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Effects of feed and draw solution temperature on the performance of Aquaporin HFFO.6 membrane in forward osmosis

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Abstract

Recently, forward osmosis (FO) has attracted attention in many potential applications including food processing, fertilizers and manufacturing industries. This study investigates the effects of feed solution (FS) and draw solution (DS) temperature on the water flux, reverse salt flux, and specific reverse salt flux. The temperature of both the DS and FS were varied at the same time. Four typical temperatures such as 20 °C, 25 °C, 30 °C and 35 °C were selected to maintain at FS and DS sides, respectively, for each iteration. Except for the temperature, the other operating conditions like concentration, flow rates, and the type of membrane used were not varied in this experiment. The experiments were performed with tap water as FS and 1.5 M of NaCl as DS. The flow rates of the DS and FS were maintained at 15 L min^{-1} and 25 L min^{-1}, respectively. The membrane used was the hollow fiber forward osmosis (HFFO.6) membrane procured from Aquaporin A/S, Denmark. The results showed that as temperature increased from 20 °C to 35 °C, the water flux, reserve salt flux (RSF), and specific reverse salt flux were enhanced. This was due to the enhanced diffusion coefficient of both DS and FS on increasing the temperature. This further reduces the concentration polarization and in turn augments the water flux. However, consequently, reverse and specific reverse solute flux also increased on temperature, which is not desirable for an efficient FO system. Hence, it is recommended to operate the FO at a minimum required temperature considering the other influencing other operational parameters such as specific reverse solute flux, recovery and rejection percentage.

Keywords: Water flux of FO; Temperature; Reverse salt flux; Specific reverse salt flux

1. Introduction

Forward osmosis (FO) is a water filtration process that uses the osmotic pressure difference as a natural driving force to transport only water from the low-concentration feed solution (FS) to the high-concentration draw solution (DS). In comparison with the other pressure-driven process, like reverse osmosis (RO), FO behaves better in many aspects, such as low fouling propensity, less energy consumption, and high salt rejection. However, high reverse salt flux (RSF) and specific reverse solute flux (SRSF) are still a serious problem to overcome in the FO process. RSF, water flux and specific reverse salt flux are affected when the temperature is varied. Therefore, temperature plays an important role in the performance of the FO process.

Recent research focused on the effects of the temperature of water flux of the FO process. For example, Feng et al. [1] experimentally investigated the effect of temperature on the performances of the FO process using ammonium bicarbonate as a draw solution. It was found that the water flux, reverse draw solute flux and forward rejection of feed solute increased when both the DS and FS temperature increased from 20℃ to 40℃. Jalab et al. [2] evaluated the influence of the flow rate and temperature on the performance of the osmotic concentration process using hollow fiber forward osmosis membrane. It was found that the most appropriate operating condition was DS flow rate: 0.35 L.min^{-1}, FS flow rate: 1.10 L.min^{-}1. The optimum temperature recommended was 27 °C on both FS and DS sides. The highest recovery of 84.5% and water flux of 1.82 LMH can be achieved under these working conditions. Zhao and Zou [3] evaluated the effects of temperature on membrane scaling and fouling in the FO process. It was found that the initial fluxes, water recoveries, and concentration factors were enhanced at higher temperatures. However, the study

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also reported that the enhanced temperature consequently increased the fouling and scaling of the FO membrane. Phuntsho et al. [4] and Sanahuja-Embuena et al. (2019) [5] investigated the effects of operating conditions of feed and draw solutions on the performance of the FO process. The results showed that increasing the temperature from 25 °C to 45 °C, enhanced the water flux.

The above studies have mainly focused on the good impacts of increasing temperature i.e. effects of temperature on water flux. But the consequence of enhancing the temperature did not get enough attention from most of the research studies. This research gap has been addressed in this paper. The main objective of this study was not only to evaluate the impacts of the temperature on the water flux but also the other performance parameters such as reverse salt flux (RSF) and specific reverse salt flux (SRSF) in FO.

2. Methodology

The membrane used for all experiments is the aquaporin hollow fiber forward osmosis (HFFO.6) membrane which was procured from Aquaporin A/S, Denmark. FO mode (active layer facing the feed) was preferred as a more stable mode and optimum mode to reach higher water flux mode rather than the pressure retarded (PRO) mode (support layer facing the feed) due to the reduced dilutive internal concentration polarization [5-8]. Hence, the FO mode was used in this experiment, the FS faced the membrane's active layer, and the DS faced the support layer of the membrane.

The bench-scale FO setup was developed at the University of Birmingham, UK. Before the experiment started, the HFFO module was rinsed with DI water for 30 minutes on both the feed and draw sides at the flow rate of 5 L/h. Furthermore, the flow direction was chosen to be in counter-current mode in this HFFO.6 module. Counter-current flow was achieved using two peristaltic pumps (once on each side i.e. FS and DS) to pump the FS into the semi-permeable membrane (HFFO.6) in the opposite direction of the DS flow. The reason for this choice was that the counter-current operation maximizes the osmotic gradient (driving force) across the full length of the HFFO.6 and hence, the maximum water flux can be achieved. As shown in Fig. 1, the membrane was positioned vertically with inside-out filtration, the FS was applied on the inner (lumen) side and the DS was applied on the outer (shell) side of the HFFO.6 membrane. During the process, the feed solution gets concentrated and the draw solution gets diluted.

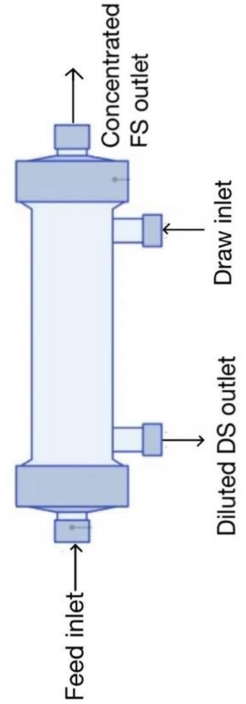

Fig. 1. HFFO.6 membrane showing the flow directions of feed and draw solutions.

The experiments were performed with tap water as FS with a flow rate of 25 L/h and with 1.5 M of NaCl as DS with a flow rate of 15 L/h. Thus, a concentration difference of 1.5 M of NaCl was maintained throughout the experiment. During the experiment, the concentration and flow rate of the DS and FS were not changed. Fig 2. shows a schematic layout of the FO set-up in the laboratory.

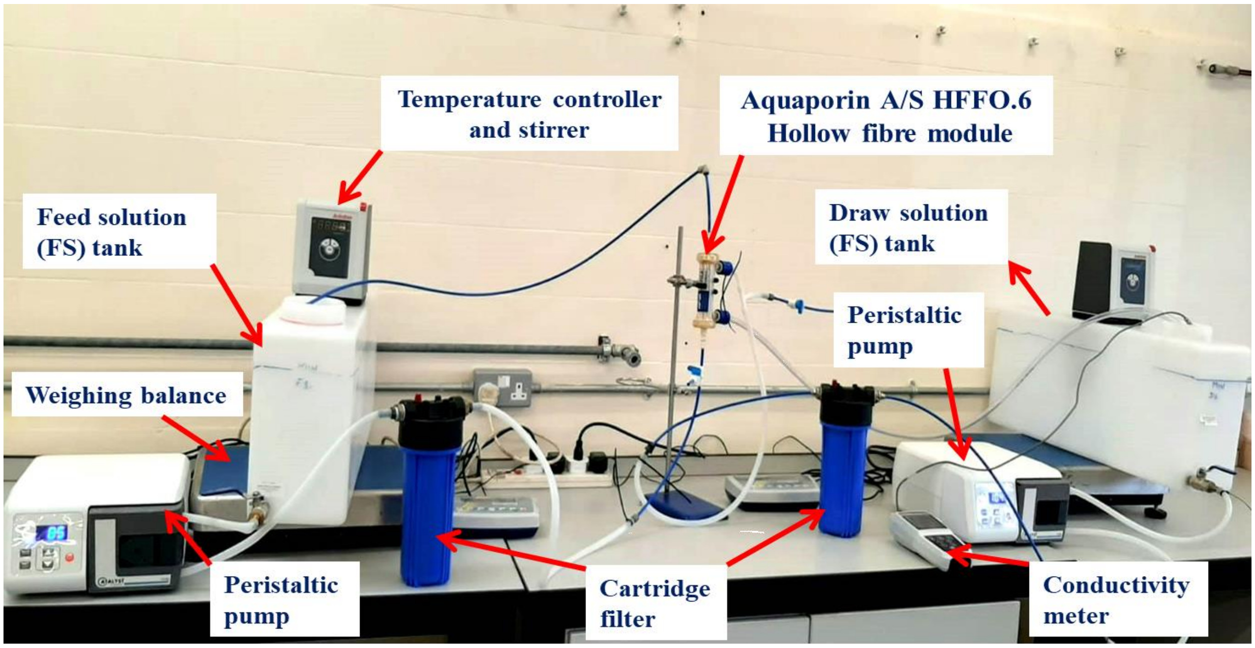

Fig. 2. The bench-scale FO system developed at the University of Birmingham, UK.

This FO system also includes components such as weighing balances, cartridge filters, conductivity meters, temperature regulators and stirrers. The balances were used to measure the variations in the weight of the FS and DS. Two temperature regulators were to regulate and maintain the temperature both at DS and FS separately during the experiment. Two peristaltic pumps were used to control the flow rates of the DS and FS. Moreover, to ensure the homogenous mixture of FS and DS stirrers were used, which constantly stird the FS and DS. The performance parameters such as water flux, reverse salt flux and specific reverse salt flux were obtained by the following equations (Eq 1,2 and 3):

Water flux (J_w), reverse salt flux (J_s), and the specific reverse salt flux (SRSF) are calculated by [9-11]:

$$J_W = \frac{Vf_{initial} - Vf_{final}}{A \times t} \qquad (1)$$

$$J_S = \frac{c_{final}Vd_{final} - c_{initial}Vd_{intial}}{A \times t} \qquad (2)$$

$$SRSF = \frac{J_s}{J_w} \qquad (3)$$

where $Vf_{initial}$ and Vf_{final} are the initial and final volume of feed in L. $C_{initial}$ and C_{final} are the initial and final concentration of draw solution in moles (M). $Vd_{initial}$ and Vd_{final} are the initial and final volume of draw solution in kg or L, A is the membrane area in m^2 and t is the duration of the experiment in minutes.

3. Results and discussion

The influence of various temperatures on water flux, reverse salt flux (RSF), and specific reverse salt flux is discussed below. The FO experiments were carried out at 20 °C, 25 °C, 30 °C, and 35 °C. It is clear from Fig. 3 that water flux increased significantly as the temperature increased from 20 to 35 °C. The percentage increment in water flux for every five degrees increment from 20 °C to 35 °C was 2.5%, 11% and 12%, respectively. Hence, the highest increment in the water flux was a 12% increment from 30 °C to 35 °C, the water flux increased from 19.67 $L.m^{-2}.h^{-1}$ to 22 $L.m^{-2}.h^{-1}$. The results showed that operating the FO process at an elevated temperature will be ideal to absorb more freshwater from FO rather than operating at a lower temperature. The experiment results have confirmed that the water flux is directly proportional to the temperature of FS and DS [1-5].

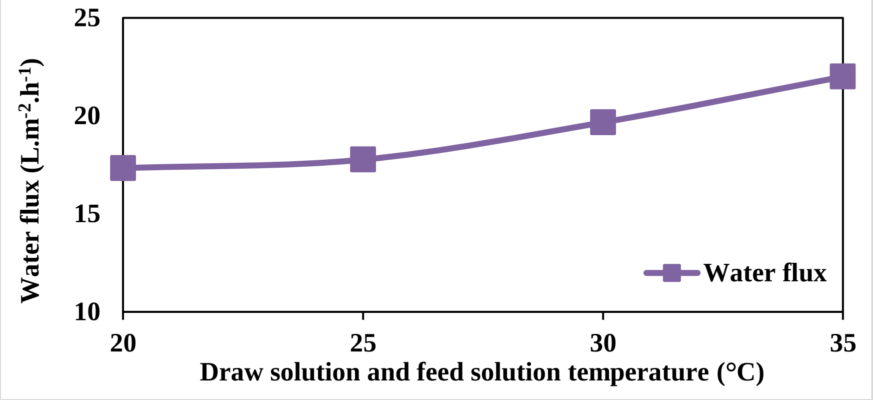

Fig. 3. Effects of increasing temperature on the FO water flux with FS as tap water (at 25L/h) and DS as 1.5 mol NaCl (at 15L/h)).

The main reason for the increasing trend of water flux concerning temperature is that at a higher temperature, the thermodynamic properties such as osmotic pressure, diffusion coefficient, and viscosity of FS are affected. It was found that the osmotic pressure and diffusion coefficient increased with an increase in temperature, but the viscosity decreased. The improvement of the above-mentioned parameters indicates that more pure water can permeate from the FS to DS. Thus, higher water flux is achieved. The increment in diffusion coefficient will decrease the solute resistivity which will then reduce internal concentration polarization (ICP) effects [4]. Moreover, viscosity decreases with the increasing rate of movement of water molecules, and the ICP effect will also decrease. As the water flux decrement is mainly due to ICP [3], an increase in temperature has a good impact on all the properties mentioned above. In general, the higher temperature in the FO process is a good way to increase the water flux. However, at higher temperatures, although the water flux can be increased, this will also accelerate the deterioration of the membrane and will in turn enhance the RSF (Fig. 4) [2].

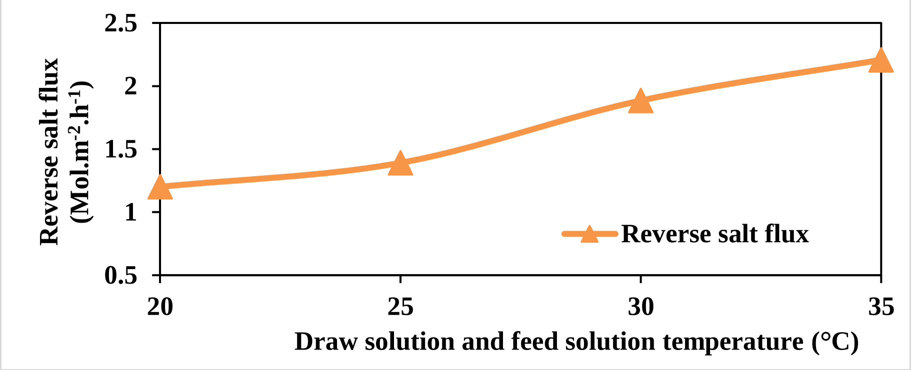

Fig. 4. Effects of increasing temperature on the FO reverse salt flux (RSF) with FS as tap water (at 25L/h) and DS as 1.5 mol NaCl (at 15L/h)).

RSF is a measure of the passage of salts diffused from the DS through the membrane to the FS over the unit membrane area per unit of time. Fig 4 shows the changes in RSF when the temperature of FS and DS increased from 20 °C to 25 °C, 30 °C and 35°C. The results showed that increasing the temperature of the FS and DS increased the RSF in the FO process. The most significant increase in reverse salt flux was when the temperature was enhanced from 30 °C to 35 °C, the RSF increases from 1.88 $Mol.m^{-2}.h^{-1}$ to 2.20 $Mol.m^{-2}.h^{-1}$. As the RSF increased at elevated temperatures, the linear relationship between the water flux and RSF can be concluded. This linear relationship was also proved by Heo et al. [12-13]. However, higher reverse salt flux is undesirable as it decreased the concentration of the DS by reducing the resistivity of DS (NaCl). As the concentration of DS is decreased, the driving force absorbing the pure water from FS to DS was declined, which results in reducing the water flux in the FO process [14-16].

Specific reverse salt flux (SRSF) is the ratio between the reverse salt flux and water flux as shown in Eq 3. SRSF is used to measure the amount of the draw salt lost per litre of the pure water produced during FO. This SRSF should be lower for an efficient FO system [17-18]. Fig.5 shows the variation of the SRSF with the DS and FS temperature increase from 20 °C to 35 °C. The SRSF was raised from 0.026 g/L to 0.05 g/L. The result showed that increasing both the temperature of DS and FS will have a negative impact on reducing SRSF.

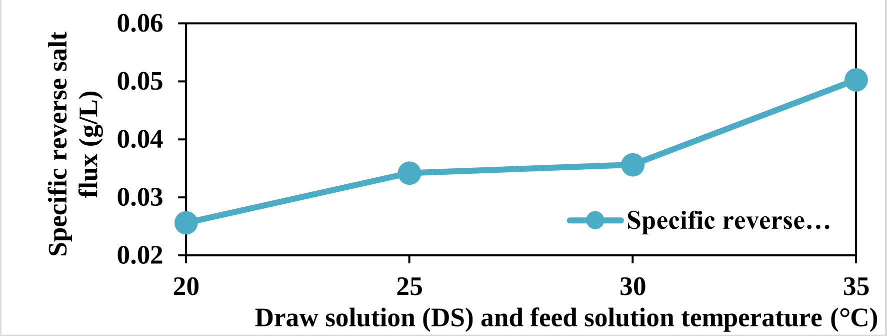

Fig. 5. Effects of increasing temperature on the specific reverse salt flux (SRSF) with FS as tap water (at 25L/h) and DS as 1.5 mol NaCl (at 15L/h)).

4. Conclusion

The influence of temperature on the performance of the FO process has been investigated in the HFFO.6 membrane, with a concentration difference of 1.5 M of NaCl between the DS and FS. Water flux, reverse salt flux (RSF) and specific reverse salt flux (SRSF) are essential operating parameters in the FO process. As the temperature of FS and DS rose from 20 °C to 35 °C, the water flux increased significantly thus having a beneficial effect on the FO process. But an increase in reverse salt flux and specific salt flux was also observed on increasing the temperature. Hence, it is concluded that even higher temperature enhanced water flux, it had an adverse effect on other parameters like reverse salt flux, and specific reverse salt flux. It is thus recommended to operate the FO system at the minimum required optimum elevated temperature (for example 25°C or 30°C), to get maximum water flux, together with minimum RSF and SRSF.

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