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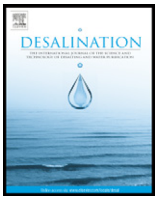

Influence of concentration polarization on flux behavior in forward osmosis during desalination using ammonium bicarbonate

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ABSTRACT

Forward osmosis is recognized as one of the promising membrane based desalination process and viable alternative to reverse osmosis as a lower cost and more environmentally friendly desalination technology. The solution of ammonium bicarbonate was used as a draw solution to extract water from a feed containing 0.5 M sodium chloride. The water was transported from feed to draw solution and it can be recovered upon moderate heating of the draw solution, which is decomposed into ammonia and carbon dioxide gases producing pure water. The mechanism of water transport in the case of feed containing pure water or sodium chloride has been elucidated depending upon the orientation of the membrane. The concentrative and dilutive internal concentration polarizations played a major role in a situation when feed was towards support layer and feed was towards active layer, respectively. For the desalination applications, the feed towards support layer was found to be best mode to achieve higher flux. An increase in draw solution concentration from 1.0 to 3.6 M, resulted in an increase in flux values from 0.58 to 1.39×10^{-6} $m^3 m^{-2} s^{-1}$ at 30 °C. Further, an increase in temperature of the draw solution from 30 to 45 °C resulted in increase in transmembrane flux from 1.39 to 2.11×10^{-6} $m^3 m^{-2} s^{-1}$ at the highest draw solution concentration. It was concluded that forward osmosis can prove to be a feasible technique for the recovery of water from saline water.

1. Introduction

Expanding global population, increasing water pollution and increasing standard of living have relentlessly put pressure on water and energy resources. Low cost methods of purifying freshwater and desalting seawater are required to contend with this destabilizing trend. Hence, the need for water is increasing rapidly and current freshwater resources may not be able to meet all requirements. Desalination of sea (or saline) water has been practiced regularly for over 50 years and is a well-established means of water supply in many countries. In the 1970s, exploration began into using membranes for water desalination. Proving successful at producing purified water from salt water, membranes became a viable alternative to evaporation-based technologies in the water treatment market. Over the years, purified water standards have become more stringent. However, membranes have risen to the challenge and continue to perform efficiently and effectively [14,23,28].

A new membrane process namely forward osmosis process has been developed as a possible alternative for desalination. It employs a semi-permeable dense hydrophilic membrane, which separates two aqueous solutions (feed and osmotic agent solution) having different osmotic pressures. The difference in osmotic pressure acts as a driving force. Osmotic pressure driven process operates on the principle of osmotic transport of water across a semi-permeable hydrophilic membrane from a dilute feed solution into a concentrated osmotic agent or draw solution [5,25]. Forward osmosis concentration process was adopted for the concentration of liquid foods and natural colors [3,4,6,8,15,18,27,29], electricity generation [1,11,16], wastewater treatment [9] as well as desalination of seawater. Several researches have reported work on desalination of seawater by forward osmosis. Ref. [22] also reported forward osmosis desalination as a lower cost and more environmentally friendly technology. The driving force was provided by a draw solution comprising highly soluble gases—ammonia and carbon dioxide. Water fluxes ranging from 3.6 to 36.0 $l\,m^{-2}\,h^{-1}$ for a wide range of draw and feed solution concentrations were reported. Desalination of very high sodium chloride feed solutions (simulating 75% recovery of seawater) was also deemed possible, leading to the possibility of brine discharge minimization. Ref. [12] devised a process coupling a forward osmosis process and reverse osmosis process to generate potable water, particularly from water having a high salt content. The forward osmosis was used to generate significant hydraulic pressure used for driving reverse osmosis process, wherein the reverse osmosis process can separate salt from seawater to generate potable water from water with high salt content.

The draw solution used in the case of desalination using forward osmosis should be highly soluble, highly recoverable, non-toxic, nonreactive with membranes, easily separable from water, and economically feasible [2]. The ammonium bicarbonate solution was used as an osmotic solution

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[10,21], which can be decomposed into ammonia and carbon dioxide gases at about 60 °C. The water transferred from feed side (seawater) to osmotic solution can be obtained by distillation methods [5,26] and the separated gases can then be recycled to use as a draw solution again [10].

The main objectives of the present work are to elucidate the mechanism of water transport from feed to osmotic agent side during forward osmosis as well as to study the effect of various process parameters such as osmotic agent concentration and feed temperature on transmembrane flux during forward osmosis process for desalination of saline water.

2. Theoretical considerations

Forward osmosis is a membrane process, which employs an asymmetric semi-permeable dense hydrophilic membrane that separates two aqueous solutions (feed and draw solution) having different osmotic pressures. Osmotic pressure gradient is the sole driving force for the transport of water. Any solution having greater osmotic pressure than the feed can be used as draw solution [21]. The asymmetric membrane employed in the case of forward osmosis consists of two layers. The one is a dense active membrane layer (active layer) and other being a loosely bound support layer (porous support layer) [25]. The membrane can be placed between the feed and the draw solution in two different orientations such as feed towards support layer (normal mode) and feed towards active layer (reverse mode), which are referred, in the present work, as modes I and II, respectively (Fig. 1a and b).

2.1. Concentration polarization when feed is towards support layer

When the feed (as pure water) is placed against porous support layer and ammonium bicarbonate solution (as osmotic solution) is kept on the draw solution side (mode I), water is diffused into the porous support layer and traversed to the draw solution side through the active layer of membrane due to osmotic pressure gradient across the membrane (Fig. 1a). At the same time, salt diffuses from the draw solution to the feed side leading to internal concentration polarization, which was referred to as internal concentration polarization coupled reverse draw salt flux [35].

On the draw solution side the external concentration polarization (dilutive) may take place in the boundary layer due to transfer of water from feed side to draw solution side. When water flux is high, the detrimental impact of draw side external concentration polarization can become the limiting effect [36].

The replacement of pure water with sodium chloride solution results in buildup of salt within the porous support layer due to the diffusion of water to the draw solution side. Subsequently, it results in a significant internal concentration polarization (concentrative) and negligible external concentration polarization (Fig. 1a). In this situation when the feed solution is saline and the water flux is low, the feed side internal concentration polarization becomes dominant [35]. At the same time, permeation of water to the draw solution side results in external concentration polarization (dilutive). Both the internal (concentrative) and external (dilutive) concentration polarization phenomena are responsible for the reduction in the effective osmotic driving force (Fig. 1a). The internal concentration polarization occurs within the porous support layer and it cannot be lessened by hydrodynamics such as turbulence (since it is occurring within the pores of the support layer) leading to drastic reduction of effective osmotic driving force [20,31]. The external concentration polarization effects are negligible when permeate water fluxes are relatively low [20]. The extent of external polarization is much less than the internal concentration polarization during forward osmosis [5].

2.2. Concentration polarization when feed is towards active layer

When the feed containing pure water or sodium chloride was placed against the active layer and the draw solution (ammonium bicarbonate) on the support layer side, the water from the feed is diffused into the active layer, which, in turn, is diffused to the porous support layer and then to the bulk through the boundary layer (Fig. 1a). The external and internal concentration polarizations towards feed side are considered to be negligible. Since the osmotic solute (ammonium bicarbonate) present in the draw solution is of low molecular weight (MW = 79.06), it must penetrate the porous support layer before flux can occur. As water flux crosses the active layer and enters into the porous support layer, it leads to the dilution of the solute within porous support layer due to convection. The solute diffuses back to the interior surface due to the concentration gradient. A steady state is quickly reached, but the concentration at the interior surface of the active layer is far lower than in the bulk draw solution [7]. The combined effect of both the diffusion of water through

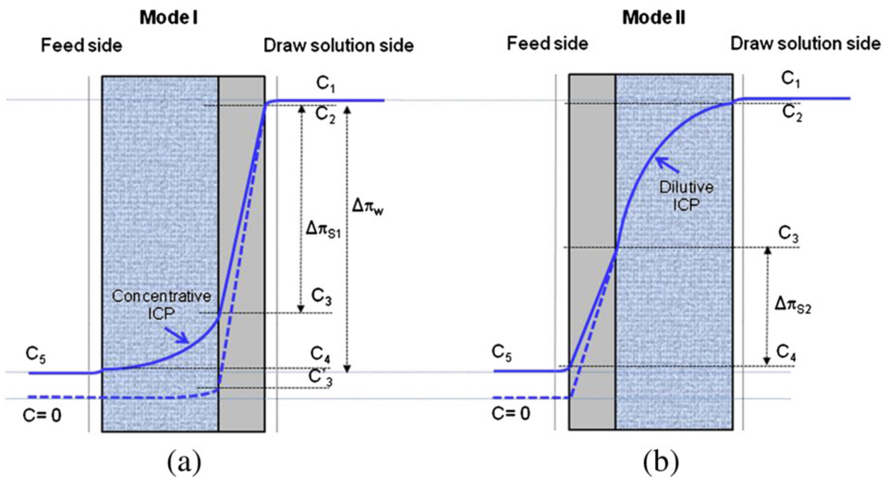

Fig. 1. Mechanism of forward osmosis indicating water transport from feed (water or sodium chloride solution) solution to draw solution. Dotted and solid lines are the concentration profiles for water and salt solutions, respectively. (a) Mode I, feed solution towards the support layer; (b) mode II, feed solution towards active layer. $\Delta\pi_w$, $\Delta\pi_{S1}$ and $\Delta\pi_{S2}$ are the corresponding effective driving forces in a situation where water or sodium chloride was taken as feed in the case of mode I, respectively, whereas $\Delta\pi_{S2}$ is the effective driving force in a situation where water or sodium chloride was taken as feed in the case of mode II. C_1 and C_5 are the bulk concentrations on draw solution and feed side, respectively. C_2 and C_4 are the boundary layer concentrations on draw solution and feed side, respectively. C_3 and C'_3 are the concentrations at the junction of active layer and support layer when water and salt solution was taken as feed, respectively. The vertical dotted lines near the active layer and support layer are the boundary lines.