A cost optimization study of flux and fouling rate for UF in the water industry

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ABSTRACT

Designing a commercial UF/MF system is an exercise in compromise. Selecting a high flux reduces capex by minimizing the membrane area required, but increases operating costs due to the increased chemical cleaning frequency, higher waste disposal volumes, and higher operating pressure. Most commercial systems are designed to run at fluxes significantly above the critical flux, so a degree of fouling and a reliance on chemical cleaning is inherent to the design.

This paper examines the relationship between flux and membrane fouling rate through a review of experimental field data. The analysis shows that fouling rate increases exponentially with flux, with a function dependent upon the characteristics of the feed. The paper then presents the results of a cost optimization study in which Total Water Cost (TWC) is evaluated as a function of feed source and plant size for different CIP cleaning frequencies.

The minimum TWC occurs in all cases for CIP frequencies of between 1/week and 1/month. Smaller plants with low fouling feeds have an optimum near 1 CIP/week using a relatively high flux design. In contrast, feeds with higher fouling propensity, and medium or large plant sizes have a TWC optimum close to 1 CIP/month, and should use a lower design flux. It is suggested that the flux corresponding to the TWC optimum should be designated the sustainable flux.

Key words | cost optimization, critical flux, fouling, sustainable flux, ultrafiltration,

BACKGROUND

The concept of critical flux has been used to describe the relationship between flux and fouling rate in controlled steady state environments (Field et al. 1995). Critical flux is that flux below which no particulate fouling occurs. Above this level, fouling occurs, the extent of which is a function of flux. However, the concept of critical flux is only applicable where a true steady state is established such as laboratory test cell or a crossflow system design. In the application of UF/MF membranes in the water industry, directflow designs are used in which a dead end filtration cycle is followed by a regular backwash cycle. This is a pseudo steady state operation with different fouling characteristics to crossflow. In directflow, a degree of fouling occurs in the filtration cycle even at low fluxes, and this fouling may not be fully removed during the backwash cycle. Accordingly, it is necessary to develop different tools to understand, predict, and control membrane fouling. A practical tool for providing design guidelines is the concept of sustainable flux.

The sustainable flux is the flux at which a modest degree of fouling occurs, providing an acceptable compromise between capex (by using a high flux) and opex (by restricting the fouling rate) (Pearce & Field 2007). The value is dependent on feed characteristics, membrane characteristics, process design, and operational requirements (e.g. by use of an acceptable cleaning frequency). Thus the sustainable flux represents a trade-off between capital and operating costs. From a purely economic point-of-view, an economically sustainable flux is one that meets a cost objective over the projected life of the membrane plant.
Commercial UF/MF systems use fouling control strategies as outlined in Table 1 below.

Normal backwash and air scour controls fouling to a degree, but a maintenance procedure is needed, called a chemical wash or Chemical Enhanced Backwash (CEB) to counter the effect of slight progressive fouling inherent to the pseudo steady state design of directflow. If fouling rates are low, the next step, i.e. Clean In Place (CIP) will be infrequent. As flux increases and fouling rates become higher, the use of CIP will have to increase (Baars et al. 2005). The last resort for a severely over-stressed system is to make operational and perhaps design changes.

The goal of a successful design is to achieve a sufficiently high flux, whilst keeping fouling rates acceptable. The relationship between flux and fouling rate can be evaluated from pilot data as described in this paper. These data have then been used to show the cost optimum for different feed sources as a function of plant size. It is suggested that the sustainable flux is defined as the flux which yields the lowest Total Water Cost for any given set of circumstances.

**PILOT STUDIES**

Pilot trials can be used to establish the relationship between flux and fouling rate for a particular set of circumstances, and evaluate a sustainable flux for a commercially competitive design and operation. The data from the pilots show that at commercial design fluxes, fouling rate increases exponentially with flux, the rate of rise being determined by feed source and process design.

Fouling data have been obtained from pilot studies with four different water types, representing the cross section of applications encountered in water and wastewater. In each case, the membrane used for the evaluation was hydrophilic polyethersulfone (PES) with a coarse UF rating of 150 kda from two different manufacturers. In all of the pilots, the system design was pressure driven with feed inside the fibre and permeate backwash.

Details of the feed sources and pilot operation are shown in Table 2 below. In each case operation was optimized during the course of the trial, with attempts to increase flux. In some cases, fouling was controlled by feed dosing, whilst in others, automated Chemical Enhanced Backwash (CEB) was used. The goal was to obtain as high a flux as possible without having to resort to an excessive cleaning frequency through the use of Clean In Place (CIP).

Alternative optimizations would have been possible with different constraints on feed dosing, and the use of CEB, and this would have affected the fouling rate. For example, feed dosing or a more frequent use of CEB is likely to allow a higher flux to be used, or reduce the fouling rate at a given flux, and thus extend the interval between CIPs.

**RESULTS**

Of the four water sources, the lowest rate of fouling occurs for the clarified surface water, where the flocculant has a beneficial effect (Kennedy et al. 2003). Secondary wastewater represents the opposite extreme. Fouling occurs at a low flux for this feed, despite the addition of coagulant to the feed, and it also has the highest rate of fouling. Raw surface water, can be operated with a somewhat higher flux than wastewater, but it has almost as high a fouling sensitivity. Ground water has the lowest fouling propensity, and therefore the highest sustainable flux.

**Figure 1** below shows how CIP frequency can affect the acceptable fouling rate. If a daily CIP would be acceptable, it would be possible to accept a fouling rate of just under 100 lhm.bar/day. For a more normal range of one CIP/week to one CIP/month, the acceptable fouling rate would be between 13 and 3 lhm.bar/day. The design flux used in the cost optimization study is the value at which the curve in Figure 1 intersects the chosen CIP frequency line. For the commonly accepted level in North America of one CIP/month, a permeability loss of 3 lhm.bar/day can be accepted. If the fouling rate is above this level, either the

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**Table 1 | Fouling control strategy for commercial systems**

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Type</th>
<th>Characteristic</th>
<th>Process Seq</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prevention</td>
<td>Frequent</td>
<td>Physical</td>
<td>Bw,air,fwd/Lc/t</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Intermittent</td>
<td>Chemical</td>
<td>CEB</td>
</tr>
<tr>
<td>Recovery, cure</td>
<td>Intervention</td>
<td>Chemical</td>
<td>CIP</td>
</tr>
<tr>
<td>Des/ops changes</td>
<td>Add hardware</td>
<td>System change</td>
<td>Repl membrane</td>
</tr>
<tr>
<td>Feed characteristics</td>
<td>Ground water under influence</td>
<td>Surface water clarified</td>
<td>Surface water raw</td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------------------------</td>
<td>------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Feed characteristics</td>
<td>Source</td>
<td>River</td>
<td>River</td>
</tr>
<tr>
<td></td>
<td>Coagulation</td>
<td>Alum dosed</td>
<td>Lime softened</td>
</tr>
<tr>
<td></td>
<td>Lime softening</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dosing</td>
<td>0.6–0.8 ppm Cl₂</td>
<td>0.25 ppm SHMP</td>
</tr>
<tr>
<td></td>
<td>Turbidity, NTU</td>
<td>0.4–0.6</td>
<td>1–3 (with excursions)</td>
</tr>
<tr>
<td></td>
<td>TOC, ppm</td>
<td>1.8–2.5</td>
<td></td>
</tr>
<tr>
<td>Process design</td>
<td>B/w interval, mins</td>
<td>120</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>B/w flux, l/m² h</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>CEB1*</td>
<td>None</td>
<td>25 ppm Cl₂, 3 min, 6–12/d</td>
</tr>
<tr>
<td></td>
<td>CEB 2</td>
<td>2% citric, 10 min, 2/d</td>
<td>50 ppm Cl₂, 15 min, 1/d‡</td>
</tr>
<tr>
<td></td>
<td>CIP1</td>
<td>pH 11.5/25 ppm Cl₂</td>
<td>pH 12</td>
</tr>
<tr>
<td></td>
<td>CIP 2</td>
<td>pH 12</td>
<td>pH 12/50 ppm Cl₂</td>
</tr>
<tr>
<td>Operation</td>
<td>Temperature, °C</td>
<td>12</td>
<td>2–23</td>
</tr>
<tr>
<td></td>
<td>No. of days</td>
<td>70</td>
<td>270</td>
</tr>
</tbody>
</table>

*Time indicates soak period.
†CEB procedure for low flux.
‡CEB procedure for high flux.
§55°C, 40 min soak.
flux has to be reduced, or chemical dosing in the feed or increased CEB frequency has to be introduced. If too high a flux is used, or the membrane permeability is allowed to drop too far before cleaning due to an insufficient CIP frequency, irreversible fouling may occur.

Table 3 provides sustainable flux values from the pilot data and suggests sustainable flux values for the main plant. Note that a main plant design normally uses a flux 10% lower than that measured on a pilot to provide an allowance for the inefficiency of main plant operation compared to a single module, and to provide tolerance for minor upsets.

**COST OPTIMIZATION**

The cost study has been undertaken for the four different water sources, using design fluxes based on the pilot data. The designs have been performed for feed temperatures of 12°C, using the temperature corrected flux from the pilot operation, then reduced by a further 10% to provide an allowance for potential inefficiency in the main plant.

Four CIP regimes have been considered, with CIP frequencies of once per day, once per week, once per month and once per year. The greater the CIP frequency, the higher the fouling rate that can be allowed, and therefore the higher the design flux. The pilot data in Figure 1 show these CIP frequencies as horizontal lines on the graph. The design flux for the main plant is developed from the pilot plant flux by taking the flux value where the fouling rate curve intersects the CIP line. The cost optimization then evaluates the capex and opex from the system design parameters for a given CIP frequency. The main plant design flux is adjusted as in Table 3 by a 10% inefficiency factor compared to the pilot and temperature corrected.

**Capex**

The capital cost of an installed UF system (including the mechanical and electrical scope, but excluding civils and building costs) can be related to the membrane area for a particular type of feed. Surveys of plant data have been used to develop algorithms for the relationship between UF system capex and flowrate (Adham et al. 2005). Since flowrate can be directly correlated with membrane area, this study has used a survey of bid data to relate capex with membrane area for different water sources.

Three plant sizes have been considered, namely:

- small plants of 4 MLD (1 MGD)
- medium plants of 20 MLD (5 MGD)
- large plants of 100 MLD (20 MGD)

Figure 2 provides the capex charge estimate as a function of flowrate for the four water sources used in the pilot studies. The flux was taken from the experimental data in Figure 1, and capex calculated at four different CIP frequencies. The capex algorithm for the groundwater feed has the highest proportion of cost attributed to membrane area. The other feed types have a lower dependence, since they are more reliant on chemical cleaning, and have extensive dosing, control, and waste handling systems.

For a large plant with an easily treatable feed such as a groundwater, membranes may comprise 36% of the system cost. At the other extreme, membranes in a small
wastewater plant may only comprise 12% of the system cost. Indicative membrane prices have been used of $55/m² for small plants, $50/m² for medium plants, and $45/m² for large plants.

The capex charge per m³ of water produced has been calculated from the capex based on a 20 year plant life with a 6% interest rate. The figure shows that the capex charge/m³ declines sharply with increasing flow from small to medium plants. Thereafter, there is a more modest rate of decline of the capex charge with increasing flow.

**Opex**

For larger plants, operating costs are normally dominated by membrane replacement costs, feed pump power, chemicals, and waste disposal. The other factors to consider are labour, maintenance, and power for other uses. Labour is highly variable depending on the size of plant, region, local circumstances, and the philosophy of the owner. For larger plants, it can be low, though for small plants it is a more important relative cost. In order to simplify comparison and eliminate site specific circumstances, it has been excluded from this study. Also, maintenance and other power costs have been excluded, since these are normally low for all plants, and should be directly related to plant size.

**Figure 3** shows capex and opex costs for medium size plants for two different CIP frequencies. The figure shows that the two sets of costs are reasonably similar for each of the four different water types. Increasing CIP frequency allows a higher flux to be used, which reduces capex. However, this is achieved at the expense of opex due to increased use of chemicals, higher pumping pressure (since fluxes are higher), and shorter membrane life. Interestingly, the capex advantage of higher flux is almost cancelled out by the higher opex in all four of the cases. The more easily treated feeds with lower fouling propensity benefit from the higher flux operating regime. Conversely, the higher fouling feeds, i.e. raw surface water and wastewater, benefit from lower flux operation.

The opex breakdown is illustrated in **Figure 4**, and shows that there is a significant variation between the different cases considered. The chemical cost is affected by the dosing regime, the use of chemical wash (CEB), and by the CIP frequency.
Chemical cost is affected by the type of chemical purchased, and the delivery volume. The three types of chemicals normally used are acids, alkalis and oxidants. The acid can be sulfuric, hydrochloric, or citric, which have a cost ratio of 1:4:10 respectively. Sulfuric is cheapest since it is purchased in a highly concentrated form (96%), though this can give handling concerns. Hydrochloric is preferred by some users since it is delivered in a more dilute form, which makes handling easier but significantly increases expense. Also, it is prone to fuming and is corrosive. Citric is considerably more expensive, and is very effective for transition metals (especially if there is Fe or Mn fouling) and any fouling that requires a chelating action rather than just acidity. The chemical used in the costing study has been sulfuric, even though hydrochloric was used for the pilots, since it has been assumed that the main plant would use the cheaper option.

The only alkali used for cleaning is caustic, which has a price equivalent to sulfuric acid.

The oxidant is usually chlorine, which is inexpensive. If neutralization is required, sodium bisulfite (SBS) is normally used, though it should be noted that it is four times the price of chlorine. Sometimes other oxidants such as H₂O₂ are preferred since there are fewer concerns with neutralization and disposal to a water course. It is about four times the price of chlorine, and has lower oxidizing and biocide potential, partly as a result of poor persistence. Excess H₂O₂ can be neutralized by passing through a carbon bed. In the cost study, it has been assumed that chlorine is used as oxidant in all cases, with SBS for neutralization if required.

There are three normal options for chemical deliveries, i.e. 25 l carbuoys, 1 tonne IBC, or 20 tonne tanker. The cost ratio for the three options is approximately 4:2:1 respectively. Tanker deliveries require handling, storage, and bunding facilities, and so increase capex. IBCs are a cost-effective compromise, since they themselves may act as a store, and so reduce capex. Carbuoys are sometimes chosen for small plants with low chemical usage, since the site chemical inventory can be minimized. The default option used in the cost study is the IBC, with tanker prices assumed for large facilities with high chemical usage.

Membrane replacement is an important cost in all cases, and is affected by membrane price and membrane life. In the cost study, it is assumed that membrane life is longer for the more easily treatable feed, i.e. groundwater, with lower life assumed for wastewater. Also operation with low CIP cleaning frequency (i.e. low flux) gives longer life. However, high flux operation requiring frequent CIP results in high chemical use and high operating pressure, and this type of operation shortens membrane life. Actual membrane life for an operating plant is dictated by the operating conditions used, but is also affected by the commercial view of the supplier, and the degree of risk they are prepared to absorb. The assumed membrane life matrix is shown in Table 4 below. Figure 4 showed that membrane replacement cost is a significant part of opex, so the assumptions in the table have an important effect on the optimnization.

**Total water cost**

Total water cost (TWC) for the three different plant sizes are shown in Figures 5 to 7. The data show that that a CIP frequency of between 1/week and 1/month provides the TWC minimum for all feed types and plant sizes. At lower CIP frequency than this range, too low a design flux has to
be used which increases capex; at higher CIP frequency, the loss of productivity due to the downtime during cleaning (assumed to be 8 hours for a CIP) has a significant effect. Clearly, a short CIP, for example at elevated temperature, would reduce this effect and displace the optimum to somewhat higher CIP frequency.

It should be noted that although chemical washes (CEB) use similar amounts of chemical to CIP, the cost impact is much less since downtime for CEB is low. CIP however has a better cleaning efficiency for a given amount of chemical, due to longer contact time and the feed-side recirculation procedure. It is therefore cost effective to control fouling as far as possible with CEB, and to use CIP with lower frequency, unless the CIP sequence downtime can be reduced.

For small plants, higher design flux and CIP frequency provides the TWC optimum. The advantage of high flux operation is clearest for low fouling feeds such as groundwater and clarified surface water. As plant size increase, the optimum is displaced towards lower flux and lower CIP frequency operation. For high fouling feeds, the optimum approaches a CIP frequency of 1/month, and this value is often used in membrane plant specifications in North America. However, the curves show that care should be exercised in deciding what the design flux and CIP frequency should be. Small plants with low fouling feeds should be allowed to utilize higher flux, and with higher CIP frequency.

**Waste disposal**

There are three options for waste disposal:
- neutralize and dispose to water course
- dispose to sewer
- tanker from site.

Normally the first two options are similar in cost, and may cost 0.5 – 1.0 US$/m³ of waste produced. Tankering is much more expensive, and may cost around $30/m³ of waste. Figure 8 shows the impact of tanker cost for small plants, and can be compared to Figure 5. Unsurprisingly, the TWC minimum is displaced towards lower CIP frequencies, with 1 CIP/month rather than 1 CIP/week providing the cost minimum in most cases. However, because waste disposal is not a dominant cost, the effect is not dramatic.

**CONCLUSIONS**

- The critical flux concept, initially proposed for steady state systems, is limited in describing the pseudo steady
state directflow systems normally used in water and wastewater applications, since a low degree of fouling is inherent to directflow, even at low flux.

- Instead it is proposed that the concept of **sustainable flux** is used to reflect an economic compromise between flux (which affects capex) and fouling (which affects opex).
- Pilot data can be used to develop a relationship between flux and fouling rate, and establish the optimum design flux for different feeds and plant sizes at any given CIP frequency.
- A cost study has been conducted which shows that for different water and wastewater feed types representing a cross section of the industry, and for a range of plant sizes, the optimum Total Water Cost (TWC) occurs in all cases for a CIP frequency of between once/week and once/month.
- It is advantageous to design and operate smaller plants at a relatively high flux, and use a high CIP frequency (e.g. approaching 1 CIP/week), whereas medium size and larger plants should be operated at lower flux with less cleaning (e.g. 1 or 2 CIP/month).
- For higher fouling feeds such as raw surface water and wastewater, low flux, low CIP frequency design should be adopted; for low fouling feeds such as groundwater and pre-treated surface water, high flux, high CIP frequency design should be adopted.
- It is suggested that the **sustainable flux** for a plant is that flux which provides the lowest TWC.

**REFERENCES**


