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Power generation with salinity gradient by pressure retarded osmosis using concentrated brine from SWRO system and treated sewage as pure water

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ABSTRACT

Salinity power generation using hollow fiber modules was examined using the pressure-retarded osmosis (PRO) system between pure water and concentrated brine. Pure water and concentrated brine were supplied from a regional sewage treatment facility and sea water desalination (sea water reverse osmosis [SWRO]) plant. To minimize the effect of the concentration polarization near the membrane surface on the pure water side, the number of open ports in the module was increased from 3 to 4 and that modification was found to be effective because non-permeating pure water, which left the module through fourth port, flushed leaked salt from the brine side through the membrane. Our prototype PRO plant got the maximum output power density, 7.7 W/m^2 at a 2.5 MPa hydraulic pressure difference and a 38% permeation of pure water into the brine. To remove the organic foulant in the pure water, a low pressure Reverse Osmosis (RO) membrane and coagulation–sedimentation method with ozonation showed good results. However, the pressure drop across the RO membrane itself and cost concerns have not yet been solved. Based on the pure water's flow simulation, the hollow fiber element was found not to effectively work if the module and element for the SWRO were used without modification because the flow pattern of pure water and brine inside the module and element during the PRO operation was different from that during the RO operation.

Keywords: Pressure retarded osmosis; Concentrated brine; Hollow fiber module; Treated sewage; Fouling; Concentration polarization

Introduction

Water shortage is one of the toughest problems that human beings have ever faced. More than one billion people, i.e. more than 15% of the world population, cannot access safe drinking water, and more than two billion people are living without proper sanitation conditions [1]. Based on this situation, more and more pure water is made from sea water. Among some procedures to desalinate saline water, reverse osmosis (sea water reverse osmosis [SWRO]) is one of the promising methods and the number of SWRO plants which have a production scale of more than several hundred thousand cubic meters per day is

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rapidly increasing worldwide. Although the SWRO is a method of lower cost and less energy, concentrated brine released from that plant sometimes causes environmental problems.

In this article, pressure-retarded osmosis (PRO) is focused on as a process that could recover energy from the salinity difference between the concentrated brine and pure water and, simultaneously, as a candidate to solve the environmental problem caused by the SWRO brine released back into the sea.

PRO was proposed by Loeb et al. some 40 years ago [2–5]. They conducted experiments of the PRO process at the Dead Sea in Israel [4] and the Great Salt Lake in the USA [5], where both concentrated saline and fresh water were available. Their results were not very good because these experiments employed semi-permeable membranes that were not for forward osmosis, but for SWRO.

Recently, some research teams are studying the process to recover salinity gradient power, especially in Europe. Statkraft AS, a Norwegian energy company, has built the first prototype PRO plant. They use semi-permeable membranes in a flat sheet spiral wound configuration, sea water as the saline water and river water as the pure water [6]. WETSUS, a research team in the Netherlands, is studying the energy recovery using selective ion exchange membranes and sea water as the saline water [7].

In Japan, Kyowakiden Industry Co., Ltd., has built a prototype PRO plant in Fukuoka, Japan, and is conducting fundamental and operational research with the cooperation of Kyushu University, Nagasaki University and Tokyo Institute of Technology.

In this study, their challenge to analyze and overcome big issues like concentration polarization and membrane fouling, that are the most difficult in a membrane process, is summarized and discussed.

Theory

Principle of PRO

An outline of osmotic processes is shown in Fig. 1. When a semi-permeable membrane is put between the brine and pure water, water molecules move across the membrane into the brine side (Fig. 1(a)). This process is called forward osmosis. The hydraulic pressure ΔP applied on the brine side to prevent fresh water from migrating to the saline side is called osmotic pressure $\Delta \Pi$ (Fig. 1(c)). In the case of $\Delta \Pi < \Delta P$, the water in the brine is filtered into the fresh water side, and this is reverse osmosis used for desalination (Fig. 1(d)). In PRO, the pressure applied to the brine

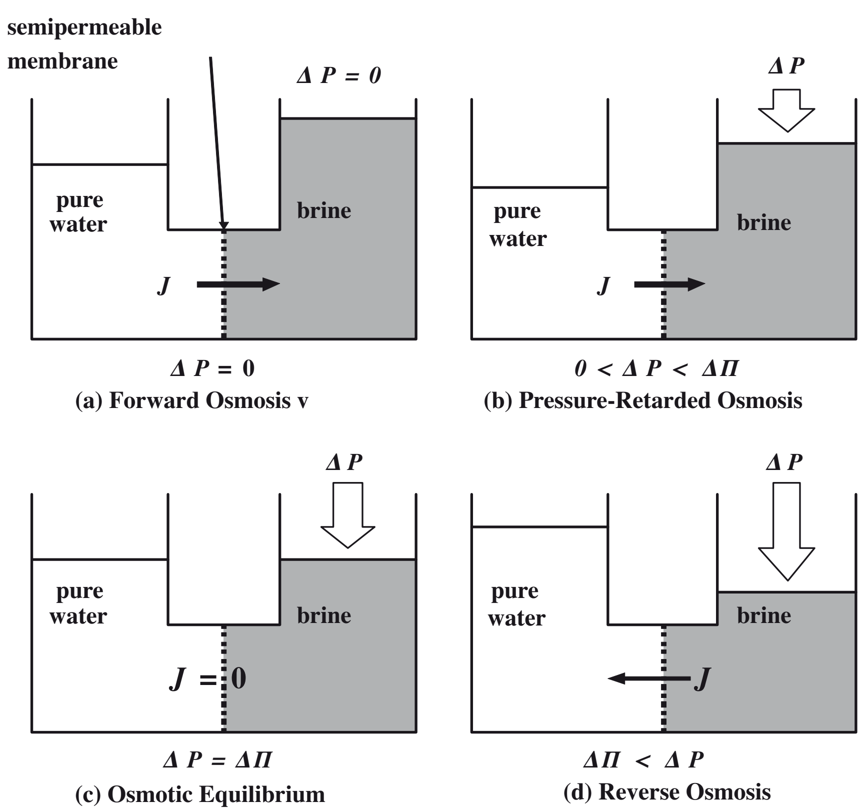

Fig. 1. Schematic representation of osmotic process.

side is lower than the osmotic pressure, and the water permeates into the brine side against the hydraulic pressure ΔP (Fig. 1(b)).

Net power and mechanical effectiveness

The relation between the water permeate rate (ΔV) and the applied pressure is described by Eq. (1).

$$\Delta V = AS(\Delta \Pi - \Delta P) \tag{1}$$

where A is the water permeation coefficient of the membrane, S is the membrane area, $\Delta \Pi$ is the osmotic pressure difference across the membrane, and ΔP is the hydrostatic pressure difference across the membrane.

Net power (W_{net} = generated power − expended power) is calculated from the pressure and flow rates using Eq. (2) [8],

$$W_{net} = \Delta P \Delta V \cdot ME \tag{2}$$

where ME is the mechanical effect.

If ME can be assumed to be 1, which is the ideal case, Eq. (2) can be written as Eq. (3)

$$W_{net}^{ideal} = \Delta P \Delta V \tag{3}$$

Finally, Eq. (1) is put into Eq. (3), and then

$$\begin{aligned} W_{net}^{ideal} &= \Delta P \cdot AS(\Delta \Pi - \Delta P) \\ &= -AS \cdot \Delta P^2 + AS \cdot \Delta \Pi \cdot \Delta P \\ &= \frac{1}{4} AS \cdot (\Delta \Pi)^2 - AS(\Delta P - \frac{1}{2}\Delta \Pi)^2 \end{aligned} \tag{3'}$$

From Eq. (3′), W_{net}^{ideal} is found to be a maximum value when $\Delta P = \frac{1}{2}\Delta \Pi$.

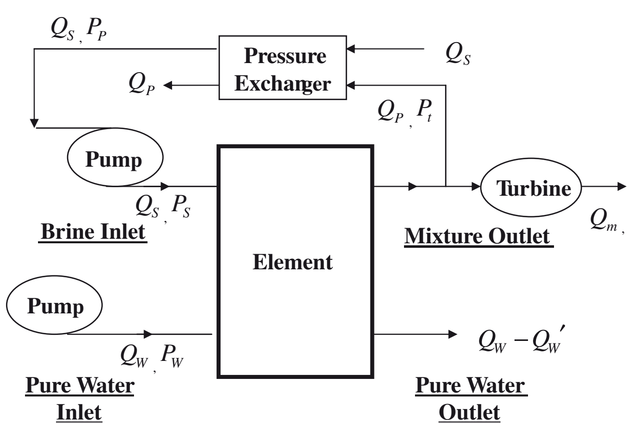

Fig. 2. Schematic diagram of bench scale plant. Symbols are summarized at the end of the text. Pure water outlet appeared only when 4-orifice module was employed.

Experimental

Bench plant construction and operation

The first trial of our research began in a bench scale plant. The schematic diagram of the system is shown in Fig. 2. The hollow fiber modules, whose element size was 5-inches and 8-inches, were purchased from Toyobo Co. Ltd. Both modules were originally the 3-orifice type, and the 8-inches module was used without further modification. On the other hand, the 5-inches module was modified into a 4-orifice type before use.

Prototype plant construction and operation

A prototype plant was constructed near the Uminonakamichi Nata Sea water Desalination Center. A plot plan of the plant and photos of the full and specific views are shown in Fig. 3. Brine came from the SWRO facility cited above. Pure water, provided by the regional sewage treatment facility, entered the PRO unit after removing any potential foulant of the osmotic membrane in the PRO unit, using the Ultra Filtration (UF) unit and low pressure RO unit. The employed hollow fiber modules were the 10-inches ones of 4-orifices, purchased from the Toyobo Co., Ltd.

Preparation of 4-orifice module

Conventional modules containing the RO membrane element usually have three open ports, each of which is a sea water inlet, concentrated brine outlet, and pure water outlet (3-orifice module). When this element was employed for the PRO operation, each port was used as a concentrated brine inlet, pure water inlet and permeate flux outlet. In this study, the modified module, which had four open ports, was prepared for the PRO operation (4-orifice module). Each port worked as a concentrated brine inlet, brine and permeate mixture outlet, pure water inlet and the last one acted as a pure water outlet, through which the non-permeating pure water left. A schematic diagram is shown in Fig. 4.

Smaller bench PRO experimental and flow pattern simulation

Using the 3-inches module, purchased from the Toyobo Co., Ltd., smaller bench scale PRO permeation experiment was carried out. The PRO experimental conditions were as follows. The brine (3.2 wt% NaCl aqueous solution) side pressure was 0.9 MPa, while the pure water side was pressurized at 0.5 MPa. The theoretical water flux was calculated using Eq. (1) in the theory section using the A-parameter as 1.14×10^{-6}

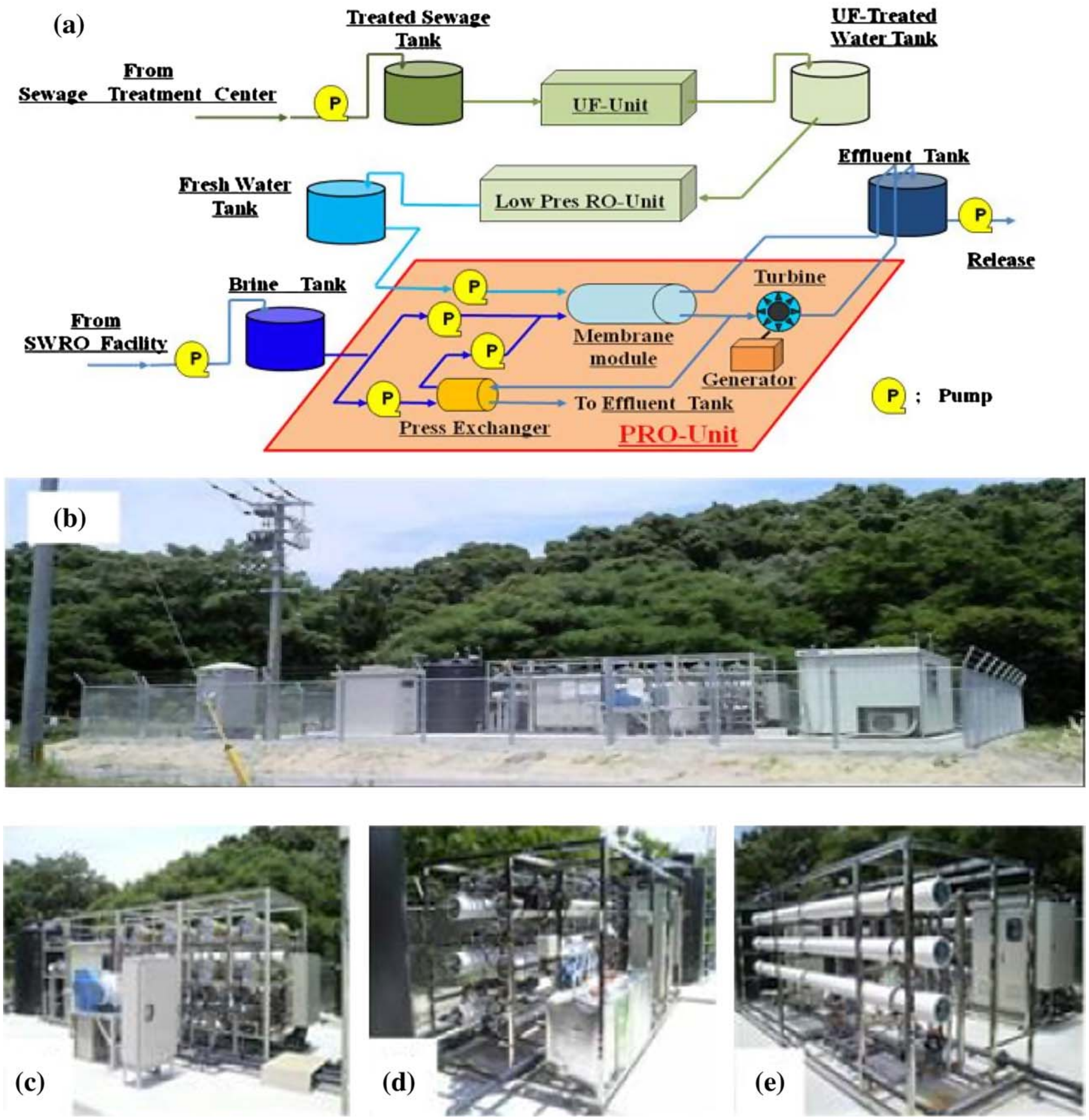

Fig. 3. (a) Schematic drawing of PRO prototype plant, (b) full view of the plant, (c) PRO-unit of the plant, (d) UF-unit of the plant, and (e) low pressure RO-unit.

(m/s MPa). The flow pattern simulation inside the module was carried out using the ANSYS CFX software.

Results and discussion

Concentration polarization near the membrane surface

In Fig. 5, the relationship between the permeate rate of the pure water and operation time, obtained from bench scale PRO experiment, is shown. Permeate rate decreased with time if the 3-orifice module (8-inches) was employed, while that rate converged to a constant value if using the 4-orifice (5-inches) module. Although the same tendency was observed at other pressures and feeding rates of the concentrated brine, the higher the pressurized brine the shorter the attenuation time. Attenuation of the permeate rate influenced the PRO's performance. The SWRO membrane

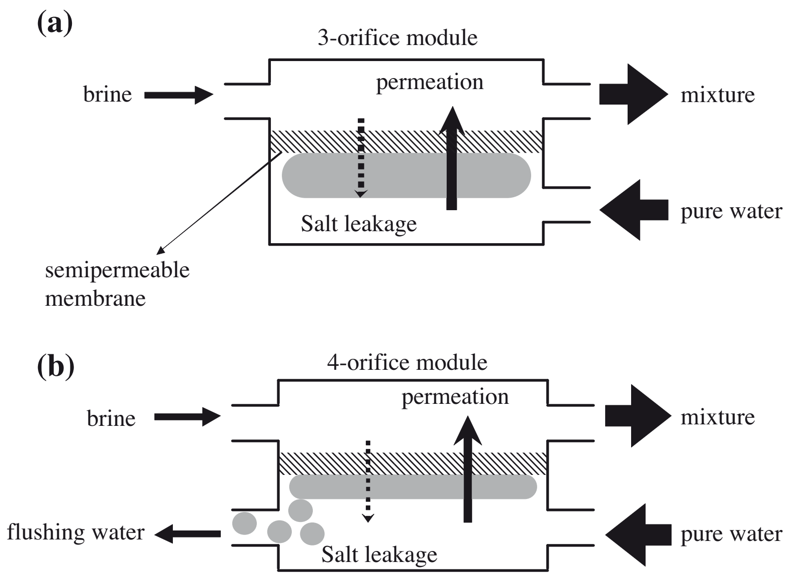

Fig. 4. Schematic picture of 4-orifice module in comparison with conventional 3-orifice module. If using 3-orifice module, salt leaks from brine side to pure water side and accumulates at the membrane surface as described by the shadowed area.

could not totally reject the salt so a small amount of salt leaked into the pure water side (Fig. 4(a)), which could have raised the concentration of the salt at the membrane surface on the pure water side and decreased the osmotic pressure difference if the 3-orifice module was employed. On the other hand, if the 4-orifice module was employed, the non-permeate pure water, which left the module through the 4th open port, worked as flushing water of the membrane surface on the pure water side (Fig. 4(b)), which might have played a role in minimizing the concentration polarization.

Membrane fouling

For use at the prototype PRO system, pure water came from the regional sewage treatment facility after treatment by the anaerobic–aerobic activated sludge method. Even after such treatments, the pure water coming from the facility could not be directly used at the PRO plant because the pure water was contaminated with organic compounds or bacterium which may cause fouling. To know about potential foulants in pure water for our PRO experimental, the pure water after the treatment facility was analyzed by carrying out an excitation and emission matrix (EEM) analysis. Based on the analysis results shown in Fig. 6 (a), compounds like fulvic acid and humic acid, which often caused membrane fouling, were found in the water treated by the UF membrane [9].

Among some peaks shown in the chart, peaks A, B, and C represent fulvic acid and humic acid. Peak D has been analyzed as a compound from human urine. Fig. 6(b) shows the EEM analysis result of the concentrated brine, from which nothing was found which caused fouling. We had to focus on the membrane fouling caused by these compounds in the pure water. To survey the effect of the treatment method on the fouling, the permeation experiment in the Forward Osmosis (FO) mode using pure water treated by several methods was carried out. Fig. 7 shows the permeation flux of the pure water using concentrated brine as the draw solution. The low pressure RO plus UF

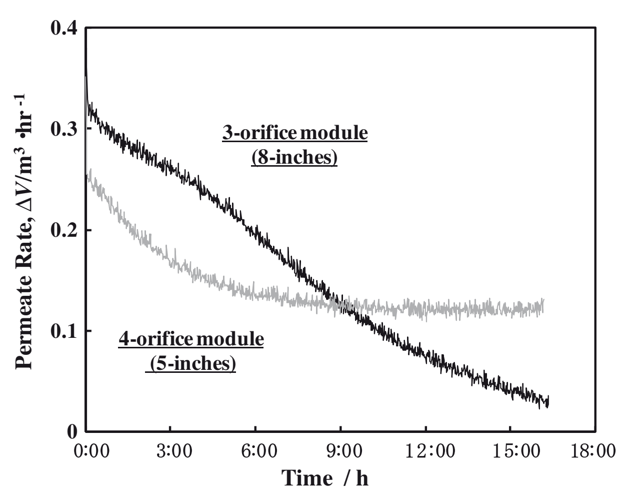

Fig. 5. Dependency of pure water's permeating rate into brine side against operation time on the number of the module orifice. Operation mode was PRO.

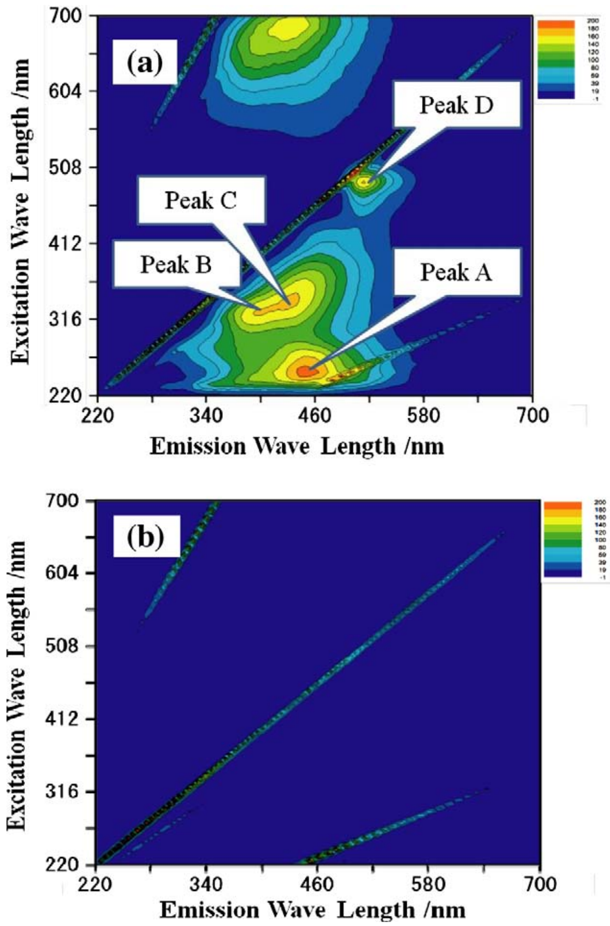

Fig. 6. EEM analysis result of (a) the pure water sample after treatment with the UF membranes and (b) concentrated brine coming from the SWRO.

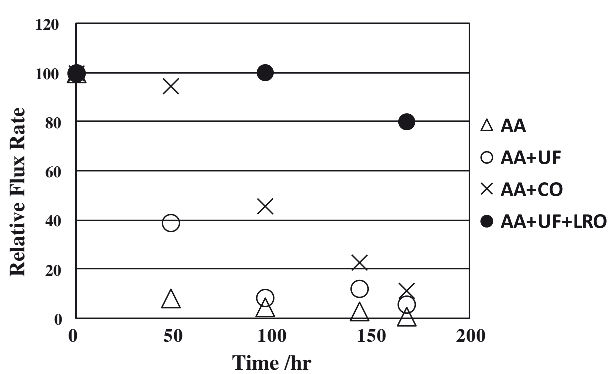

Fig. 7. Relative flux rate is shown compared with the flux value, as of the operation beginning, assumed as 100. AA; treated with anaerobic–aerobic activated sludge method AA + UF; treated with anaerobic–aerobic activated sludge method and then UF-unit AA + CO; treated with anaerobic–aerobic activated sludge method and then coagulation–sedimentation method with ozonation AA + UF + LRO; treated with anaerobic–aerobic activated sludge method, UF-unit and finally low pressure RO-unit.

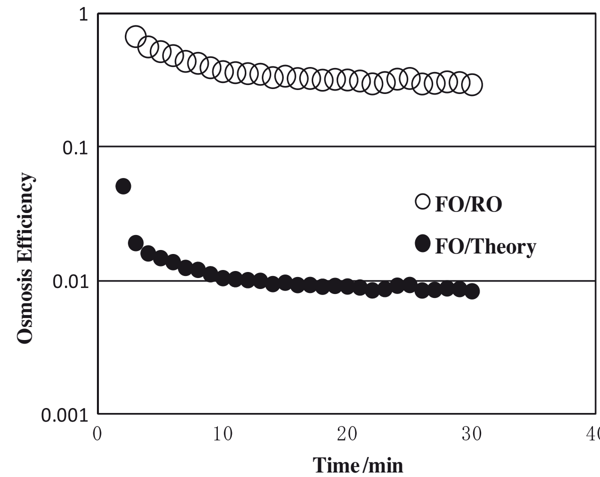

Fig. 8. Actual permeation flux ratio of PRO to RO mode, or to theoretically calculated PRO flux. The former one is denoted by open circle and the latter one by closed circle.

membrane treatment was found to work well against fouling, and the coagulation–sedimentation method with ozonation was effective because the potential foulants were effectively removed. Besides these methods cited above, UV radiation was reported to be effective against membrane fouling [10].

Relationship between PRO permeation and module structure

As a result of the smaller bench PRO experiment, the water flux through the membrane was much lower than the theoretical value or RO mode flux. The actual PRO flux ratio to RO mode is shown in Fig. 8.

Flux in the RO mode was obtained from the manufacturer, which was measured at the following condition. The salty water was concentrated at 3.2 wt % NaCl, the hydraulic pressure applied at the salty water side was 5.4 MPa, and the recovery ratio was 30%. The ratio of the actual PRO value to the theoretically calculated PRO flux is also shown in the same figure. The PRO mode permeation was found to be up to 30% of the value for the RO operation and only 1% of the theoretically calculated value. The reason for such a low permeation might be caused by concentration polarization or a structural problem with the SWRO element and module. To consider the structural problem of the SWRO element, a flow simulation of the saline water inside the element was carried out. The employed software was ANSYS CFX and the simulation parameter was the same as the actual condition except for the flow resistance within the element. In these simulations, saline water was assumed to flow outside of hollow

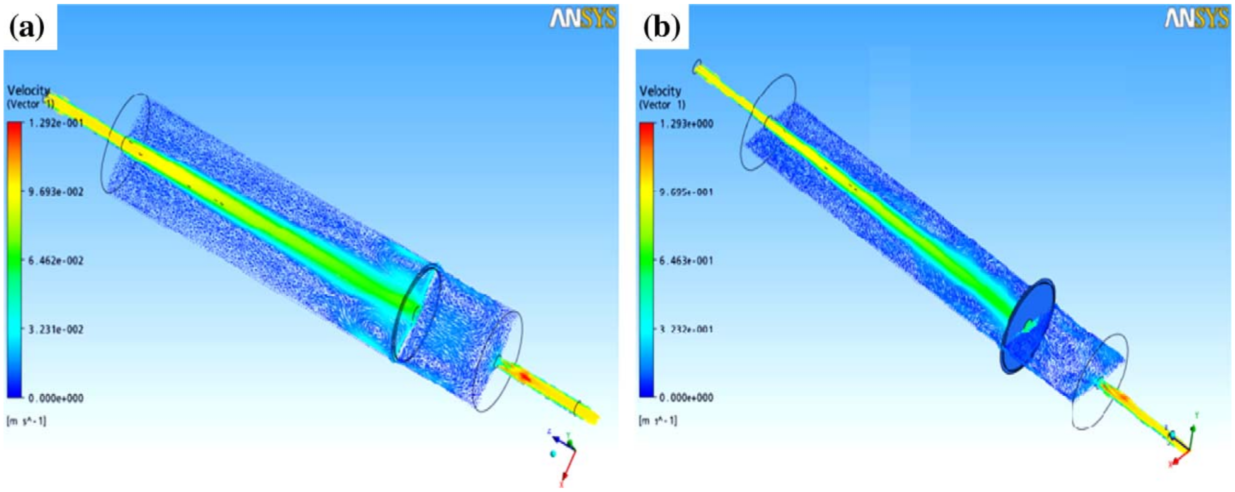

Fig. 9. Simulation results of brine flow inside the SWRO element at PRO operation. Pressure drop inside element is zero (a) and several hundred kPa (b).

fiber, while pure water was assumed to flow inside. Because the flow parameters inside the SWRO element were unknown, two simulation cases, for each of which the parameter for the flow resistance was set to be extremely different from each other, were carried out to estimate whether the SWRO element and module were proper for the FO operation. Results of these computer simulations are shown in Fig. 9. Fig. 9(a) and (b) shows the results of the simulation when the pressure drop in the element was set to zero ((a)) and several hundred kPa ((b)). Fig. 9 (a) showed that most of the saline water coming into the module did not go to hollow fiber but travelled through the center pipe towards the baffle plate located near the end section of the module.

Fig. 9(b) showed that the saline water drifted inside the module, having a high flux in some parts but nothing in other parts of the module. From these simulations under extremely different conditions, it could be that only a small part of the hollow fiber in the module was working during the PRO operation under the studied condition of the resistance range. The flow condition under the PRO mode was much different from the RO mode and the SWRO element should be modified before being used for the PRO operation.

Actual Output of the prototype plant

Fig. 10 explains the result of actual PRO operation using our prototype plant, showing the relationship between the pressure difference across the membrane and the output power density. The word "density" means the calculated power per unit membrane area. The hydraulic pressure applied to the pure water was varied in the range between 100 kPa and 500 kPa while the brine pressure was kept at 3 MPa. In other words, the hydraulic pressure difference ΔP across the membrane ranged between 2.5 MPa and 2.9 MPa. The output power density at a 2.5 MPa reached to 7.7 W/m^2. The power decline along with the ΔP was heightened because flushing of leak salt got less effective as the pure water pressure lowered. Under this condition, continual operation has been carried out for several months and no noticeable loss of performance was observed.

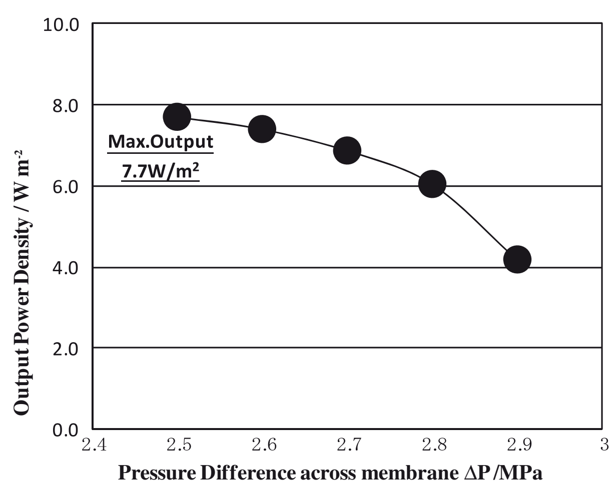

Fig. 10. Dependency of input and output power density on hydraulic pressure difference across membrane.

Conclusion

PRO is one of the future promising power generation systems although there are still some problems to be solved. This study focused on some of them.

The first one was the concentration polarization near the membrane surface, which could be overcome by modifying the number of the open port on the module from 3 to 4. The "non-permeating" portion of the pure water, which left the element through the fourth outlet port, was sure to flush the salt permeating through the membrane. Our prototype PRO plant got the maximum output power density, 7.7 W/m^2 at a 2.5 MPa hydraulic pressure difference and a 42% permeation of pure water into the brine.

The second one was the membrane fouling. As pure water provided from regional sewage treatment facilities was found to contain a potential agent causing fouling, cleansing of pure water was required. In this study, treatment by a UF membrane, low pressure RO membrane and coagulation–sedimentation method with ozonation were examined. Among them, low pressure RO membrane and coagulation–sedimentation method with ozonation showed good results while the pressure drop at that RO membrane itself and cost problem were yet to be solved.

The last one concerned the module and element design. From a computer simulation, there was the possibility that the hollow fiber element was not effectively used because pure water did not expand to the element and flow like "drifting" caused by the difference in the flow condition during the PRO operation from that during the RO operation.

It was concluded that the conventional membrane for the SWRO cannot be used for an effective PRO operation as another research team suggested [11,12]. We have to continue developing a new membrane system for PRO use.

Acknowledgments

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Symbols

ΔV — water permeate rate, m^3/s
A — water permeate coefficient, m/s
S — membrane area, m^2
$\Delta\Pi$ — osmotic pressure difference, Pa
ΔP — hydraulic pressure difference, Pa
Q_s — incoming brine amount, m^3 /s
Q_w — incoming pure water amount, m^3 /s
Q_m — outgoing mixture amount, m^3 /s
$Q_w{}'$ — permeating pure water amount, m^3 /s
P_s — hydraulic pressure of incoming brine before PRO module, Pa
P_w — hydraulic pressure of incoming pure water before PRO module, Pa
P_p — hydraulic pressure of incoming brine before pump, Pa
P_t — hydraulic pressure of outgoing mixture before turbine, Pa

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