The Analysis and Design of a Both Open Ended Hollow Fiber Type RO Module

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ABSTRACT: The use of seawater desalination plants using RO technology has spread and the scale of the plants has increased. In such a situation, a larger-sized RO module has been strongly required. The conventional hollow fiber type RO element is a single open-ended (SOE) structure. That is, one side of the hollow fibers in the modules is opened and the other side is closed. In this SOE structure, the increase in the flow pressure loss of the permeated water which flows in the bore side of the hollow fibers prevents development of a large-sized (longer) RO element. In this work, a both open-ended (BOE) element was devised which can reduce the flow pressure loss of the permeated water. It has been confirmed by analysis and experiment that the permeate flow rate of BOE is greater by about 30% than that of SOE. Furthermore, the large-sized RO module with high volume efficiency was designed using the performance analysis method that was confirmed to be applicable to BOE. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 110: 2267–2277, 2008

Key words: reverse osmosis membrane; both open-ended element; performance analysis; large module

INTRODUCTION

Performance requirements for the reverse osmosis (RO) modules for desalination plants include high salt rejection ratio, resistance to pressure, durability, and elimination of biofouling. In addition to these performance requirements, the current growth of larger desalination plants based on the RO method have demanded greater economical efficiency. This efficiency is pursued increasingly toward both lower initial plant construction costs and long-term operating costs. For example, to reduce construction cost of the pretreatment facilities, a high recovery system was developed.[1] In view of the plant construction, the seawater intake/outfall and pretreatment facility are said to account for 40% of the cost and installation space.[2] The capacity of the pretreatment facilities can be decreased to two thirds by increasing the recovery from 40% for a conventional system to 60% recovery. This high recovery system was applied to the largest desalination plant in Japan and is working favorably.[3] Concerning the reduction of operation costs, reduction of energy cost is most effective. It is important to recover energy efficiently from the high-pressure brine discharged by the RO module. In addition to the conventional energy-recovery device, such as a Pellton turbine, the energy-recovery method based on a new concept has been put in practical use.[4]

In this situation, to reduce plant construction costs and operating costs further, a large-sized RO module has been strongly required.[5] By enlarging the RO module, the number of RO modules to be installed can be significantly reduced and additional advantages, such as reducing the number of piping connections to RO modules, and more simple design of the RO unit can be achieved.

An RO module consists of one or more RO elements and a pressure vessel. Since the number of replacement RO elements decreases in the case of large-sized RO module because of less numbers of installed RO modules, maintenance costs can be reduced. Furthermore, the design of the large-sized RO module leads to optimization of its volume efficiency that makes it possible to reduce the footprint of a building and therefore, the construction cost of the RO plant.

There are two methods to make the large-sized RO module, one is to increase diameter of the RO element and the other is to extend the length of the RO element. The developments towards increasing the diameter were progressed by others, and the large diameter elements were put in practical use in a small-sized plant of the 10,000 m^3/d capacity.[6,7] However, the method of increasing a diameter has a

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weak point. If a diameter is increased, since it is necessary to increase thickness of a vessel wall and end plates greatly, the cost of a pressure vessel goes up significantly, especially in the seawater desalination case which needs to be operated at high pressure. On the other hand, in lengthening a pressure vessel, since thickness does not change, the cost of a pressure vessel does not increase so much. Therefore, we conducted development of a large-sized module towards lengthening the RO element.

The conventional hollow fiber type RO element is a single open-ended (SOE) structure. That is, one side of the hollow fibers in the bundle is opened and the other side of fibers is closed. In this SOE structure, the increase in the flow pressure loss of the permeated water which flows down the bore side of hollow fibers prevents development of a large-sized RO element. If the RO element length is extended, the permeated water channels of bore side of hollow fibers become longer and the pressure loss of permeated water will increase and the performance efficiency will drop. Therefore, to obtain greater performance efficiency, the new both open-ended (BOE) element structure was devised.

Since both ends of the hollow fibers are open in the BOE element, even if the element length is the same as the SOE element, the permeated water channel of a hollow fiber bore side is reduced by half, and reduces flow pressure loss. In this work, it is confirmed by experiment that the performance analysis model devised for the analysis of the SOE element could also be applied to a BOE element. The large-sized RO module with high volume efficiency was designed using this performance analysis method.

TABLE I
Specification of RO Module HJ9155

Module specification	
Length of module	2.05 m
Outer diameter of module[a]	0.27 m
Initial product flow rate[b]	34 m^3/d
Initial salt rejection[b]	99.6%
Number of elements	1
Element specification	
Material	Cellulose tri-acetate
Length of element	1.61 m
Outer diameter of element (at Tube-sheet)	0.24 m
Outer diameter of element (at Hollow fiber bundle)	0.22 m
Inner diameter of element	0.04 m
Membrane surface area	870 m^2

[a] Cylindrical body of FRP pressure vessel.
[b] Feed water (NaCl solution) 35 kg/m^3, Pressure 5.5 MPa.
Temperature 25°C, Recovery 30%.

EXPERIMENTAL

Performance tests of BOE and SOE elements

The performance tests of the SOE and BOE were carried out using the same element. The RO module used for the test is the Toyobo HJ9155 type which has one element in one pressure vessel. HJ9155 type is a medium size RO module. The field test with this module was carried out in the Middle East Arabian Gulf and the reliability was confirmed.[8] The specification of HJ9155 is shown in Table I and a schematic drawing is shown in Figure 1(a). As shown in Figure 1(a), both ends of HJ9155 are opened, and each of both ends has a permeated water port. In the test of the BOE, permeated water was taken out from the port of both ends, and the total of the permeate flow rates from both ends was the permeate flow rate as a module. Water quality was the average of the water quality of the permeated water obtained from both ports.

In the SOE test using the same module tested by BOE, one permeated water port was closed by a blind plug as shown in Figure 1(b). The permeated water was taken out only from one permeated water port and the permeate flow rate and water quality were measured. To perform comparison with the analysis, the operating conditions were changed and the performance was measured. The feed water pressure was set as 5.5, 6.0, 6.5, and 7 MPa levels, and the recovery showing the percentage of a permeate flow rate to feed water flow rate was changed to 30, 40, and 50% levels. The temperature of the feed water was controlled at 25°C, using the sodium chloride solution adjusted to 35 kg/m^3 as feed water.

RESULTS AND DISCUSSION

Performance analysis of BOE hollow fiber membrane

The structures of conventional SOE and newly developed BOE are shown in Figure 2. In the SOE structure, only one end of the hollow fibers is open, the opposite end is closed. In the manufacturing process of a hollow fiber type RO module, both ends of hollow fibers are once bonded by resin. In the SOE structure, the surface of the resin layer of one side is cut and an end of hollow fibers is made to open. In the BOE structure, both resin layer ends are cut to open both ends of hollow fibers.

In hollow fiber RO membrane, seawater flows through the shell side of hollow fibers, and water permeates into the bore side through the wall of hollow fibers. Since the flux of the water to permeate is very small and is about 4×10^{-7} m/s, the permeated water flow rate which flows through the bore side of a hollow fiber is small as about 3×10^{-10} m^3/s. However, since the bore of a hollow

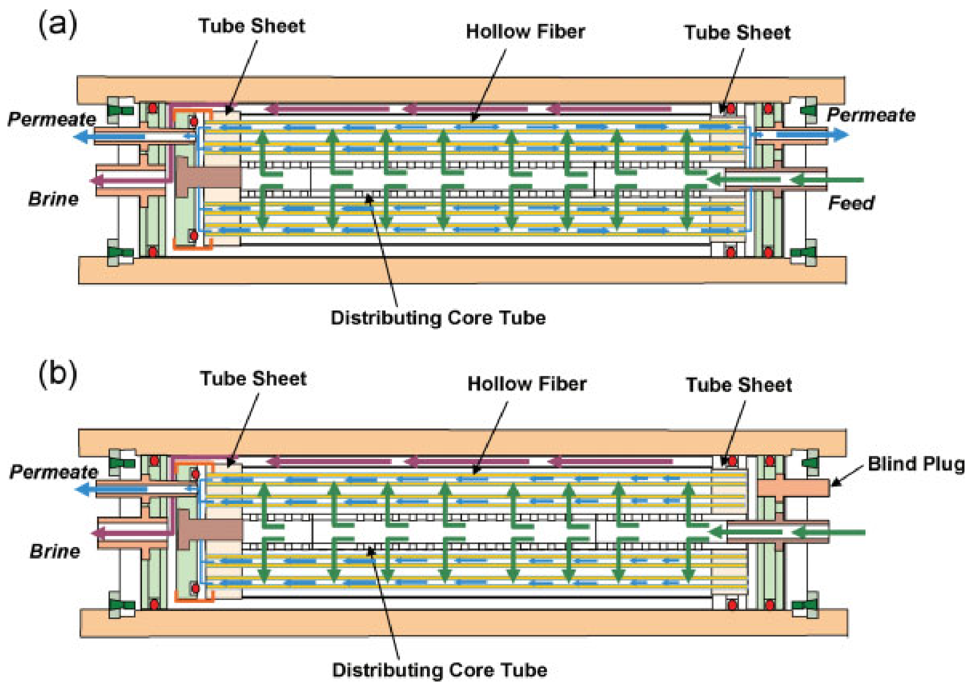

Figure 1 Schematic drawings of RO module HJ9155 for BOE (a) and for SOE (b). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

fiber is as small as 53 μm and hollow fiber length generally exceeds 1 m, the flow pressure loss becomes large in the SOE structure.

In the BOE structure, since both ends are open, even if hollow fiber length is the same, the channel length of the permeated water which flows through the bore side of a hollow fiber becomes half, and flow pressure loss is reduced. A simple calculation method of pressure loss of bore side of hollow fiber and the effect which it has on permeated water flux is explained below.

Generally, the solution diffusion model can explain the performance of RO module.[9] The solution diffusion model can express the permeated water flux J_W and salt flux J_S by the eqs. (1) and (2) shown below.

$$J_W = A(\Delta P - \Delta\pi) = A\left[(P_F - P_P) - (\pi_F - \pi_P)\right] \quad (1)$$

Here, A is a pure water permeability coefficient, P_F is feed seawater pressure at shell side of hollow fiber, P_P is a permeated water pressure at bore side of hollow fiber, π_F is an osmotic pressure of the feed seawater, and π_P is an osmotic pressure of permeated water.

$$J_S = B\Delta C = B(C_F - C_P) \quad (2)$$

Here, B is a salt permeability coefficient, C_F is a feed seawater concentration, C_P is a permeated water concentration. The volume flux J_V which added salt flux J_S to J_W can be expressed as follows.

$$J_V = (J_W + J_S)/\rho_P \quad (3)$$

The Hagen-Poiseuille equation can be applied to the flow pressure loss in bore side of hollow fiber from the analysis result of Hermans, Orofino and Sekino.[10–12]

$$\frac{dP_P}{dz} = \frac{128 \cdot \mu_P \cdot Q_P}{\pi \cdot d_i^{\,4}} \quad (4)$$

Here, μ_P is viscosity of permeated water, Q_P is permeated water flow rate, d_i is inner diameter of hollow fiber and z is axial coordinate.

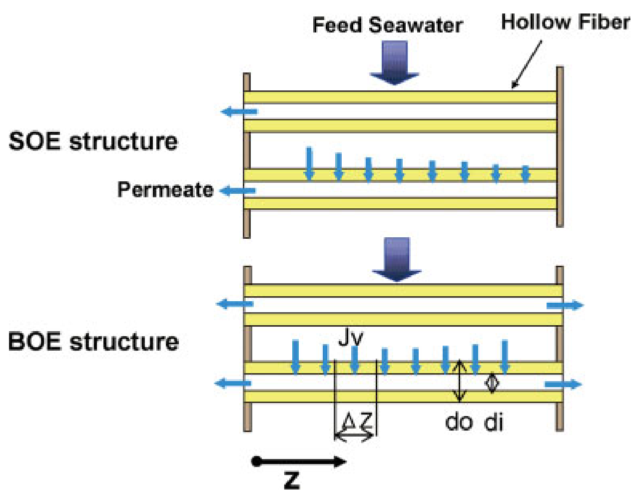

Figure 2 Comparison between single open-ended (SOE) and both open-ended (BOE) hollow fiber membrane. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

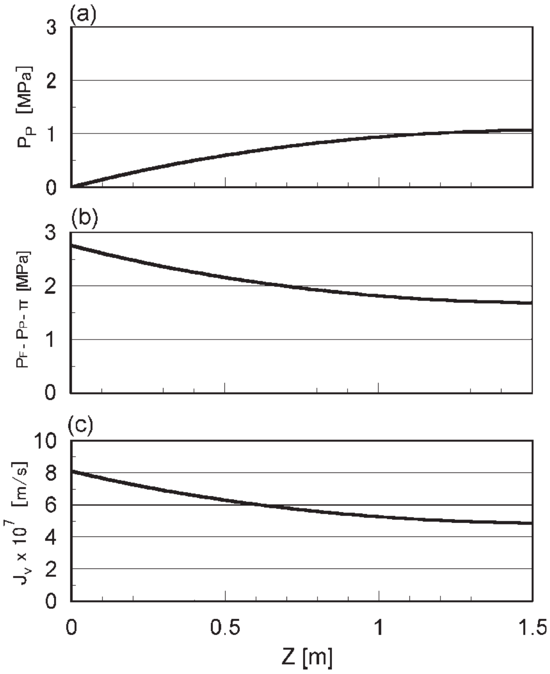

Figure 3 Profiles of permeated water pressure (a), driving force (b) and flux (c) in single open-ended (SOE) hollow fiber membrane (P_F = 5.5 MPa, C_F = 35 kg/m^3, T = 25°C).

The mass balance equation in a hollow fiber is as follows.

$$\frac{dQ_P}{dz} = \pi \cdot d_O \cdot J_V \tag{5}$$

The eq. (5) is substituted for the differentiated eq. (4), and the following equation is obtained.

$$\frac{d^2 P_P}{dz^2} = \frac{128\mu_P}{d_i{}^4} \cdot d_O \cdot J_V = \frac{128\mu_P}{d_i{}^4} \cdot d_O \cdot \frac{J_W + J_S}{\rho_P} \tag{6}$$

Here, a boundary condition is $P_P = 0$ at $Z = 0$.

Since J_S is much smaller compared with J_W, J_S can be neglected in this simple calculation method. Besides, in the eq. (1), since π_P which is an osmotic pressure of permeated water is much smaller than π_F of feed seawater, π_p can be neglected. Therefore, in the simple calculation, the eq. (6) will become the following eq. (7).

$$\frac{d^2 P_P}{dz^2} = \frac{128\mu_P \cdot d_O}{d_i{}^4 \rho_P} \cdot A(P_F - P_P - \pi_F) \tag{7}$$

In the SOE structure, an eq. (7) is applicable for the full length of a hollow fiber. In the BOE structure, the center of hollow fiber length is assumed to be equivalent to the closed end of hollow fiber in the SOE structure, namely, the hollow fiber length is assumed to be half. The remaining hollow fiber portion becomes symmetrical with the half length hollow fiber portion that was calculated.

The calculation results obtained by the calculus of finite differences are shown in Figures 3 and 4. In the calculation, the hollow fiber was divided equally in the direction of z of the length direction. Figures 3(a) and 4(a) show the profiles of permeated water pressure in bore side of hollow fiber. Figures 3(b) and 4(b) show the profiles of $P_F - P_P - \pi_F$ which expresses a driving force in the eq. (1). Figures 3(c) and 4(c) show the profiles of J_V. In this calculation, the full length of the hollow fiber was assumed 1.5 m which is the general length of Toyobo hollow fiber type RO modules. Other conditions are shown in Table II.

In the SOE structure, as clearly shown in Figure 3(a,c), it turns out that the permeated water pressure at the end which the hollow fiber closed exceeds 1 MPa, and J_V decrease greatly by the effect of high permeated water pressure. In the BOE structure, as shown in Figure 4(a,c), although permeated water pressure becomes the maximum in the central part of full length, the pressure does not exceed 0.4 MPa. Therefore, the average of J_V of BOE becomes higher compared with that of SOE.

From these results, it was predicted that the BOE structure can bring out the more efficient performance of a hollow fiber compared with SOE structure.

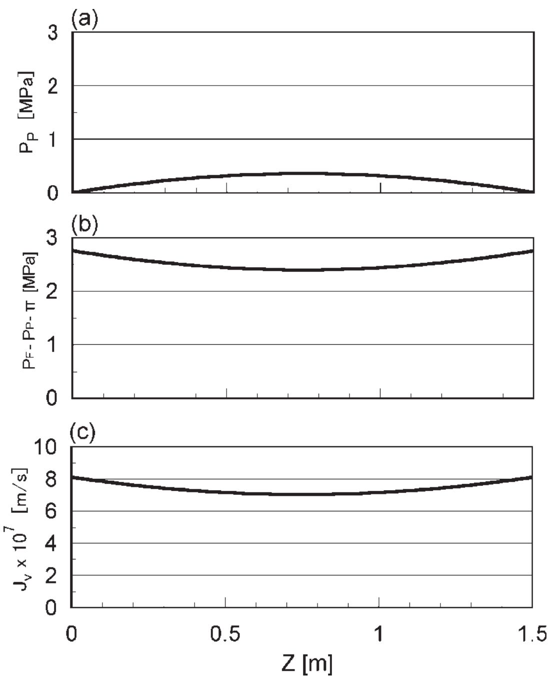

Figure 4 Profiles of permeated water pressure (a), driving force (b) and flux (c) in both open-ended (BOE) hollow fiber membrane (P_F = 5.5 MPa, C_F = 35 kg/m^3, T = 25°C).

TABLE II
Specification of Hollow Fiber and Other Conditions Used in the Calculation of Results in Figures 3 and 4

Hollow fiber specification	
Outer diameter of hollow fiber	1.37×10^{-4} m
Inner diameter of hollow fiber	5.3×10^{-5} m
Pure water permeability coefficient, A	3.0×10^{-10} kg/(m^2 s Pa)
Salt permeability coefficient, B	1.3×10^{-9} m/s
Conditions	
Feed pressure	5.5 MPa
Feed concentration (NaCl solution)	35 kg/m^3
Temperature	25°C
Length of a hollow fiber	1.5 m

Performance analysis method of BOE element

The aforementioned analysis method is a simplified method and can be applied for the hollow fiber membrane. However, the performance analysis method of RO element which bundled one million or more hollow fibers becomes more complicated. The schematic diagram of BOE element system is shown in Figure 5. The seawater pressurized by the high pressure pump is distributed in the radial direction in an element from the distributing core tube set in the element central part. Supplied seawater is separated into permeated water and a nonpermeated concentrate in the process distributed in the radiation direction. Permeated water flows into bore side of hollow fibers, passes through the bore in hollow fibers, and is discharged from both ends. On the other hand, a concentrate flows through the space between hollow fibers, and is discharged via the annular channel between hollow fiber bundle and the pressure vessel. Seawater is gradually concentrated in the process which flows radially, and pressure loss is also generated in the process which flows through the outside of hollow fibers.

We devised the analysis model called a friction-concentration-polarization model (FCP model) for the SOE structure hollow fiber module by previous study and reported it in detail.[12–15] Performance analysis of the BOE element was conducted by using this analysis method of SOE element as a base. Since the details of the FCP model were already reported, an outline is shown below.

The solution diffusion model used in the analysis of one hollow fiber in the preceding section was applied to the basis of the analysis of RO module performance. However, as shown in the upper right in Figure 5, concentration polarization phenomena by which salt is concentrated at membrane surface, should be taken into consideration. The concentration polarization factor ϕ can be expressed by the following equation.

$$\phi = \frac{C_M - C_P}{C_B - C_P} = \exp(J_V/k) \tag{8}$$

Here, C_B is a salt concentration of bulk solution, C_M is a salt concentration at membrane surface. The mass transfer coefficient k in the right side of the equation can be expressed by the following equation.

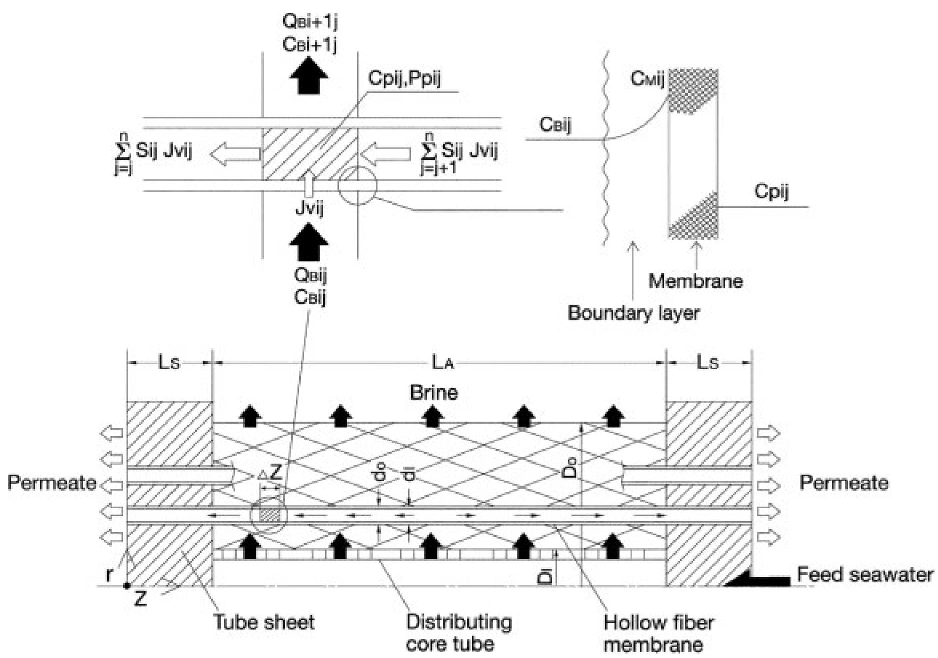

Figure 5 Schematic diagram of both open-ended (BOE) module.

$$Sh = \frac{kd_O}{D} = Sh(Re, Sc) \quad (9)$$

Here, d_O is outer diameter of a hollow fiber and D is diffusion coefficient.

The following equation have been obtained from the experimental result in Toyobo hollow fiber RO modules.[5]

$$Sh = 0.048 \cdot Re^{0.6} \cdot Sc^{1/3} \quad (10)$$

Therefore, mass transfer coefficient k can be calculated by the following equation.

$$k = 0.048 \cdot Re^{0.6} \cdot Sc^{1/3}\ (D/d_O) \quad (11)$$

J_W and J_S expressed by eqs. (1) and (2) become the following equations when the increase of salt concentration at the membrane surface is taken into consideration.

$$J_W = A\left[(P_B - P_P) - (\pi_M - \pi_P)\right] = A\left[(P_B - P_P) - \alpha\phi(C_B - C_P)\right] \quad (12)$$

$$J_S = B(C_M - C_P) = B\phi(C_B - C_P) \quad (13)$$

Here, the pressure P_B at the shell side of hollow fibers is a pressure which deducted the pressure loss generated when seawater flows through a hollow fiber bundle from feed seawater pressure. α is an osmotic pressure constant and the osmotic pressure π is calculated by $\pi = \alpha C$.

Salt concentration C_P of permeated water is calculated by the following formula.

$$C_P = \frac{J_S}{J_V} \quad (14)$$

Besides, Ergun equation is applied for concerning the flow pressure loss of a hollow fiber bundle.[16]

$$\frac{dP}{dr} = \frac{150(1-\varepsilon)^2}{\varepsilon^3} \cdot \frac{\mu_B}{(1.5d_O)^2} \cdot V_S + \frac{1.75(1-\varepsilon)}{\varepsilon^3} \cdot \frac{\rho_B}{(1.5d_O)} \cdot V_S^2 \quad (15)$$

Here, ε is void fraction, μ_B is viscosity of bulk solution, V_S is superficial velocity, ρ_B is density of bulk solution and r is radial coordinate.

As shown in Figure 5, analysis was done by dividing into a certain number equally in the hollow fiber length direction (Z), and dividing into a certain number equally in the radial direction (r) of a hollow fiber bundle. In the upper left graph in Figure 5, subscript "i" shows the i-th division portion in the radial direction and subscript "j" shows the j-th division portion in the length direction. S is a membrane surface area.

In Figure 5, the both ends of an element bonded by resin are called the tube sheet. Since a tube sheet portion (L_S) does not contact seawater, RO phenomenon does not occur, but the flow pressure loss in a hollow fiber is generated. In the portion of L_A, RO phenomenon occurs and flow pressure loss is also generated. In analyzing the simultaneous equations of the aforementioned mathematical model, the numerical-analysis method by calculus of finite differences was used. In the analysis of BOE, the element length is assumed to be a half, same as the analysis method for a hollow fiber in the preceding section. Performance distribution of the remaining portion is symmetrical with the calculated performance of the half length of the element.

Analysis and experimental result of BOE and SOE element

To judge whether the FCP model devised for the analysis of a SOE element is also applicable to a BOE element, the RO performance obtained by the using the actual element was compared with the analysis result of SOE and BOE, and validity was evaluated.

Analysis result of BOE and SOE element

The analysis of HJ9155, which is a single element of BOE, was carried out. The specification of HJ9155 is shown in the Table I. In this analysis, the element was divided into 10 equally in the hollow fiber length direction, and 10 in the radial direction. An analysis result is shown in Figure 6. Distribution of P_P, J_V, and C_P in the length direction (z) at the fifth division portion from an inner side, mostly at the middle portion in the radial direction is shown in Figures 6(a,b,c) as a sample of the analysis result. In SOE, the left-hand side of the Figure 6 is open end, and right-hand side is closed end. As shown in Figure 6(b), J_V in BOE is large and flat compared with that in SOE. In addition, as shown in Figure 6(c), permeated water concentration C_P is better quality compared with SOE result. It is clear that these results are due to the low permeated water pressure in BOE as shown in Figure 6(a).

Experimental result of BOE and SOE element

HJ9155 which is a single element of BOE structure was used for the test. To eliminate the error by the individual differences of element performance, SOE and BOE were tested using the same element. In the examination of BOE, the module was evaluated as it

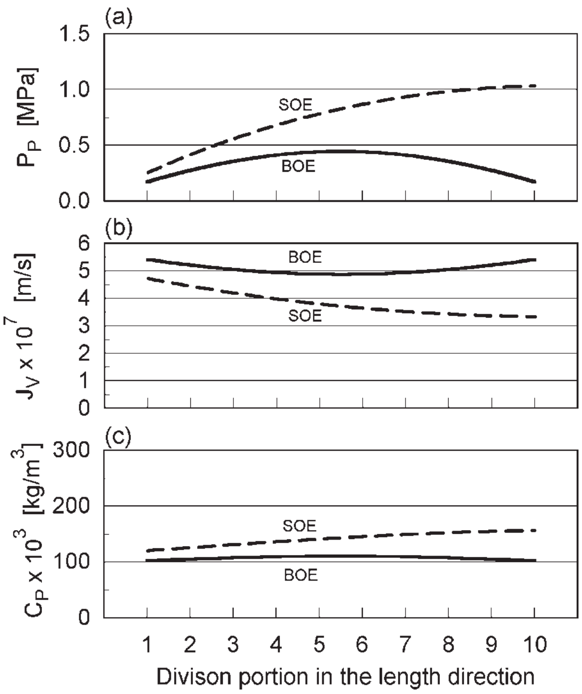

Figure 6 Typical profiles of permeated water pressure (a), flux (b) and permeated water concentration (c) in single open-ended (SOE) and both open-ended (BOE) module (Module = HJ9155, P_F = 5.5 MPa, C_F = 35 kg/m^3, RC = 30%, T = 25°C).

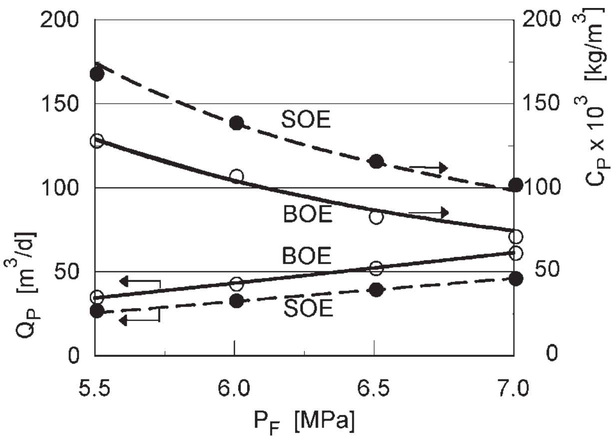

Figure 7 Comparison of both open-ended (BOE) with single open-ended (SOE) in relationship between feed pressure, and permeated water flow rate and concentration (Module = HJ9155, C_F = 35 kg/m^3, RC = 30%, T = 25°C).

was. In SOE, one permeated water port was closed by a blind plug, and thus permeated water was taken out only from one permeated water port. The relation between a permeated water flow rate (Q_P) and the feed pressure, and the relation with permeated water concentration (C_p) are shown in Figure 7. The lines are results of analysis and the plots are experimental values. In both BOE and SOE, the simulation values and the experimental values are in good agreement. In addition, it turns out that the permeate flow rate of BOE is larger by about 30% compared with SOE. Besides, it was confirmed in the analysis and the experiment that permeated water concentration of BOE is lower by about 25% compared with SOE.

The analysis and experimental result concerning a relation of RO performance and a recovery are shown in Figure 8. Clearly from the result of Figures 7and 8, the permeated water flow rate and quality of BOE are much better than SOE, and the capability of hollow fibers is realized more efficiently in BOE. Finally, it was confirmed that the FCP model devised for the performance analysis of SOE can be used for the analysis of BOE.

Design of large-sized RO module for seawater desalination

The scale of seawater RO desalination plants are increasing rapidly. To reduce construction costs of a plant and maintenance costs, enlargement of the RO module has been required. However, it is difficult to lengthen the element length of SOE due to the increase of bore side pressure loss of permeated water flow. Since bore side pressure loss can be reduced in BOE, it has the possibility of enlargement of an element and a module by increasing the length. Therefore, the optimal design of the large-sized RO module was carried out.

As for the conventional largest Toyobo RO element with SOE structure, outside diameter was 0.28 m and length was 1.35 m. RO module consists of a pressure vessel which bears the feed pressure of 7–8.4 MPa and two elements inserted in it. In the simulation of optimization, the outside diameter of the element was fixed to 0.28 m and only the length of the element was changed. The specification of the hollow fiber used for the simulation and the

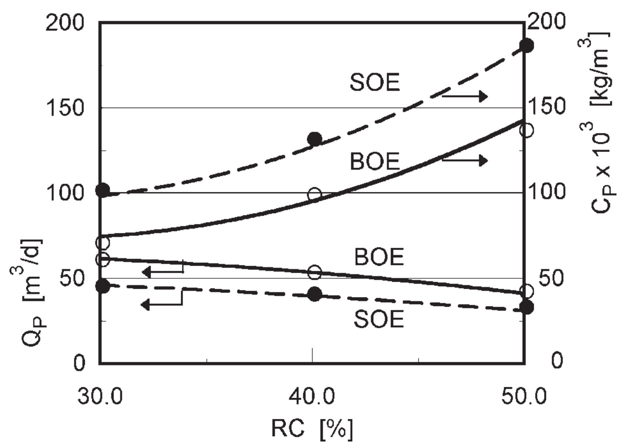

Figure 8 Comparison of both open-ended (BOE) with single open-ended (SOE) in relationship between recovery, and permeate water flow rate and concentration (Module = HJ9155, P_F = 7 MPa, C_F = 35 kg/m^3, T = 25°C).

TABLE III
Specification and Dimensions of Hollow Fiber and Large-Sized Element Used for RO Module Simulation

Hollow fiber specification	
Outer diameter of hollow fiber	1.37×10^{-4} m
Inner diameter of hollow fiber	5.3×10^{-5} m
Pure water permeability coefficient, A	3.0×10^{-10} kg/(m^2 s Pa)
Salt permeability coefficient, B	1.3×10^{-9} m/s
Element specification	
Outer diameter of element (at Tube-sheet)	0.28 m
Outer diameter of element (at Hollow fiber bundle)	0.26 m
Inner diameter of element	0.08 m
Length of tube-sheets	0.16 m

specification of an element are shown in Table III. The outside diameter of the hollow fiber is 137 μm and the bore diameter is 53 μm. Concerning the element, the outer diameter of a tube-sheet part is 0.28 m, but the outside diameter of hollow fibers layer is 0.26 m, and the inner diameter is 0.08 m. The FCP model that was confirmed applicable to BOE was used for the simulation.

The relation between element length and a permeated water flow rate is shown in Figure 9. In SOE, when element length exceeds 2 m, even if element length is lengthened, the permeated water flow rate hardly increases. It is because the bore side pressure of permeated water flow increases and the net driving force decreases. Although a membrane surface area increases by lengthening an element, it is canceled by reduction in driving force. On the other hand, in BOE, in the range of 3.5 m of element length, a permeate flow rate increases as element length becomes greater.

The relation between element length and permeated water salt concentration is shown in Figure 9. Permeated water salt concentration increases as element length becomes long in both cases of BOE and SOE. However, the degree of the increase is remarkable in SOE case. Judging from Figure 9, it was confirmed that the element length of more than 3 m can be used in BOE.

However, the degree of increase of a permeated water flow rate decreases as the element length becomes longer. Therefore, the simulation which considered volume efficiency was carried out. The volume of an element is calculated based on the outer diameter of the tube-sheet part of an element, and the permeate flow rate divided by the element volume (V_{EL}) is shown in Figure 10. When element length is short, efficiency is low because tube-sheet part does not contribute to RO performance. In a tube-sheet part, hollow fibers are bonded by resin, and do not contact seawater. For example, in case element length is 0.5 m, since 0.16 m of both ends

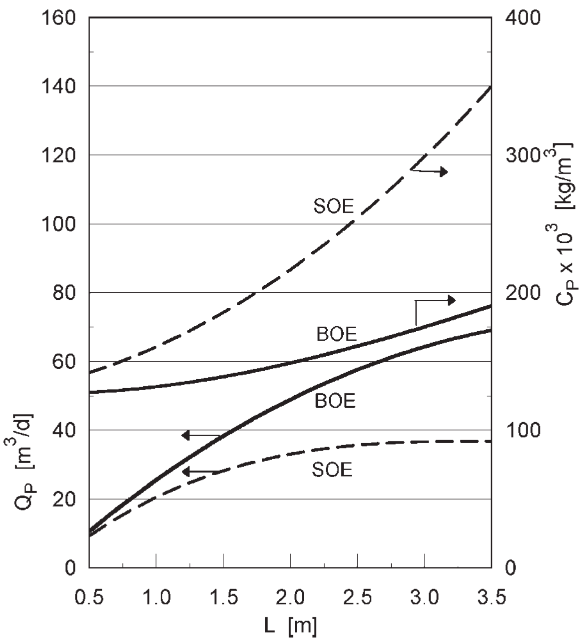

Figure 9 Relationship between hollow fiber length, and permeate water flow rate and concentration in single open-ended (SOE) and both open-ended (BOE) element (D_O = 0.28 m, P_F = 5.5 MPa, C_F = 35 kg/m^3, RC = 30%, T = 25°C.

does not contribute to RO performance, effective element length is 0.34 m. As shown in Figure 10, it turns out that efficiency has a maximum at the element length of about 0.9 m in SOE and about 1.25 m in BOE.

Although about 1.25 m is the optimal length as taking the volume efficiency of only an element into consideration, the volume efficiency of RO module in which the pressure vessel is also taken into consideration is more important in the actual RO plant. Therefore, optimization of the volume efficiency of

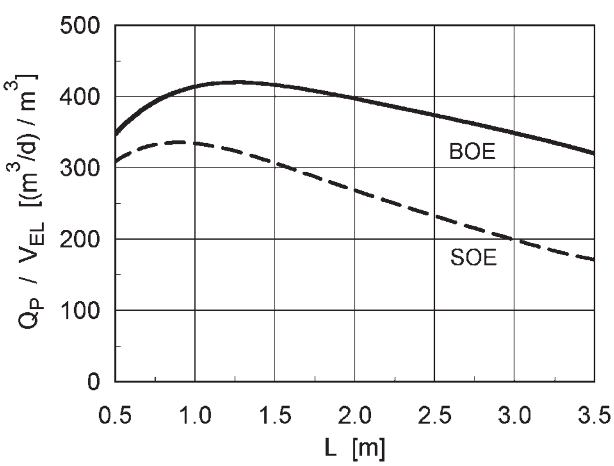

Figure 10 Relationship between element length and volume efficiency of element in single open-ended (SOE) and both open-ended (BOE) element (D_O = 0.28 m, P_F = 5.5 MPa, C_F = 35 kg/m^3, RC = 30%, T = 25°C.

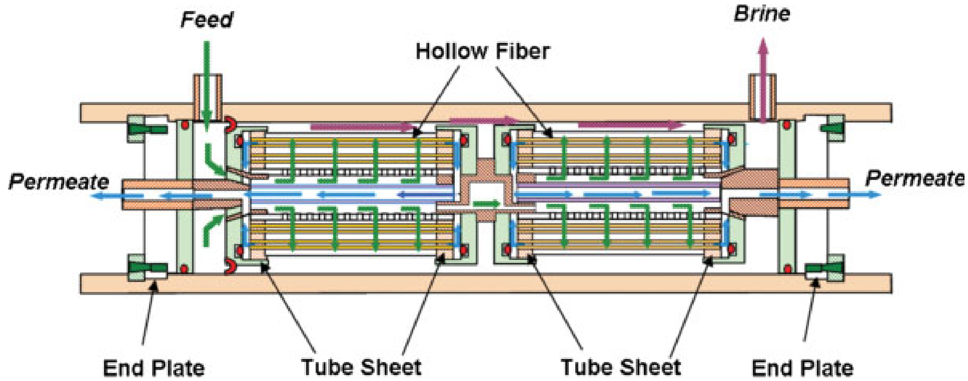

Figure 11 Schematic drawing of large-sized both open-ended (BOE) RO module. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

RO module which equips two elements which are a standard of a Toyobo large-sized module was considered. As for a pressure vessel, the resistance to pressure of 7–8.4 MPa is required for the working pressure range of the RO module, depending on the specification of a desalination plant. Generally, the material of the cylindrical body is FRP and the material for end plates is metal, such as stainless steel and aluminum. End plates are thick to bear a high pressure. Besides, shearing stress is also generated in FRP fixing the end plates which receive a load. Therefore, to bear the stress, sufficient length is required for the distance from a fixing point of an end plate to the end of FRP cylindrical body.

The schematic drawing of a side port type BOE RO module is shown in Figure 11. In the case of a side port, a space is also necessary between an element and an end plate. Therefore, in consideration of the aforementioned required length, the final length of the RO module is a sum of about 0.8 m and the length of two elements. For example, when the length of RO element is 1.25 m, the length of RO module becomes 3.3 m.

The RO module volume efficiency was calculated by dividing the permeated water flow rate of two elements by the RO module volume (V_{MO}) using the outside diameter of 0.32 m of the cylindrical body. The result is shown in Figure 12. As for element length, a maximum appears in nearly 1.3 m in SOE case. In case of BOE, since a maximum point is not sharp, it can be said that it is between 1.5 and 2 m. Considering the construction cost of a plant, the module with a large permeated water flow rate can reduce the required number of modules, and can reduce piping cost. Therefore, the module with high volume efficiency and a large permeated water flow rate is the most efficient. From this viewpoint, the length of the new BOE type element for a large-sized module was determined as 2 m. Module specification is shown in Table IV. The permeated water flow rate of the BOE module is about 100 m^3/d. Alternatively, the permeated water flow rate per element is

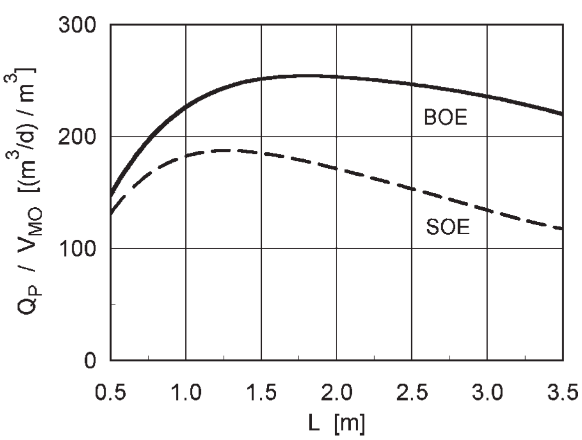

Figure 12 Relationship between element length and volume efficiency of module in single open-ended (SOE) and both open-ended (BOE) element (D_O = 0.28 m, P_F = 5.5 MPa, C_F = 35 kg/m^3, RC = 30%, T = 25°C).

TABLE IV
Specification of Large-Sized RO Module (HU10255)

Module specification	
Length of module	4.80 m
Outer diameter of module[a]	0.32 m
Initial product flow rate[b]	100 m^3/d
Initial salt rejection[b]	99.6%
Number of elements	2
Element specification	
Material	Cellulose tri-acetate
Length of element	2.00 m
Outer diameter of element (at Tube-sheet)	0.28 m
Outer diameter of element (at Hollow fiber bundle)	0.26 m
Inner diameter of element	0.08 m
Membrane surface area	1400 m^2

[a] Cylindrical body of FRP pressure vessel.
[b] Feed water (NaCl solution) 35 kg/m^3, Pressure 5.5 MPa.
Temperature 25°C, Recovery 30%.

about 50 m^3/d, and is twice the flow rate of a conventional-type element. In periodical element replacement, since the number of the element replaced compared with a conventional type becomes half, not only a construction cost but a maintenance cost can be reduced.

The new large-sized RO module which is equipped with a BOE type element will be used for the 205,000 m^3/d Rabigh seawater desalination plant and the 240,000 m^3/d Shuqaiq plant in Saudi Arabia.[17] Operations will be started in 2008 and 2010, respectively.

CONCLUSIONS

The BOE element, a new structure which reduces the flow pressure loss of the permeated water which flows through the bore side of a hollow fiber, was successfully devised. It was confirmed by basic experiments that the FCP model established for the performance analysis of SOE can be also applied to BOE. The permeate flow rate of BOE is greater by about 30% compared with SOE and the permeated water concentration of BOE is lower by about 25% compared with SOE. Furthermore, the large-sized RO module with high volume efficiency was designed using a performance analysis method.

These large-sized RO modules containing BOE element structures are already planned to be used in huge seawater desalination plants which have capability to produce water capacity of more than 200,000 m^3/d in Saudi Arabia. Further use of these highly volume efficient RO modules is expected to meet future needs for desalination plants in the Middle East.

NOMENCLATUTRE

Symbols

A	Pure water permeability coefficient [kg/(m^2 s Pa)]
B	Salt permeability coefficient (m/s)
C_B	Salt concentration of bulk solution (kg/m^3)
C_F	Feed seawater concentration (kg/m^3)
C_M	Salt concentration at membrane surface (kg/m^3)
C_P	Permeated water concentration (kg/m^3)
D	Diffusion coefficient (m^2/s)
D_O	Outer diameter of element at tube-sheet (m)
d_i	Inner diameter of hollow fiber (m)
d_o	Outer diameter of hollow fiber (m)
J_S	Salt flux [kg/(m^2 s)]
J_W	Water flux [kg/(m^2 s)]
J_V	Volume flux (m/s)
k	Mass transfer coefficient (m/s)
P_F	Feed seawater pressure (Pa)
P_P	Permeated water pressure (Pa)
P_B	Pressure at the shell side of hollow fiber (Pa)
Q_P	Permeated water flow rate (m^3/s)
r	Radial coordinate (m)
RC	Recovery (%)
Re	Reynolds number (-)
S	Membrane surface area (m^2)
Sc	Schmidt number (-)
Sh	Sherwood number (-)
T	Temperature (°C)
V_{EL}	Element volume (m^3)
V_{MO}	Module volume (m^3)
V_S	Superficial velocity (m/s)
z	Axial coordinate (m)

Greek letters

α	Osmotic pressure constant (Pa m^3/kg)
ΔC	Salt concentration difference, $C_F - C_P$ (kg/m^3)
ΔP	Pressure difference, $P_F - P_P$ (Pa)
$\Delta\pi$	Osmotic pressure difference, $\pi_F - \pi_P$, (Pa)
ε	Void fraction (-)
ϕ	Concentration polarization factor (-)
μ	Viscosity (Pa s)
π	Osmotic pressure (Pa)
ρ	Density (kg/m^3)

Subscripts

B	bulk
F	feed
i	i-th division portion in the radial direction
j	j-th division portion in the length direction
M	membrane surface
P	permeate

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