Reduced Model of a Beer Microfiltration Plant

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Abstract: The use of membrane microfiltration in the production of beer is becoming an attractive alternative. This paper discusses the opportunities for a more efficient operation of such a plant, shows the simulations results of a detailed distributed dynamical model of the filtering medium, and presents a reduced order model which is deemed appropriate for on-line optimization.

1. INTRODUCTION

Filtering is an important unit operation which is needed as part of the so called downstream processing in beer production. The traditional way of performing it by means of the Kieselguhr process, which uses a diatomaceous earth in the form of silica as the filtering medium, is effective but presents serious environmental threats.

A relatively recent alternative is offered by the microfiltration technology using membranes. The benefits are immediate concerning the cleaner operation but there are still remaining issues to be solved in order to realize the full potential by diminishing the cost of operations.

The filtering of the beer is performed in crossflow using an installation as the one shown in figure 1. As the process proceeds, a stagnant layer of yeast is created in the walls of the filtering channel, while the smaller sized aggregates of proteins and macromolecules produce the fouling of the membrane pores. The presence of the yeast cake constrict the channel but the agglomerates and macromolecules that reach the membrane, transported by the filtrate flow, provoke the obstruction of the pores and hence the radical reduction of its filtering capacity. So, there is the need of periodically performing the cleaning of the medium by injecting water in the reverse direction. These so called backflushes eliminates completely the cake and are also capable of removing part of the membrane fouling, but not all. After some backflush cycles, the compounded fouling is such that the membrane is no longer effective and a chemical, more costly, cleaning has to be made in order to restore the original permeability of the medium.

Typically, plants as the above briefly described, are operated either by keeping the trasmembrane (TMP) pressure constant, resulting in a diminishing filtrate flow, or by fixing the latter by increasing the pressure to compensate the rise in resistance as fouling proceeds. Other possibilities are, of course conceivable. A better election of the operation policy, chosen by optimizing an economical motivated performance index, would give a definite competitive edge to the technology. The optimal operation problem should be solved on-line using a good enough model of the factory but not too demanding computationally.

The article is organized as follows: in section 2 a description of the plant and a discussion of a recently developed distributed model is given, showing results of a dynamic simulation of the complete filtering cycle of the installation; section 3 discusses the benefits to be obtained by an optimal operation of the plant; section 4 describes a drastically reduced model of the same system which is more apt for on-line optimization and finally in section 5 the roadmap for the future application to the real beer microfiltration plant is laid out.

2. PROCESS AND MODEL DESCRIPTION

Beer microfiltration is performed following a scheme as the one shown in figure 1. Beer is buffered in a tank which is pressurized to avoid foaming and is then pumped through the filter with some resultant crossflow velocity. The filtered beer is obtained at the filtrate side and is completely free of yeast and of aggregates and of a percentage of the original amount of macromolecules. The retentate is obtained at the other end of the filter to be feedback to the tank. The latter also receives a flow of fresh beer from the upstream process with a proportion relative to the retentate (the bleed ratio) which is...
appropriate to keep the continuous operation of the installation.

![Membrane filtration diagram](image)

**Fig. 2.** Membrane filtration.

The use of crossflow filtering diminishes the creation of a particle cake on the membrane due to the shear stress exerted by the flow. Nevertheless, a packed profile of yeast cells develops along the axial direction, restricting the effective cross section area of the channel and thus increasing the resistance to the crossflow.

The membrane filter model is described in van der Sman et al. (2010), van der Sman et al. (2009) and Vollbregt et al. (2010). A scale analysis of the flowing conditions in the membrane suggests that it is safe to state a 1D mode along the axial x direction, postulating the existence of three separated phases which are defined radially, as shown in figure 2: the bulk of the solution with the volume fraction of yeast φ_{0, bulk} of aggregates φ_{aggr} and of macromolecules φ_{macro}; a flowing cake layer and a stagnant yeast cake layer.

\[ \int_0^x u(\rho - \rho_0) dy = \int u_{wall}(\rho_0 d\rho) dx = 0 \]  

(1)

A key equation at work here is (1), (Davies and Leighton, 1987; Romero and Davies, 1990), which, loosely interpreted, says that, in the static regime, all the excess volume concentration of yeast flow per unit of filter width Q (m^2/s) at a given axial position x occupying a flowing height \( \delta_{fl} \) should be equal to the yeast taken to the wall by the filtrate \( u_{wall} \) from the entrance of the channel to the x position considered. It is obvious that the term Q should increase with x if the existence of filtrate is postulated. Since the bulk packaging of particles has a limit, which is typically estimated around 0.6, so the equation (1) would break at a critical distance \( x_{cr} \) corresponding to a critical excess particle flow of Q_{cr}. The notion that Q cannot exceed the quantity Q_{cr} is clearly wrong, since that would mean the cease of filtering, so what really happens, as reasoned in Romero and Davies, (1990), is that a stagnant layer of yeast develops under the flowing layer. The creation of this fixed cake, starting at \( x_{cr} \) restricts the channel increasing the shear stress and the filtering resistance. The ensuing diminution of \( u_{wall} \) is such that (1) remains valid.

\[ Q_p = \frac{\Delta p}{R_{mb} + R_{cake}} \]  

(2)

The model of the membrane has an unavoidable distributed character which is approached performing a discretization along the axial direction (see fig. 3). The profile of pressure at each interval is found by iteration taking into consideration the applied pressure at each end and the resistance of the channel considering the radius available to flow which is affected by the existence of the yeast cake. The filtrate flow at each interval (Q_p) is determined by a Darcy type of relation as shown in (2), where R_{mb} and R_{cake} represent the resistance of the membrane and of the yeast cake respectively. The values of these last two variables are constantly increasing as filtering proceeds due to progressive fouling. To characterize this key process, the following considerations need to be heeded.

![Membrane channel diagram](image)

**Fig. 3.** Membrane channel.

For those intervals downstream \( x_{cr} \), where there is cake, a portion of the aggregates, with a smaller average diameter than the yeast, gets retained in the free space between the particles in the bed, but the remaining fraction that gets through, is retained by the membrane. Each aggregate molecule blocks completely a pore of the membrane.

On the other hand, the macromolecules are not affected by the existence of the yeast stagnant layer. The greater part of them goes with the filtrate unaffected by the membrane. But the rest is adsorbed in the pores internal walls, reducing its internal free volume, thus contributing to its fouling and the increase of \( R_{mb} \).

It should be noted that the impact of the aggregates on the decrease of the permeability comes then not only at the expense of the direct fouling of the membrane but also as a consequence of the increase of the packaging of the yeast cake. Relevant information concerning the fouling of membranes in fermented beverages and beer applications can be obtained by consulting Blanpain and Lalande, (1997) and Czekaj et al. (2000).

One important conclusion to be drawn of the previous account is that the existence of the cake is beneficial in the sense that it serves the purpose of catching a fraction of the aggregates that otherwise would go completely to affect the permeability of the membrane. So the yeast cake act as an agent that changes an important fraction of the aggregates provoked fouling from irreversible to reversible. The latter being so called since it can be completely washed out with a...
backflush (BF), while the former has to wait for the chemical treatment at the end of the filtering cycle.

In addition to removing all the reversible fouling, the model considers that each BF is able to remove part on the membrane fouling.

The distributed membrane model along with the lumped model of the beer tank has been implemented in EcosimPro, a model oriented modelling and simulation tool (E.A. International, 2008) which is also able of performing mathematical optimization.

The figure 4 shows a simulation result of a complete filtering cycle exhibiting four backflushes. The operation policy followed in this example is to maintain a constant filtrate flow. As each backflush stretch advances, the pressures both at the retentate and at the filtrate sides diminish. The first effect is due to the restriction of the channel by the yeast cake and the second is imposed by the operation policy and the need to keep fixed the filtrate flow, as fouling progresses and the membrane and cake permeabilities diminish. From figure 4 it is also apparent that at each subsequent BF section, the effort needed to maintain the filtrate flow is greater due to the cumulative effect of the irreversible fouling: the required TMP is larger and the next BF comes earlier. When the period between succeeding BFs is shorter that some predefined duration, the filtering cycle is deemed concluded and a chemical cleaning is performed.

The spatial profile of fouling related variables at the fifth BF section is shown in figures 6. The profiles include the number of pores $N_{pores}$ and the aggregated volume of pores $V_{pores}$ which are both normalized with respect to their initial, not fouled values. The profile of the resulting normalized membrane resistance $R_{mb}$ is also depicted. It is to be noted the relative steep change at $x_{cr}$ position, highlighting the protective role of the stagnant yeast cake.

3. PROCESS OPERATION

The operation of the system described in Fig.1 follows a pattern represented in Fig. 4, where a certain permeate flow is maintained while the trans-membrane pressure (TMP) increases as a result of the growing cake layer and increasingly reduced pore volume. When the TMP reaches a
certain value, the filtering is stopped and the membrane is cleaned by backflush. In this way the filtering can be restarted. Nevertheless, the cleaning is not complete and the starting point of the TMP is above the value it had at the beginning of the process. The operation is repeated, but each cycle the time required to reach the maximum TMP is shorter, so that, after several cycles, a deep chemical cleaning must be performed that restores the original flowing characteristics of the membrane but damages it internally shortening its life.

![Diagram of process steps]

**Fig. 7.** Optimal operation strategy.

The main objectives when operating the plant are increasing the life of the membranes expanding the time between chemical cleanings, maximizing profits and minimizing the operation time for the filtration of a fixed amount of beer. An optimal operation strategy, as the one depicted in fig. 7, could be an effective approach. Mathematically, the problem can be formulated as a multi-objective optimization. Equation (3) shows a way of calculating the profit.

The optimization problem could be stated as in (4), where \( \alpha_1 \) is the price of beer minus the pumping costs in the permeate pump, \( \alpha_2 \) the energy of the crossflow pump, \( \alpha_3 \) the price of cooling, \( \alpha_4 \) the price of a single backflush and \( \alpha_5 \) the cost of a chemical cleaning. The integer variables \( N_c \) represents the number of chemical cleaning cycles, each one with \( N_B \) backflushes, needed for completing the assignment of filtering a \( V_T \) volume of raw beer. The problem has as restrictions the ones explicitly stated in (4), but also the dynamic model and other operational constraints.

Equation (3) shows a way of calculating the profit.

The problem involves continuous decision variables, as the maximum trans-membrane pressure, the permeate and cross flows, but it also has variable structure, because the number of cycles between chemical cleanings is not pre-defined. It can be formulated as a dynamic optimization problem with discontinuities in the model and a set of associated constraints. Being a hybrid optimization, the computation time is expected to be quite high, so that, if a distributed model like the one described in section 2 was used, there are no chances of finding a solution in real time. In order to overcome this difficulty, a reduced model has been proposed that maintains the main characteristics of the full one but which is notably faster.

### 4. REDUCED MODEL

The main idea behind the reduced model is to differentiate between the main two zones inside the membrane: the one where the cake layer has been formed and the one where the pores are exposed directly to aggregates and macromolecules (see Fig. 8). The model assumes that there is a uniform behaviour in each zone but, as the cake layer is not static, the size of both zones changes over time according to the operating conditions. Additional terms have to be added in the balance equations of the model to take into account this change.

The model is composed of several groups of equations. Hydraulic equations:

**First zone:**

\[
Q_{in}[1] = Q_F = Q_p + Q_R \\
Q_{in}[1]R_{up}[1] = p_{in} - p_{up}[1] \\
Q_{out}[1](R_{wall}[1] + R_{cake}[1]) = \frac{p_{in} + p_{up}[1]}{2} - p_{out}[1] \quad \text{with} \quad R_{cake}[1] = 0 \\
Q_{low}[1] = Q_{out}[1] \\
\omega_{wall}[1] = \frac{Q_{out}[1]}{A[1]} \quad \text{where} \quad A[1] = 2\pi r_c x_c \\
\Omega[1] = \frac{Q_{in}[1] + Q_{in}[2]}{2} \quad \text{with} \quad S[1] = \pi r_c^2 \\
R_{up}[1] = \frac{8\mu\nu cr}{r_c^5 S[1]} 
\]

The optimization problem could be stated as in (4), where \( \alpha_1 \) is the price of beer minus the pumping costs in the permeate pump, \( \alpha_2 \) the energy of the crossflow pump, \( \alpha_3 \) the price of cooling, \( \alpha_4 \) the price of a single backflush and \( \alpha_5 \) the cost of a chemical cleaning. The integer variables \( N_c \) represents the number of chemical cleaning cycles, each one with \( N_B \) backflushes, needed for completing the assignment of filtering a \( V_T \) volume of raw beer. The problem has as restrictions the ones explicitly stated in (4), but also the dynamic model and other operational constraints.

**Equation (3):**

\[
J_T = N_c \left[ \alpha_1 \int_0^t Q_p \, dt - \alpha_2 \int_0^t p_F Q_F \, dt - \alpha_3 \int_0^t Q_F \, dt - \alpha_4 N_B - \alpha_5 \right] 
\]
\[ R_{\text{low}}[i] = \frac{R_N}{N} \quad i = 1, 2; \quad (12) \]

Second zone:
\[ Q_{\text{in}}[2] = Q_{\text{in}}[1] - Q_{\text{out}}[1] \quad (13) \]
\[ Q_{\text{in}}[2] R_{\text{up}}[2] = p_{\text{up}}[1] - p_{\text{up}}[2] \quad (14) \]
\[ Q_{\text{out}}[2](R_{\text{mb}}[2] + R_{\text{cake}}[2]) = \frac{p_{\text{up}}[1] + p_{\text{up}}[2]}{2} - p_{\text{low}}[2] \quad (15) \]
\[ P_{\text{up}}[2] = P_{\text{out}} \]
\[ Q_{\text{low}}[2] = Q_p \]
\[ u_{\text{wall}}[2] = \frac{Q_{\text{out}}[2]}{A[2]} \quad \text{where} \quad A[2] = 2\pi[2](L - x_{cr}) \quad (16) \]
\[ \bar{U}[2] = \frac{Q_{\text{in}}[2] + Q_R}{2S[2]} \quad \text{with} \quad S[2] = \pi r[2]^2 \quad (17) \]
\[ \bar{U}[2] = \frac{Q_{\text{in}}[2] + Q_R}{2S[2]} \quad \text{with} \quad S[2] = \pi r[2]^2 \quad (18) \]
\[ R_{\text{up}}[2] = \frac{8\mu(L - x_{cr})}{r[2]^2 S[2]} \quad (19) \]

Cake equations:
First zone:
\[ V_{\text{cake}}[1] = 0; \quad k[1] = 1 \quad (20) \]
\[ \frac{dV_{\text{cake}}[1](t)}{dt} = \frac{V_{\text{cake}}[1]}{k[1] p_{\text{up}}[1]} - k[1] p_{\text{up}}[1] Q_{\text{out}}[1]; \quad (21) \]
\[ V_{\text{cake}}[1](0) = 0 \]
\[ q[1] = \phi \text{y} x_{\text{wall}}[1] \quad \text{where} \quad \gamma = 4 \frac{S[1]}{r[1]} \quad (22) \]

Cleaning model
After a BF the reversible fouling is removed and consequently:
\[ V_{\text{cake}}[1](0) = 0 \quad V_{\text{sec}}[1](0) = 0 \quad (23) \]
But a partial cleaning of the membrane is also considered. In this way a fraction of the irreversible fouling is retained. Considering \( n_f \) the number of the filtration periods, \( t_{\text{start}}^{(j)} \) the initial time for the period \( j (j=1..n_f) \) and \( t_{\text{fil}}^{(j)} \) the duration of the filtration time, the initial conditions are:

\[
N_{\text{pore}}[i](t = t_{\text{start}}^{(j)}) = N_{\text{pore}}[i](t = t_{\text{fil}}^{(j-1)}) + c_{BF}(N_{\text{pore}}[i](t = t_{\text{start}}^{(j-1)}) - N_{\text{pore}}[i](t = t_{\text{fil}}^{(j-1)}))\\
V_{\text{pore}}[i](t = t_{\text{start}}^{(j)}) = V_{\text{pore}}[i](t = t_{\text{fil}}^{(j-1)}) + c_{BF}(V_{\text{pore}}[i](t = t_{\text{start}}^{(j-1)}) - V_{\text{pore}}[i](t = t_{\text{fil}}^{(j-1)}))
\] (31)

where \( i = 1, 2; \ j = 2..n_f; \ t_{\text{start}}^{(1)} = 0 \)

### Table 1. Estimated parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial value</th>
<th>Optimized value</th>
</tr>
</thead>
<tbody>
<tr>
<td>First period</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R_k )</td>
<td>10.2</td>
<td>9.04</td>
</tr>
<tr>
<td>( x_{cr}^{(1)} )</td>
<td>0.07</td>
<td>0.1926</td>
</tr>
<tr>
<td>( c_{cr} )</td>
<td>0.001</td>
<td>0.0082</td>
</tr>
<tr>
<td>( \mu_0 )</td>
<td>4x10^{-10}</td>
<td>2.98x10^{-10}</td>
</tr>
<tr>
<td>( x_f )</td>
<td>5x10^{-1}</td>
<td>2.378x10^{-1}</td>
</tr>
<tr>
<td>Future periods</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( x_{cr}^{(j=2:5)} )</td>
<td>0.11, 0.125, 0.13, 0.14</td>
<td>0.05849, 0.04763, 0.02199, 0.01154</td>
</tr>
<tr>
<td>( c_{cr}^{(j=2:5)} )</td>
<td>0.001, 0.001, 0.001, 0.001</td>
<td>0.0126, 0.0226, 0.03478, 0.04738</td>
</tr>
<tr>
<td>( C_{BF} )</td>
<td>0.655</td>
<td>0.6482</td>
</tr>
</tbody>
</table>

Fig. 9. Reduced model parameter estimation scheme.

Fig. 10. Full and reduced model reproduction of TMP.

Figure 9 describes the parameter estimation scheme used, while figure 10 shows the ability of the reduced model to essentially reproduce the shape of the full order model over the complete filtering cycle when the adjustable parameters are set to the optimal values of table 1.

### 5. CONCLUSIONS

The complete distributed model of the membrane is too computationally demanding to be applied in an on-line optimal operation scheme. Therefore, it has been imperative the development of a reduced order model with the intention for it to be faithful enough so as to capture the essential behaviour of the distributed plant but with a drastically reduced number of equations.

The developed reduced model must be tuned and validated off-line as exhaustively as possible, but it will very convenient to use measurements of the plant, at the beginning of each filtering cycle and in a run to run fashion over several subsequent cycles, to perform some kind of on-line parameter adaption as a means of increasing the robustness of the optimal microfiltration operation scheme.

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