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Application of sodium bicarbonate as draw solution in forward osmosis desalination: influence of temperature and linear flow velocity

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ABSTRACT

Forward osmosis (FO) has been recently drawn the attention as an emerging sustainable desalination technology. This article focuses on the effect of temperature and linear flow velocity of feed and draw solution on permeation of water through forward osmosis membrane, using FO process. A bench-scale FO setup was used, in which sodium bicarbonate ($NaHCO_3$) and sodium chloride (NaCl) were used as draw solutions. The draw solutions were initially compared for their permeation flux at the same osmotic pressure, using distilled water as feed solution. However, for FO desalination of a model saline feed solution, just, $NaHCO_3$ draw solution was employed. Increasing the temperature from 25 to 45°C led to 33 and 30.64% water flux increase for NaCl and $NaHCO_3$ systems, respectively. Higher permeability dependency of $NaHCO_3$ on the temperature would be attributed to the larger effect of temperature on its molecular diffusion coefficient in the membrane. By equally increasing the linear velocity of flow in the feed and draw solution sides of the membrane, from 0.088 to 0.231 m s^{-1}, the water flux was enhanced. This would be due to the reduction of external concentration polarization effect on both interfaces of the membrane. As expected, for the saline feed water, the water flux had a 1.7-fold reduction, as compared to the distilled water.

Keywords: Forward osmosis; Desalination; Sodium bicarbonate draw solution; Temperature; Linear velocity flow

1. Introduction

How to deal with the water shortage and, on the other hand, water demand increase is a critical issue in many parts of the world. The availability of fresh water in these regions determines the lifestyle, health, and economic and social standards [1–3].

In the last two decades, the treatment of unconventional waters including wastewater and saline and brackish waters has been taken into consideration as viable solutions to deal with the very near future water demand increase. For saline and brackish water, achieving sustainable desalination methods, in terms of energy, economy, and environment, is of great importance. The common desalination methods include multistage flash

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distillation, multistage distillation, vapor compression, and reverse osmosis (RO). Currently, the main desalination process used throughout the world is reverse osmosis which accounts for the production of more than 80% of the water in the world [4,5].

The problems in the pressurized membrane processes, such as reverse osmosis, include high energy consumption, relatively high price, low water recovery (35–50% for sea water) as well as the discharge of highly concentrated salt solution into the sea. These problems, in addition to its environmental damages, limit its application to coastal areas. Definitely, the future of desalination process depends on energy price and technology. Therefore, researchers are searching for a suitable technology with higher recovery and lower price to produce drinking water from all type of saline water and reuse water sources [6,7]. Forward osmosis (FO) is one of the technologies that could obtain promising achievements over the last few years. FO, with its many advantages and capabilities, would be a suitable alternative method over its rivals, RO and the other high-pressure membrane processes, due to its low energy consumption, high water recovery and low fouling [8].

So far, the application of FO has been studied in desalination of brackish water and seawater [9,10], wastewater condensing [11,12], food and pharmaceuticals processing [13,14], electricity generation [8,15], and slow-release of drugs [16,17]. Two main challenges affecting the technology development of FO are improvement of the selectivity of semi-permeable membrane and identification of the appropriate draw solution [13,18–22].

Given that the forward osmosis is not a final process, the draw solution should be inert, stable, nontoxic, and also should be separated easily without being consumed in the recycling process. Many compounds, as draw solutions, and the relevant separation processes have been proposed by researchers during recent years for the production of drinking water. Thermal processes were used for the separation and recycling of volatile minerals draw solutions such as sulfur dioxide and ammonium bicarbonate [23,24]. For sugars, such as sucrose and fructose as nutritious solution, no separation process was required [25,26]. For hydrophilic nanoparticles, a magnetic field or ultrafiltration was employed for their separation [27]. Reverse osmosis and nanofiltration were applied for regeneration of mineral salts such as sodium chloride, ammonium chloride, and magnesium chloride [18,28]. More recent proposed draw agents are polymeric hydrogels [29], polyelectrolytes [19,20], hexavalent phosphazene salts [21], and switchable polarity solvents [22].

Sodium bicarbonate ($NaHCO_3$) has been offered as an appropriate draw solution due to its low specific cost for development of osmotic pressure [18]. Achill et al. [18] evaluated the hybrid system of forward osmosis–reverse osmosis and introduced sodium bicarbonate as a draw solution with appropriate flux and low reverse diffusion. Considering above work, however, a little work has been reported about the influence of process parameters on the performance of $NaHCO_3$ in FO.

In forward osmosis, parameters such as osmotic pressure, solubility, mass transfer and, particularly, concentration polarization are related to the temperature and the linear flow velocity. Therefore, in this article, the influence of temperature and circulating linear flow velocity of the draw solution and feed on the performance of FO process are investigated, using sodium bicarbonate and sodium chloride as draw solutions. The draw solutions of $NaHCO_3$ and NaCl are initially compared, using distilled water as feed. However, the results of water flux as a function of time are also presented for desalination of a model salty feed water, using sodium bicarbonate as draw solution.

2. Materials and methods

2.1. Materials

Sodium bicarbonate ($NaHCO_3$) and sodium chloride (NaCl) in laboratory grade were obtained from Merck Co. As feed in the experiments, distilled water and NaCl solution, the latter with the concentration equivalent to the osmotic pressure of the Caspian Sea (a large lake located in northern part of Iran) were prepared. Considering the location, the salinity of the Caspian Sea varies between 13,000 and 16,000 mg L^{-1} which is equivalent to osmotic pressure of 10–15 bar. Therefore, Caspian Sea water salinity was simulated by preparing 0.33 M NaCl solution, which leads to an osmotic pressure of 15 bar.

$NaHCO_3$ solutions in concentration of 0.72 and 1.16 M, and 0.6 M NaCl solution were used as the draw solutions. The osmotic pressures of these solutions at different temperatures are presented in Table 1 [18].

2.2. Membrane and membrane orientation

In all experiments, flat-sheet cellulose triacetate (CTA) FO membrane with embedded polyester screen support (CTA-ES Membrane, Hydration Technologies Inc.) was used in normal orientation (draw solution in contact with the active layer of the membrane) as

Table 1
The osmotic pressure of the applied draw solutions [18]

Draw solutions	Osmotic pressure (bar)		
	25℃	35℃	45℃
$NaHCO_3$, 0.72 M	26.91	28.10	29.15
$NaHCO_3$, 1.16 M	43.86	43.78	45.12
NaCl, 0.60 M	27.44	28.18	28.90

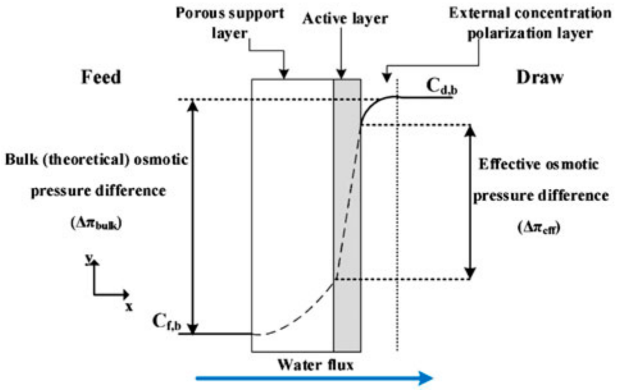

Fig. 1. Normal orientation in forward osmosis using an asymmetric membrane, where $C_{f,b}$ is the bulk concentration of the feed solution, and $C_{d,b}$ is the bulk concentration of the draw solution.

shown in Fig. 1. By this orientation, it was expected that the internal concentration polarization is minimized and higher water flux is obtained [30].

2.3. Test setup and FO experiments

Experiments were carried out using a bench-scale FO membrane cell system (Fig. 2). A plate-and-frame membrane module was installed in the system, maintaining the membrane with 95.76 cm^2 effective surface area. To reduce the stresses exerted on the membrane, co-current flows of feed and draw solutions were aligned into the cell, using low pressure magnetic pumps (MP-045B, CSE Co., Korea). The flux of draw solution was obtained, continuously, by weight measurement of the permeated water, using a load cell (Model 640 single point, Revere Transducers Europe BV, Denmark) connected to a computer. In all experiments, the linear flow velocities of the feed and draw solutions were set, equally, at both sides of the membrane, on 0.088, 0.131, and 0.231 m s^{-1} (corresponds to flow rates of 2, 3, and 4 L min^{-1}, and Reynolds number of 924, 1,376, and 2,426). The temperature of draw and feed tanks was kept at 25, 35, and 45℃ (±1℃), using temperature sensor, heating coils, and thermostat. The volumetric flux of water through the membrane was calculated using Eq. (1):

$$\text{Volumetric flux of water} = \frac{\text{weight difference}}{(\text{Water density})\,(\text{membrane area})\,(\text{time difference})} \tag{1}$$

An electrical conductivity meter (LF96, WTW Co., Germany) was employed to measure the solution conductivity and consequently to calculate the reverse diffusion of salts to the feed solution, according to Eq. (2). The salt concentration change of the feed solution was determined each 15 min, using the calibration curve of concentration vs. the electrical conductivity:

$$\text{Salt reverse diffusion} = \frac{\text{Salt concentration} \times (\text{Initial volume} - \text{Permeation volume}) \times \text{Molecular weight of salt}}{(\text{Membrane area})\,(\text{Time difference})} \tag{2}$$

3. Results and discussion

3.1. Selection of the draw solution

In this research, sodium bicarbonate and sodium chloride, with appropriate osmotic efficiencies, were used as draw agents for investigating the FO process parameters. Sodium chloride was selected as the second draw solution for comparison.

3.2. The effect of temperature on water flux and reverse diffusion of draw solution

Many phenomena in FO depend on the temperature and affect the membrane performance. The most important ones are mineral solubility, osmotic pressure, mass transfer coefficient, concentration polarization, and water flux. The water flux of draw solutions

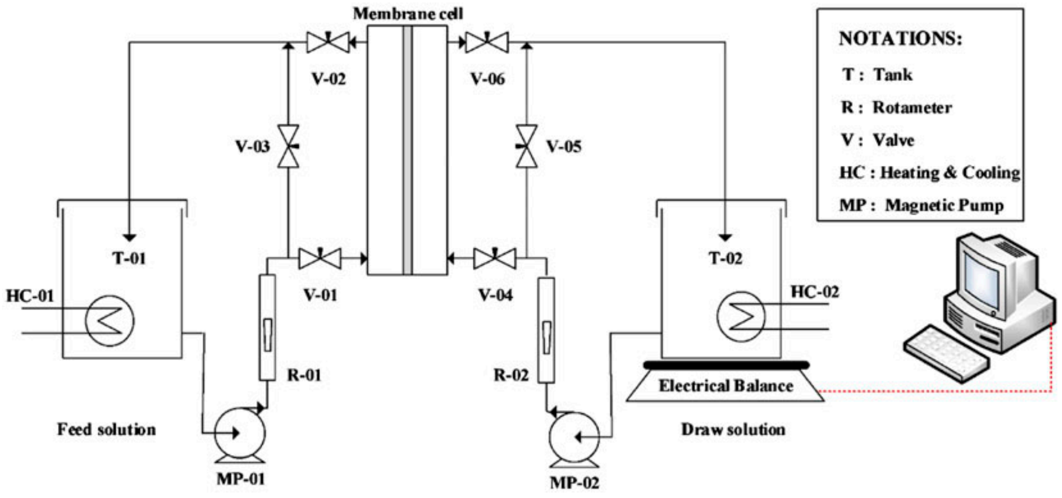

Fig. 2. Schematic diagram of the bench-scale forward osmosis system.

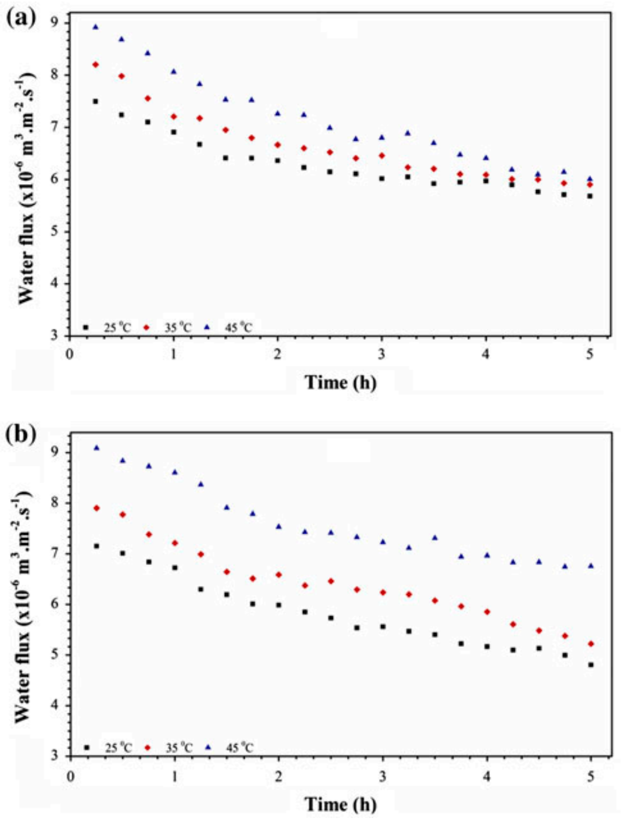

Fig. 3. The effect of temperature on water fluxes: (a) 0.6 M NaCl and (b) 0.72 M $NaHCO_3$ as the draw solutions; and distilled water as feed. The linear velocity flow was 0.131 m s^{-1}.

for 0.72 M $NaHCO_3$ and 0.60 M NaCl (with the identical osmotic pressure of approximately 28 bar) at temperatures between 25 and 45°C are presented in Fig. 3 and Table 2. As compared to $NaHCO_3$, the water flux was higher, for almost all experiments, when NaCl was used as draw solution, although the osmotic pressures were identical. As the results indicate, the water flux increases by increasing the temperature for both draw solutions. For instance, the water flux of 0.6 M NaCl showed an increase of 5.55 and 13.33% for 35 and 45°C, respectively, as compared to the flux at 25°C. Meanwhile, the water fluxes of 0.72 M $NaHCO_3$ draw solution indicated 10.32 and 30.64% increase at higher temperatures relative to 25°C. A 30 % flux increase had been, previously, reported for 1.5 M Na_2SO_4 draw solution and 0.06 M NaCl feed solution for temperature changes from 25 to 45°C [31]. The rising water flux with the increase in temperature can be attributed to lower viscosity, higher osmotic pressure, and enhancement of the water permeability. The exceeding flux using $NaHCO_3$ draw solution at higher temperatures can be attributed to its greater dissociation which leads to an increase in osmotic pressure and diffusion coefficient, as compared to sodium chloride. It can be also caused by the increase in permeability of ions in membrane layers and less reverse diffusion of $NaHCO_3$ and membrane clogging due to the larger hydrated ion size, as compared to sodium chloride [31–33]. The higher reverse diffusion reduces the effective osmotic pressure across the membrane and decrease the water flux.

By the increase of permeability, the reverse diffusion of solutes to the feed solution is also expected. The influence of temperature on the reverse salt diffusion is presented in Table 2 and Fig. 4 for both of draw solutions, when the temperature rises from 25 to 45°C. The reverse diffusion ratio of NaCl/$NaHCO_3$, within the studied temperature range, was 2.54, 3.12

Table 2
The average water flux (J_W) and the reverse diffusion of salt (J_S) for the employed draw solutions at different temperatures. Distilled water was used as the feed solution, while the initial concentrations of NaCl and $NaHCO_3$ were considered as 0.6 and 0.72 M, respectively

Temperature (℃)	Draw solution	Osmotic pressure (bar)	J_W ($\times 10^{-6}$ m^3 m^{-2} s^{-1})	J_S (g m^{-2} h^{-1})
25	NaCl	27.44	6.3	7.25
	$NaHCO_3$	26.91	5.81	2.85
35	NaCl	28.18	6.65	10.50
	$NaHCO_3$	28.10	6.41	3.36
45	NaCl	28.90	7.14	13.76
	$NaHCO_3$	29.15	7.59	3.99

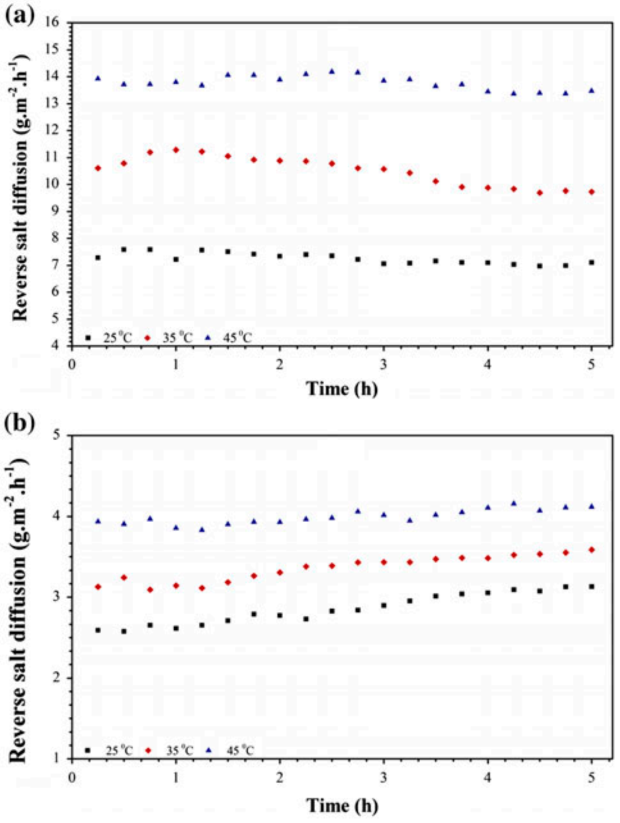

Fig. 4. The effect of temperature on salt reverse diffusion to the feed solution: (a) 0.6 M NaCl and (b) 0.72 M $NaHCO_3$ as draw solutions. The feed solution was distilled water and the linear velocity flow was 0.131 m s^{-1}.

and 3.45, respectively. The lower reverse diffusion of $NaHCO_3$, as compared to NaCl, would be related to the greater ionic size of this salt and the lower permeation through the membrane. The low reverse diffusion of $NaHCO_3$ is an advantage for FO process and has been also reported by other researchers [18]. The reverse diffusion of the salts through the membrane, showed a substantial increase for both draw solutions by increasing the temperature. For 0.72 M $NaHCO_3$ and 0.60 M NaCl, 1.40- and 1.9-fold increase in reverse diffusion was seen after 5 h, respectively, when temperature was changed from 25 to 45℃. These findings represented the higher dependency of permeability of $NaHCO_3$ to the temperature. Further to the reduction of osmotic pressure of draw solution, increase in the reverse diffusion causes contamination of the feed solution and intensified fouling of the membrane in the long term [33]. Therefore, although the higher temperature can cause higher water flux, it may also increase the possibility of membrane fouling.

3.3. The effect of linear velocity flow on water flux and reverse diffusion of draw solution

The effect of the fluid linear velocity, in the range of 0.088–0.231 m s^{-1}, on the water flux is presented in Table 3 and Fig. 5 for each of the tested draw solutions. The water flux increases with the increase in linear flow velocity for both draw solutions. Water flux augmentation was also reported for 0.1−2 M NaCl draw solutions and distilled water feed solution, when the linear velocity was increased from 0.222 to 0.978 m s^{-1} [34]. In fact, with the increase in the linear flow velocity, the Reynolds number of the fluid in the cell membrane channel increases. The higher flow turbulence reduces the external concentration polarization and pressure drop across the cell membrane and enhances the mass transfer coefficient which improves the system performance [7]. The water flux raise differed for the two draw solutions, 27.92 and 26.85% for NaCl and $NaHCO_3$, respectively, when the linear velocity was increased from 0.088 to 0.231 m s^{-1}. This finding shows nearly identical influence of linear velocity on water flux for both draw solutions.

The changes in the salt reverse diffusion of the draw solution with linear flow velocity are presented in Table 3 and Fig. 6. As it can be seen, the reverse diffusion of draw solution increases with the increase

Table 3
The water flux (J_W) for the employed draw solutions at different linear velocities flow. The feed solution was distilled water. Concentrations of NaCl and $NaHCO_3$ were 0.6 and 0.72 M, respectively; corresponding osmotic pressure was 28 bar

Linear flow velocity (m s^{-1})	Draw solution	J_W ($\times10^{-6}$ m^3 m^{-2} s^{-1})	J_S (g m^{-2} h^{-1})
0.088	NaCl	5.48	6.56
	$NaHCO_3$	5.14	2.62
0.131	NaCl	6.32	7.25
	$NaHCO_3$	5.81	2.85
0.231	NaCl	7.01	8.17
	$NaHCO_3$	6.52	3.22

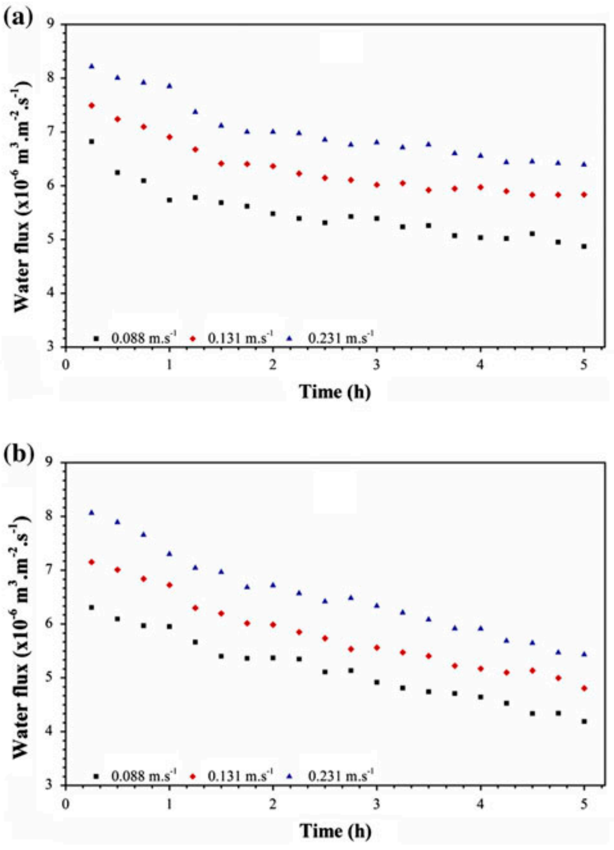

Fig. 5. The effect of linear velocity flow on water flux: (a) 0.6 M NaCl and (b) 0.72 M $NaHCO_3$ draw solutions at 35℃. The osmotic pressure of both draw solutions was 28 bar and the feed solution was distilled water.

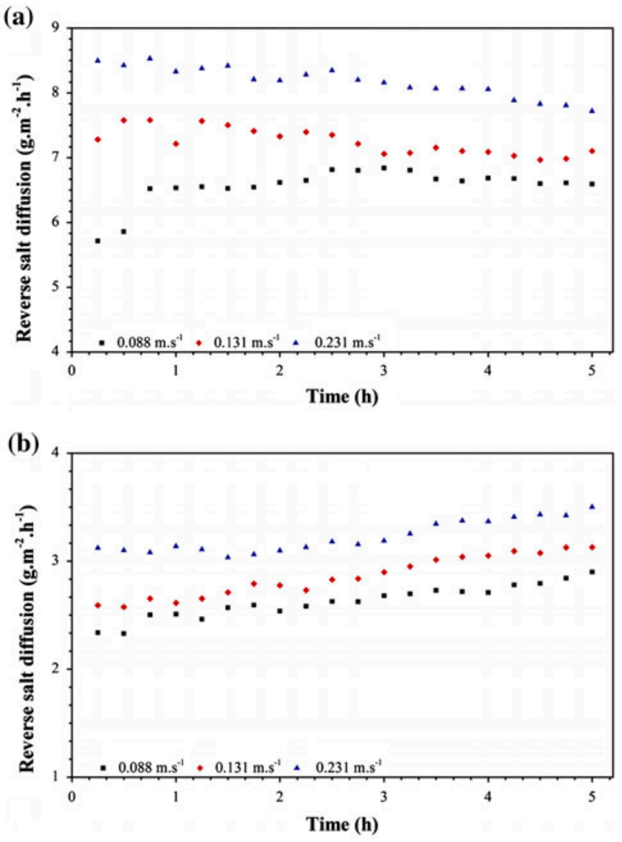

Fig. 6. The effect of linear velocity flow on salt reverse diffusion to the feed solution at 35℃: (a) 0.6 M NaCl and (b) 0.72 M $NaHCO_3$ as draw solution. The feed solution was distilled water.

in the linear velocity flow. This effect would be due to the slight increase in pressure at the inlet and along the both cell membrane channels, because of the increase in cross-flow velocity, which increases the reverse diffusion of draw solutes [34].

Similar to the previous section, the reverse diffusion of NaCl is almost 2.5 times higher than $NaHCO_3$. Given the presence of sodium ions in both solutions, the difference in their reverse diffusion is due to the size of the hydrated anions. The larger size of the HCO_3^{-1} hydrated anion (450×10^{-12} m) than the Cl^{-1} hydrated anion (300×10^{-12} m) causes its lower diffusion through the membrane. Similar results were reported by Achill et al. who investigated various mineral salts with distilled water feed solution using commercial FO membrane [18].

3.4. Water production from saline feed solution using $NaHCO_3$ draw solution

In order to investigate the application of FO process for desalination of saline water, a solution of 0.33 M NaCl with the osmotic pressure of 15 bar, nearly identical to salinity of Caspian Sea water, was used as the feed solution. To create an appropriate osmotic pressure difference, a solution of 1.16 M $NaHCO_3$ with an osmotic pressure of 41.86 bar was used as draw solution. Fig. 7 represents the water flux as a function of time under the temperature of 25°C and linear flow velocity of 0.131 m s^{-1}. The water flux was considerably reduced, as compared to distilled water feed solution (3.44×10^{-6} m^3 m^{-2} s^{-1} compared to 5.81×10^{-6} m^3 m^{-2} s^{-1}), under identical operating condition and equal osmotic pressure difference ($\Delta\pi \approx 27$). This difference is caused by the membrane internal concentration polarization and the intensified effect of the external concentration polarization at the two sides of the membrane due to the use of saline feed solution instead of deionized water. According to the results of other researchers, the role of internal concentration polarization on the feed side of the membrane is more prominent [27,34]. The results show a low difference in water flux between two feed solutions (i.e. distilled and simulated saline water) at the initial time of the experimental run. But this difference was increased with time due to the intensification of internal concentration polarization. Hence, further investigations are needed to reduce these effects and therefore, to increase the water flux.

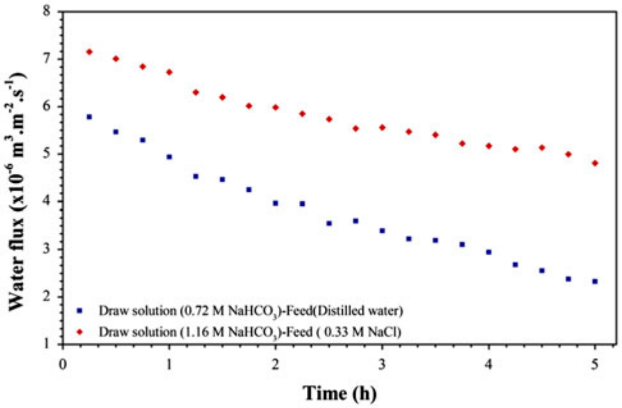

Fig. 7. The water flux difference for various draw and feed solutions under equal osmotic pressure difference ($\Delta\pi \approx 27$) at 25°C and linear velocity flow of 0.131 m s^{-1}.

4. Conclusion

In this study, the effects of temperature and linear flow velocity on FO water permeation were evaluated, using $NaHCO_3$ and NaCl as draw solutions, at identical osmotic pressure. As the temperature increases from 25 to 45°C, the water flux enhances. However, the temperature rise would also increase the reverse diffusion of draw minerals. The positive effects of temperature rise on the improvement of FO performance could be intensified in draw minerals, where their dissociation and diffusivity considerably depended on temperature, such as $NaHCO_3$. The water flux showed a dramatic increase with the increase in the linear flow velocity as a result of highly turbulent flow and the reduction in the external concentration polarization. The performance of FO was also evaluated for saline feed water, using sodium bicarbonate as the draw solution. In the latter case, the water flux had an approximately 1.7-fold reduction, as compared to the distilled water. This would be as a result of feed side internal concentration polarization and the intensified effect of the external concentration polarization at both sides of the membrane.

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