An experimental assessment of centrifugal membrane separation using spiral wound RO membrane elements


Abstract

The influence of the rotating environment created in a centrifugal membrane separation (CMS) system on the performance of commercial spiral wound RO membrane elements has been examined. In CMS the membrane elements are located at the periphery of a centrifuge rotor. The spinning action develops the process pressure and alters the fluid flow pattern within the element due to Coriolis and centripetal acceleration. CMS has been shown to improve performance of a small-scale plate and frame element by reducing concentration polarization and fouling. The current study probes the benefits of spinning commercial spiral wound RO membrane elements in a radial orientation. Mechanical element stability at over 3000 'g' has been demonstrated as well as concentration polarization reduction and fouling alleviation. Results also indicate that rotation induced secondary flows are more effective in reducing concentration polarization than increasing cross-flow velocities for the non-rotating condition.

Keywords: Centrifuge; Membrane elements; Reverse osmosis; Fouling

1. Introduction

Membrane separation technologies have evolved at a rapid rate over the past decade. Research activities have focused primarily on developing new membranes with higher productivity, better selectivity, increased chemical tolerance, lower energy requirements, and longer life expectancy. Although membrane materials have advanced the manner in which they are utilized within membrane systems has remained essentially unchanged. Centrifugal Membrane Separation (CMS) is a new way to operate a membrane separation process within the dynamic environment of a centrifuge. The initial motivation...
for CMS was the reduced energy requirements of
the centrifugal design for membrane processes
that operate at high pressures and relatively low
recovery ratios. In addition to the energy efficiency
of CMS, current research has indicated that flux
enhancement and fouling reduction can be achieved
by operating a conventional spiral wound membrane
element in the CMS centrifuge.

In a CMS system, the process pressure is
developed within a spinning centrifuge rotor. Feed
solution enters the centrifuge rotor at the axis and
flows outward to the periphery. During this
transition, the feed is pressurized by centripetal
acceleration. The feed is directed to the membrane
elements located at the periphery. The permeate
stream is released at the periphery while the
concentrate stream is returned to the rotation axis
and exits the rotor at low pressure. The energy
contained in the high-pressure concentrate stream
is inherently recovered resulting in energy saving
relative to a conventional high-pressure membrane
system [1].

The benefit of secondary flows and instabili-
ties in enhancing mixing and reducing fouling and
concentration polarization have been recognized
for some time and several methods have been
investigated to realize these effects. These methods
include oscillating pressure gradients [2], pulsatile
flow [3,4], centrifugal acceleration [2,5,6], and
Dean vortices [7]. In the dynamic CMS environ-
ment, Coriolis and centripetal acceleration alter
the feed flow patterns within the elements [8].
Element performance can be manipulated by
altering the membrane orientation and the feed
flow direction. In a previous study by the authors,
a variety of membrane orientations were surveyed
experimentally using a small custom plate and
frame element [9]. The test elements were con-
structed with a single membrane orientation and
open channel flow. The results indicated that both
Coriolis and centripetal acceleration enhance
membrane performance [10,11], with best per-
formance achieved for orientations where both
accelerations are maximized.

Although the experimental results with custom
made plate and frame element were very positive,
a commercially viable CMS device would require
a much larger active membrane area. The most
cost effective approach to increasing the membrane
area would be to utilize conventional spiral wound
membrane elements. However, the dynamic
environment exerts forces on the membrane
elements that are not present in a conventional
system. Furthermore the orientation of the
membrane surface in a commercial element is not
constant. The objective of the current research
was to assess the mechanical survival and
performance of a conventional spiral wound
membrane element in a dynamic environment.

2. The CMS test centrifuge

A special centrifuge test rotor was designed
to hold a standard 2514 spiral wound membrane
element. In a previous survey of membrane
orientations and feed flow directions conducted
with the plate and frame rotor, the best overall
performance was observed when the membrane
surface normal was aligned with the rotation axis
and the feed flow was in a radial direction [12].
Reasonable results were also obtained for the
tangential orientation with radial feed flow. To
obtain these membrane orientations with a spiral
wound element the element axis must be aligned
in the radial direction. Hence, a single spoke rotor
design was developed with a cylindrical pressure
vessel located at the periphery, see Fig. 1. A single
element is employed to simplify the experimental
procedure.

The membrane element is loaded into the rotor
via a removable end cap which contains the
appropriate fluid porting. The rotor is enclosed
in a protective housing which is evacuated to
reduce windage power consumption. A dual
passage rotary union transfers the feed and
concentrate streams between the stationary and
rotating frames. External feed tubes carry the
solutions from the axis to the membrane element.
The permeate stream is directed into a stationary catch ring by a nozzle fixed to the rotor. The permeate drains into a calibrated external transfer tank mounted below the centrifuge housing. The fill time is monitored and used to determine the permeate flow rate. A computer controlled airlock system is used to transfer the permeate to the main feed tanks at the appropriate time. The rotor, membrane element, and permeate catch ring are illustrated in Fig. 2.

The test rotor is housed in the CMS test centrifuge described in [9]. The fluid handling capability of the system was expanded for this series of experiments. The system is capable of delivering 25 L/min of feed solution at up to 7 MPa at a constant temperature. The centrifuge uses a high-pressure rotary fluid coupling so that ‘hybrid’ experiments can be conducted in which a portion of the operating pressure is developed by rotation, while the external feed pump provides the additional pressure. These pressures will be referred to as the dynamic and the pump pressure respectively. The dynamic pressure is a direct function of the rotation rate $\omega$, the radius $r$, and the fluid density $\rho_{\text{fluid}}$ as given by [11]:

$$P(r, \omega) = \frac{1}{2} \rho_{\text{fluid}} \omega^2 r^2$$

The rotation rate can be varied between 0–2700 RPM which generates dynamic pressure of 0–7 MPa at the inside edge of the membrane element located at 0.41 m from the rotation axis. The hybrid capability facilitates experiments that span the full range of rotational rates. A second membrane element operated in a conventional static (i.e. non-rotating) mode provides base line data for direct static versus dynamic comparisons. A computer control and data acquisition system is used to supervise long duration experiments and collect data from the various flow meters, pressure transducers, temperature sensors etc.

3. Do standard spiral wound membrane elements survive in a centrifugal environment?

Mechanical integrity tests were conducted with Filmtec SW30 2514 RO membrane elements performing a brine separation. The elements were initially tested in a conventional static operating mode to obtain basic flux and rejection characteristics. Once the initial break-in was complete, the elements were operated dynamically and the flux and rejection were observed. Initial experiments demonstrated that the centripetal environ-
ment does not damage the RO membrane elements. Elements were subjected to over 3000 'g' without any decline in flux. The permeate quality remained similar to the static operating case indicating that the RO membrane was not compromised by the inertial forces associated with rotation.

Element telescoping was envisioned as a potential problem with the radial membrane orientation. To minimize this issue, the centrifuge rotor was designed to physically support the element against radial movement via the end cap and not by the permeate tube. Telescoping of the inner membrane leaves is not observed. Furthermore, the fiberglass outer windings provide sufficient mechanical support to keep the element from buckling under the centripetal load.

Experiments with a tape wound Filmtec TW30 2514 tap water RO membrane elements were also conducted but at a lower rotation speed due the element transmembrane pressure limit. There were no signs of rotation induced element damage at the test condition of 750 'g'.

4. Does spinning reduce concentration polarization?

The dynamic environment created by the centrifuge reduces the effect of concentration polarization relative to the conventional static operation of a spiral wound element. At a specified transmembrane pressure, the permeate flux associated with dynamic operation is greater than for static operation. The enhancement occurs without a degradation in permeate quality.

A similar phenomenon was previously observed in the small plate and frame experiments. A recent computational fluid dynamics (CFD) study [13] indicates that the feed flow patterns in rectangular channels with various orientations corresponding to angular positions in a spiral wound element are dramatically altered by rotation leading to enhanced mixing. In a conventional spiral wound element, the feed spacer is used to promote mixing and reduce concentration polarization. Since higher permeate fluxes are obtained by operating the elements in the centrifuge, it is apparent that the dynamic environment can improve the mixing occurring within a standard element.

The extent of concentration polarization alleviation is dependant on the feed solution composition and operating conditions. A flux enhancement factor defined as:

\[ F = \frac{\text{permeate flux (dynamic)}}{\text{permeate flux (static)}} \]

can be used to account for variations in absolute flux between tests. The enhancement factors obtained for three feed solution compositions are given in Table 1. The effect of concentration polarization is negligible for the tap water feed. Operation at this concentration confirms that the experimental conditions (pressure, temperature etc.) are well matched between the static and dynamic environments. The enhancement factors increase with increasing feed concentration. Experiments conducted at 50,000 ppm NaCl indicate that dynamic operation has significant advantages for applications where concentration polarization limits permeate flux. The magnitude of the enhancement factors are smaller then in plate and frame experiments [10] indicating that

<table>
<thead>
<tr>
<th>Feed concentration, ppm NaCl</th>
<th>Feed flow, L/min</th>
<th>Transmembrane pressure, MPa</th>
<th>Enhancement factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap water</td>
<td>10</td>
<td>2.1</td>
<td>1.0</td>
</tr>
<tr>
<td>27,000</td>
<td>12</td>
<td>5.7</td>
<td>1.07±0.03</td>
</tr>
<tr>
<td>50,000</td>
<td>12</td>
<td>5.7</td>
<td>1.18±0.04</td>
</tr>
</tbody>
</table>
the feed spacers play a significant role in reducing concentration polarization effects in the static reference case.

Hybrid experiments at constant transmembrane pressure with various rotational rates were conducted to determine if a critical speed exists to initiate concentration polarization alleviation. The results for a 50,000 ppm feed indicate that the alleviation is directly related to the dynamic pressure as illustrated in Fig. 3. A minimum threshold was not observed. Operation under full dynamic conditions generates the maximum benefits.

5. Is spinning as effective as high feed circulation rates?

High cross-flow velocities are employed in conventional membrane systems to enhance the mixing in the membrane elements and to thereby reduce concentration polarization and fouling [14]. Operation at high cross-flow velocities requires high feed rates, increasing the overall energy consumption. The maximum feed rate is limited by the maximum allowable pressure drop per element. CFD analysis has indicated that strong secondary flows are created within the dynamic environment of the centrifuge [15]. These secondary flows have the potential to enhance mixing to a greater extent than by high cross-flow velocities [16]. Experiments have been conducted to determine the relative effects of feed flow rate in both the static and dynamic environments.

A FilmTec brackish water RO element was used to examine the effects at 2000 ppm NaCl feed concentration. Increasing the feed rate from 7 to 21 L/min resulted in a 2% increase in permeate flux for both the static and dynamic cases. This result indicates that the element performance is not limited by mixing at a low feed concentration.

At high feed concentrations, the benefits of CMS are clearly evident as illustrated in Fig. 4 for an experiment conducted with FilmTec RO membrane and 50,000 ppm NaCl feed solution. Dynamic operation at the minimum feed flow rate of 6 L/min produced 5% more permeate flux than static operation at the maximum feed rate of 18 L/min. The results also indicate that altering the feed flow rate in the dynamic environment has a larger impact than in the static case. Increasing the feed rate from 6 to 18 L/min resulted in a 6% increase in permeate flux in the static environment.

**Fig. 3.** Permeate flow rate as a function of pressure developed due to rotation for a constant 5.7 MPa transmembrane pressure. FilmTec SW 2514 RO element, 50,000 ppm NaCl feed at 12 L/min.

**Fig. 4.** Permeate flow rate as a function of feed flow rate for a FilmTec SW 2514 RO element. 50,000 ppm NaCl feed at 815 psi transmembrane pressure.
case compared to 14% increase in the dynamic environment. This finding is consistent with enhanced secondary flows generated by Coriolis acceleration, the magnitude of which increases directly with cross-flow velocity.

6. Does spinning reduce fouling?

Experiments with colloidal silica were conducted to determine if fouling characteristic of a standard spiral wound element would be altered by dynamic operation. Previous experimental work with the small plate and frame elements indicated that the particulate fouling could be reduced or accelerated by altering the membrane orientation [11]. The geometry of a spiral wound element is inherently more complex than that of the plate and frame elements because of the range of membrane orientations. Flow obstructions caused by the mesh feed spacers add another set of variables that may impact the potential benefits of dynamic operation.

The experiments were conducted by adding DuPont Ludox HS-40 colloidal silica to a 10,000 ppm NaCl feed solution after an initial portion of baseline data was collected. Preliminary experiments revealed the importance of maintaining the feed pH during the silica addition to avoid a flux decline related to a temporary pH jump. These preliminary experiments indicated that solution concentration of 5 g/L silica was not sufficient to cause noticeable flux decline in a 24 h period. Subsequent experiments with silica concentrations of 15 g/L or higher resulted in substantial flux decline in the static operating mode.

The results for a 27 g/L experiment conducted with two new FilmTec RO elements, one static and one dynamic, are presented in Fig. 5. The results are normalized to the respective baseline flux at the time of silica addition to account for the usual minor differences in absolute permeate flow rates between elements. An immediate drop in flux from the static element was observed following the silica addition. The flux from the dynamic element increased during the first 6 h after silica addition then declined at a similar rate as the static case. Subsequent non-fouling experiments have shown that the decline in flux prior to silica addition is due primarily to element break-in. The general conclusion derived from this experiment is that the dynamic environment can provide significant alleviation of the short-term flux decline experienced by the static system following the onset of the silica feed.

An additional experiment was conducted to observe the dynamic behavior over a longer duration, see Fig. 6. The break-in period was extended to over 200 h to arrive at a stable initial flux. In this experiment, flux enhancement was not observed when the silica was added to make a 15 g/L feed solution. A net flux decrease of 3% occurred during the first 36 h followed by a steady decline of 1% per day for the next 4 days. The small undulations in the data correspond to feed solution pH adjustments. Although static data was not obtained for this experiment, previous tests indicate that static operation at this feed concentration is sufficient to cause an immediate 10% decrease in flux followed by a long term flux decline.

![Normalized permeate flow rate as a function of time following the addition of colloidal silica. FilmTec SW 2514 RO element, 10,000 ppm NaCl + 27 g/L silica at 6 L/min, 600 psi transmembrane pressure.](image-url)
The silica experiments clearly illustrate that the fouling characteristics of spiral wound elements are significantly altered by operation in the dynamic environment. CFD analysis indicates that additional benefits may be realized by optimizing the feed spacers for the dynamic case [16].

7. Conclusions

The performance of a conventional spiral wound element can be enhanced by dynamic operation in a CMS centrifuge. The current study confirmed that a standard 2514 RO membrane elements mechanically survive operation in a radial orientation at up to 3000 ‘g’.

Experiments conducted with brine feed solutions indicate that the dynamic environment reduces the effects of concentration polarization. The benefits are directly related to the portion of the transmembrane pressure developed by rotation and increase with increasing feed concentration. An enhancement factor of 1.18 was obtained for full dynamic operation on a 50,000 ppm NaCl feed solution. The enhancement occurs without a degradation in permeate quality.

Varying the feed flow rate has a larger impact on dynamic element performance than for static operation. Furthermore, the permeate flux obtained by dynamic operation at low feed rates is larger than static operation at high feed rates.

Dynamic operation also alters the fouling characteristics of a spiral wound element. Experiments with colloidal silica indicate that the initial static flux decline after the addition of the colloidal solution can be reduced by dynamic operation.

The results indicate that commercial CMS with standard spiral wound RO elements has the potential to deliver superior performance for streams limited by both concentration polarization and fouling.

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References


