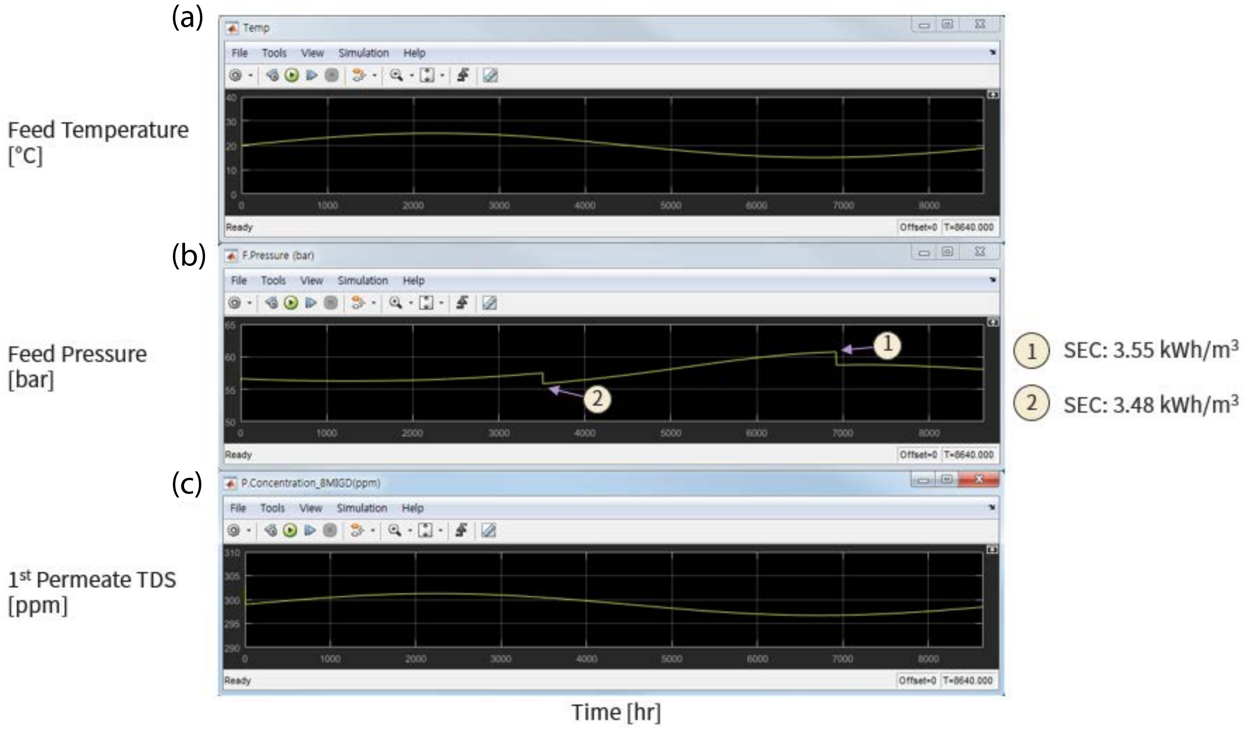

Fig. 7. Simulation results of seasonal variation of feed temperature according to filtration time (hours): (a) Feed temperature; (b) Feed pressure; (c) 1st pass RO permeate TDS.

membranes according to the temperature. Furthermore, the specific energy consumption (SEC) of RO system is simulated as approximately 3.55 kWh/m^3 when the HP is required. The results are similar to the projected SEC of 3.6 kWh/m^3.

The results from the simulation indicate that it could describe overall performances of the SWRO plant. The model developed in this study would be applied for the development of OTS system in Gijang SWRO desalination plant, which enables a cost-effective operator training, and it can further enhance the competitiveness of SWRO desalination O&M PJT.

5. Conclusion

In the study, the dynamic process model including DAF, DMF, UF, and RO with ERD was developed for the high-fidelity OTS system of Gijang SWRO desalination plant. Through this study, the following conclusions have been made:

- The simulation results of the developed process model were well followed to the design values of process flow diagram of Gijang SWRO desalination plant.
- Both the increase of DP and cleaning activities such as BW, CEB, and CIP at DMF, UF, and RO unit process were simulated with a decay rate according to the process time.
- Additionally, it can also predict the performance of the plant according to the seasonal temperature variation of raw seawater.
- As a future study, the developed unit process model in this study will be applied to the detailed process model based on commercial OTS S/W; then, it will be combined with an actual DCS server and VC for the development of the high-fidelity OTS system of Gijang SWRO desalination plant.

Acknowledgements

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