High Recovery System in Seawater Reverse Osmosis Plants

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ABSTRACT: Seawater desalination by the reverse osmosis (RO) method is an energy-saving system compared with the evaporating method, and can perform seawater desalination efficiently. Seawater RO desalination technology has been established and become a reliable system. Seawater desalination plants using RO technology have spread and the scale of the plants has increased significantly. More economical and efficient RO method seawater desalination systems have come to be required. A high recovery system, which offers reduction of plant construction cost and running cost was devised. Towards realization of this high recovery system, simulation and the field tests were done to confirm the practicality. Furthermore, a high recovery system was adopted for the biggest desalination plant in Japan, and it is performing favorably. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 108: 3403–3410, 2008

Key words: reverse osmosis membrane; high recovery; high pressure; field test

INTRODUCTION

Key requirements for the reverse osmosis (RO) membrane modules for successful desalination plants include high salt rejection, resistance to high pressure, durability, and elimination of biofouling. Today the successful spread of these desalination plants using RO modules has progressed and the scale of these plants have become larger and economical efficiency is pursued increasingly. Reduction of the construction costs of a plant and operating costs are key areas for improvement. In view of the entire plant construction, the seawater intake/outfall and pretreatment facility are said to account for 40% of the cost and installation space, and the chemical cost accounts for 20% of running cost.[1] Consequently, cost reduction of these facilities and the reduction of chemical consumption are strongly desired.

Higher recovery of a plant system allows cost reduction in construction and operation. For example, if a recovery is raised from 40% for a conventional system to 60% recovery, the capacity of intake system and pretreatment facility, and the chemical cost, etc. can be decreased to two thirds as shown in Figure 1. In our previous research, we devised the high recovery system, which raised a recovery from 40% to 60% in standard seawater (TDS 35,000 mg/L) and we reported the concept of the system and the test result of a basic experiment using standard seawater in Japan.[2]

In this new research, the simulation that grasps the transport phenomena in RO module and the field tests were performed. On the basis of these results, this high recovery system was applied to the 50,000 m^3/day seawater desalination plant in Japan. Moreover, in order to apply a high recovery system also to the Middle East, which is a huge market of seawater desalination, field test aimed at increasing a recovery from 35% for the conventional system to 50% in Middle East seawater (TDS 43,000 mg/L) was carried out.

EXPERIMENTAL

Field test by standard sea water

Field test equipment was installed in Iwakuni City facing the Setonaikai Sea in Japan. The flow sheet of this test equipment is shown in Figure 2. It consists of a sand filtration, a micro cartridge filter, and a high-pressure pump. $FeCl_3$ as a coagulant was injected before sand filter and chlorine was injected intermittently. Sulfuric acid was injected before the micro cartridge filter to reduce pH to 6.5. The specification of the RO module and operating conditions are indicated in Table I.

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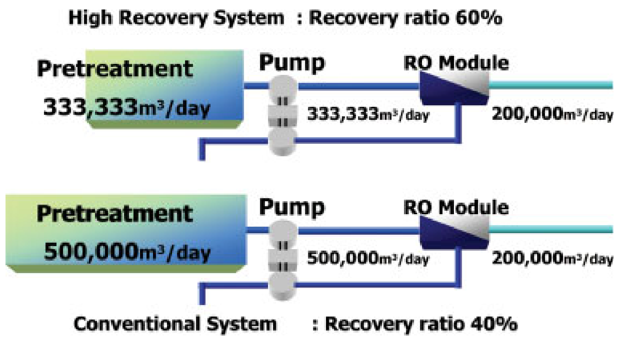

Figure 1 Comparison between high recovery system and conventional system. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE I
Specification of RO Membrane and Operating Conditions (Field Test in Standard Seawater)

Membrane Specification	
Model	HB9155 (TOYOBO)
Material	Cellulose Tri-acetate
Initial product flow rate[a]	14 m^3/day
Initial salt rejection[a]	99.6%
Membrane surface area	430 m^2
Operating conditions	
Feed seawater TDS	35,000 mg/L
Feed seawater temperature	16 – 32°C
Feed pressure	8.2 MPa
Recovery	60%
Product flow rate	20 m^3/day

[a] Feed water (NaCl solution) 35,000 mg/L; Pressure 5.4 MPa; Temperature 25°C, Recovery 30%.

Field test by Middle East sea water

The field test equipment was installed in the Kindasa RO plant at the Jeddah City seaport in Saudi Arabia. The flow sheet of the equipment is shown in Figure 3. Since pretreated seawater of the existing 14,000 m^3/day RO plant was used for this test, the test equipment did not have separate pre-treatment equipment such as sand filter. The capacity of this equipment was larger than that tested in Japan. The RO modules were arranged in two stage brine reject series (1 + 1 array) to simulate the design for a larger capacity desalination plant. The specification of the RO module and operating conditions are indicated in Table II.

RESULTS AND DISCUSSION

Basis of high recovery system

To realize a high recovery system, there are two important points to increase the recovery. One is to increase the pressure resistance of the membrane and module, and the other is to control the increase of a concentration polarization on the membrane surface. Generally a solution diffusion model which is expressed by the following equations can explain the performance of RO module well.[3]

$$J_W = A \times (P - \Delta\pi) \quad (1)$$

$$J_S = B \times \Delta C \quad (2)$$

$$C_P = J_S/(J_W + J_S) \quad (3)$$

$$J_V = (J_W + J_S)/\rho \quad (4)$$

Here, J_W and J_s are the water and salt flux, respectively, A is the pure water permeability coefficient and B is the salt permeability coefficient. P is the feed pressure, and $\Delta\pi$ and ΔC are the osmotic pressure difference and salt concentration difference between the feed and permeated water, respectively. C_P is the salt concentration of permeated water, and ρ is density.

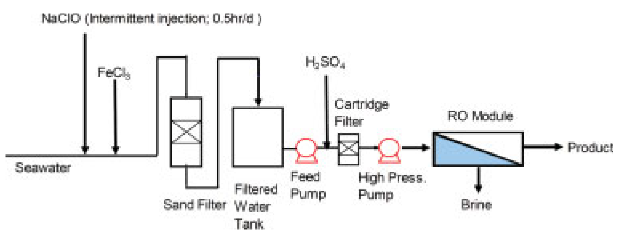

Figure 2 The flow sheet of the test equipment for field test by standard seawater. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

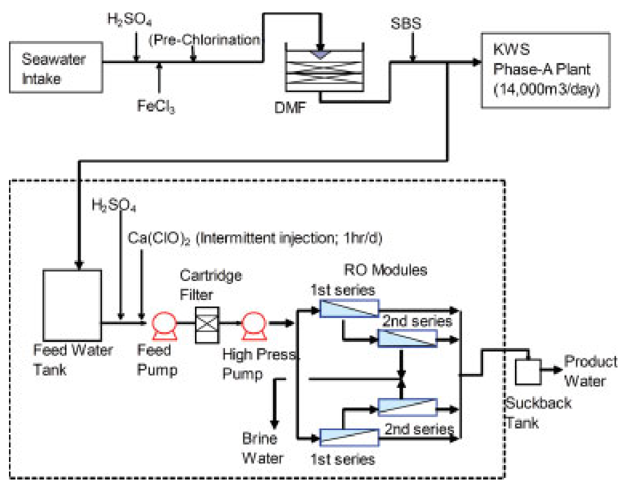

Figure 3 The flow sheet of the test equipment for field test by Middle East seawater. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE II
Specification of RO Membrane and Operating Conditions (Field Test in Middle East Seawater)

Membrane Specification	
Model	HB9155 (TOYOBO)
Material	Cellulose Tri-acetate
Initial product flow rate[a]	14 m^3/day
Initial salt rejection[a]	99.6%
Membrane surface area	430 m^2
Membrane Arrangement	
Number of membranes	4 pcs.
Arrangement	(1+1, Brine reject series) × 2 li
Operating conditions	
Feed seawater TDS	42,500 mg/L
Feed seawater temperature	25 – 35°C
Feed pressure	Max 8.3 MPa
Recovery	45 – 55%
Product flow rate	35 – 40 m^3/day

[a] Feed water (NaCl solution) 35,000 mg/L; Pressure 5.4 MPa; Temperature 25°C, Recovery 30%.

The osmotic pressure π is calculated by the following formula.

$$\pi = \alpha \times C \times T \tag{5}$$

Here, α is osmotic pressure coefficient, C is salt concentration, and T is absolute temperature.

The conceptual diagram of RO module is shown in Figure 4. As shown in the figure, the concentration C_B of the brine is the highest concentration in RO module. The concentration C_B of the brine can be expressed with the following formula from the salt concentration C_F of feed seawater, the salt concentration C_P of the permeated water, and the recovery RC defined by Q_P/Q_F.

$$\begin{aligned} C_B &= (Q_F C_F - Q_P C_P)/Q_B \\ &= (C_F - RC \times C_P)/(1 - RC) \end{aligned} \tag{6}$$

Here, since C_P is very small compared with C_F, if it is neglected, the equation will become the following formula.

$$C_B = C_F/(1 - RC) \tag{7}$$

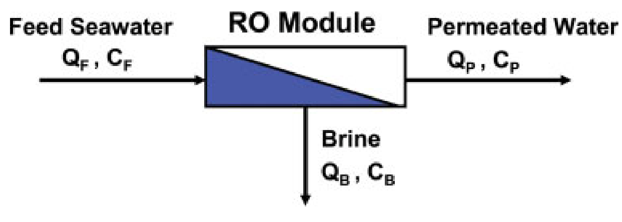

Figure 4 The conceptual diagram of RO module. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

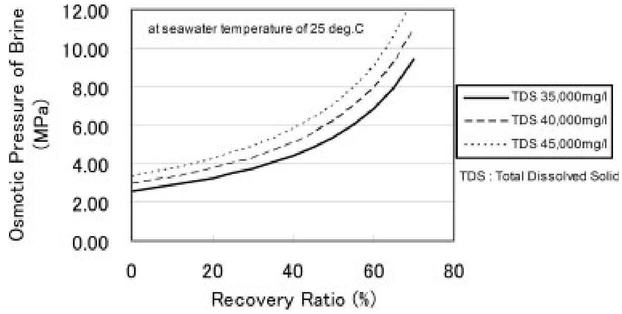

Figure 5 Relationship between Recovery ratio and Osmotic Pressure of Brine.

Formulas (5) and (7) are substituted in formula (1), and the following (8) formula is obtained.

$$J_{WB} = A \times (P - \alpha \times C_F/(1 - RC) \times T) \tag{8}$$

Here, J_{WB} is water flux at the brine.

To cause a reverse osmosis phenomenon, the right side of the equation must be positive. A recovery ratio in case the driving force becomes almost zero is the maximum recovery ratio in feed concentration C_F. It is necessary to increase feed pressure P to make the maximum recovery ratio increase, so that clearly from a formula (8). That is, in order to perform high recovery operation, it is necessary to increase the resistance to pressure of the RO membrane and module. In Figure 5, the recovery ratio is plotted on the horizontal axis and the osmotic pressure of brine is plotted on the axis of ordinate. The osmotic pressure was calculated by ASTM standard (D4516-00).[4] The osmotic pressure of brine at a certain recovery ratio is a guide of the required feed pressure.

Furthermore, by the RO method, concentration on RO membrane surface increases from concentration of bulk solution. The concentration polarization coefficient ϕ expresses this increasing ratio, and is defined by the following formula

$$\phi = (C_m - C_P)/(C_b - C_P) = \exp(J_V/k) \tag{9}$$

where, C_m is the salt concentration on membrane surface, C_b is the salt concentration in bulk solution and k is the mass transfer coefficient.

Since the permeated water C_P is much smaller compared with seawater concentration, if it neglected, seawater concentration on membrane surface will become the following.

$$C_m = \phi \times C_b \tag{10}$$

This formula (10) is substituted for (8) formulas, and the following formula is obtained.

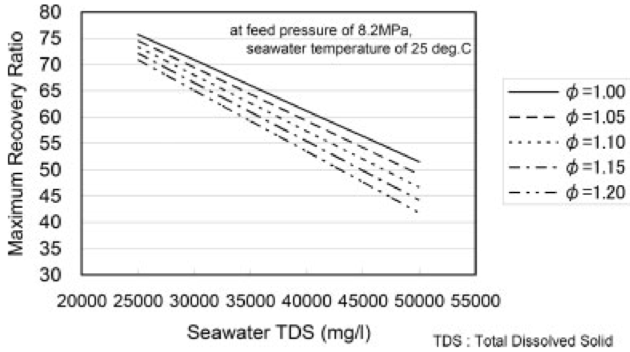

Figure 6 Relationship between Seawater TDS and the maximum Recovery ratio as a function of concentration polarization coefficient ϕ.

$$J_{WB} = A \times (P - \alpha \times \phi \times C_F/(1 - RC) \times T) \qquad (11)$$

That is, if ϕ becomes large, permeated water flow rate will decrease and the maximum recovery will also decrease. The simulation result of taking ϕ as the parameter for the relation between seawater salt concentration and the maximum recovery ratio is shown in Figure 6. And the simulation result of the relation between seawater concentration and the J_W at the brine in the case of the recovery of 60%, is shown in Figure 7. Since J_S is much smaller compared with J_W, salt concentration of permeated water at the brine can be expressed with the following formula.

$$C_P = J_S/J_W = \frac{B \times \phi \times C_F/(1 - RC)}{A \times (P - \alpha \times \phi \times C_F/(1 - RC) \times T)} \qquad (12)$$

If ϕ becomes large, clearly from the formula (12), salt concentration of permeated water will also increase. The simulation result of the relation between the feed seawater concentration and the

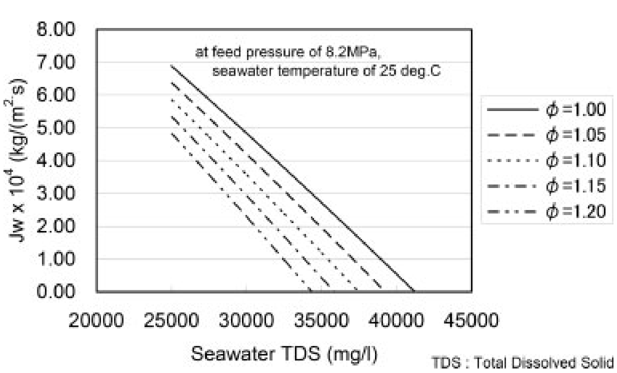

Figure 7 Relationship between Seawater TDS and the J_W at the brine as a function of concentration polarization coefficient ϕ, in case of the recovery ratio of 60%.

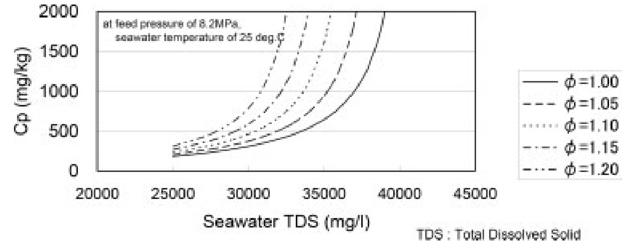

Figure 8 Relationship between Seawater TDS and the C_P at the brine as a function of concentration polarization coefficient ϕ, in case of the recovery ratio of 60%.

permeated water concentration at the brine, in the case of the recovery of 60%, is shown in Figure 8. To realize high recovery operation, it is required to suppress concentration polarization in the moderate range in addition to higher pressure operation. As shown in Figures 6–8, to obtain 60% recovery in standard seawater, it is necessary to control ϕ at least to less than 1.15, and desirably to less than 1.1.

Simulation of concentration polarization coefficient

To judge whether a concentration–polarization coefficient is in the suitable range in high recovery operation, the simulation was carried out. As indicated in formula (9), a concentration polarization coefficient is calculated by $\phi = (J_V/k)$. If J_V is lowered, it is possible to reduce a concentration polarization coefficient. Since the feature of a hollow fiber type RO module is that it can take the large membrane surface area per volume, it can make J_V low. The membrane surface area per volume of the hollow fiber type RO module is about 10 times larger than the spiral wound type membrane, therefore, J_V of hollow fiber type can be lowered to about 1/10 of spiral wound type. In previous work, the authors devised the simulation method of the hollow fiber type RO module.[5,6] It is called the Friction–Concentration–Polarization model, the mass transfer coefficient of a shell side and bore side pressure loss of hollow fiber is also taken into consideration, and the transport parameters of each part of module can be calculated. Distribution of each parameter in a module at the recovery of 60% in the case of standard seawater was calculated using this simulation method. The simulation of two stage brine reject series was performed modeling an actual large-sized plant. The brine from the 1st stage is fed into the 2nd stage module directly. Since the fluid velocity of a shell side of hollow fiber can increase by adopting this system, there is an advantage which can increase a mass transfer coefficient in the high recovery system. The mass transfer coefficient k obtained by our past work is as follows.[4]

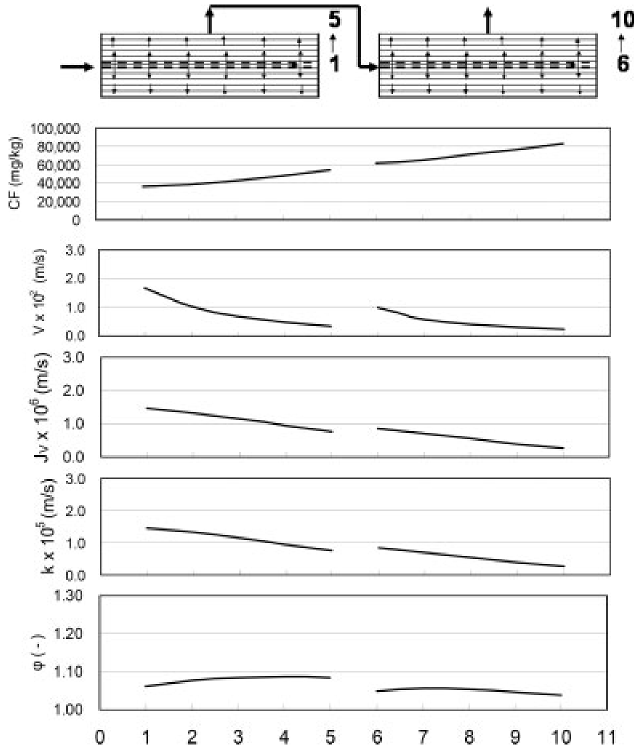

Figure 9 The simulation of two stage brine reject series, distribution of C_F, V, J_V, k, ϕ in RO module, in case of the recovery ratio of 60%.

$$k = 0.048 \times Re^{0.6} \times Sc^{1/3} \times (D/d_O) \qquad (13)$$

Here, Re is Reynolds number, Sc is Schmidt number, D is diffusion coefficient and d_o is outer diameter of hollow fiber.

The simulation result is shown in Figure 9. In this figure, the number of the horizontal axis expresses the position in a module in the direction through which seawater flows. Consequently, seawater is gradually concentrated towards the direction of position 1–10. While concentration increases, the fluid velocity V of a shell side decreases and a mass transfer coefficient k decreases, but in order that J_V will also decrease, it turns out that the concentration–polarization coefficient ϕ always becomes 1.1 or less as shown in the figure. Since the concentration polarization coefficient is 1.1 or less, operation at the recovery of 60% in standard seawater is in a range which can perform efficient operation. Therefore, it is shown that operation of 60% recovery is possible for the result of this simulation in standard seawater.

Moreover, these results show that 60% recovery is a limit in standard seawater at the feed pressure of 8.2 MPa. To make a recovery ratio still higher, it is necessary to increase feed pressure further. Furthermore, if a recovery ratio is made still higher, seawater will be concentrated more and it is estimated that there is possibility of generating of scales in RO module, such as calcium sulfate. From these considerations, it is estimated that with the present technology a recovery ratio maximum is 60%.

Result of field test by standard seawater

To confirm the reliability of high recovery operation in actual standard seawater, the field test of 60% of recovery operation was carried out using the seawater in Setonaikai in Japan.[2] The field test was performed using one RO module instead of two stage brine reject series due to the shortage of capacity of feed seawater. Therefore, it means the operating condition is more severe than the actual large-sized plant assumed in high recovery system. The operating condition of a test plant is shown in Figure 10. As explained in Basis of High Recovery System section, in order to realize high recovery operation, one of the important points is increasing pressure resistance of RO module. An RO module with increased resistance to pressure from 7 to 8.2 MPa was used for this test.[7] The RO membrane consisted of two layers, a skin layer with the function to separate salt, and a support layer which has high pressure resistance. To increase pressure resistance of support layer, the heat treatment process after manufacturing the membrane was improved.

The pressure was adjusted to 8.2 MPa and the recovery was adjusted to 60% during the whole period of testing. The temperature range of the seawater in this period was 17–32°C. Change of the permeate flow rate, the quality of permeated water, and differential pressure are shown in Figure 11. During the operating period of about 6000 hrs, the permeated water flow rate was mainly stable although it decreased a little due to natural compaction. TDS of the permeate water was stable and less than 200 mg/L. The differential

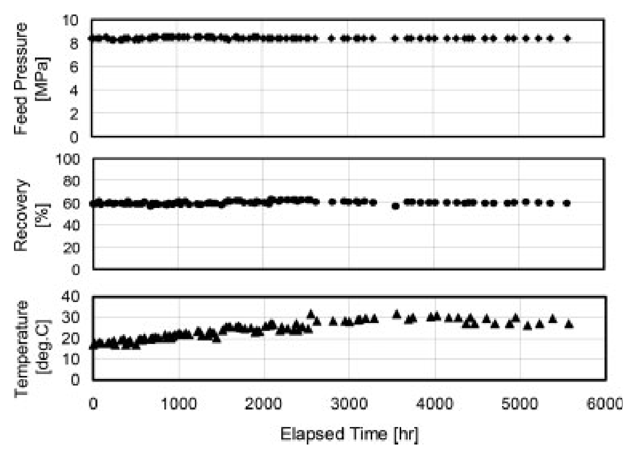

Figure 10 Change of operating conditions in the filed test by standard seawater.

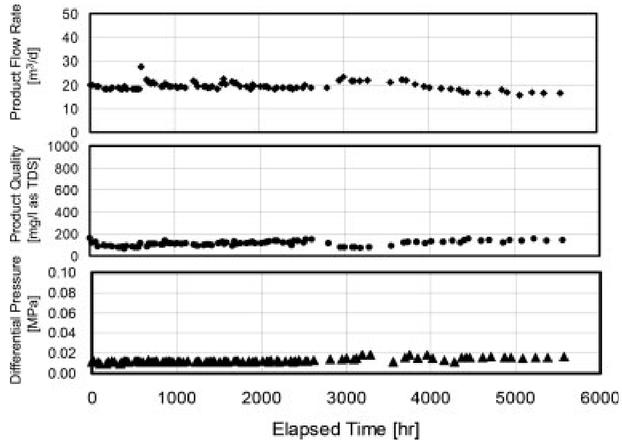

Figure 11 Change of performance in the field test by standard seawater.

pressure was mostly stable without chemical cleaning, although it increased slightly due to natural fouling. After the field test was completed, the used module was disassembled and the fouling substance was analyzed. The main component was shown to be iron as a result of analysis. It is presumed that a small amount of $FeCl_3$ used as a coagulant in pretreatment leaked through the sand filtration as $Fe(OH)_3$, and accumulated little by little in the RO module. Judging from the rate of increase of the differential pressure, it is estimated that chemical cleaning using citric acid is enough in about 1 time/year. Citric acid is suitable for cleaning of iron fouling in RO modules, and is used commonly.

From these results, it was confirmed that operation at 60% recovery in standard seawater is satisfactory.

Result of field test by Middle East seawater

Field testing in Middle East seawater was carried out in order to confirm the high recovery operation using the seawater in Saudi Arabia where seawater concentration and osmotic pressure is high.[8] Since the osmotic pressure is higher than standard seawater, 50% recovery was targeted and experiments were performed at Jeddah City. The two stage brine reject series was performed for consideration of the application in actual large plants. The brine from the 1st stage is fed into the 2nd stage module directly. The operating condition of the test plant is shown in Figure 12. The electrical conductivity of seawater was mostly stable at 57,000 μS/cm, and temperature changed in the 25–36°C range. Although the recovery was set to 48% at the beginning of operation, it was gradually increased to 50% and 53%, and, finally was increased to 55%. The increase of a recovery was set by adjustment of the feed pressure. The feed pressure was increased to 7 Mpa at the recovery of 50%, 7.5 MPa at 53% and 8 MPa at 55%.

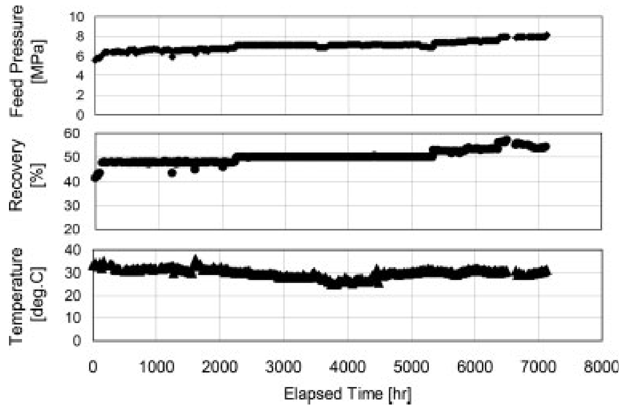

Figure 12 Change of operating conditions in the field test by Middle East seawater.

Change of a permeated water flow rate, the quality of permeated water, and differential pressure are shown in Figure 13. It was confirmed that a permeate flow rate and the quality of product water were stable at each recovery, and stable up to 55% recovery. In addition, differential pressure was also stable, changing less than 0.05 MPa, without chemical cleaning. Incidentally, the differential pressure was higher than the experimental result of standard seawater because a two stage reject series was adopted. After the field test was completed, the used module was disassembled and the fouling substance was analyzed. The main component was iron, like the result of the field test in Japan. Therefore, it is estimated that chemical cleaning using citric acid about 1 time/year is also sufficient in the Middle East seawater.

From these results, it was confirmed that operation at 50% recovery in Middle East seawater is satisfactory.

Application in large-sized plant

As mentioned above, the simulation and the field test were carried out towards realization of a higher

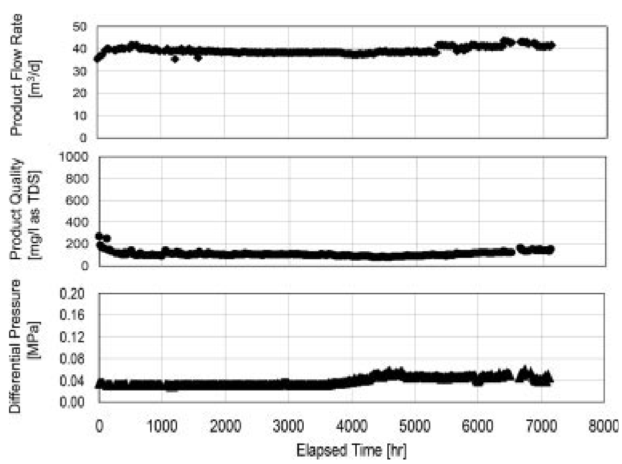

Figure 13 Change of performance in the field test by Middle East seawater.

TABLE III
Plant Specification and Designed Operation Conditions

Plant Specification	
Production capacity	50,000 m^3/day
Seawater TDS	35,000 mg/L
Product water TDS	Less than 200 mg/L
System	
Intake	Infiltration intake
Pretreatment	Ultra filtration
Seawater desalination	High pressure RO
Post treatment	Low pressure RO (Partial 2 pass)
Specification of High Pressure RO System	
Number of Units	5
Product water TDS	Less than 350 mg/L
Designed Operation Conditions of High pressure RO unit	
Seawater temperature	10 – 30°C
Production capacity	11,988 m^3/day per unit at 30°C
	11,988 m^3/day per unit at 10°C
Recovery	62.5% at 30°C
	57.5% at 10°C
Feed pressure	Max. 8.2 MPa
RO membrane	
Model	HD10255 (TOYOBO)
Material	Cellulose Tri-acetate
Initial product flow rate[a]	60 m^3/day
Initial salt rejection[a]	99.6%
Membrane surface area	2000 m^2
Number of membranes	200 pcs. × 5 units (Two stage brine reject series)

[a] Feed water (NaCl solution) 35,000 mg/L; Pressure 5.4 MPa; Temperature 25°C. Recovery 30%.

recovery operation. On the basis of these result, high recovery operation was applied to the Fukuoka plant which is the biggest desalination plant in Japan.[9,10] The outline of the Fukuoka desalination plant is shown in Table III, and photographs are shown in Figure 14. Desalination capacity of drinking water is 50,000 m^3/day and quality of product water is less than 200 mg/L as TDS. To meet the required product water quality, a post treatment system of low pressure RO is installed. Some portion of permeated water of the high recovery seawater RO is treated by post treatment system, and it is blended with permeated water.

Two stage brine reject series was adopted as the high recovery seawater desalination system. The recovery is designed to change with seawater temperature in order to meet required water quality. At the time of the high temperature of summer, it is set as 62.5% recovery, and is set as 57.5% of a recovery at the time of the low temperature of winter so that the average annual recovery is about 60%. In the case of 60% recovery, concentration of brine becomes higher than in the case of conventional 40% recovery ratio. Concentration of brine is about TDS 58,000 mg/L at 40% recovery, and is about TDS 87,000 mg/L at 60% recovery. To minimize the influence that discharge of the high concentration brine has on the environment, brine is discharged to the sea after blending with treated sewage water. Since the amount of treated water of the sewage-treatment plant is about 30,000 m^3/d, and it blends with the 40,000 m^3/d of brine from desalination plant, concentration of brine is diluted to about TDS 50,000 mg/L, and is lower than brine concentration in the case of 40% of a recovery.

Figure 14 Photo of seawater RO modules for high recovery system in Fukuoka desalination plant in Japan (50,000 m^3/d). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

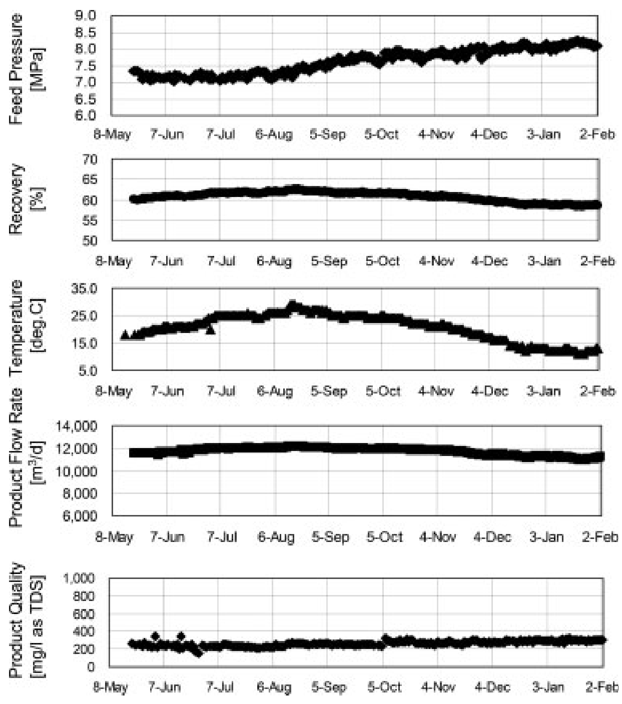

Figure 15 Change of operating conditions and performance of Fukuoka seawater desalination plant in Japan.

The permeated water flow rate also increases as well as increases in the percent recovery at the time of high temperature and decreases at the time of low temperature. This uses the feature that a permeated water flow rate of reverse osmosis membrane will increase when temperature increases. Since permeated water quality of high recovery seawater RO will become good when temperature decreases, the number of operated low pressure RO trains in post treatment system is reduced at the time of the low temperature of winter, and it is designed so that the amount of final product water always becomes 50,000 m^3/day.

Change of the recovery ratio, feed pressure, temperature, product flow rate and product quality are shown in Figure 15. The range of temperature was 13–30°C and the pressure was changing from 7 to 8.2 MPa. The recovery is 57.5% at the lowest temperature in winter and 62.5% in summer in accordance with the plant design described in above.

From the operation results of the actual plant, it has been confirmed that a large-scale plant succeeded in operating satisfactorily with a high recovery, namely 60%, in standard seawater of TDS 35,000 mg/L.

CONCLUSION

A high recovery RO system can reduce construction cost of the pretreatment facilities and chemical consumption in operations. Simulation and actual field tests were carried out towards realization of this high recovery system. From those results, it was confirmed that operation of 60% recovery is possible in standard seawater and 50% in Middle East seawater by applying a pressure of 8.2 MPa. Moreover, it was confirmed that a concentration polarization factor was also in an adequate range. Furthermore, this high recovery system design was applied to the largest desalination plant of 50,000 m^3/day capacity in Japan and operations continue favorably.

It is expected that a high recovery system is adopted in the future in high salt concentration seawater such as the Middle East region as well as standard seawater.

NOMENCLATURE

Symbols

A	pure water permeability coefficient [kg/(m^2 s Pa)]
B	salt permeability coefficient [kg/(m^2 s)]
C	Salt concentration [mg/kg]
D	diffusion coefficient [m^2/s]
d_o	outer diameter of hollow fiber [m]
J_S	salt flux [mg/(m^2 s)]
J_W	water flux [kg/(m^2 s)]
J_v	volume flux [m/s]
k	mass transfer coefficient [m/s]
P	feed Pressure [Pa]
Q	flow rate [m^3/s]
RC	recovery ratio [-]
Re	Reynolds number [-]
Sc	Schmidt number [-]
T	temperature [k]
V	fluid velocity of shell side flow [m/s]
ΔC	salt concentration difference between the feed and permeate at the membrane surfaces [mg/kg]
$\Delta\pi$	osmotic pressure difference between the feed and permeate at the membrane surfaces [Pa]
α	osmotic pressure constant [Pa m^3/kg]
ϕ	concentration polarization factor [-]

Subscripts

B	brine
b	bulk
F	feed
m	membrane surface
P	permeate

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