Effect of salt concentration on permeation performance in hollow fiber type PRO membrane module

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Abstract
The new sustainable power generation technique which can convert the salinity gradient energy to the hydroelectric energy is expected. This technique is called Pressure Retarded Osmosis (PRO). Clarification of the relationship between the performance of the PRO module and permeation characteristics is important. It’s already known that increase of salt concentration can increase the permeation flux through the membrane. As the conventional researches, the effects of increase of fresh water concentration and concentration polarization have evaluated. In this research, relationship between the salt concentration and membrane module is focused. The effects of fresh water dissipation and flow state of salt water in hollow fiber membrane module as new factors are researched with experiment and numerical simulation. As result, in the case of low salt concentration, permeation is not caused sufficiently in module. On the other hand, in the case of high salt concentration, very low permeation flux area exists extensively, and the effects of concentration polarization and fresh water dissipation are relatively large. Therefore salt water flow rate and module shape should be changed for each salt concentration.

Key words : Pressure Retarded Osmosis(PRO), Forward Osmosis(FO), Hollow fiber, Salt concentration, Concentration polarization, Hollow fiber membrane module

1. Introduction
Global warming has been proceeding in the world, because a large amount of carbon dioxide is exhausted. Nuclear power generation is undesirable, because safety of radiation exposure is concerned. Then, reduction of carbon dioxide and improvement of safety for power generation are required. For these requirements, a lot of conversion power generation techniques with sustainable energy like the solar, wind, biomass, and ocean energy have been suggested. Particularly, Pressure Retarded Osmosis (PRO) suggested by S.Loeb is expected as one of these power generations with sustainable energy (Loeb and Norman, 1975). PRO is one of osmosis, solution of high osmotic pressure is pressurized. This pressure is lower than osmotic pressure difference between fresh water and salt water. In PRO, pressure of the fresh water is increased without the pump power. This pressurized mixed water can generate the electric power. However, Lee et al. mentioned that PRO is technically feasible, but not economically viable with currently available membrane (Lee et al., 1981). This means that the permeation flow rate is low and the required power to supply the salt water and fresh water is large. Thus the permeation flow rate from membrane module is important to generate power.
Three principal problems to reduce the permeation flow rate have been researched. These problems are concentration polarization, membrane fouling, and increase of fresh water concentration. Concentration polarization cause salinity gradient in membrane and on membrane surface. This phenomenon leads to reduction of osmotic pressure difference through the membrane. Sagiv et al. had evaluated the effect of internal concentration polarization (ICP) and external concentration polarization (ECP) on permeation performance of FO flat membrane with CFD analysis, and it had been
suggested that improvements in the fields of membrane skin and flow channel which can decrease ECP are required (Sagiv et al., 2015). Membrane fouling is caused by accumulating of solute in membrane and on membrane surface. This phenomenon refuses to permeate the water molecule.

| Nomenclature | Description |
|--------------|-------------|
| $Q_w$ | Permeation flow rate [$m^3/s$] |
| $J_w$ | Permeation flux [$m^3/(m^2 \cdot s)$] |
| $A$ | Permeation coefficient of water molecules [m/(Pa \cdot s)] |
| $P_d$ | Pressure of salt water side [MPa] |
| $P_f$ | Pressure of fresh water side [MPa] |
| $S_{mem}$ | Membrane surface area [$m^2$] |
| $J_s$ | Permeation flux of NaCl [$kg/(m^2 \cdot s)$] |
| $B$ | Permeation coefficient of NaCl [m/s] |
| $C_{d,b}$ | Mass concentration of salt water in bulk [kg/m$^3$] |
| $C_{d,m}$ | Mass concentration of salt water on membrane surface [kg/m$^3$] |
| $C_{f,b}$ | Mass concentration of fresh water in bulk [kg/m$^3$] |
| $C_{f,m}$ | Mass concentration of fresh water on membrane surface [kg/m$^3$] |
| $C_{f,i}$ | Mass concentration of fresh water at interface between support layer and active layer [kg/m$^3$] |
| $R_{perm}$ | Rejection rate of NaCl [-] |
| $K$ | Diffusion resistance [s/m] |
| $\pi_{d,m}$ | Osmotic pressure of salt water on membrane surface [Pa] |
| $\pi_{f,m}$ | Osmotic pressure of fresh water on membrane surface [Pa] |
| $\pi_{d,b}$ | Osmotic pressure of salt water in bulk [Pa] |
| $\pi_{f,b}$ | Osmotic pressure of fresh water in bulk [Pa] |
| $k_d$ | Mass transfer coefficient [m/s] |
| $\lambda$ | Pipe friction coefficient [-] |
| $V_f$ | Velocity of fresh water [m/s] |
| $Re$ | Reynolds number [-] |
| $d_i$ | Inner diameter of hollow fiber [m] |
| $d_o$ | Outer diameter of hollow fiber [m] |
| $\tau_s$ | Stress tensor [Pa] |
| $q$ | Fresh water flow rate in a hollow fiber [$m^3/s$] |
| $l$ | Length of hollow fiber [m] |
| $P_0$ | Pressure of fresh water at inlet [Pa] |
| $\nu$ | Dynamic viscosity [$m^2/s$] |
| $\rho$ | Density [kg/m$^3$] |
| $q_0$ | Fresh water flow rate at inlet [$m^3/s$] |
| $P_s$ | Pressure of salt water [Pa] |
| $K_{perm}$ | Permeation coefficient in momentum source [1/m] |
| $K_{loss}$ | Resistance loss coefficient in momentum source [$m^2$] |

Imada et al. had researched the effect of ozone treatment on the reduction of red tide. Effect of membrane fouling by general sea water is relatively small, effect by red tide is large. However, ozone treatment can make plankton in red tide die. (Imada et al., 1990). Increase of fresh water concentration is caused by concentration of solute in fresh water, and by leakage of salt. Then it leads to increase the osmotic pressure of fresh water, and osmotic pressure difference between salt water and fresh water become small. Improvements of structure in membrane and flow state around the membrane are required. In 1965, Lonsdale et al. had researched the transport phenomenon of solute around membrane, and clarified the characteristics about diffusion coefficient, water molecules, and salt (Lonsdale et al., 1965). Improvement the membrane structure to decrease the effects of internal concentration polarization (ICP) by the leakage of salt is required, Ng et al. had suggested that FO membrane should be consisted of thin dense layer without support layer (Ng et al., 2006). Many researchers have worked on these improvements so far. Then the system included the
membrane module should be researched. This system means optimized salt water flow rate, fresh water flow rate, salt concentration, pressure supply, and module shape.

Honda had researched the generated power and the loss of interesting PRO system set under the sea level. Generated power of new type power plant had improved more than four times of conventional generated power. Power density which means generated power per membrane area power was 0.5 [W/m²]. Additionally, generated power per fresh water flow rate was 0.1 [kWh/m³]. (Honda, 1990). Yasugahira et al. had compared power generation performance in considered concentration polarization with one of non-concentration polarization, and it had been clarified that generated power based on main river in Japan correspond to 1000MW nuclear power plant (Yasugahira et al., 2003). Tan and Ng had established prediction model of the osmotic power, and high water velocity and high temperature were needed to reduce the ECP. In terms of ICP, thickness of porous support layer should be reduce, tortuosity of support layer should be enhanced by altering the internal structure of the support layer, porosity of support layer should have a more open structure (Tan and Ng, 2008). Achilli et al. compared the experimental PRO results and model predictions. The model was developed to predict water flux and power density under specific experimental conditions (Achilli et al., 2009). Statkraft which is a leading company in hydropower internationally and Europe’s largest generator of renewable energy had attempted the PRO prototype (Gerstandt et al., 2008) and obtained a few output from the sea water (Halper, 2010). Sivertsen et al. had researched the relation between power production efficiency and pressure drop characteristics in hollow fiber membrane module. The flow configurations with co-current and counter current flow had been studied (Sivertsen et al., 2013). Saito et al. had developed the PRO system from 2003 and obtained the net output for the concentrated sea water. According to this research, the number of the open port on the module was modified from 3 to 4. The non-permeating portion of the pure water can flush the salt permeating through the membrane. Additionally, the prototype PRO plant got the maximum output power density, 7.7 [W/m²] at a 2.5 [MPa] hydraulic pressure difference and a 42% permeation of fresh water (Saito et al., 2012).

However, flow state in hollow fiber and outer side of hollow fiber haven’t considered so far. When the membrane module is evaluated, dissipation of fresh water and deviation flow in module as factor for reduction of permeation flow rate should be discussed. Dissipation of fresh water means that fresh water flow rate is zero. When the length of hollow fiber in module is focused, hollow fiber is so long. Fresh water in hollow fiber is gradually decreased by permeation. Hollow fiber where fresh water is dissipated can’t cause osmosis. In this length, permeation flow rate is zero. Deviation flow means that salt water stagnate or circulate in module. However these two factors have not been researched yet.

Thus dissipation of fresh water and deviation flow should be discussed with three principal problems: concentration polarization, membrane fouling, and increase of fresh water concentration. In this research, flow state in membrane module is focused. The flow state can’t affect on the membrane fouling. Then it’s assumed that effect of membrane fouling on reduction of permeation flow rate is so small.

The permeation and flow characteristics in module can be changed by salt water flow rate, fresh water flow rate, salt concentration, and module shape. In previous research, the effects of fresh water flow rate on permeation performance had been clarified. In the case that fresh water flow rate is large, the main factors for decrease of permeation flow rate are concentration of fresh water and leakage of salt. On the other hand, in the case that fresh water flow rate is low, the main factors for decrease of permeation flow rate are dissolution of fresh water and concentration polarization. Then, effects of concentration of fresh water and leakage of salt were small, and the effects of dissolution of fresh water and concentration polarization were large. Thus, it’s suggested that the optimal fresh water flow exist.

In this paper, the effect of salt concentration of salt water on permeation and flow characteristics is focused. Sea water of high concentration is usually in the center of the ocean basins away from the mouths of rivers. Sea water of high salt concentration is also in sub-tropical regions, because these regions have high rate of evaporation, little rain, and prevailing winds. Additionally in the land locked area like the Gulf of Mexico, salt concentration of sea water is high. On the other hand, at high latitudes area, salt concentration of sea water is low, because these area have lower evaporation rates and the melting of ice. Thus salt concentration can be changed at each location. Membrane module should be applied like this area of various salt concentrations.

The permeation and flow state in membrane module for the various salt concentrations is clarified. Then the desirable permeation and flow state can be suggested. The effect of concentration polarization, increase of fresh water concentration, dissolution of fresh water, and deviation flow on permeation performance for salt concentration is evaluated in this research.
Hollow fiber is used as semi-permeable membrane in this research. The shape of hollow fiber membrane is cylindrical. The hollow fiber type module is used in many desalination plant and PRO plant because its surface area is much larger than that of flat sheet type module. This hollow fiber is polymer membrane made by cellulose tri-acetate (CTA).

Inner diameter and outer diameter are 60[μm], 160[μm]. This hollow fiber has asymmetric characteristics as shown in Fig.1. The hollow fiber membrane is consisted of outer surface and inner layer. Outer surface of hollow fiber is active layer with dense pore. Solute in salt water is refused on outer surface. Inner layer is support layer and give active layer strength. The effective osmotic pressure difference is defined with the difference between salt concentration of salt water on active layer \( C_{d,m} \) and solute concentration of fresh water at interface of active layer and support layer \( C_{f,i} \). This osmotic pressure difference can give permeation flux. Fresh water permeates to salt water as permeation flux \( J_w \). Permeation flow rate is expressed with permeation flux as eq.(1). Salt water on active layer is diluted by permeation of fresh water as the difference of salt concentration on membrane surface \( C_{d,m} \) and salt concentration in bulk \( C_{d,b} \). A little salt can leak to fresh water. Then salt concentration in support layer increase. In addition, salt concentration on support layer also increase. However the difference of salt concentration on support layer surface \( C_{f,m} \) and salt concentration of fresh water in bulk \( C_{f,b} \) is very small, because salt water velocity is large on support layer.

\[
Q_w = J_w S_{mem} = A \left\{ (P_{d,b} - P_f) - (P_d - P_f) \right\} S_{mem} \quad \cdots (1)
\]

| Table 1 Main dimensions of 5-inch membrane module |
|---------------------------------------------------|
| Module diameter | 130 [mm] |
| Module length   | 641.8 [mm] |
| Total area of hollow fiber membrane               | 58 [m²] |
| Number of hollow fiber                            | 180,000 |
| Outer diameter of hollow fiber                     | 160 [μm] |
| Inner diameter of hollow fiber                     | 60 [μm] |

The hollow fibers are wound around center pipe which located at shaft-center as shown in Fig.2. Salt water inflows to the center-pipe. Some holes are made on the side surface of center-pipe. Salt water can spread from center pipe to hollow fiber element area. The fresh water inflows to each fiber with pressure. The drain water which don’t permeate to salt water flow out at left side of membrane module. And, the dimension and other parameter value of membrane module and hollow fiber used in this experiment are shown in Table1.

When the flow in membrane module is observed, the flow state can’t be seen directly. Because many hollow fibers
are wound in hollow fiber element area. Thus numerical simulation is required. In this simulation, hollow fiber element has directional loss characteristics. The details are written in section 5.1.

The experimental system is shown in Fig.3. This experimental system is consisted of salt water flow path, fresh water flow path, mixed water flow path, and drain flow path. In salt water flow path and fresh water flow path, tank, pump, flow meter, and pressure gauge are installed. In the mixed water flow path, pressure gauge, a flow meter, and an electrical conductivity meter are installed. In drain water flow path, electric conductivity meter is installed.

Permeation flow rate is obtained by difference of the mixed water flow rate and salt water flow rate. After this experiment, membrane module is washed with tap water to remove salt in each experiment.

Experimental conditions are written in Table2. Salt concentration is set based on the permeation flow rate. When the salt concentration is set over 3.5[%], fresh water don’t flow out from outlet of membrane module. Then, pressure of fresh water can’t be controlled. On the other hand, if the fresh water flow rate is increased, pressure of fresh water is over the maximum pressure of fresh water pump used in this experiment. RO water from tap water through the RO filtering system is used as fresh water. Then concentration of fresh water is sufficiently low.
Table 2 Experimental conditions

|                  |             |
|------------------|-------------|
| Fresh water flow rate | 3.0 [l/min] |
| Salt water flow rate   | 1.0 [l/min] |
| Salt concentration     | 0.5, 1.5, 2.5, 3.5 [%] |
| Solute concentration of fresh water | 0.0015 [%] |

3. Result of experiment

3-1. Permeation performance

Permeation flow rate obtained in this experiment against salt concentration is shown in Fig.4. Solid line is theoretical value which calculated with water permeation coefficient $A=4.6 \times 10^{-7}$ [m/(MPa s)]. This coefficient value is obtained by the previous research at the case of changing the salt water flow rate. According to this result, permeation flow rate increase with increasing of salt concentration. When theoretical line can be ideal state, permeation flow rate as performance is low at high salt concentration area, because the difference between the ideal value and experimental value is large at high salt concentration. For this low performance, increase of fresh water concentration, concentration polarization, dissipation of fresh water, and deviation flow of salt water can become the factors which make the permeation flow rate decrease.

3-2. Effects of fresh water concentration and concentration polarization

Permeation flow rate can be calculated with eq.(1). When the osmotic pressure of fresh water side $\pi_{f,b}$ is high, permeation flow rate become low. This effect is classified “concentration of fresh water” and “salt leakage”. For the concentration of fresh water, the water molecules permeate to salt water. Then, fresh water is concentrated, and concentration of fresh water increases. In addition, the salt leakage through the hollow fiber can be caused. If salt leaks from salt water to fresh water, concentration of fresh water increases.

At first, the effect of concentration of fresh water is focused. The theory is very simple. Firstly the mass flow rate of solute in fresh water at inlet is calculated. And the mass concentration of fresh water at outlet is calculated with amount of solute in fresh water at inlet. As the result, solute concentration of fresh water at outlet against salt concentration of salt water can be obtained as shown in Fig.5. Horizontal solid line means the solute concentration of fresh water at inlet. When the solute concentration in fresh water at outlet is compared to salt concentration in salt water, solute concentration in fresh water is very low because RO water is used in this experimental as fresh water. Thus if some processes to remove un-necessities are installed in plant, this effect is so small in whole range of salt concentration.
The effect of salt leakage is evaluated in below. Solute ideally doesn’t permeate through the semi-permeable membrane. However, a little salt can permeate from salt water to fresh water as the direction in Fig.1. The salt flux $J_s$ [kg/(m²·s)] is expressed as below.

$$J_s = B(C_{d,m} - C_{f,i}) \cdots (2)$$

where $B$ [m/s] is permeation coefficient of salt, $C_{d,m}$ [kg/m³] is salt concentration on the membrane surface of salt water side, $C_{f,i}$ [kg/m³] is salt concentration at the interface between support layer and active layer. As the results, permeated salt flux is shown in Fig.6. The permeated salt flux $J_s$ increase against the salt concentration. This permeated salt flux is by diffusion around the membrane. This is not by convection flow because FO is caused in membrane module. When salt concentration is high, effect of diffusion is large because salt concentration gradient is large. In addition, the permeation flow rate is large, when the effect of diffusion is increased. Thus salt flux $J_s$ is large at high salt concentration. These solute concentration of fresh water correspond to osmotic pressure 0.001-0.04 [MPa] as shown in Fig.6. This value of osmotic pressure of fresh water is very lower than that of salt water. Therefore salt leakage doesn’t affect on the reduction of permeation flow rate. If this experiment is under the RO condition, effect of salt leakage is large. Because the direction of permeation flux of fresh water is same to the direction of salt penetration. This means that effect by the convection flow can be increased.

The effect of concentration polarization on reduction of permeation flow rate is discussed in below. McCutcheon and Elimelech had derived the theory of permeation flux considered the external concentration polarization (ECP) which cause at outside of hollow fiber and of internal concentration polarization (ICP) which cause in support layer (McCutcheon and Elimelech, 2006). In fresh water side, solute included in fresh water is concentrated on support layer surface. Then, osmotic pressure is increased on membrane surface. On salt water side, permeated fresh water dilutes the salt water on membrane surface. Then, osmotic pressure is decreased on membrane surface. The permeation flux considered ICP and ECP is expressed as eq.(3).

$$J_W = \frac{1}{K} \ln \frac{B - J_W + \pi_{d,b} \cdot \exp \left( -\frac{J_W}{k_d} \right)}{B + A\pi_{f,b} \cdot \exp \left( \frac{J_W}{k_d} \right)} \cdots (3)$$

Where $K$ [s/m] is diffusion resistance in support layer, $B$ [m/s] is permeation coefficient of salt. This equation is expressed with concentrative ECP modulus and dilutive ECP modulus. The concentrative ECP modulus means the ratio between osmotic pressure of bulk solution and osmotic pressure on membrane surface of fresh water. The dilutive ECP modulus means the ratio between osmotic pressure of bulk solution and osmotic pressure on membrane surface of salt water. In this eq.(3), mass transfer coefficient $k_d$ [m/s] is defined with Sherwood number, diffusion coefficient, and hydraulic diameter. The osmotic pressure around the membrane surface can be calculated based on the theory written above.

Calculation results of fresh water and salt water are shown in Fig.7 respectively. On the fresh water, the difference of osmotic pressure is so small because RO water is used as fresh water in this experiment. Thus ECP of fresh water is so small. However, osmotic pressure of salt water is largely changed at high salt concentration because permeation flow rate is large. It’s easy that the diluted layer can be caused by permeated fresh water, when permeation flux is large. Therefore the effect of concentration polarization is caused at the salt water side in this experiment.

4. Effect of fresh water dissipation

The calculation theory which can calculate the pressure distribution and fresh water flow rate distribution in hollow fiber can be derived from a permeation model shown in Fig.8. Resistance in Fig.8 means friction loss on inner surface of hollow fiber. Fresh water flows in hollow fiber with permeation and friction loss. In the micro length $dx$ of hollow fiber, the relational expression between the rate of change for fresh water flow rate $dq/dx$ and permeation flow rate $J_W$ can be derived as follow eq.(4).
\[
\frac{dq}{dx} = -J_W \pi d_i \quad \ldots (4)
\]
\[
dP = \frac{\lambda \rho \Delta x}{2d_i} v_i^2 = \frac{32\nu \rho \Delta x}{d_i^2} q \quad \ldots (5)
\]

Where \(d_i\) [m] is inner diameter of hollow fiber, \(q\) [\(m^3/s\)] is fresh water flow rate in hollow fiber. The expression for pressure gradient against the hollow fiber length \(dP/dx\) can be obtained by using Darcy-Weisbach equation as eq.(5). In here, it can be supposed that permeation don’t influence on pressure drop in hollow fiber because permeation flow rate is sufficiently low than fresh water flow rate in hollow fiber and salt water flow rate outside of the hollow fiber. Additionally, pipe friction coefficient is defined as \((64/Re)\), the representative length is inner diameter of hollow fiber.

In the figure, \(J_W\) is the permeation flux of salt to fresh water. The osmotic pressure of the salt water side and fresh water side is also shown. The permeation and osmotic pressure are important factors in the performance of the hollow fiber membrane.

**Fig. 6** Permeation flux of salt to fresh water

**Fig. 7** Osmotic pressure of salt water side and fresh water side

\(R_{\text{mem}} = 98.5\%\)

\(\nu\) is dynamic viscosity, \(\rho\) is density. With these equations, pressure distribution and distribution of fresh water flow rate in hollow fiber against the fiber length \(x\) can be derived as follow eq.(6),(7). The effect of fresh water dissipation in hollow fiber on permeation flow rate can be considered by using these eq.(6),(7). Additionally, the change of
osmotic pressure difference and hollow fiber length against radial direction of membrane module is considered. When the pressure of fresh water $P_f$ is zero and fresh water flow rate $q$ is zero, the $x$ value can be obtained as effective length of hollow fiber.

$$P_f = p_0 + \sqrt{\frac{128\nu\rho}{A\pi^2d_i^3}} \left(1 - \exp \left(\frac{128\nu\rho A}{d_i^3} x\right)\right) q_0 \cdots (6)$$

$$q = q_0 \exp \left(\frac{128\nu\rho A}{d_i^3} x\right) - A\pi d_i \left(p_0 + (\Delta\pi - P_d) + \sqrt{\frac{128\nu\rho}{A\pi^2d_i^3}} q_0\right) x \cdots (7)$$

As the result, the effective length against the radial position is obtained as shown in Fig.9. Dashed line is the effective length of real module. Firstly, the gradient of effective length against the radial position is focused. This effective length is gradually increased against the radial position. In addition, the gradient at the case of high salt concentration is slightly rapid than low salt concentration. It means that effective length near the center-pipe is shorter compared to that of outer diameter area. The reason is that salt concentration is high near the center pipe. Thus a lot of fresh water can permeate to salt water near the center pipe. Then effective length becomes short. However, at outer diameter area of hollow fiber element, salt concentration is relatively low because a little fresh water permeates to salt water as permeation flow rate. Therefore, a lot of fresh water can leave in hollow fiber, and the effective length becomes long.

In the case of salt concentration 0.5, 1.5 [%], calculated effective length is longer than real one at whole radial position. Thus, fresh water exists over the length of hollow fiber, and permeation can be caused all length of hollow fiber. On the other hand, in the case of high salt concentration 2.5, 3.5 [%], calculated effective length is shorter than real one. This means that the length where fresh water dissipates exists at every radial position. Permeation flow rate doesn’t exist in the hollow fiber length where the fresh water is dissipated. The amount of dissipated fresh water in this length is shown as reduction of permeation flow rate in Fig.10. This reduction of permeation flow rate can’t be ignored at high salt concentration, and fresh water dissipation should be considered.

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**Fig.9** Effective length for each salt water flow rate

**Fig.10** Lost permeation flow rate at each salt concentration
5. Effect of deviation flow
5.1 Simulation conditions

The geometry model for simulation in this research is shown in Fig.11. The region of the salt water flow is consisted of the three parts: the center pipe, hollow fiber element area, and the vessel. The vessel means clearance between the hollow fiber element area and pressure vessel. Additionally, this vessel area is combined with outlet. The permeation flux in hollow fiber element area is estimated by $J_w$ in eq.(1). In hollow fiber element area, salt water velocity is very small. The Reynolds number is under 30. Then, in this area, salt water flow state is laminar. Thus, turbulence model for simulation isn’t needed to consider. Additionally, Reynold number of fresh water in hollow fiber is under 4, and permeation velocity is about 1.0[$\mu$m]. Therefore, with permeation flux from fresh water to salt water, turbulence model for simulation isn’t also needed to consider. The number of mesh is 320,000, mesh structure is tetrahedron and non-structured mesh. In this simulation, continuous equation eq.(8) and Navier-Stokes equation eq.(9) are solved as dominant equation of salt water flow.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = Q_w \quad \cdots (8)
\]

\[
\frac{\partial}{\partial t} (\rho U) + \nabla \cdot (\rho U \otimes U) = -\nabla P + \nabla \cdot \tau_s + S_M \quad \cdots (9)
\]

Where $\rho$[kg/m$^3$] is density, $U$[m/s] is velocity, $P$[Pa] is pressure, $S_M$ is mass source, $\tau_s$[Pa] is stress tensor, $S_M$ is momentum source. The mass source : $Q_w$ is defined by eq.(1) express the permeation flux. In this simulation, it’s so difficult to create the all hollow fibers because the number of hollow fiber is 180,000 and hollow fiber has asymmetric structure.

![Fig.11 Geometry model for simulation](image)

Then, it’s supposed that the hollow fiber element area is made by one resistance body. The hollow fiber element area of real module has directional loss characteristics. Thus, the directional loss characteristics of inertia loss and viscous loss should be considered. The directional loss characteristics of inertia loss and viscous loss can be defined as eq.(10).

\[
S_{M,i} = -\frac{\mu}{K_{perm}} U_i - K_{loss} \frac{\rho}{2} |U_i|U_i \quad \cdots (10)
\]

The boundary condition and initial condition are shown in Table3. This condition is same to experiment conditions, the salt concentration at inlet is changed from 0.5 to 3.5%. Salt water flow rate at inlet is 1.0[l/min]. Salt water pressure
at inlet and fresh water pressure at inlet is from 0.18 to 0.33[MPa] corresponded to salt concentration of salt water 0.5-3.5[%]. For the fresh water pressure, pressure drop by pipe friction can be considered with eq.(11).

\[ P_f = P_0 - \frac{x - 80}{613} P_0 \]  

(11)

Where 80[mm] means length from inlet to hollow fiber element area, 613[mm] means length of hollow fiber element area. According to this equation, hydrodynamic pressure of fresh water at outlet side is smaller than that of salt water. However osmotic pressure of fresh water is also smaller than that of salt water. Thus permeation can be caused as the direction from fresh water to salt water. This means PRO state.

| Table 3 Simulation condition |
|-------------------------------|
| Salt water flow rate | 1.0 [l/min] |
| Salt concentration | 0.5, 1.5, 2.5, 3.5 [%] |
| Pressure of salt water and fresh water at inlet | 0.18, 0.20, 0.25, 0.33 [MPa] |
| Module length | 613 [mm] |
| Module diameter | 130 [mm] |

5.2 Result of simulation

In this section, the optimal flow state in membrane module is clarified. In here, optimal flow state means to be able to utilize all membrane in membrane module. Permeation flow rate by numerical simulation and experiment is shown in Fig.12. There is difference between simulation and experiment. This difference is caused by concentration polarization. In the experiment, concentration polarization is caused. On the other hand, concentration polarization and salt leakage aren’t considered in this simulation. Because effect of salt leakage on reduction of permeation flow rate is very small, this difference is caused by concentration polarization.

\[ A = 4.6 \times 10^{-7} \text{[m/(MPa s)]} \]

Fig.12 Flow and permeation model of fresh water in hollow fiber

Fig.13 shows the permeation flux distribution in the module. Fig.14 shows velocity vector in the module. In this simulation, permeation coefficient \( A \) is based on the experimental values, not based on the theoretical values. Then, the value is \( A = 4.6 \times 10^{-7} \text{[m/(MPa s)]} \).
Firstly, the permeation flux distribution shown in Fig.13 is focused. Warm color is high flux, and cool color is low flux. In this research, it’s required to clarify the desirable flow state in membrane module. In here, desirable flow state means to be able to utilize all membrane in membrane module. It’s desirable that salt concentration is gradually decreased, and permeation flux is nearly zero at outlet area. “Gradually” means that permeation can be caused at every position. In addition, zero permeation flux at outlet area means that permeation is caused sufficiently. On the other hand, it’s undesirable that salt concentration is rapidly decreased. “Rapidly” means that permeation can be caused near the center pipe. Then membrane can’t be utilized at every position.

According to the result shown in Fig.13, the permeation flux mainly varies for radial direction. At the case of high salt concentration, salt concentration 2.5 and 3.5[%], large permeation flux area exists near the center-pipe. But low permeation flux area exists near the outer diameter area. This low permeation area is spread extensively. This means that permeation can be caused sufficiently, but the membrane near the outer diameter is not needed. Thus membrane in module is not utilized efficiently.
On the other hand, at the case of low salt concentration, salt concentration 0.5[%], large permeation flux area is spread extensively. In addition, relatively low permeation flux area exists near the outer diameter area. This means that permeation don’t cause sufficiently, but permeation can be caused at every position of membrane module. If module diameter is large, permeation flow rate can be larger than that of this case. The permeation flux distribution at 1.5[%] salt concentration is comparatively better than that at other salt concentration.

Next, the velocity vector distribution of salt water is focused. In here, it’s required to clarify the flow state at the case of 1.5[%] salt concentration. In all salt concentration, almost velocities are radial direction, and large velocities are near the inlet area. There is no difference for every salt concentration because the flow area in the radial direction is large. The velocity may be changed in module because permeation flow rate is large at high salt concentration. However, because flow area in membrane module is very large, almost velocities are not changed even though permeation flow rate is large. Therefore, optimal salt water flow state is not obtained for various salt concentration. But the optimal salt concentration for membrane module used now is clarified. It doesn’t need the thickness of hollow fiber element for radial direction near the outlet at the case of high salt concentration. Additionally, at the case of this module geometry, high salt concentration is not desirable.

6 Conclusions

The experiment and numerical simulation are performed to clarify the desirable flow state in the hollow fiber membrane module for each salt concentration. The following results are obtained.

1. Permeation flow rate by experiment is increased with increasing of salt concentration. But the difference between the theoretical value and experimental value is gradually increased at high salt concentration.
2. In whole range of salt concentration, the effect of increase of fresh water concentration is so small.
3. At the case of high salt concentration, effect of concentration polarization can be caused at only salt water side, and fresh water can be dissipated.
4. At the case of high salt concentration, permeation can be caused rapidly. Then, present hollow fiber membrane module cannot be utilized.
5. According to results 1-4, control condition at high salt concentration is not desirable.

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