A geometry based optimal control approach for low pressure filtration processes: a secondary effluent upgrading case study

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Abstract: The current paper presents a geometrically inspired approach for the optimization and control of low pressure filtration units for (waste)water treatment. The optimization aims at minimizing the operational costs, encompassing both energy and chemical cleaning costs (and, hence, accounting for reversible as well as irreversible fouling), while ensuring a minimum required nett water flux. Advantage has been taken of the process’ cyclic nature. In each cycle the transmembrane pressure increases during the forward flow phase due to fouling and decreases again due to backflushing. Assuming linear increases/decreases allows the use of simple geometric approaches for computing analytical cost and constraint expressions. Relating both slopes to operational parameters as forward flux and filtration time, provides the handles for the actual control and optimization. However, due to the discrete nature of the number of cycles in one operation run, a relaxation strategy is employed for solving the optimization problem. Simulation results are presented for a preliminary filtration model inferred from a microfiltration plant for secondary effluent upgrading in the context of a research project with the Keppel Seghers company.

Keywords: optimization, cost reduction, wastewater treatment, low pressure filtration

1. INTRODUCTION

Given the dramatically decreasing fresh water supplies, the water demand from industry, agriculture and human consumption, can no longer be satisfied unless other sources than ground water supplies are exploited. To this end, sea (or brackish) water or surface water are extensively being used but only after thorough treatment. In addition, with an increased focus on closing the water cycle and the corresponding water reuse schemes, more efficient wastewater treatment techniques to ensure high and constant quality effluents are required.

For this water quality upgrading, membrane filtration processes have become indispensable since a cascade of low and high pressure filtration steps can meet the above specified target. The high pressure filtration is most often a reverse osmosis (RO) step, able to retain up to monovalent ions (Wintgens et al., 2005). To ensure stable operation, RO requires proper pretreatment which may involve combinations of some of the following (López-Ramírez et al., 2003): flocculation/coagulation, lime clarification, sand filtration, UV and sodium hypochlorite disinfection, anti-scalant addition, pH adjustment and/or microfiltration (MF) or ultrafiltration (UF). The latter low pressure filtration pretreatment techniques yield the most satisfactory results given, again, their high and consistent quality effluent (Kim et al., 2002).

However, although the quality of produced water can be most often guaranteed over time, operational costs can vary unfavorably as membrane fouling occurs.

Since the causes of fouling and its consequences are not yet well understood, today, the operational variables of water filtration processes are set to fixed parameters. Operators supervise the process and intervene or adjust the input parameters when they judge it to be necessary, based on previous experience. When the intervention is too late, irreversible damage to the membranes can occur; when it is too soon, the plant is operated suboptimally. Hence, there is a clear need for optimization and (feedback) control of the operational strategy in low pressure based membrane processes, as also indicated in a recent review paper by Drews (2010). More specifically, the filtration settings should be adjusted according to the wastewater and operational characteristics (or demands) at that specific time instant.

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Such optimization and control strategies are still desired. In the membrane bioreactor field (in which the sedimentation step of a conventional activated sludge system is replaced by a micro- or ultrafiltration step) the work of Smith et al. (2005); Jeison and van Lier (2006); Busch et al. (2007) and Busch and Marquardt (2008) can be reported. In the context of surface water filtration, Cabassud et al. (2002) performed pioneering work with only very few more recent contributions apart from the work of, e.g., Zonder-van et al. (2008) and Choi et al. (2009). Finally, in the field of secondary effluent treatment (i.e., upgrading the quality of the water that leaves the conventional biological wastewater treatment systems) hardly any optimization or control strategies are reported to the best of the authors’ knowledge. Therefore, the application to illustrate the performance of the in this paper proposed optimization strategy will be secondary effluent upgrading by a microfiltration step, but the strategy is generic in nature for all the mentioned low pressure filtration processes.

The paper is structured as follows. Section 2 discusses the experimental set-up that has been employed to collect relevant data. Section 3 introduces the optimization problem formulation, while in Section 4 a geometrically inspired solution approach is proposed. Afterwards, simulation results are presented and discussed in Section 5. Finally, Section 6 summarizes the main conclusions and provides directions for future research.

2. EXPERIMENTAL SET-UP

Effluent from a municipal wastewater treatment plant (WWTP) is pumped to a containerized microfiltration set-up. From a feed tank the water is pumped over the membrane module with a nominal pore size of 0.1 μm (Asahi Kasei Microza® UNA 620-A hollow fiber membrane (PVDF), 55 m² membrane surface), Filtration is semi dead-end (outside-in configuration) combined with a 5% cross-flow. Permeate is collected in a storage tank from which the overflow is discharged. The data collection program included filtration fluxes of 55, 65, 70, 75, 80, 85 L/m²/h for a fixed filtration time of 27.5 minutes. For a fixed filtration flux of 75 L/m²/h, the filtration time was varied from 27.5 to 40 minutes in steps of 2.5 minutes. For all tested conditions, the backwash flux and time was 70 L/m²/h and 105 seconds, respectively. The details of the microfiltration pilot plant are summarized in Figure 1.

3. OPTIMIZATION PROBLEM FORMULATION

In contrast to the reported control strategies which are (i) focusing on only one filtration cycle (e.g., Jeison and van Lier, 2006; Busch et al., 2007) and can, therefore, not (directly) account for irreversible fouling, or (ii) are not taking into account energy related costs (e.g., Cabassud et al., 2002), the here proposed optimization strategy is fully compliant with the current industrial demand in meeting a pre-specified nett production of water while minimizing all operating costs, encompassing both the power and chemical cleaning costs. Furthermore, in the optimization scheme, the cyclic nature of the process is exploited.

More specifically, the aim is to optimize the operation of the low pressure filtration in between two chemical cleanings. This time span is called an operation run $t_{op}$ [min]. One operation run consists of several cycles $t_{c}$ [min], which each contain a forward flux phase $t_{ff}$ [min] and a backflush phase $t_{bf}$ [min]. Also the time for a chemical cleaning has to be accounted for $t_{cc}$ [min]. See also Figure 2 for a schematic representation.

3.1 Assumptions

To facilitate the optimization problem formulation the following assumptions are made. See also Figure 2.

- The fluxes during the forward and backflush phase, i.e., $J_{ff}$ [L/m²/h] and $J_{bf}$ [L/m²/h], are assumed to be constant over the entire operation run $t_{op}$.
- An operation run starts with the initial transmembrane pressure $TMP_{0}$ and ends when the maximum admissible transmembrane pressure $TMP_{max}$ is reached.
- The transmembrane pressure $TMP$ [bar] exhibits a linear behavior over one cycle, i.e., a linear increase with slope $a$ [bar/h] during the forward flow phase and a linear decrease with slope $b$ [bar/h] during the backflush. This gives rise to transmembrane pressure changes $\Delta TMP_{ff} = at_{ff}$ during the forward flush phase, $\Delta TMP_{bf} = bt_{bf}$ during the backflush and $\Delta TMP = at_{ff} + bt_{bf}$ over one filtration-backwash cycle.
- The slopes $a(t_{ff}, J_{ff})$ and $b(t_{bf}, J_{bf})$ depend on the duration and flux of the forward phase.
- The backflush time is fixed and to ensure the feasibility of the proposed approach the forward flow time and filtration flux have to be selected such that the pressure at the start of the next cycle exceeds the one at the start of the previous cycle. The idea behind this assumption is that during each cycle, both reversible and irreversible fouling of the membrane takes place. As a result, the transmembrane pressure during one operation run evolves approximately according to a piecewise linear or sawtooth profile.
- To meet operational constraints, a lower bound on the nett flux has to be imposed.
- For chemical cleaning, it is assumed that always the same amount of chemicals has to be used, irrespective of the degree of membrane fouling.
3.2 Objective function and decision variables

The objective function accounts for the energy used by the pump $E$ [kWh] and the chemicals $C$ [kg] employed for cleaning. This cleaning cost may also include a cost for membrane degradation due to chemical cleaning. To enable a fair comparison the costs are averaged over the entire operation run time $t_{op}$ increased with the time for chemical cleaning $t_{cc}$. The decision variables, i.e., the variables that can be manipulated, are the duration $t_{ff}$ and the flux $J_{ff}$ of the filtration phase.

$$\min_{t_{ff}, J_{ff}} = \frac{p_E E + p_C C}{t_{op} + t_{cc}}$$

Here, $p_E$ [€/kWh] and $p_C$ [€/kg] indicate the energy and the chemical price, respectively. The energy is the integral of the power used to impose the transmembrane pressure:

$$E = \int_{t_{ff}}^{t_{op}} \frac{TMP J_{ff} A}{\eta_p} dt$$

with $A$ [m$^2$] the membrane area and $\eta_p$ [-] the pump efficiency. However, as the forward flux, the membrane area and the pump efficiency are all constant over time, the energy used is proportional to the integral of the transmembrane pressure or alternatively, the area below the $\text{TMP}(t)$-curve. Since the transmembrane pressure during the backflush phases is hard to determine exactly, only the pressure during the forward flux is accounted for. As the $\text{TMP}(t)$-curve is described by repeating piecewise linear cycles, the integral can be computed algebraically.

3.3 Constraints

The piecewise linear transmembrane pressure evolution to model the filtration process is regarded as the first constraint. In addition, this pressure has to be bounded:

$$\text{TMP}_{\text{min}} \leq \text{TMP} \leq \text{TMP}_{\text{max}}$$  \hspace{1cm} (3)

When the upper bound is reached the process is stopped immediately. Second, bounds on the decision variables are imposed:

$$t_{\text{ff, min}} \leq t_{\text{ff}} \leq t_{\text{ff, max}}$$  \hspace{1cm} (4)

$$J_{\text{ff, min}} \leq J_{\text{ff}} \leq J_{\text{ff, max}}.$$  \hspace{1cm} (5)

Also the feasibility constraint has to be satisfied:

$$\Delta P_{\text{c}} = a t_{\text{ff}} + b_{\text{bf}} \geq \epsilon.$$  \hspace{1cm} (6)

Finally, the operational constraint requires that at least a given amount of water is treated during the operation run, which can be reformulated as a lower bound on the net flux:

$$\frac{n_c J_{\text{ff}}}{t_{\text{ff}}} - (n_c - 1)J_{\text{bf}} + J_{\text{cc}} \geq J_{\text{min}}$$  \hspace{1cm} (7)

with $n_c$ the number of cycles.

4. SOLUTION STRATEGY

4.1 Approach

The optimization follows a two-step approach. First a continuous optimization problem is solved based on relaxing the number of cycles. The solution of this relaxed optimization problem is then compared to the corresponding simulation without relaxation.

4.2 The discrete nature of the number of cycles $n_c$ ...

Before starting it has to be emphasized that the number of cycles is -in principle- an integer. This discrete aspect has implications for the cost and constraint formulations. When the transmembrane pressure $\text{TMP}$ at the end of one cycle exactly coincides with the maximum transmembrane pressure $\text{TMP}_{\text{max}}$, the number of cycles is exactly computed as follows:

$$n_c = \frac{\text{TMP}_{\text{max}} - \text{TMP}_0 + \Delta P_{\text{bf}}}{\Delta P_{\text{c}}}.$$  \hspace{1cm} (8)

However, most of the time the maximum transmembrane pressure is not reached exactly at the end of one cycle. Hence, the floor value of the number of cycles $n_c$, i.e., the largest previous integer value, and the relaxed number of cycles $\hat{n}_c$ are defined as follows:

$$n_c = \left\lfloor \frac{\text{TMP}_{\text{max}} - \text{TMP}_0 + \Delta P_{\text{bf}}}{\Delta P_{\text{c}}} \right\rfloor$$  \hspace{1cm} (9)

$$\hat{n}_c = \frac{\text{TMP}_{\text{max}} - \text{TMP}_0 + \Delta P_{\text{bf}}}{\Delta P_{\text{c}}}.$$  \hspace{1cm} (10)
Fig. 3. Discrete nature of number of cycles \( n_c \) and the resulting discontinuous exact operation time \( t_{op} \), averaged energy and chemical cleaning cost versus the continuous (relaxed) approximation.

4.3 ... and its influence

This discrete nature has a direct impact on several variables, the first of which being the total operation time \( t_{op} \). The exact operation time is given by:

\[
t_{op} = \frac{\eta_p}{\xi} (t_{ff} + t_{bf}) + t_{add}
\]

where the additional time \( t_{add} \) is given by:

\[
t_{add} = \frac{\text{TMP}_{\text{max}} - \text{TMP}_0 - \eta_c \Delta P_c}{a}.
\]

Hence, when using the relaxed number of cycles \( \hat{n}_c \) also a relaxed operation time can be computed:

\[
t_{c} = \hat{n}_c (t_{ff} + t_{bf}) - t_{bf}.
\]

Second, the total pressure energy can be computed based on geometric considerations. The total energy corresponds to the integral over the transmembrane pressure curve (Equation (2)) which, due to the discrete nature, can also be written explicitly as follows when an integer number of cycles is assumed:

\[
E = \frac{A}{\eta_p} J_{ff} \left( \frac{n_c}{2} \Delta P_c t_{ff} + \frac{(n_c - 1) n_c}{2} \Delta P_c t_{ff} + n_c \hat{t}_{ff} \text{TMP}_0 \right) + E_{add},
\]

where the additional energy \( E_{add} \) is given as:

\[
E_{add} = \frac{A}{\eta_p} J_{ff} \left( \frac{1}{2} \Delta P_c t_{add} \hat{t}_{add} + \frac{\hat{n}_c}{2} \Delta P_c \hat{t}_{ff} + \frac{\hat{n}_c}{2} \Delta P_c \hat{t}_{cc} \right).
\]

Hence, again a relaxed energy value can be defined as:

\[
E = \frac{A}{\eta_p} J_{ff} \left( \frac{n_c}{2} \Delta P_c t_{ff} + \frac{(n_c - 1) n_c}{2} \Delta P_c t_{ff} + \hat{n}_c \hat{t}_{ff} \text{TMP}_0 \right).
\]

It should be mentioned that the relaxed values are only equal to the exact ones if the transmembrane pressure at the end of a forward flow phase exactly coincides with the maximum admissible pressure. The discrete nature is illustrated in Figure 3 in which the discontinuous evolution of the different operational variables and cost related factors are contrasted with a continuous (relaxed) approach.

Finally, the operational constraint on the nett flux (Equation (6)) has to be adapted. The exact formulation is:

\[
\frac{\eta_c J_{ff} t_{ff} - \eta_c J_{bf} t_{bf} + J_{bf} t_{add} + J_{bf} t_{cc}}{\eta_c t_{ff} + \hat{n}_c \hat{t}_{ff} + t_{cc}} \geq J_{min}.
\]

while under the assumption that the additional time during the last incomplete cycle \( t_{add} \) is much smaller than the total filtration time, this formulation reduces to a relaxed one:

\[
\frac{\hat{n}_c J_{ff} t_{ff} - \hat{n}_c J_{bf} t_{bf}}{\hat{n}_c t_{ff} + \hat{n}_c \hat{t}_{bf} + t_{cc}} \geq J_{min}.
\]

5. RESULTS

As a start, the solution to the relaxed optimization problem is computed using Matlab’s \texttt{fmincon} function from the Optimization Toolbox (Coleman and Zhang, 2010). On the basis of the gathered data, the forward and backflush slopes \( a \) [bar/h] and \( b \) [bar/h] are modeled as:

\[
a = \frac{1}{2} \frac{a_1 + a_2}{24},
\]

\[
b = \frac{1}{2} (b_1 + b_2)
\]

with:

\[
a_1 = 0.023 e^{0.078 J_{ff}}
\]

\[
a_2 = 3.216 e^{0.0477 J_{ff}}
\]

\[
b_1 = 9 \cdot 10^{-6} e^{0.159 J_{ff}}
\]

\[
b_2 = 0.0032 e^{0.2381 J_{ff}}
\]

The resulting slopes in function of the filtration time and flux are depicted in Figures 4 and 5.

The other parameter values used are tabulated in Table 1. It has to be stressed that this modeling approach is only a preliminary one but it does serve the purpose of this paper to demonstrate the optimization approach.
Table 1. Parameter values.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Units</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>55</td>
<td>[m²]</td>
<td>membrane surface</td>
</tr>
<tr>
<td>( J_{ff} )</td>
<td>50-90</td>
<td>[L/m²/h]</td>
<td>flux during forward phase</td>
</tr>
<tr>
<td>( t_{ff} )</td>
<td>27.5-40</td>
<td>[min]</td>
<td>forward phase duration</td>
</tr>
<tr>
<td>( J_{bf} )</td>
<td>70</td>
<td>[L/m²/h]</td>
<td>flux during backflush phase</td>
</tr>
<tr>
<td>( t_{bf} )</td>
<td>105/60</td>
<td>[min]</td>
<td>backflush phase duration</td>
</tr>
<tr>
<td>( \text{TMP}_{\text{max}} )</td>
<td>2.0</td>
<td>[bar]</td>
<td>max transmembrane pressure</td>
</tr>
<tr>
<td>( \text{TMP}_0 )</td>
<td>0.2</td>
<td>[bar]</td>
<td>initial transmembrane pressure</td>
</tr>
<tr>
<td>( \eta_p )</td>
<td>1.0</td>
<td>[-]</td>
<td>pump efficiency</td>
</tr>
<tr>
<td>( J_{\text{min}} )</td>
<td>60</td>
<td>[L/m²/h]</td>
<td>minimum nett flux</td>
</tr>
<tr>
<td>( P_{c} )</td>
<td>2.6</td>
<td>[€/h]</td>
<td>cost of one chemical cleaning</td>
</tr>
<tr>
<td>( p_{ce} )</td>
<td>0.09</td>
<td>[€/h]</td>
<td>energy cost price</td>
</tr>
<tr>
<td>( t_{cc} )</td>
<td>120</td>
<td>[min]</td>
<td>time for chemical cleaning</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>0.001</td>
<td>[bar]</td>
<td>minimum ( \Delta P_c ) increase per cycle</td>
</tr>
</tbody>
</table>

Fig. 4. Model for the forward flux (top) and backflush (bottom) slopes in bar/h.

Fig. 5. \( \Delta P_c \) after one filtration-backwash cycle.

The resulting transmembrane pressure profiles are illustrated in Figure 6 (top) with a zoom on the first 400 minutes in the bottom plot. In green the current case with parameters as listed in Table 1 is shown while, in addition, a mere focus on energy (blue) and a mere focus on chemical cleaning costs (cyan) is depicted. The resulting optimal values are summarized in Table 2. When energy costs dominate, one filters at high flux but during a short(er) time interval resulting in a limited total operation time since more frequent chemical cleanings are not penalized. In contrast, when the chemical cleanings are more expensive, the time to initiate such cleanings is postponed as long as possible. Indeed, those settings are selected that ensure the smallest \( \Delta P_c \) increase possible.

When computing the exact values for the operation time, energy consumption, cleaning cost and nett flux constraint, starting from the optimized operation variables for the relaxed formulation (see also Table 2), it is clearly observed that the differences with respect to the relaxed values are small, e.g., at maximum in the order of 0.1% for the costs. Also, it should be noted that the operational nett flux constraint is always satisfied, which is of major importance in practice. As expected, the differences decrease as the operation time increases because the relative importance of the additional uncompleted cycle decreases. In summary, it can be expected that errors due to relaxation will not significantly decrease the optimal performance of a practical plant (also given the total operation time of 20 h vs. cycle times in the order of 40 min). More prominent performance losses can be expected due to modeling uncertainties and plant-model mismatch.

When balancing the energy and chemical cost in the overall cost objective (Equation (1)) by a weight value \( w \) from 0 to 1, with a shifting focus from energy towards chemical cleaning, the fact that the current operation coincides with the chemical cleaning focus (see Figure 6) is confirmed. Indeed, with the imposed parameter values the chemical cleaning costs immediately take the overhand once \( w \) deviates from 0, as demonstrated in Figure 7. Note that more advanced techniques than a weighted sum can be employed to check the (non-)convexity of the entire set of Pareto optimal solutions (Logist et al., 2010).
Table 2. Optimization results.

<table>
<thead>
<tr>
<th></th>
<th>Energy consumption focus</th>
<th>Current situation</th>
<th>Chemical cleaning focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{\text{ff},\text{opt}}$ [min]</td>
<td>34.48</td>
<td>36.51</td>
<td>36.51</td>
</tr>
<tr>
<td>$J_{\text{ff},\text{opt}}$ [L/m²/h]</td>
<td>85.78</td>
<td>60.36</td>
<td>66.36</td>
</tr>
<tr>
<td>Relaxed operation time [min]</td>
<td>392.6</td>
<td>58039.0</td>
<td>58039.0</td>
</tr>
<tr>
<td>Relaxed averaged energy Cost [€/s]</td>
<td>2.64 $10^{-6}$</td>
<td>2.66 $10^{-6}$</td>
<td>2.66 $10^{-6}$</td>
</tr>
<tr>
<td>Relaxed averaged cleaning Cost [€/s]</td>
<td>8.46 $10^{-5}$</td>
<td>7.46 $10^{-7}$</td>
<td>7.46 $10^{-7}$</td>
</tr>
<tr>
<td>Relaxed nett flux constraint [L/m²/h]</td>
<td>60.0</td>
<td>60.0</td>
<td>60.0</td>
</tr>
<tr>
<td>Exact operation time [min]</td>
<td>395.5</td>
<td>58039.7</td>
<td>58039.7</td>
</tr>
<tr>
<td>Exact averaged energy Cost [€/s]</td>
<td>2.65 $10^{-6}$</td>
<td>2.66 $10^{-6}$</td>
<td>2.66 $10^{-6}$</td>
</tr>
<tr>
<td>Exact averaged cleaning Cost [€/s]</td>
<td>8.41 $10^{-4}$</td>
<td>7.46 $10^{-7}$</td>
<td>7.46 $10^{-7}$</td>
</tr>
<tr>
<td>Exact nett flux constraint [L/m²/h]</td>
<td>60.5</td>
<td>60.0</td>
<td>60.0</td>
</tr>
</tbody>
</table>

Fig. 7. Impact of the variation of weighting factor $w$ on, from top to bottom: optimal filtration time, optimal filtration flux, averaged energy cost, averaged chemical cost and nett flux.

The approach’s conceptual nature is both a blessing and a curse. The approach is simple and can readily be understood. However, the price to be paid are assumptions which may not entirely coincide with reality, e.g., linearity of the pressure evolution and absence of irreversible fouling after chemical cleaning. However, these effects can partially be captured by adaptation strategies or in the cost.

6. CONCLUSIONS AND FUTURE RESEARCH

It can be stated that the preliminary results of the control strategy look promising. While a nett water flux can be guaranteed, a trade-off between the electrical (pump) costs (reversible fouling) and the chemical cleaning costs (irreversible fouling) can be made by imposing the proper (financially based) weighting. Due to the assumption of piecewise and constant increases and decreases during, respectively, the filtration and backwash phase, a geometrical approach can be implemented and the (energy) cost can be computed algebraically. Evidently, such linear models are not compliant with reality. Current research, therefore, focuses on an adaptive and moving horizon implementation to compensate for model mismatches and parameter uncertainties due to changing water characteristics.

REFERENCES


