Flux flow and cleaning enhancement in a spiral membrane element, using continuous infrasonic backpulsing#

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Abstract

The effect of backpulsing, into the permeate space of a 2.5 inch spiral wrap membrane, on the prevention of fouling (flux enhancement) was investigated experimentally. These experiments were performed using a 500 $mg \cdot \ell^{-1}$ dextrin solution and a 100 000 MCWO polypropylene membrane, with a feed pressure of 100 kPa and a cross-flow rate of 1 000 $\ell \cdot h^{-1}$. Experimental results showed that a backpulse with a duration of about 170 ms, a repeat frequency of 1 s and differential peak pulse pressure, measured at the outlet of the permeate space, of 38 kPa gave the best results for the parameters used in the current experiments. In this case the saturation flux with backpulsing was 82% of the clean water value and 3.9 times the saturation flux obtained with no backpulsing.

Keywords: Spiral wrap element, membrane cleaning, infrasonic, back pulsing

Introduction

The supply of cheap potable water in sufficient quantities is a worldwide problem. Water filtration through polymer membranes provides a good solution to obtaining potable water, if sufficient capital and running expenses are available. Unfortunately, membranes always foul during the water purification, and the flux drops with time. Therefore, an additional expense in running a polymer membrane water filtration plant is the periodic closing down of the plant (or sections thereof) to chemically clean the membrane elements, when the flux falls below a specified value. A further disadvantage is that the soap solutions used during this process have to be disposed of in an environmentally-friendly way. Therefore, physical cleaning methods, which operate continuously and do not require the plant to be shut down for lengthy periods (if at all), are very attractive and do not generate any waste fluids.

There are a number of non-chemical membrane cleaning techniques available, including back-flushing, cross-flushing and back-shocking (Redkar and Davies, 1995; Wenten, 1995; Parnham and Davis, 1996; Kuberkar et al., 1998; Redkar et al., 1996; Tanaka et al., 1995; Kuruzovich and Piergiovanni , 1996). In most previous work using these techniques, the flushing pulses have been applied to the feed space. Although these techniques, applied in a non-continuous way, can be successfully used to clean some foulant layers off membranes and (partially) restore the flux, they seem to be inefficient in the removal of adhesive foulants (Czekaj et al., 2001). There has been a limited amount of backpulsing work where the pulsing has been applied to the permeate space, but, to date, experiments have only been performed on flat sheet membranes (Czekaj et al., 2000; Czekaj et al., 2001; Sondi et al., 2000; Kuberkar et al., 1998; Wenten 1995; Ramirez and Davis, 1998; Mores et al., 2000; Parnham and Davis, 1996; Mairal et al., 1999; Shugman et al., 2009). In this study, rapid, continuous backpulsing into the permeate space was found to be very effective in maintaining a higher flux in a spiral wrap element. Note that in order to avoid back-side contamination of the membrane, a clean feed (the permeate itself or reverse osmosis (RO) water) was used for backpulsing into the permeate space.

As the spiral wrap elements contain deformable membrane envelopes (with a total membrane area of up to several square metres) and involve much larger volumes than in flat cells, and because of the geometry of the spiral wrap elements the optimal repetition frequencies for backpulsing are lower (< 1 Hz) than the 1-10 Hz used for flat cells (Czekaj et al., 2000; Czekaj et al., 2001; Sondi et al., 2000; Kuberkar et al., 1998; Wenten, 1995; Ramirez and Davis, 1998; Mores et al., 2000; Parnham and Davis, 1996; Mairal et al., 1999; Shugman et al., 2009), which have smaller membrane areas and volumes, two cases should be distinguished: If the amplitude of the infrasonic pressure pulses applied to the permeate space is less than the pressure applied on the feed side, the membrane can only be vibrated, which can shake or peel the fouling layer off the membrane (Czekaj et al., 2001). If the pulse pressure is higher than that in the feed space, in addition to the vibrating action the permeate can also flow back, through the membrane, from the permeate to the feed side and wash the foulant out of the accessible pores of the membrane as well as lift the foulant layer from underneath. Note that a negative trans-membrane pressure (TMP), if applied for a large enough fraction of the cycle, will significantly lower the nett permeate flux.

Czekaj (1999) presented a mathematical model for the permeate flux when infrasonic pulsing is applied to a flat sheet membrane. No theory currently exists to describe the

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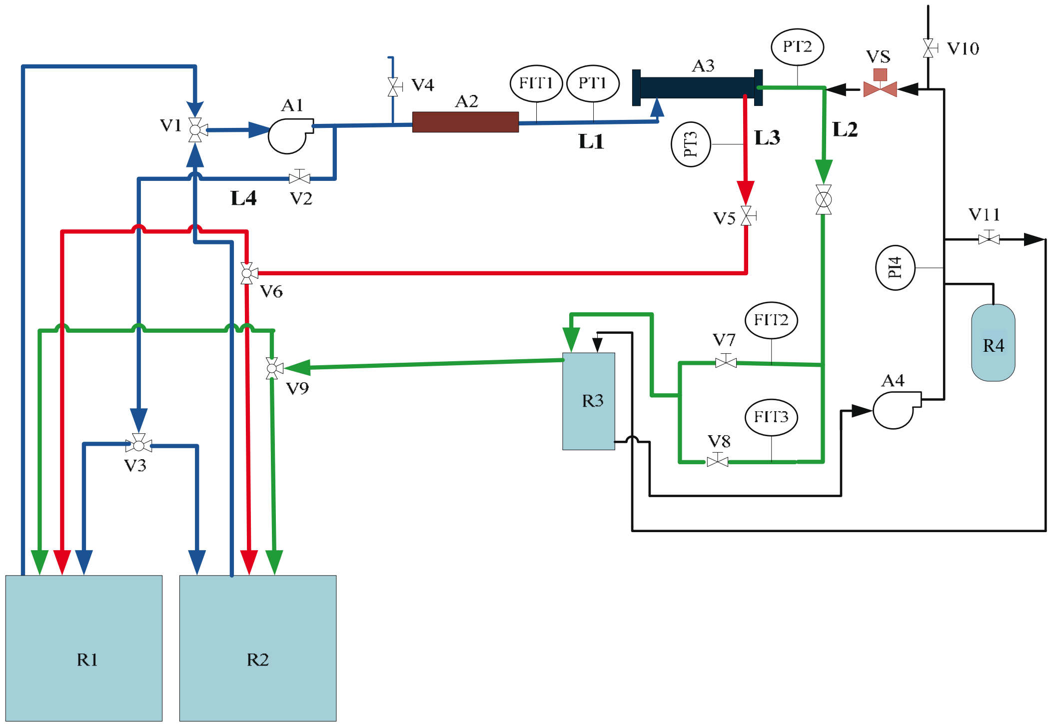

- A1: Feed pump
- A2: Damper
- A3: Cross-flow module
- A4: Backpulse pump
- L1: Feed line
- L2: Permeate line
- L3: Retentate line
- L4: Bypass flow line
- V1/V3/V6/V9: 3-way valve
- V2/V4/V5/V7/V8/V10: Proportional valve
- VS: Solenoid valve
- PT1/PT2/PT3: Pressure transmitter
- PL1: Pressure gauge
- FIT1/FIT2/FIT3: Flow indicator transmitter
- R1: Clean water tank
- R2: Fouling solution tank
- R3: Permeate tank
- R4: Pressurised tank

Figure 1
Flow diagram for the spiral wrap plant

effects of backpulsing into the permeate space of spiral wrap elements, and this appears to be the first study investigating this process. The lack of theoretical studies is due to the extreme complexity of the system, which consists of a number of membrane envelopes spirally wound onto a central permeate tube. The result is that the water driven by the pulse has to propagate down the permeate space (wrapped membrane envelopes), which contains a spacer cloth. The situation is made even more complex because envelopes contact each other in the feed space, through another spacer cloth. In terms of distortion, a flat cell membrane is far easier to model; however, rigorous modelling of this not been done (to the best of the authors' knowledge). A capillary membrane would be much simpler to model due to the symmetrical cylindrical distortion that is caused by a backpulse travelling down each tube. No experimental or theoretical studies of backpulsing in capillary membranes appear to have been made.

Experimental apparatus and procedure

Figure 1 shows a flow diagram of the fairly standard spiral wrap plant used in these experiments, an Alpha Laval GR40PP 100000 MWCO element with a Polysulphone membrane. The mono-spiral pump (A1) had a maximum flow rate of 10 $m^3 \cdot h^{-1}$ at 500 kPa, but a bypass valve (V2) was used to reduce both the flow and pressure. There were direct digital readout Wika pressure gauges (0 to 600 kPa) in the feed line (PT1), the permeate line (PT2) and the retentate line (PT3). As can be seen from Fig. 1, the pressure and flow into the feed space was controlled by V2 and V5.

The feed flow was recorded using a Burkert flow meter (100-1 000 $\ell \cdot h^{-1}$) in the feed input line (FIT1). One of two Burkert flow meters (2-100 $\ell \cdot h^{-1}$ and (100-1 000 $\ell \cdot h^{-1}$) was installed in the permeate line (FIT2 and FIT3) to measure the permeate flow rate. The flow could be switched between the 2 permeated flow meters by hand using V7 and V8. However, due to continual problems with the smaller Burkert flow meter the permeate readings recorded here were made using a measuring cylinder and a stop watch. Note that during the pulsing experiments the pulsing had to be switched off for 30 s before the 'true' flow rate could be measured. The flow measurements were made for 30 s, at the point where the permeate entered the tank (R3). At the beginning of an experiment, a RO (clean-water) value was recorded. The backpulsing was then switched on and the feed to the pump was switched between RO water and the dextrin solution using the 2-way valve (V1) shown in Fig. 1. The flux falls rapidly at first and then approaches the equilibrium value, which depends on the backpulsing conditions for that particular experiment. Note that the actual readings were made at the points shown in Figs. 2 and 4, and the points joined by straight lines. The data for the first point in experiments is not reliable as it included the period during which the fouling solution and RO were interchanged and

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when rapid initial fouling occurred; the first reliable point in all experiments is the second one.

The pressure used for the backpulse was generated by the pump (A4), using permeate water, in combination with V11 and stored in R5. The fast-acting solenoid valve (VS) opened whenever a signal was applied to a solid state switch (not shown), giving rise to a pressure pulse. The signal came from a signal generator, which gave pulses with various pulse widths and repartition frequencies. Experiments were performed with the pressure in the 'backpulse' pressure system at 200 kPa and 350 kPa.

In order to obtain a finite backpulsing pressure in the permeate space, the throttling valve, shown at the exit of the permeate space, was adjusted to obtain the desired pulse amplitude. This valve caused a back pressure in the permeate space of about 10 kPa, when the pulsing was off. Therefore, the actual 'equilibrium' TMP was 90 kPa, when a static feed pressure of 100 kPa was recorded.

To record the pressure pulses, 2 Wika pressure (0-600 kPa, 4-20 mA) transmitters were placed at the permeate output (PT2) and the feed input (PT1) of the element. The signals (currents) from the 2 transmitters were resistively coupled to the 2 inputs of an oscilloscope. The voltage–time (V-t) plots on the oscilloscope recorded the pressure pulses. The first channel records the primary (permeate space) pulse, while the second monitors the response in the feed space to the pulses produced in the permeate space, the coupling of the permeate signal to the feed space signal being through the spirally-wound membrane envelopes in the element. It is to be noted that both of these pulse pressure measurements, an example of which is given later, are oscillations of the pressure around the equilibrium pressure in the feed space and permeate space, respectively. The principal parameters of the pulse were: the pulse duration, the pulse amplitude and the pulse interval or repetition frequency, all of which could be controlled over a limited range using the signal generator. There was no means of controlling the pulse shape. In these experiments, the infrasonic backpulsing system, was used to produce backpulses, about 94 ms wide at 0.5 s intervals and about 170 ms wide at 1-, 2- and 10-s intervals.

As previously mentioned, all of these measurements were made at an input pressure of 100 kPa (TMP 90 kPa) and a flow rate of 1 000 $\ell\cdot h^{-1}$. It is clearly indicated in Fig. 4, where the backpulsing is on and when it is off. Before commencing an experiment the plant was run, using RO water from R1 to measure the clean water flux, which was always between 133 and 137 $\ell\cdot m^{-2}\cdot hr^{-1}$ and is in effect the first point in all of the figures. During the experiments, the flux was measured at regular intervals and recorded as the flux against time plots given below. Note that the second point shown always lies lower than the original clean water value.

The 500 $mg\cdot\ell^{-1}$ solutions were prepared by dissolving 25 g dextrin in 2 ℓ of warmed water using a magnetic stirrer; this was added to the RO water in a 100 ℓ storage tank. This process was repeated and the water in the tank topped up to 100 ℓ.

It was found that, after using the cleaning procedure described below, a reproducible clean water flux of 133-137 $\ell\cdot m^{-2}\cdot h^{-1}$ could be obtained. When the value of 133 $\ell\cdot m^{-2}\cdot h^{-1}$ was not achieved, the cleaning procedure was repeated.

Between runs the element was cleaned using a sodium lauryl sulphate (SLS) solution, rinsed using RO water, and backpulsed, using pulses similar to that shown in Fig. 3. The SLS cleaning solution consists of 1 g sodium lauryl sulphate, 1 g calcium hypochloride and 1 g ethylene diamine-tetraacetic acid, per litre of RO water. First the cleaning solution was circulated (50 kPa and 1 000 $\ell\cdot h^{-1}$) together with backpulsing and then the circulation pump and backpulsing were switched off for 1 h. After some experimentation the parameters for the backpulsing used to obtain the results given in Fig. 4 were used. This was repeated 3 further times. The cleaning solution was then rinsed out of the plant using first tap water and then RO water at 50 kPa and 1 000 $\ell\cdot h^{-1}$. The tap water was then flushed out using RO water, after which the clean water flux value was measured. If this was below 133 $\ell\cdot m^{-2}\cdot h^{-1}$, the process was repeated.

Results

Figure 2 shows one of the three fouling curves, obtained using no backpulsing, with the standard feed pressure of 100 kPa and

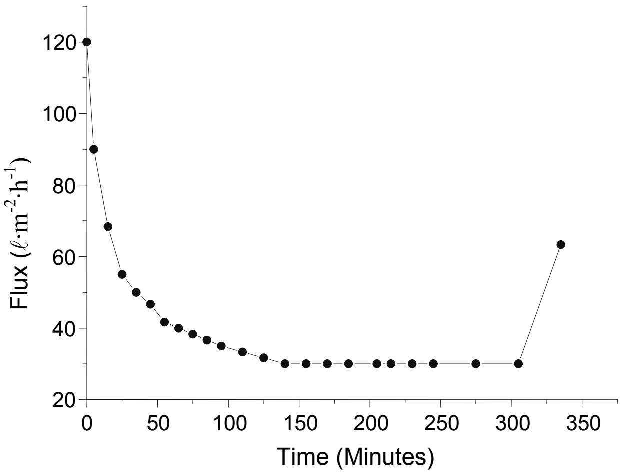

Figure 2
Permeate flow rate as a function of time. The feed pressure and flow are given in the text. The last point shows the increase in the permeate flux after the feed had been switched to RO water for 15 min.

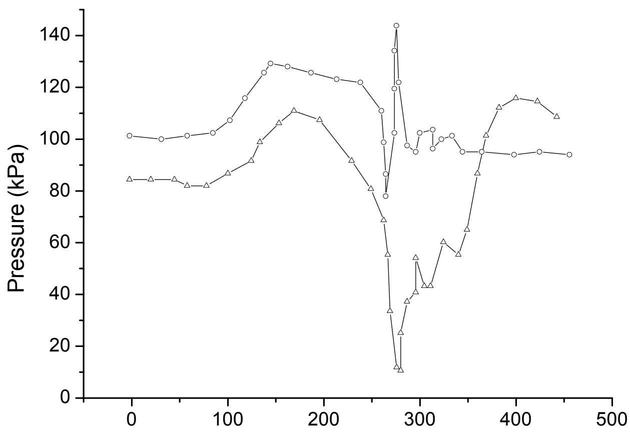

Figure 3
Reproductions of traces of the pressure against time. Voltages from the transmitters were recorded on an oscilloscope as a function of time. As the original figure was only obtainable as a computer printout (dump), it had to be digitized. The voltages were the converted to pressure and re-plotted. The upper trace shows the primary pulse in the permeate space and the lower the secondary pulse in the feed space (enhanced by a factor of ten). The lower trace has been moved down by about 20 kPa and has a base pressure of 10 kPa.

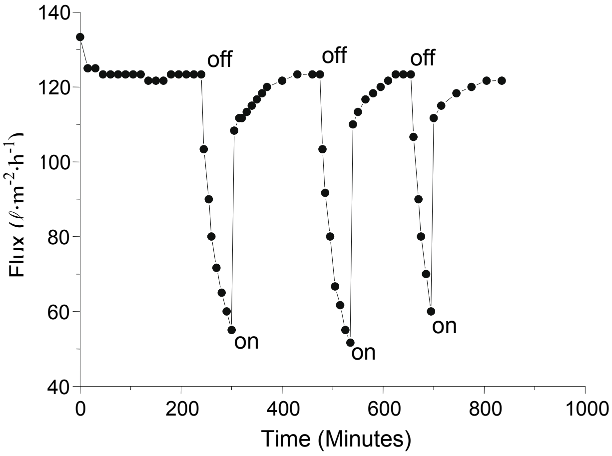

Figure 4
The permeate flow rate as a function of time, using a pulse with a 175 ms pulse width and a 1 s repartition rate (1 Hz). The pressure reservoir was set at 350 kPa and the peak primary pulse pressure was 30 kPa (See Fig. 3).

a flow rate of 1 000 $\ell\cdot h^{-1}$. The important parameter here is the saturated flux value, which was found to lie between 30 and 33 $\ell\cdot m^{-2}\cdot h^{-1}$.

Figure 3 shows the pressure-time traces for one of the pressure pulses, which was used to obtain the results shown in Fig. 4. These 2 pulses all resulted from a pressure in the pulse reservoir of 350 kPa, a pulse width from the function generator of about 180 ms, and a repartition rate of 1 Hz. From the figure, it can be seen that the primary pulse width, which was defined as the interval between the point at which the pressure starts to rise and the point at which it drops sharply, was about 170 ms and the maximum peak pressure was 38 kPa. The 'peak pressure' of 38 kPa is the excess pressure which drives the negative flux. It is obtained by subtracting the base pressure of 100 kPa in the feed space from the total pressure of 138 kPa. The pulse was followed by some 'ringing', especially after the solenoid valve closed. Recalling that the base pressure in the feed space is 100 kPa, reverse flow occurs during the pulse, driven by the negative TMP of 38 kPa. An examination of Fig. 3 shows that the flux is reversed for about 18% of the cycle, i. e. positive flow could only occur for 82% of the time. Higher backpulse pressures were not used for fear of damaging the membrane, which was being operated outside of the manufacturer's specifications, namely that of 'no significant reverse TMP'. Very similar pulses where observed when monitoring the backpulses used to clean the element.

The secondary pulse (enhanced by a factor of 10), as observed at the input of the feed space, is also shown in Fig. 3, where the base pressure was about 10 kPa. Compared to the primary (permeate) pulse, there was a small delay before the pressure reached its maximum. It also decayed more rapidly, which was probably due to the pressure leaking out of the feed and/or the retaintate ports. The peak pressure was 2.6 kPa after about 158 ms. In this case the peak pressure is measured with respect to the pressure at zero time. Note that the feed space pressure has dropped significantly below the equilibrium value during the ringing mode. The ringing mode was followed by a large positive peak. After the conclusion of these experiments it was found that the primary source of the ringing signal and the positive 'ringing' peak was in the flexible hoses connecting the plant from V5 through V6 to the tank (R1). Ringing signals were observed in all experiments, but the amplitude and shape varied somewhat from case to case. However the ringing response in the feed space should have no effect on the results obtained here.

The best of two very similar results, using the specified parameters, which are close to the optimum values, are shown in Fig. 4. (Results from several experiments performed with parameters close to those used to obtain Fig. 4, give similar results to those shown in Fig. 4). Here the pressure pulse width was again about 170 ms and the repetition rate 1 s (1 Hz), and the pressure in the pulsing reservoir was 350 kPa. The saturation flux value, which is reached very rapidly, is 123 $\ell\cdot h^{-1}$ (90% of the clean water value or 3.9 times more than the saturation flux) and remained at this value until the backpulsing had been switched off. The results also show that whenever the backpulsing was switched off the element fouls rapidly, in a manner similar to the 'no pulsing' results shown in Fig. 2. Note that the backpulsing enhancement factor of the saturation value given above was obtained by dividing the appropriate saturation flux by 31.5 $\ell\cdot m^{-2}\cdot h^{-1}$.

The results of the effect of changing some of the parameters away from the nearly optimum ones are discussed next. Two experiments also using an aprox. 170 ms wide pulse width and 38 kPa high backpulse, but with a repetition rate of 10 s (i.e. positive flux flowing for 98% of the time), gave final fluxes of 98 and 100 $\ell\cdot m^{-2}\cdot h^{-1}$ (i.e. about 72% of the clean water value and 3.15 times the saturation value) after 180 min. The backpulsing was then switched off, and the flux was observed to decease in a manner somewhat similar to that shown in Fig. 4. When the backpulsing was switched on again, after 60 min, the flow had recovered to 58 $\ell\cdot m^{-2}\cdot h^{-1}$ in 30 min but only reached 98 $\ell\cdot m^{-2}\cdot h^{-1}$, again after about 180 min. These results showed that, in spite of the higher fraction of time (98%, as opposed to the previous case of 82% (Fig. 4)) for which there was a positive TMP and that a positive flux could occur, a lower equilibrium flux was observed. These results illustrate the effect on the nett flux

Table 1
A summary of the input parameters and the resulting relative flux and flux enhancement values in the experiments reported on in this paper

Pulse duration (seconds)	Pulse interval (seconds)	Pulse TMP pressure (kPa)	Final flux % Clean water flux	Saturation enhancement
0.175	1	38	90	3.9
0.175	10	38	72	3.15
0.175	1	8	55	2.15
0.094	1	8	34	1.45

of the time during which there was a positive TMP and a positive flux, and when there was a negative TMP and a negative flux.

When the amplitude of the pulse was decreased from 38 kPa to 8 kPa (the reservoir pressure was dropped from 350 to 200 kPa), with the primary pulse still about 170 ms wide, it took a very long time (300 min) to reach the first saturation flux of 80 $\ell \cdot m^{-2} \cdot h^{-1}$. The final saturation value in this case, after 2 on-off cycles, was 72 $\ell \cdot m^{-2} \cdot h^{-1}$ (55% of the clean water value and 2.3 times the saturation value). A second experiment gave a final comparable flux of 67 $\ell \cdot m^{-2} \cdot h^{-1}$. These results clearly show that raising the pulse pressure improves the cleaning. Unfortunately, the back-pulse pressure has an upper limit, because the membrane structure and the glue joints of the membrane envelopes will only withstand a finite pressure. There is also the possibility that fatigue will lead to membrane or joint failure. Note that these experiments ran over a period of 6 months and this included several hundred hours with the maximum back pressure (350 kPa) in the pressure reservoir and peak pressures in the permeate space of up to 38 kPa. The integrity of the module was maintained during this period.

Experiments were carried out with a 0.5 second repartition interval and a pressure pulse width of about 94 ms, which means that there was a positive flux for about 80% of the time. From the traces similar to those shown in Fig. 4, it was observed that the primary peak pressure was 8 kPa, which was reached after 62 ms. Note that for this pulse width the opening and closing time of 25 ms (manufacturer's data) for the solenoid valve must have had a significant effect on the pulse width and shape. The feed peak pulse pressure was delayed compared to the primary pulse, which had a peak of about 0.9 kPa and was about 82 ms wide. The final saturation flux value, after 1 on-off cycle, is low (45 $\ell \cdot m^{-2} \cdot h^{-1}$or 34% of the clean water value) compared with those obtained at higher repartition rates, but still 1.45 times the 'no pulsing' saturation value. The explanation for this poor performance is thought to be that the pulse length is too short and the amplitude too low for the water to get from the permeate tube into the extremities of the envelope and flow backwards through the membrane (reverse flow). This meant that all of the membrane envelopes were not properly cleaned by a reverse flow through the membrane. The final saturation value and the small decrease and increase during an on-off cycle show that there is still some cleaning action with these rather weak pulses.

Note that some experiments were performed with the pressure reservoir set below 200 kPa. In all of these experiments no significant cleaning action was observed, which is believed to be because the peak pressure was insufficient for reverse flow through the membrane to occur. This indicates, as could be expected from the structure of an element compared to a flat cell, that no 'vibrational' type cleaning motion occurs under these conditions. It also shows that work on flat cells (described in Czekaj et al., 2000; Czekaj et al., 2001; Sondi et al., 2000; Kuberkar et al., 1998; Wenten, 1995; Ramirez and Davis, 1998; Mores et al., 2000; Parnham and Davis, 1996; Mairal et al., 1999; Shugman et al., 2009) is not applicable to spiral wrap membrane. Note that all the results given and described above were performed on membranes which have been cleaned, using the procedure previously described, so that the clean water flux was above 133 $\ell \cdot m^{-2} \cdot h^{-1}$.

Conclusions

Continuous backpulsing can keep the fouling in a spiral wrap element at a sufficiently low level that the flow rate/flux remains fairly close to its clean-water value over a long period. In the present case (dextrin and a polysulphone 100000 MWCO membrane), the best result achieved was 90% of the clean-water value or 3.9 times the saturation flux after fouling. Recall that taking all of the preliminary experiments and those reported on here into account the membrane has been backpulsed with peak pressures close to 38 kPa for over a hundred hours with no apparent signs of damage. Note this does not include the time spent on experiments with peak pressures significantly below 38 kPa. In spite of these positive indications, this method is unlikely to be used in practice, until both the element and the membranes therein have been thoroughly tested, under operating conditions. Therefore, it may prove necessary to specifically design membranes and elements to be operated in this manner.

The experiments also showed that a combination of permeate backpulsing and chemical cleaning can reliably clean the membrane back to a clean-water flux of 130 to 133 $\ell \cdot m^{-2} \cdot h^{-1}$.

These results agree with similar work currently being done on flat sheet membranes in this institute (Shugman et al., 2009). These results show that several membranes (Alpha Leval GRO 100 000 MWCO polysulphone and PAL Biodyne 0.20 and 0.45 nylon membranes), using several different foulants (dextrin, cleaned yeast and 1.0 alumina powder), can be effectively cleaned using permeate backpulsing . These flat cells were also operated at 100 kPa feed pressure and used backpulsing into the membrane space. For most successful cleaning the frequency used was close to 7 Hz and the 'sharp' peak pressure just over 140 kPa. These results also showed that the peak backpulse pressure must exceed the feed pressure for any significant cleaning to be observed.

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