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Effect of combined positions of feed spacer-type tricot on the performance in pressure retarded osmosis (PRO)

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ABSTRACT

Pressure retarded osmosis (PRO) is a promising technology for renewable energy. However, its performance can be influenced by deformation of the PRO membrane caused by feed spacers at the high applied pressure and changed flow direction in the PRO membrane cell. The feed spacer-type tricot (tricot) for a flat-sheet membrane of the PRO module provides the structural support to withstand high pressure from the draw side. This keeps the feed channel open during turbulent flow at the vicinity of the membrane surface. The purpose of this study was to investigate the effect of combined positions of feed tricot on membrane performance. The surface shapes of tricot were different; one side was uneven and the other side was soft. Furthermore, when tricot was combined with the feed cell of a PRO membrane module, there were two types of positions; depending on the lines of feedwater holes of the feed cell, when placed parallel to thick lines of the tricot with the feedwater holes it was named the vertical line, and when placed across was named the horizontal line. The different surface shape and combined positions of the tricot had a big impact on this study. The study results showed that the soft surface and vertical line conditions in the PRO could operate stably, and subsequently achieved higher performance compared with other combined conditions.

Keywords: Feed spacer-type tricot; Combined position; Pressure retarded membrane

1. Introduction

With the continuous increase in the human population, the world is facing an energy shortage. As a result, the demand for renewable energy sources is increasing [1]. Power generation by salinity-gradient energy is one of the new desalination technologies. Among these new technologies, pressure retarded osmosis (PRO) is one of the desalination technologies used for extracting renewable energy. When different concentrated solutions mix, the free energy is released from mixing solutions [2]. Unlike other renewable energies (wind, solar, etc.), PRO is not influenced by climatic change. It uses seawater and freshwater to generate osmotic power, it is guaranteed that there will be no shortage of resources, it is estimated that up to 2 terawatt (TW) in salinity-gradient renewable energy could be generated based on osmotic power [3]. Of the desalination technologies, reverse osmosis (RO) is commonly used for desalination, and its separation performance has been proved not only for desalination, but also for purifying contaminated surface water. Current RO technology is approaching its maximum level, making it important to find other processes with better performance [4,5]. RO–PRO hybrid process has been studied. In this hybrid process, the PRO uses RO brine as a draw solution (DS) and gives the RO the energy produced during the PRO process to support operational energy and reduce operational cost. PRO relies on a semipermeable membrane placed in between two different concentrated solutions: higher concentrated salt water (i.e., DS) and lower concentrated freshwater (i.e., feed solution [FS]). The PRO uses same process as the forward osmosis (FO) process that can permeate only solvents from FS to DS. However, that point of using pressure in the

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PRO is different from the FO [6]. Because of the pressure used in the PRO, when combining the PRO membrane module, it is necessary to place a spacer inside the feed membrane cell to withstand the applied pressure from DS. The feed spacer-type tricot obtained from Toray (Japan), a commercial module for a flat-sheet PRO membrane cell, affected PRO membrane performance. It is well known that the geometry of the feed spacer has a big impact on the PRO performance [7]. Previous studies have shown that feed spacer geometry can affect hydrodynamics of flow and induce membrane deformation [8–10].

This lab-scale study investigated flat-sheet PRO membrane performance with the tricot in combined positions. First, to understand the difference when the tricot was used, PRO performance was monitored through the test depending on the presence of the tricot. Then, the combined positions of the tricot were investigated, directly comparing the PRO membrane performance. After finishing the test, a study on the effect of combinations of single and double sheet of the tricot was conducted. In this study, to compare the performance, water flux (J_w) and power density (W) were used.

2. Materials and methods

2.1. Lab-scale test

In this study, as shown in Fig. 1, a cross-flow experimental setup was used. The operating method for the PRO was AL-DS (active layer facing draw solution). The PRO membrane cell for the flat-sheet membrane was made from steel use stainless, and has an effective membrane area of 0.064 m^2 (0.08 m length × 0.08 m width). A PRO membrane was comprised of active layer and support layer. To withstand the applied pressure from the draw side, a support layer is produced that is thicker than the FO membrane. A polyamide (PA) membrane and spacer-type tricot were obtained from a Toray, Inc. commercial module. During each of the experimental conditions run, the membrane was first tested at FO process, P = 0 bar, and then the pressure in the DS was increased (P = 0, 5, 10, 15, 20, and 30 bar). The applied pressure in the DS and pressure resistance in the FS were monitored using an electronic pressure gauge (GR200 graphic recorder, Hanyoung nux, Korea). To measure water flux and power density, an electronic scale (Ranger 7000, Ohaus, USA) was placed under the FS container and the decrease in the water amount was recorded. The water flux was calculated based on the weight changes of the water. A chiller (RW-0525G, Jeiotech, Korea) was used to maintain a stable temperature (DS, FS = 20°C). By using a booster pump (Hyosung, Korea), pressure conditions were controlled. DS was made from NaCl (Samchun, Korea) to maintain 70,000 ppm NaCl, which is same concentration of the brine from RO process in RO–PRO hybrid process. Flow rate of both FS and DS were fixed at 1 L/min, and FS and DS volume were maintained as constant (2 L).

Table 1 shows the testing conditions applied for all experiments.

The effective applied pressure (ΔP) during the PRO run was different. Each power density (W) in the PRO was calculated by the J_w and ΔP:

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

where A is the water permeation coefficient of the membrane, $\Delta\pi$ is the osmotic pressure difference, and ΔP is the hydraulic pressure difference in PRO membrane.

$$\text{Differential pressure (DP)} = P_f - P_c \quad (2)$$

where P_f is the feed pressure; and P_c is the concentrate pressure.

$$W = J_w \times \Delta P \quad (3)$$

Table 1
Operating conditions of the PRO process

Items	Conditions
Membrane	Toray, Inc. (PA membrane)
Effective membrane area	0.0064 m^2 (0.08 m × 0.08 m)
Pressure	0, 5, 10, 15, 20, and 30 bar
Membrane orientation	AL-DS (PRO mode)
Temperature	20°C
Flow rate	Both (feed, draw) 1 LPM

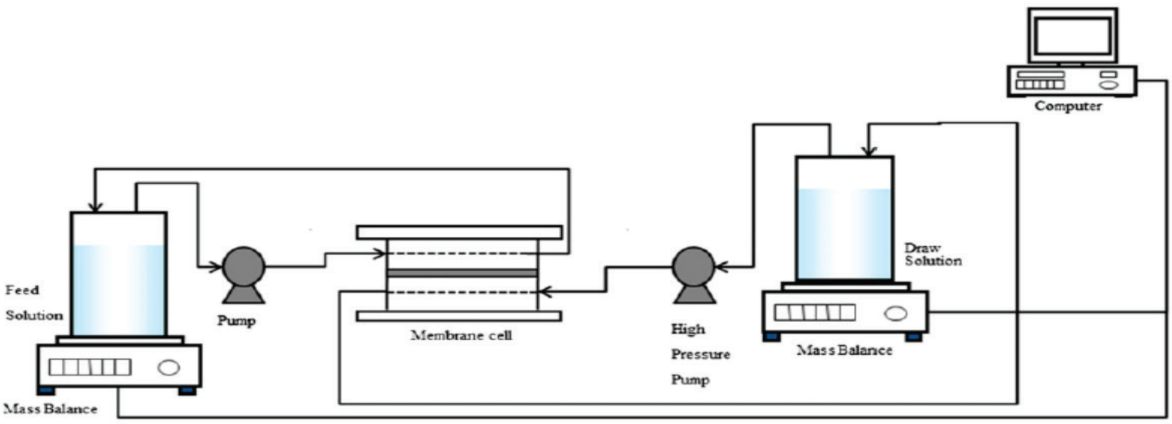

Fig. 1. Schematic diagram of lab-scale pressure retarded osmosis (PRO) device.

2.2. Detailed description of combination conditions

In this study, combination conditions of feed spacer-type tricot were classified into seven cases. Surface of the tricot: (1) soft – one side of the tricot surface had a soft property and (2) uneven – the other side of the tricot surface had thick lines and rough property. Placed position: (1) vertical – the thick lines of the tricot were placed parallel to the water holes of the feed cell, (2) horizon – the thick lines of the tricot were placed across against the water holes of the feed cell, and (3) cross – two sheets of the tricot were placed across like a cross on the water holes of the feed cell; double – two sheets of tricot were stacked.

Thus, seven cases were classified: (1) soft-vertical (SV), (2) soft-horizon (SH), (3) uneven-vertical (UV), (4) uneven-horizon (UH), (5) double-layer-soft-vertical (2SV), (6) double-layer-uneven-vertical (2UV), and (7) double-layer-soft-cross (2SC). All cases are listed in Table 2.

Photographs and microscope images of tricoat spacers are shown in Fig. 2 and 3.

3. Results and discussion

3.1. Pressure difference depending on the existence of the tricot

Pressure difference is a factor affecting the water flux and power density. The lower the feed resistance, the higher the water flux and power density that can be achieved. To investigate the effects of the existence of the tricot, a tricot with membrane and a non-tricot with membrane are compared. As shown in Fig. 4, the results showed that the feed resistance of the non-tricot case was higher than the tricot with the membrane case. Therefore, because pressure difference is an important factor affecting PRO performance, it is better to use the tricot with the membrane during operation. As shown in Fig. 4, right one, it was expected that placed different orientation of the tricot on the membrane affected to the feed resistance, but contrary to expectation, different combined orientation of the tricot did not have a big impact on feed resistance during the PRO process. Therefore, seven cases of results of the pressure difference were similar. It assumed that the feed resistance was more influenced by just the existence of the tricot than different combined orientation of the tricot.

3.2. Comparison between SV, SH, UV, and UH

Differential surface of the tricot and combined positions had brought different results. As shown in Fig. 5, when the SV and SH conditions were compared, there was no significant difference in power density under 5 bar. However, when operating

Table 2
Combination conditions of the spacer-type tricot

Combination conditions
(1) Soft-vertical (SV)
(2) Soft-horizon (SH)
(3) Uneven-vertical (UV)
(4) Uneven-horizon (UH)
(5) Double-layer-soft-vertical (2SV)
(6) Double-layer-uneven-vertical (2UV)
(7) Double-layer-soft-cross (2SC)

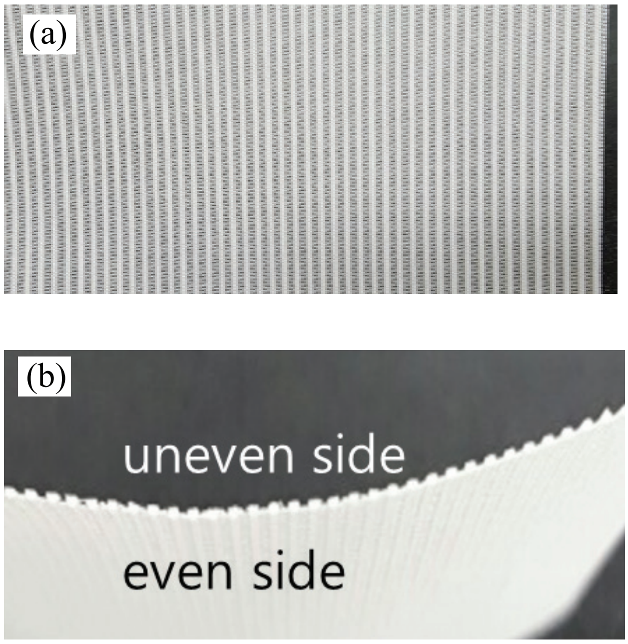

Fig. 2. Visual of the spacer-type tricot: (a) front side of the tricot and (b) side of the tricot.

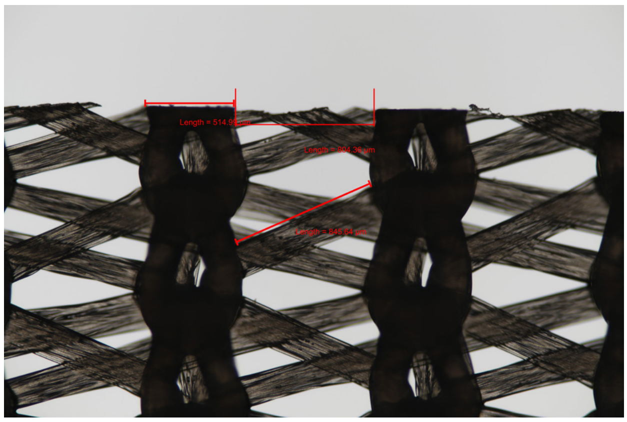

Fig. 3. Microscopic images of tricoat spacer for feed solution channel.

pressure of 10 bar or more was applied, the difference between the two conditions was obvious, and the SV condition was better than the SH mode. This same phenomenon appeared in the comparison between UV and UH. This had been assumed to be because the thick line of the tricot placed at right angles to the water holes of the feed cell had blocked and changed the flow direction inside of the feed cell. Second, when it comes to the effects of the surface, at $P = 30$ bar, SV had 6.57 W/m^2 and UV had 5.01 W/m^2, SV had 23.7% efficiency more than UV. These results indicated that the surface of the tricot might induce membrane deformation, and could change the membrane properties.

3.3. Comparison between single-layer and double-layer tricot

To investigate the impact on the number and combined compositions of the tricot, single-layer and double-layer

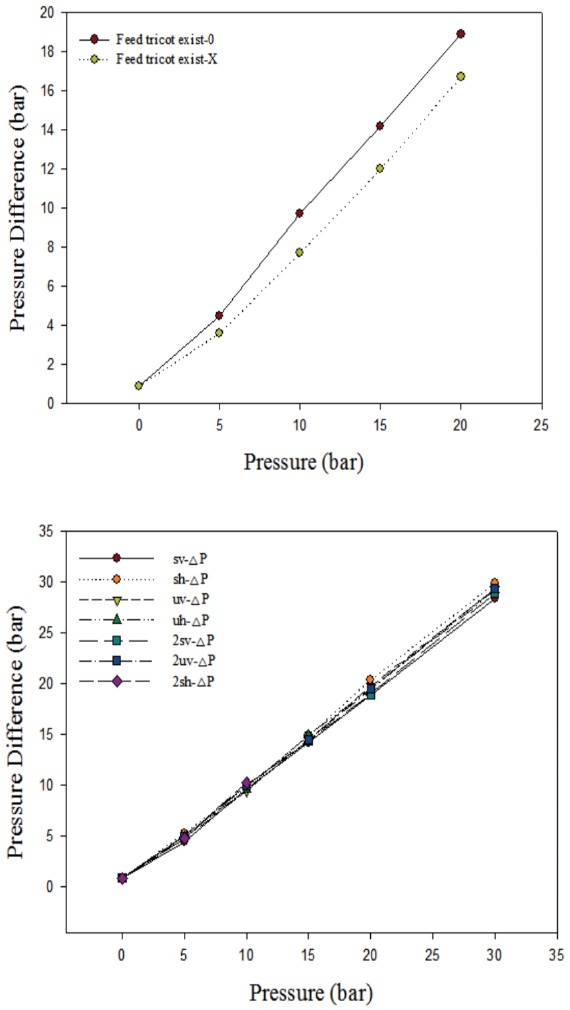

Fig. 4. Pressure difference according to the combination of the tricot.

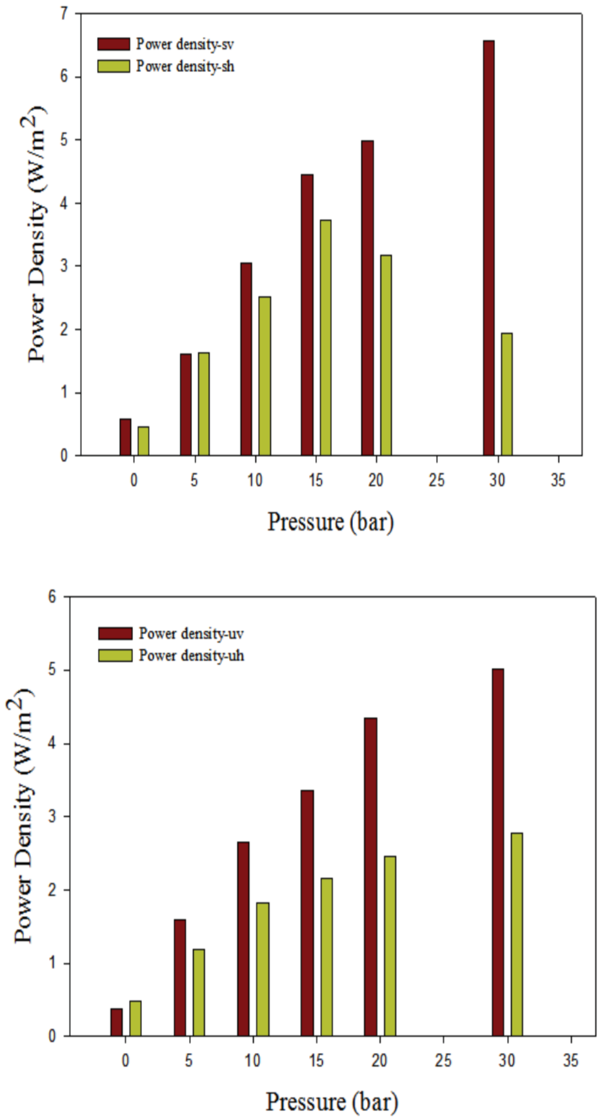

Fig. 5. Comparison according to surface and combined compositions of tricot.

tricot study had been conducted. First, the double-layer tricot was evaluated against the single-layer tricot to identify performance differential. Further impact of the tricot on the membrane performance in the PRO process is shown in Fig. 6. The 2SC had the worst performance of the three cases of double-layer conditions (2SV, 2UV, and 2SC). In the 2SC case, because the uneven surfaces of the tricot faced each other and the thick line of the tricot placed across, in more pressurized conditions the surfaces could press down on each other and block the holes of the tricot, stopping the PRO process. Before conducting the 2SV and the 2UV test, according to the previous results of the SV and the UV, when the soft surface of the tricot met the membrane directly, it had better performance. So, in this comparative experiment it was expected that the 2SV would have better performance than the 2UV. But the opposite result was shown, as until 10 bar condition there was little differential performance between the 2SV and the 2UV. In the high-pressure conditions after 10 bar, the gap in the performance was increasingly widening. Even though the soft surface met the membrane directly, it was assumed that because the uneven surfaces of the tricot faced each other, with increasing hydraulic pressure, they became pressed down and meshed with each other like a gear wheel. This phenomenon also had an influence on the performance.

Second, the single-bond and double-bond conditions without the 2SC were evaluated. This changing tendency was not distinctly shown in the lower pressure conditions. Even double-bond conditions had better power density before 15 bar condition. As shown in Fig. 6, right one, after 15 bar condition, the performance gap had been distinctly characterized. The combined orientation of the tricot increasingly affected the performance during operation. The SV condition was the most efficient of other conditions. This result indicates that the shape of the tricot is an important factor in the PRO process.

As shown in Fig. 7, depending on the combined conditions of the tricot, the PRO process can operate stably in the correct tricot combination conditions. The hydraulic pressure

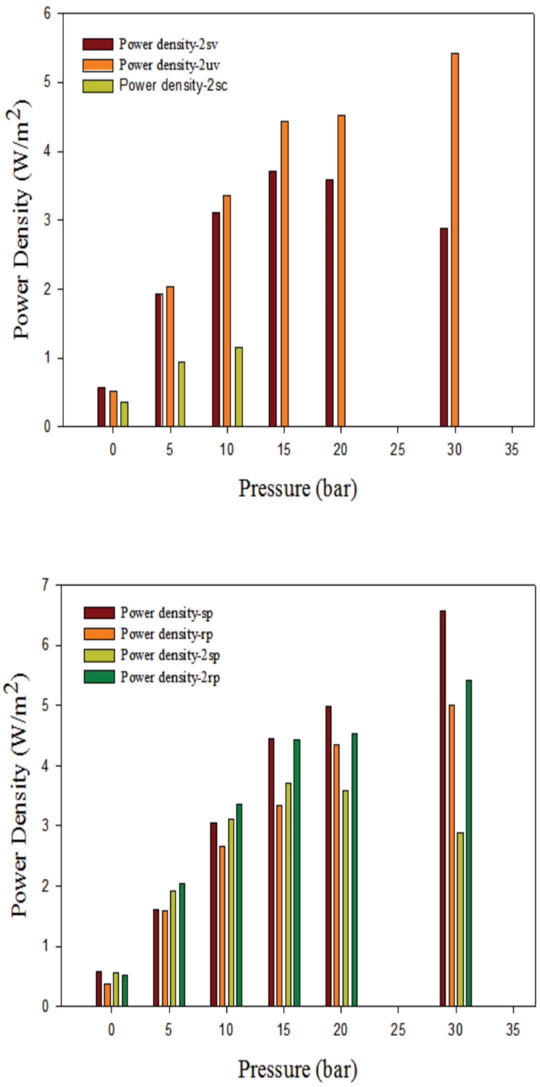

Fig. 6. Comparison between single-layer and double-layer tricot.

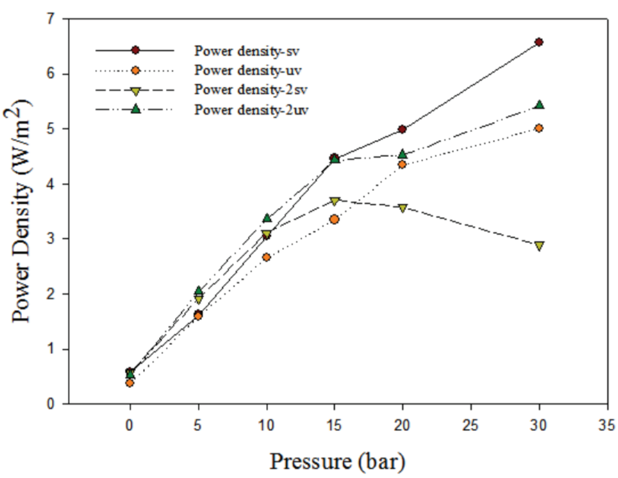

Fig. 7. Comparison of power density by different tricot combination.

condition of the PRO is an integral factor influencing the PRO performance. In the flat-sheet PRO membrane module, just by fixing a spacer in the correct position, PRO can attain higher performance, and reduce total operational cost.

4. Conclusions

This study was undertaken to investigate the effects of the tricot in terms of the combined positions. At first, when the tricot was placed on the membrane, the feed resistance was lower than when the tricot was not present. The PRO membrane's performance was affected by the pressure difference. However, the combined positions of the tricot did not have a big impact on the feed resistance during the PRO process run. Then, in terms of the tricot surface, the results showed when the soft surface of the tricot faced to the membrane were better than the uneven surface, thick lines of the uneven tricot provided evidence that more membrane deformation might have been induced, changing the property of the membrane. In terms of the thick lines of the tricot, placing it parallel to the water holes of the feed cell case was better than placing it across. This meant that the thick lines of the tricot influenced the hydraulic feed flow. The comparison between single-layer tricot and double-bond tricot, in the conditions of the FO mode or low pressure conditions, did not show a distinct difference, but while applying higher pressure, it showed a big difference with the combined conditions. Specifically, in the double-layer case, before performing the experiment, because the soft surface of the tricot faced the membrane like in SV condition, it was expected that 2SV would be better than 2UV. However, the opposite result was attained (2SV < 2UV). This is assumed to be because each uneven surface of the both tricot faced to each other, when pressure was applied, it was pressed down and meshed like a gear wheel. This phenomenon indicated that it made flow change and block the flow way. This study showed that applying a better combination of spacers can result in better membrane performance and reduced operation costs, specifically in the PRO process using hydraulic pressure.

Acknowledgments

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