A study of Forward Osmosis Performance and its Application on Sodium Succinate Feed Solution Using Ionic Salt Draw Solution

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Abstract

Osmotically driven forward osmosis (FO) process is gaining increasing attentions among researchers. At present, the application of FO technology in the downstream recovery for biorefinery products is not common. With the increasing demand of energy intensive and economical technologies that are capable to concentrate dilute aqueous solutions, FO may find its potential in biorefinery application. In this paper, the osmotic pressure of different types of draw solution compound (sodium chloride, sodium acetate, sodium formate, ethylene glycol, and sodium lactate) was simulated. Experimental results were compared to the neutral compound and inorganic salt compound obtained from the previous literature and the performance of permeation flux was evaluated. It is desirable to carry out the FO process at higher draw solution concentration in order to achieve a fast water permeation process. The draw solution dilution effect was more pronounced at high solution concentration as a result of greater water permeation flux. Higher conductivities were obtained at increasing draw solution concentration indicating higher electrolyte concentration in the feed solution due to the reverse solute permeation. The application of FO technology for concentrating sodium succinate feed solution has shown encouraging results.

Key words : forward osmosis, osmotic pressure, water transport flux, conductivity, reverse solute permeation

1. Introduction

In recent years, biorefinery production of organic compound has gained increasing attentions from the world [1]. Biorefinery process technology provides an alternative to the existing conventional methods for the production of various valuable products including succinic acid [2]. Nevertheless, downstream recovery remains the ultimate challenge as downstream technologies are the cost intensive steps in the entire manufacturing processes [1,3]. Hence, constant explorations of an efficient and cost effective technology are deemed necessary.

Forward osmosis (FO) is an osmotic pressure-driven process which draws water molecule from the feed solution to the higher osmotic pressure draw solution. During operation of the FO process, feed solution and draw solution are fed into different solution reservoirs. Water molecule is transported from the feed solution reservoir across a semi-permeable membrane to the draw solution reservoir as a result of osmotic pressure driving force [4]. The difference in solution concentrations or osmotic pressures of the feed solution and draw solution is therefore minimised by the migration of water molecules through the semi-permeable membrane.

FO water flux is calculated via measuring the variation in the weight of the feed solution or draw solution as shown in the following equations [5]:

$$J_w = \frac{\Delta weight}{water\ density \times membrane\ effective\ area \times \Delta time} \quad (1)$$

$$J_w = \frac{\Delta m}{1000 \times A \times \Delta t} \quad (2)$$

Eq. 1 could be simplified as Eq. 2 in which the density of water is assumed as 1000 g L-1 [6].

Many researchers have shown great interest in applying FO process for seawater desalination [5,7] and water treatment. In the field of water technology, reverse osmosis (RO) is a well-known membrane technology as compared to FO technology. Nevertheless, some of the attractions and benefits offered by FO technology have generated increasing interest among the researchers. Table 1 summarizes the comparisons between FO and RO process. Generally, RO uses high hydraulic pressure as driving force to produce high quality water while nearly all colloidal or dissolved matters are being rejected [8]. Several attempts to use FO technology for concentrating or dewatering desired liquid stream had also been performed by some researchers [9–11].

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Table 1 Summary of the comparisons between FO and RO process

Items	Forward Osmosis	Reverse Osmosis
Driving force	Osmotic pressure difference	High hydraulic pressure
Energy consumption	Low energy consumption due to very low hydraulic pressures [12]	High energy consumption for high hydraulic pressure supplied [13]
Membrane fouling	Low membrane fouling propensity and is considered reversible [14]	High membrane fouling propensity and may require chemical cleaning [14]
Equipment set-up	Peristaltic pumps, silicone tubing [15]	High pressure pump, high pressure resistant pipelines [13]
Cost	Low operating and investment costs [13,16]	High operating and investment costs [13]

This paper is an attempt to explore FO process for concentrating sodium succinate solution. Osmotic pressure of selected organic salt, inorganic salt and neutral compounds was simulated and compared. Water flux permeation of pure water stream and sodium succinate feed solutions were conducted using FO CTA membrane. Conductivity characteristic curve and the draw solution dilution effect were also investigated.

2. Materials and Methods

2.1 Chemicals and membrane

Sodium acetate, sodium formate, and sodium chloride were selected as draw solution. Ultrapure water with a high resistivity of 18.2 MΩ·cm was supplied by lab water system (arium® pro ultrapure water systems, Sartorius, Germany). All solutions in the present study were prepared by dissolving the solutes in ultrapure water. The commercial cellulose triacetate membrane (CTA-ES) supplied by Hydration Technologies Innovations (Albany, OR, USA) as flat sheet was employed in this study.

2.2 Bench-scale experimental set-up

Bench-scale FO experimental setup consisted of a cross flow FO cell (Sterlitech CF042 Cell) was used to perform FO experiments. Fig. 1 illustrates the experimental apparatus of the bench-scale FO system. The area of FO membrane was 42 cm^2. The membrane orientation was arranged in AL-FS mode in which the active layer of the membrane is facing the feed solution. Peristaltic pumps (BT600-2J, LongerPump, China) were used to circulate the feed solution and draw solution in co-current mode on each side of the membrane. The solution flow rate was maintained at 0.53 L/min. The feed solution weight was measured using a weighing balance (PGL10001, Adam, United Kingdom). Conductivity meter (Mi306, Martini, Romania), ion chromatography (858 Professional Sample Processor, 882 Compact IC Plus, Metrohm, Switzerland), and HPLC (Dionex Ultimate 3000, Thermo Scientific, USA) were used to analyse the ion transport behavior.

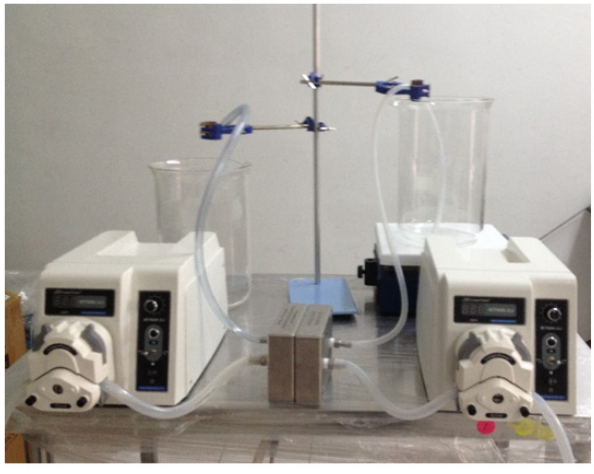


Figure 1 Bench-scale forward osmosis experimental setup

3. Results and Discussion

3.1 Osmotic pressure of different types of draw solution

The separation of water via FO process is driven by osmotic pressure difference across the semi-permeable membrane. Hence, it is crucial to ensure that appropriate draw solution is being selected. Fig. 2 presents the osmotic pressure of the selected draw solution with the concentration ranging from 0.20 mol/L to 2.00 mol/L. The osmotic pressure was simulated using OLI Stream Analyzer 9.2.2 (OLI Systems Inc., Morris Plains, NJ, USA). Several types of draw solution were investigated: sodium chloride, sodium acetate, sodium formate, ethylene glycol, and sodium lactate. The selected draw solutions can be divided into different categories. Sodium chloride is an inorganic salt compound that is widely used as draw solution in FO process. Sodium acetate, sodium formate, and sodium lactate are organic salt compound. They are often produced via various microbial fermentation processes [17–19]. Ethylene glycol is a neutral compound and thus it does not dissociate

in an aqueous solution. According to Fig. 2, osmotic pressure increases with the elevated draw solution concentrations. It was found that ethylene glycol solution demonstrated the lowest osmotic pressure among all the species. Unlike neutral solution, salt solutions such as sodium chloride, sodium acetate, sodium formate, and sodium lactate are able to form ions in an aqueous solution, and hence generating higher osmotic pressures [20]. Additionally, greater osmotic pressure is also shown by inorganic salt sodium chloride as compared to the organic salt compounds at higher concentrations above 1.4 mol/L.

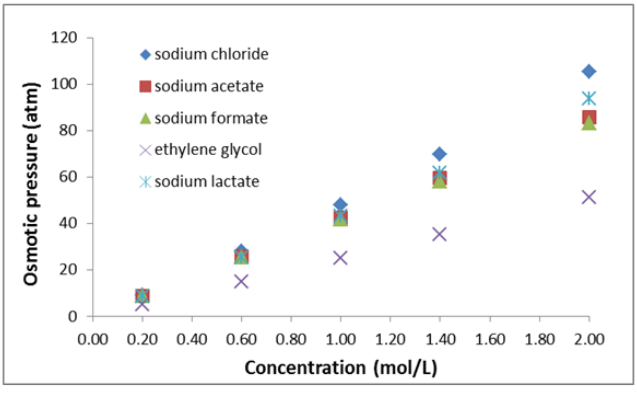


Figure 2 Simulated osmotic pressure of selected draw solutions at various concentrations using OLI Stream Analyzer 9.2.2.

3.2 Water permeability

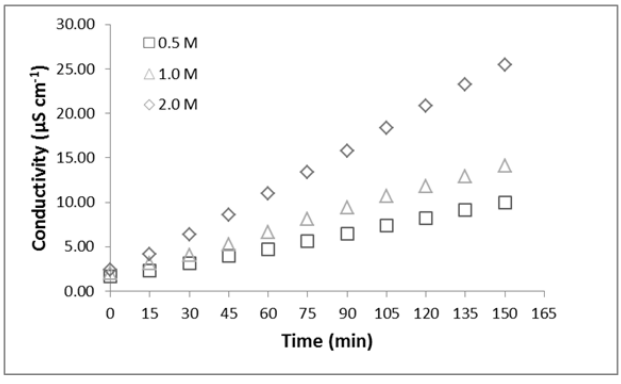
Two types of organic salt draw solution, sodium acetate and sodium formate, were tested for FO process performance using ultrapure water as the feed solution. Water permeability was evaluated using water flux as shown in Table 2. Comparisons of water flux were made with the neutral compound (ethylene glycol) and inorganic salt compound (sodium chloride) obtained from Yong et al. [20]. It can be seen that the experimental water flux obtained in the study increased with the increase of draw solution concentration. For all draw solutes, relatively higher osmotic pressures were generated at increasing concentration (Fig. 2). As a consequent, greater number of water molecule was transported across the FO membrane. Both sodium acetate and sodium formate were able to generate comparable osmotic pressures at 1.0 mol/L and 2.0 mol/L concentrations and thus the water fluxes differences between sodium acetate and sodium formate draw solution were not significant. According to Table 2, the water fluxes reported in the literature for sodium chloride draw solution were higher than the organic salt draw solution obtained in the study. Nevertheless, sodium formate and sodium acetate have exhibited competitive performances as potential draw solutions. Overall, all selected draw solutions have shown significantly higher water fluxes than the neutral solute ethylene glycol draw solutions at same concentrations.

Table 2 Comparison of experimental water flux for organic salt draw solution with sodium chloride and ethylene glycol draw solutions results from Yong et al. [20]

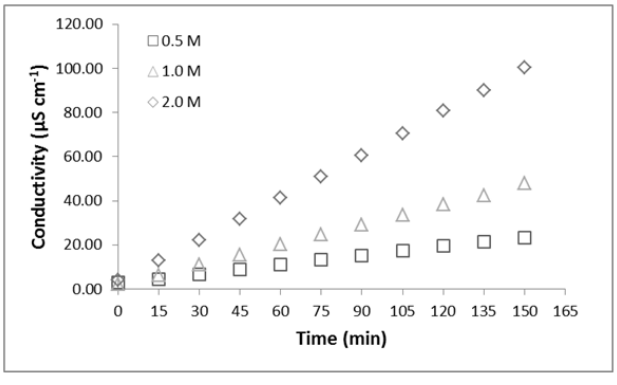
Draw solution	Water flux, J_w (L/ m^2.h)	
	1.0 mol/L concentration	2.0 mol/L concentration
Sodium acetate	5.07	7.30
Sodium formate	4.96	7.36
Sodium chloride	<10.0	<14.0
Ethylene glycol	<3.0	<5.0

3.3 Electrical conductivity and reverse draw solute permeation

Reverse draw solute permeation or draw solute leakage is another significant concern in FO process. In the evaluation of FO performance, it is vital to investigate the draw solute permeation across the semi-permeable membrane as it is an undesired phenomenon. In most of the FO experiments reported in previous literatures, draw solute leakage was inevitable [20,21]. In this study, conductivity measurements were performed to investigate draw solute permeation for each of the organic salt draw solutions. Fig. 3 presents the electrical conductivity generated at feed solution as a function of time. Similar trends were noted using different types of draw solution at varying concentrations. At higher draw solution concentration, relatively higher conductivity was observed. Since ultrapure water was used as the feed solution, the generation of conductivity at feed solution compartment clearly showed that the solute leakage from draw solution compartment was observed. The increment of number of charged ions in the feed solution led to an increase in electrical conductivity. Comparing sodium acetate and sodium formate solution, it was found that higher conductivity was generated by sodium formate draw solution, which is attributed to its smaller molecular size. Sodium formate draw solution at 2.0 M concentration exhibited the highest conductivity of 100.2 mS/cm. As for sodium acetate solution, the reverse solute permeation remained at much lower level for all concentrations employed.



(a)



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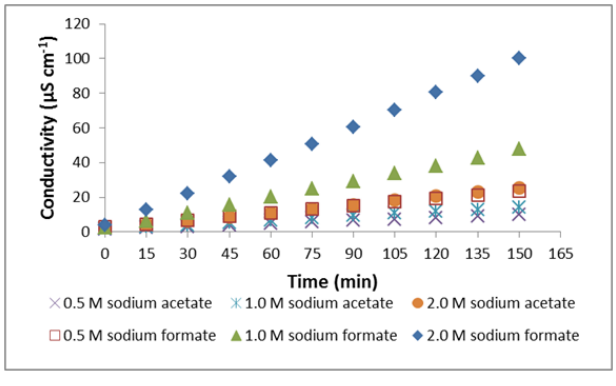

(c)

Figure 3 (a) Experimental conductivity generated using sodium acetate as draw solution. (b) Experimental conductivity generated using sodium formate as draw solution. (c) Combined curves of experimental conductivity at varying draw solution concentration.

3.4 Draw solution dilution effect

As presented in the earlier section, the water transport occurred as a result of osmotic pressure gradient. Despite of the increase of feed solution concentration, the permeation of water molecule across the FO membrane joining the draw solution compartment has resulted in the dilution of draw solution. It is evident from Table 3 that the concentrations of draw solution were diluted during the FO experiments for both sodium acetate and sodium formate solution after the duration of 150 min. The dilution effect was higher for sodium acetate as compared to the sodium formate solution. This is particularly significant at 2.0 mol/L initial solution concentration in which the final concentration of sodium formate and sodium acetate was 1.726 mol/L and 1.565 mol/L, respectively. Since the water permeability in FO is induced by the effective osmotic pressure difference across the semi-permeable membrane, the dilution of the draw solution may reduce the water transport flux of the process resulting in longer experimental duration for targeting concentration. In general, solution with higher concentration and greater osmotic pressure could induce higher water transport flux but also led to higher dilution rate of draw solution. As long as the water flux does not show any sign of apparent deterioration, replenishment of draw solution may not be necessary.

Table 3 Dilution effect of sodium acetate and sodium formate draw solutions in FO experiments

Initial draw solution Concentration (mol/L)	Diluted concentration (mol/L)	
	Sodium formate	Sodium acetate
0.50	0.456	0.399
1.00	0.876	0.856
2.00	1.726	1.565

3.5 Sodium succinate concentrated using sodium chloride draw solution

The concentration of sodium succinate feed solution were carried out using 1.0 mol/L sodium chloride draw solution. Sodium chloride is cheap and can be easily obtained from the market [22]. The measured water flux from the experiment is depicted in Fig. 4. According to the results, the average water flux obtained from the experiment was 5.03 L/m^2.h. Comparing to the pure water flux using sodium chloride draw solution as presented in the previous section (Table 2), water flux reduction was observed in this study using sodium succinate feed solution. Theoretically, feed solution is a solution of low solute concentration (low osmotic pressure) for which the net osmotic pressure across the FO membrane might be slightly reduced.

Reverse chloride permeation and succinate ion diffusion were also studied. Figs. 5 and 6 illustrate the chromatograms

obtained from the sample analysis of FO feed and draw solution, respectively. According to Fig. 5, chloride peak is identified at the retention time of 4.60 min. The concentration of chloride ion found in the feed solution was 30.51 ppm. Encouragingly, succinate ion with the retention time of 14.5 min was not found in the draw solution chromatogram (Fig. 6). Hence, the concern on the diffusion of succinate ion from the feed solution across the FO membrane to the draw solution was eliminated.

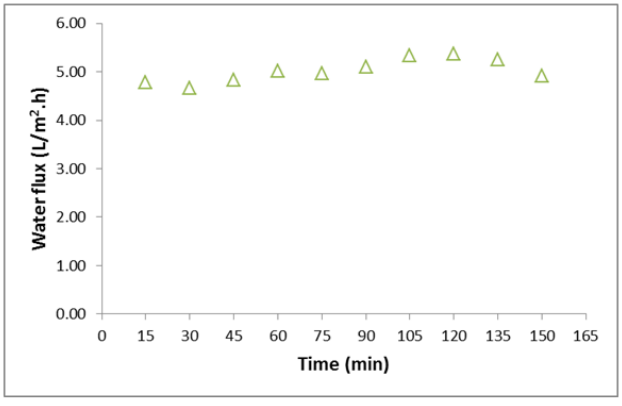

Figure 4 Experimental water flux as a function of time for concentrating 10 g/l sodium succinate using 1.0 mol/L sodium chloride draw solution.

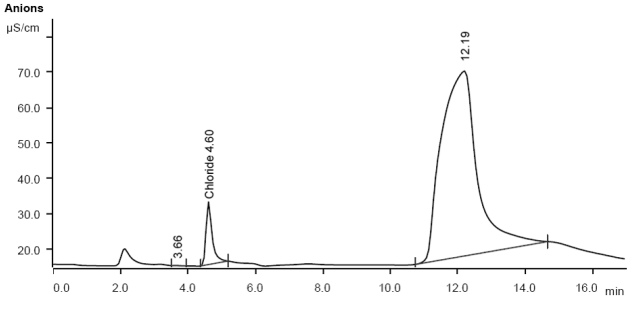

Figure 5 Chromatogram of feed solution analysis using IC (858 Professional Sample Processor, 882 Compact IC Plus, Metrohm, Switzerland).

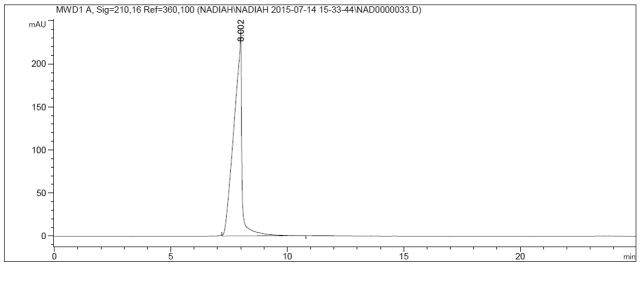

Figure 6 Chromatogram of draw solution analysis using HPLC (Dionex Ultimate 3000, Thermo Scientific, USA).

4. Conclusion

Osmotic pressure has been considered as an ultimate parameter concerning FO process. It is evident from the draw solutions comparative study that neutral compound such as ethylene glycol was unlikely to induce significant water flux owing to the much lower osmotic pressure generated. On the contrary, ionic salts compound appeared to be more promising in the separation of water molecule from the feed solution. FO performance of organic salts draw solution (sodium acetate and sodium formate) has been encouraging. The reverse draw solute permeation of sodium acetate and sodium formate was found using conductivity measurement. Consistent conductivity curves were observed indicating increment of reverse solute permeation but overall the draw solute leakage remained at low level. The draw solution dilution effect was more pronounced at high solution concentration attributed to greater water transport flux. Considering water transport flux and reverse chloride permeation performances, FO process is feasible for concentrating sodium succinate solution.

Acknowledgements

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