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Forward osmosis dialysate production using spiral-wound reverse-osmosis membrane elements: Practical limitations

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ABSTRACT

We present here an experimental method of dialysate production by forward osmosis (FO) using an inexpensive reverse osmosis (RO) membrane element. This method was developed in response to the increasing need for dialysis treatment in remote and desert regions of Australia where water is precious and electricity supplies are generally unreliable.

A 4040 RO membrane element was oriented for FO, using dialysate concentrate as a draw-solution and pre-treated tap-water as a feed-solution. Diluted draw-side output was collected and mixed over a range of target flow-rates. After each test the element was osmotically backwashed. Measurements were made of production time, volume and equivalent flow rates.

The benefits of FO were diminished by the process' need for osmotic backwashing. Our system had an equivalent water recovery ranging from 65 to 75%. Its energy efficiency was 66% of its RO equivalent. Its operation was almost silent. Two 4040-size RO membrane elements would be necessary to complete a dialysis treatment. Dialysate production may be possible by this method, but its economic and conservation benefits appear to be modest.

1. Introduction and background

1.1. The need for efficient dialysate production

Australian Aboriginal desert communities experience kidney disease at a rate that approaches 10 times the national average [1]. The corresponding increase in dialysis services [2] places additional pressure on already-stretched desert water supplies [3]. With the recent advent of mobile dialysis trucks, there is now a need for compact, energy efficient dialysis systems that can handle the harshness of remote regions with their heat, dust, corrugated roads and brackish water supplies.

We have previously proposed a system for the FO production of dialysate using a standard RO membrane element [4]. We have suggested that this system might be able to exploit the water and energy efficiency advantages of FO-based processes [5,6] to improve the suitability of dialysis systems for remote desert conditions. The working principles of our proposed system are briefly described here, followed by an experimental study of its production limitations.

1.1.1. Haemodialysis

Haemodialysis (or *dialysis*) is a medical treatment used in place of human kidney function in patients with varying degrees of kidney disease or failure. Its basic operation involves the exchange of fluid and solutes between a patient's blood and a prepared fluid called *dialysate* [7]. The blood and dialysate paths are separated by a semi-permeable membrane. Waste products pass from the blood-path to the dialysate path which is then discarded.

Dialysate fluid is typically generated within a haemodialysis machine by the injection of dialysate concentrate (*Part A*) and a buffering agent (*Part B*) into a stream of RO water, which is usually generated by a separate RO system [8]. The dilution rate is such that 1.0 part of *Part A* would be combined with 1.225 parts of *Part B* and 32.775 parts of RO water [9]. A typical, chronic dialysis treatment may require 150 l of dialysate, generated on-demand at ~500 ml/min over a five-hour treatment [10].

1.1.2. Forward osmosis

The production of dialysate seems to be a process suitable for adaptation for FO [11,12]. We have previously suggested [4] that dialysate concentrate *Part A* may be used as a convenient draw-solution, which would then be diluted by feedwater drawn through a membrane, with unwanted contaminants being left behind. Bicarbonate buffer (*Part B*) would then be added to complete the mixture. However, unlike power generation or product concentration applications [13], FO dialysate production must include the control of its output concentration and flow rate, to enable medical targets to be met.

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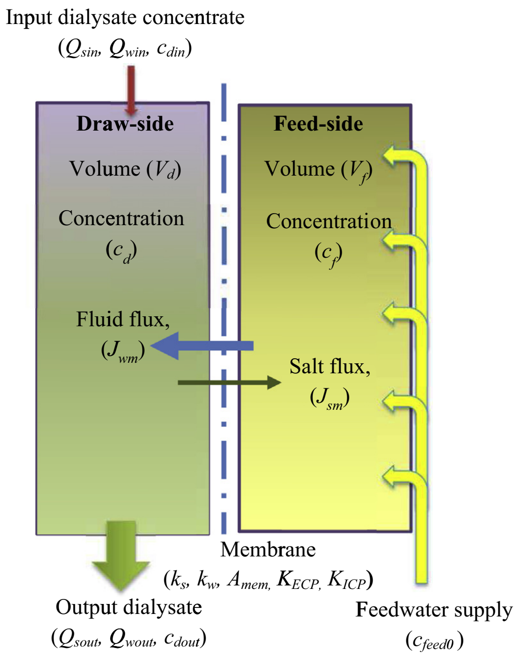

Fig. 1. Salt and fluid variables for dialysate production by FO.

1.1.3. FO and RO membranes

As FO has yet to become mainstream technology, FO membrane packages are still relatively expensive and exclusive [14,15]. By comparison, RO elements are relatively inexpensive and abundant [16,17]. RO elements are also more compact than their FO equivalents: a 4040 RO element may have twice the active membrane area compared with an FO package of the same size [18]. For these reasons, we have attempted to use an RO element in FO mode for dialysate production.

1.2. Considerations when using an RO membrane in FO mode

As highlighted by others, RO membrane elements are difficult to use in FO mode [19]. The difficulties stem from the fact that the permeate side of an RO membrane element is formed in envelopes that are sealed on three edges, having been designed for fluid to exit the permeate side rather than enter it. This means that for FO, the membrane draw-side must be the side which is normally used for feedwater and brine in an RO process. Feedwater must therefore be supplied to the element via its permeate tube, causing salt to accumulate within the feed-side envelopes and a corresponding loss of osmotic drive. This arrangement of draw- and feed-side compartments and their parameters is shown in Fig. 1. We have discussed the mechanisms and management of this in our previous work [4]. We suggest that this accumulation be compensated for by injecting excess concentrate until the element reaches its saturated capacity, at which point the membrane may be recovered by osmotic backwashing.

1.2.1. Feed-side salt accumulation

In an ideal process, draw-solution injectate of concentration, c_{din}, would be added at a rate, Q_{win0}, to match the loss of salt via the production output flow and concentration targets, $Q_{wtarget}$ and $c_{dtarget}$

$$Q_{win0} = \frac{Q_{wtarget} \cdot c_{dtarget}}{c_{din}} \tag{1.1}$$

Our previous analysis [4] discusses two sources of salt accumulation in our FO dialysate production process: reverse-solute flux from the draw-solution and rejection of feedwater solutes. Both these rates are closely related to membrane characteristics, osmotic potential difference and feedwater quality. With a practical membrane, excess concentrate must be injected into the process' draw-side at a rate of Q_{win}, to compensate for these two sources of accumulation and to maintain sufficient osmotic potential to drive the process. Our previous work has shown that the factor by which the injection rate must be increased can be estimated from knowledge of the trans-membrane water and solute flux constants, k_w and k_s,[1] the volume of the element's draw- and feed-side compartments, V_d and V_f, and the concentrations of the various key fluids, such as the feedwater, c_{feed0}, the dialysate concentrate, c_{din}, and the dialysate target concentration, $c_{dtarget}$. The compartment volumes must be adjusted for external and internal membrane polarisation (ECP and ICP) by varying the parameters λ and μ

$$\frac{Q_{win}}{Q_{win0}} = \frac{\frac{\lambda}{V_f}\left(\frac{k_s}{k_w} + c_{feed0}\right) + \frac{\mu}{V_d}\left(\frac{k_s}{k_w} + c_{dtarget}\right)}{\frac{\lambda}{V_f}\left(\frac{k_s}{k_w} + c_{feed0}\right) + \frac{\mu}{V_d} \cdot \left(\frac{k_s}{k_w} + c_{din}\right)} \cdot \frac{c_{din}}{c_{dtarget}} \tag{1.2}$$

This *overprime* factor is independent of the target flow rate ($Q_{wtarget}$), provided that appropriate approximations for ECP and ICP are made via μ and λ.[2] By injecting excess draw-side salt, the total salt mass on both sides of the membrane can be expected to gradually increase, until high draw-side concentration causes the system's output concentration to increase above its target level, at which point the output will no longer useful. We have called this point *saturation*, and it is the point at which the element can produce no further useful output and must be backwashed.

1.2.2. Osmotic backwashing

We propose that our system could be recovered from its saturation state by displacing its salt-rich draw-side fluid with a lower-osmolarity one, and allowing that fluid to diffuse across the membrane to flush salt from the feed-side. The use of osmotic principles to backwash a membrane has been described by others [20–22] but not yet used for this particular application. Our team has carried out some pilot experiments exploring the nature of osmotic backwashing in this application and some preliminary results have been used to estimate some values here (see Section 3.1.4). Its use in this application is worthy of deeper examination and will be the subject of further analysis and future publication.

There is a particular complication associated with the introduction of fluid into the draw-side of a *medical* FO process: the displacing fluid must also be of medical grade. The use of this approach in any practical application would require an additional, high-quality water source, such as that supplied by a separate RO unit. This implies that FO dialysate production using an RO element cannot be effective without also using an additional RO supply.

1.2.3. Production limits

Our previous analysis shows that the total useful volume produced by our proposed system is limited by the salt-storage capacity of the membrane element's feed-side. If the initial and saturated feed-side salt concentrations, c_{ft0} and c_{fts}, can be estimated, an upper

[1] These constants k_w and k_s are taken from our earlier work [4] and are closely related to the traditional constants for membrane hydraulic permeability and reverse solute flux, A and B, such that $k_w = i \cdot A \cdot R \cdot T$, where i and R are the van 't Hoff and ideal gas constants, and T is the value for temperature as used in the usual formulation of Morse' law. The solute flux constant is simply re-labeled for consistency as $k_s = B$.

[2] A discussion of the approximation of these constants can be seen in our previous work [4].