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Modeling and optimization of a sequence of chemical cleaning cycles in dead-end ultrafiltration

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Abstract

In this paper a chemical cleaning sequence model is proposed that can be used to predict the fouling status of a membrane during multiple chemical cleaning cycles. The proposed model is used to minimize the overall operating costs – based on chemicals consumption, energy consumption and investment costs – over a fixed time horizon, guaranteeing production of a specified volume of permeate, where the number of cycles, the net production flux, the duration of a production phase and the duration of a subsequent cleaning phase are calculated. It was found that at the chemical cleaning cycle level, optimization of the cleaning variables does not strongly influence operational costs, however, optimization of the chemical cleaning cycle may be useful as a means of effective fouling control.

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Keywords: Ultrafiltration; Chemical cleaning; Modeling; Optimization

1. Introduction

Ultrafiltration (UF) is increasingly used as a complete or intermediate surface water purification technique. UF membranes have a high selectivity, are easy to scale up and have become economically attractive during the last 15 years. However, during filtration, UF membranes are subject to fouling and frequent cleaning is required. In the short term, membrane fouling is removed from the membrane by means of backwashes, in the long-term the membrane is treated with cleaning chemicals.

Currently operating settings for UF membranes are based on rules of thumb and pilot plant studies. The settings are generally conservative and it is expected that operating costs can be significantly reduced by means of process optimization.

In this paper an overall ultrafiltration process will be optimized by hierarchical decomposition of the optimization problem into simpler subproblems.

Process optimization of membranes is not done extensively. Dynamic optimization of membranes to minimize filtration costs and to control membrane fouling was first reported in the 1990s

by van Boxtel et al. [1,2]. Also some efforts were reported concerning the automation and advanced control of membrane units [3–5].

A membrane filtration process shows a cyclic behavior (switching between filtration, backwashing and chemical cleaning). The process takes place over different time horizons and optimization should subsequently be performed at different levels. These issues have not been addressed extensively in the literature on membrane operation. On optimization of a membrane unit over multiple production cycles a few publications appeared [6,7], however, for other applications in the field of chemical engineering, the mentioned issues have been studied more extensively. Optimization of cyclic processes has been reported for tubular reactors [8,9] and amongst others, steam generators [10]. Mixed integer maintenance scheduling problems are often used to deal with cyclic behavior of processes [11–15]. Hierarchical optimization, or multi-level optimization is often performed in management systems, computer networks or electronic circuits [16–18].

Multi-level optimization may be very useful if a process can be divided into several decision layers. In Fig. 1 the cyclic nature of an ultrafiltration process as studied in this paper, is visualized.

Subsequently, in Fig. 2 the multi-level optimization structure for the ultrafiltration process is shown schematically. Optimal

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Fig. 1. Schematic representation of the cyclic behavior of an ultrafiltration process.

control values are calculated in each layer and passed downwards, while calculated costs are passed upwards. In the lowest layers, or short-term levels (filtration (F), backwash (B) and chemical cleaning phase (C)) decisions are made concerning actual process control (settings for valves, pumps, sensors, etc.). In the upper layers, or intermediate-term-levels, (filtration cycle and chemical cleaning cycle) decisions are made concerning settings at the production level (assignment of volumes and times over the cycles). In principle a third layer or long-term-level can be added where strategic decisions are made (operational settings with respect to membrane life time).

During the filtration phase (F) surface water is filtrated in dead-end mode, as a result fouling builds up and a backwash phase (B) is performed to restore the membrane fouling status. A filtration phase followed by a backwash phase is called a filtration cycle (FC). During a production phase (P), or filtration

sequence (FS) a number of filtration cycles are performed. During the filtration sequence backwashing does not always result in complete membrane fouling status recovery, for this reason, a filtration sequence is normally followed by a chemical cleaning phase (C), in which the membrane is cleaned with chemicals to restore the membrane fouling status. A filtration sequence followed by a chemical cleaning phase is called a chemical cleaning cycle (CC) and a number of chemical cleaning cycles is called a chemical cleaning sequence (CS).

Blankert et al. already reported on the modeling and optimization of the filtration phase [19,20] and backwash phase [21,22] in membrane operation. In addition, the modeling and optimization aspects of the chemical cleaning phase were reported by Zondervan et al. [23,24]. Blankert et al. also published results on the modeling and optimization of a sequence of filtration cycles [25,26].

Fig. 2. Hierarchical optimization structure for an ultrafiltration process.

In this paper the results of the modeling and optimization aspects of a sequence of chemical cleaning cycles will be discussed.

2. Theory

Process optimization requires suitable process models, cost functions and constraints.

2.1. The process models

Darcy's equation is given as:

$$R_M + R_f = \frac{\Delta P}{\mu J} \quad (1)$$

where ΔP is the trans membrane pressure, μ is the viscosity, J is the flux, R_M is the membrane resistance and R_f is the resistance as a result of fouling. For ideal cake filtration, the membrane fouling resistance can be described as:

$$R_f = \alpha(x_{W,i} + x_{W,s} + x_{W,f}) \quad (2)$$

where α is the specific cake resistance and where $x_{W,i}$, $x_{W,s}$ and $x_{W,f}$ are fouling state variables for irreversible, slow and fast fouling removal. The fouling states can be modeled for filtration, backwashing and chemical cleaning.

2.1.1. Filtration phase model

In Blankert [25], the following filtration model is proposed:

$$\frac{dx_{W,i}}{dt} = y_i J_F \quad (3)$$

$$\frac{dx_{W,s}}{dt} = y_s J_F \quad (4)$$

$$\frac{dx_{W,f}}{dt} = y_f J_F \quad (5)$$

where y_i , y_s and y_f are filtration model parameters describing the rate at which irreversible, slow and fast fouling accumulates to the membrane. J_F is the filtration flux.

2.1.2. Backwash phase model

If it is assumed that irreversible fouling is not removed during the backwash phase, the following backwash model can be proposed [25]:

$$\frac{dx_{W,i}}{dt} = 0 \quad (6)$$

$$\frac{dx_{W,s}}{dt} = -\frac{K}{V_M} J_B x_{W,s} \quad (7)$$

$$\frac{dx_{W,f}}{dt} = -\frac{1}{V_M} J_B x_{W,f} \quad (8)$$

where K is a backwash model parameter and V_M is the specific module volume defined as $V_M = V_{\text{mod}}/A_{\text{mod}}$, the ratio between the module volume and the membrane surface. J_B is the backwash flux.

2.1.3. Chemical cleaning phase model

If it is assumed that $x_{W,s}(0) = 0$ and $x_{W,f}(0) = 0$ and that irreversible fouling can be removed by means of chemical cleaning, the following chemical cleaning model can be proposed [23]:

$$\frac{dx_{W,i}}{dt} = -k' J_C (x_{W,i} - x_{W,\infty}) + r_W'' \quad (9)$$

$$\frac{dx_{W,s}}{dt} = 0 \quad (10)$$

$$\frac{dx_{W,f}}{dt} = 0 \quad (11)$$

where the cleaning rate r_W'' is:

$$r_W'' = -k'' x_C (x_{W,i} - x_{W,\infty}) \quad (12)$$

The cleaning agent state can be described by:

$$\frac{dx_C}{dt} = k J_C (x_{C,\text{in}} - x_C) + n_c r_W'' \quad (13)$$

where $x_{C,\text{in}}$ is the cleaning agent concentration at the inlet of the membrane, J_C is the cleaning flux, k' is a flushing rate parameter, k'' is a cleaning rate parameter, n_c is a pseudo-stoichiometric coefficient and $x_{W,\infty}$ is the membrane fouling state at infinite cleaning time.

2.1.4. Filtration sequence model

The filtration sequence model proposed by Blankert [25] acts as a scheduler between the filtration phase and the backwash phase.

The parameters in the filtration sequence model: y_i , y_s , y_f and K are experimentally related to the filtration flux and coagulant concentration. If a linear dependency is assumed we may write:

$$y_i = a_{yi,0} + a_{yi,1} J_F + a_{yi,2} C_F \quad (14)$$

$$y_s = a_{ys,0} + a_{ys,1} J_F + a_{ys,2} C_F \quad (15)$$

$$K = a_{K,0} + a_{K,1} J_F + a_{K,2} C_F \quad (16)$$

The coefficients $a_{yi,0}$, $a_{yi,1}$, $a_{yi,2}$, $a_{ys,0}$, $a_{ys,1}$, $a_{ys,2}$, $a_{K,0}$, $a_{K,1}$ and $a_{K,2}$ are ordinary fit parameters, normally determined by means of experimental protocol. It is further noted that by definition $y_i + y_s + y_f = 1$.

The duration of a filtration sequence (t_{FS}), is the sum of the durations of the individual phases, with N_F as the total number of filtration cycles, and is given as:

$$t_{FS} = \sum_{n_F=1}^{N_F} (t_F + t_B) \quad (17)$$

where t_F is the filtration time and t_B the backwash time.

The net produced volume of permeate V_{FS} during a filtration sequence is the sum of the produced volumes of the individual filtration phases V_F minus the volumes consumed during the

Fig. 3. Schematic model structure.

subsequent backwash phases V_B :

$$V_{FS} = \sum_{n_F=1}^{N_F} (V_F - V_B) \quad (18)$$

The net flux during the filtration sequence, can be defined as the ratio between net volume and filtration sequence duration: $J_{FS} = V_{FS}/t_{FS}$.

2.1.5. The chemical cleaning sequence model

The model has been extended to a chemical cleaning sequence model, by including the chemical cleaning phase model. The chemical cleaning sequence model is a piece wise function that works as a scheduler between filtration sequence and the chemical cleaning phase. In Fig. 3 the filtration sequence model and the chemical cleaning sequence model are graphically illustrated.

If the chemical cleaning phase model is added to the filtration sequence model, the duration of a chemical cleaning sequence (t_{CS}) is given as the sum of the durations of the individual filtration sequences and the chemical cleaning phases, with N_C as the total number of chemical cleaning cycles:

$$t_{CS} = \sum_{n_C=1}^{N_C} (t_{FS} + t_C) \quad (19)$$

the sum of the net produced volumes of the individual filtration sequences V_{FS} minus the volumes consumed during the subsequent chemical cleaning phases V_C :

$$V_{CS} = \sum_{n_C=1}^{N_C} (V_{FS} - V_C) \quad (20)$$

The net flux can be accordingly calculated as:

$$J_{CS} = \frac{V_{CS}}{t_{CS}} \quad (21)$$

2.2. The cost function

The operating costs define the economic performance of the process. The operating costs can be divided into:

- energy costs (typically short term),
- materials costs (typically intermediate term), and
- depreciation and maintenance costs (typically long-term).

The total energy consumption $C_{E,CS}$ during a chemical cleaning sequence is the sum of the energy consumption of all filtration phases, backwash phases and chemical cleaning phases:

$$C_{E,CS} = \frac{W_E}{V_{CS}} \sum_{n_C=1}^{N_C} \left(\int_0^{t_C} \frac{\mu J_C^2 R}{\eta_P} dt + \sum_{n_F=1}^{N_F} \left(\int_0^{t_F} \frac{\mu J_F^2 R}{\eta_P} dt + \int_0^{t_B} \frac{\mu J_B^2 R}{\eta_P} dt \right) \right) \quad (22)$$

where t_{FS} is the duration of a filtration sequence and t_C is the duration of a chemical cleaning phase. The net produced volume of permeate v_{CS} during a chemical cleaning sequence is

where W_E is a cost factor and η_P the pump efficiency. The total costs for material streams $C_{M,CS}$ are based on waste disposal costs, chemicals consumption and feedwater costs (pretreatment and legal fees). These costs do not need to be written in integral form, since the final value of the produced or consumed volume

is fixed for each operating phase:

$$C_{M,CS} = \frac{1}{V_{CS}} \sum_{n_C=1}^{N_C} \left(V_C x_{C,in} W_C + \sum_{n_F=1}^{N_F} (V_F (W_F + C_F W_{FI}) + W_W V_B) \right) \quad (23)$$

in which W_F is a cost factor representing the feedwater costs, W_W represents the waste disposal costs, W_{FI} represents the coagulant costs, C_F the coagulant concentration, W_C are the costs for cleaning chemicals and $x_{C,in}$ is the cleaning agent concentration. The depreciation costs $C_{I,CS}$ of the membranes are proportional to the duration of the chemical cleaning sequence:

$$C_{I,CS} = \frac{1}{V_{CS}} W_I t_{CS} \quad (24)$$

in which the cost factor W_I representing the depreciation costs is normalized for the membrane life time. These costs do not influence the results of an optimization with a fixed final volume and fixed final time. When the final volume per area is a degree of freedom, the depreciation costs are balanced against the other costs. The total costs are the sum of the energy costs, materials costs and depreciation costs:

$$C_{tot} = C_{E,CS} + C_{M,CS} + C_{I,CS} \quad (25)$$

2.3. Optimization

In this problem there are two integer control variables (N_C and N_F) and eleven continuous control variables (V_F , t_F , C_F , V_B , t_B , V_{FS} , t_{FS} , V_C , t_C , V_{CS} and t_{CS}). In principle, the continuous variables can assume different values for each individual filtration, backwash or chemical cleaning. However, in this study the optimal stationary values are determined.

The optimization objective is to minimize the overall operating costs, while producing a specified volume V_H within a specified time t_H .

For this reason, this optimization problem deals with a fixed time, t_H :

$$t_{CS} = t_H \quad (26)$$

and a fixed final volume V_H :

$$V_{CS} = V_H \quad (27)$$

Consequently, the optimization variables cannot all be chosen independently. If we assume that conditions are equal for each cycle, Eq. (19) becomes:

$$t_{FS} = \frac{t_H}{N_C} - t_C \quad (28)$$

Eq. (19) becomes:

$$t_F = \frac{t_{FS}}{N_F} - t_B \quad (29)$$

Eq. (20) becomes:

$$V_{FS} = \frac{V_H}{N_C} + V_C \quad (30)$$

And Eq. (18) becomes:

$$V_F = \frac{V_{FS}}{N_F} + V_B \quad (31)$$

The backwash strategy is to backwash at a constant, maximum flux. Hence, the backwash volume and backwash duration cannot be chosen independently:

$$V_B = J_{B,max} t_B \quad (32)$$

Given the constraints of Eqs. (26)–(32), there are six degrees of freedom, namely the backwash time t_B , the coagulant concentration C_F , the cleaning agent volume V_C , the chemical cleaning time t_C , the number of filtration cycles N_F and the number of chemical cleaning cycles N_C . The total number of filtration cycles and chemical cleaning cycles are integer variables, which pose problems for normal optimization algorithms. For this reason, the following optimization procedure is used: for a certain number of filtration cycles and chemical cleaning cycles, the minimal costs are calculated as a function of the backwash duration, the coagulant concentration, the cleaning time and the cleaning agent volume. By repeating this for different values of the number of chemical cleaning cycles, the values of N_F and N_C are found for which these costs are minimal. The optimal value of the number of cycles can be found by a direct search method. The objective function is in this case given as a bi-level-programming problem:

$$\mathcal{J} = \min_{N_C, N_F} \left(\min_{t_C, V_C, t_B, C_F} (C_{tot}) \right) \quad (33)$$

3. Results and discussion

3.1. Simulations

Simulations were performed with the parameter settings of Table 1. The parameter values were extracted from experimental data. The parameters of the models are reasonably robust, and it is expected that different parameter settings (within admissible range) will not significantly change the outcomes. In Fig. 4, optimal calculated fouling profiles are shown for a production horizon of $t_{CS}=72$ h, with a net production flux of 66 l/h/m², for three different values of N_C , respectively 1, 9 and 24 times.

Fig. 4 shows that the maximum resistance level decreases when the number of chemical cleaning cycles over a given time horizon is increased.

For increasing values of N_C , Figs. 5 and 6 show that the filtration time decreases, the filtration flux increases and the backwash time and coagulant concentration remain constant.

As N_C is increasing, the available production time decreases. Consequently the filtration flux is higher and the filtration time and the number of filtration cycles is decreasing. As the filtration flux is increasing, the fouling rate also increases.

To counter the increased fouling rate, the backwash duration or flocculant concentration can be increased. However, this is not necessary, due to the fact that the fouling rate is controlled by increasing the number of chemical cleaning phases.

Table 1
Parameters used for optimization

R_M (1/m)	9.80×10^{11}
α (1/m ²)	1.50×10^{13}
μ (Pa s)	1.01×10^{-3}
W_E (EURO/kW h)	0.10
W_F (EURO/m ³)	0.03
W_W (EURO/m ³)	0.25
W_I (EURO/m ² /y)	14.0
W_{FI} (EURO/m ³ ppm)	5000
W_C (EURO/m ³)	500
J_B (l/h/m ²)	250
J_C (l/h/m ²)	125
V_M (m)	2.6×10^{-4}
η_P	0.35
$a_{yi,0}$ (s/m)	0.005
$a_{yi,1}$	0
$a_{yi,2}$ (ppm ⁻¹)	0
$a_{ys,0}$	1.481
$a_{ys,1}$ (s/m)	6.01×10^4
$a_{ys,2}$ (ppm ⁻¹)	-2.33
$a_{K,0}$	-0.0145
$a_{K,1}$ (s/m)	1.03×10^4
$a_{K,2}$ (ppm ⁻¹)	0.4
k' (1 ms)	2×10^{-4}
k'' (m ³ /mol s)	0.0
n_C	3×10^{-6}
$x_{W,\infty}$ (m)	0.0

The optimization shows that the backwash time and the coagulant concentration remain constant. As N_C is increasing, the cleaning agent volume is decreasing and the cleaning time remains constant, at the level of the starting value. This is an interesting observation. In principle two strategies exist to obtain the desired cleaning effectiveness. In the first case the volume of cleaning agent flushed through the membrane can be increased,

Fig. 5. Calculated values for filtration time, filtration flux, backwash time and coagulant concentration as function of the number of cleaning cycles for an operating horizon of 72 h, with a net production flux of 66 l/h/m².

Fig. 4. Resistance trajectories for an operating horizon of 72 h, for different values of N_C : 1, 9 and 24.

while keeping the cleaning time short, in the second case the volume may be kept minimal and the cleaning time is increased. It can be expected that in order to minimize costs, while reaching the desired cleaning effectiveness, the volume of cleaning agent should be reduced, while increasing the cleaning time.

In Fig. 7, the relationship between the costs, t_C and V_C is plotted for a given situation ($t_H=144$, $N_C=6$, $N_F=21$, $C_F=1.15$ and $t_B=11$). A large plane can be seen where the costs are minimal for different values of t_C and V_C .

Fig. 8 shows an operating window for the cleaning time and cleaning agent volume. A line separates the optimal area from the non-optimal area. In the non-optimal region the costs are not

Fig. 6. Calculated values for cleaning time, cleaning agent volume, overall costs and number of filtration cycles as function of the number of cleaning cycles for an operating horizon of 72 h, with a net production flux of 66 l/h/m².

minimal. In the optimal region any combination of t_C and V_C will lead to minimal operating costs.

For this reason, the optimization results of Figs. 5 and 6 show that the cleaning agent volume is decreasing with increasing N_C , while the cleaning time remains constant at the level of the initial estimate.

In Figs. 9 and 10 optimal settings for the control variables are shown for different values of the chemical cleaning cost W_C : 50 EURO/m³ (low), 500 EURO/m³ (reference) and 5000 EURO/m³ (high). The optimal values for t_F , C_F , t_C and N_F are not sensitive to changes in W_C .

V_C decreases as function of N_C for higher values of W_C . If chemical cleaning becomes more expensive, optimization results in lower cleaning volumes.

The operational costs do not have a minimum for a specific value of N_C within the admissible range. However, from environmental view point, N_C should not be chosen too high, in order to reduce chemicals consumption and it should also not be chosen too low, in order to meet legal hygienic regulations.

In Table 2 the most important optimization results are summarized. A reference case is compared to four other cases: (1) a high chemical cleaning interval, (2) a low chemical cleaning

Fig. 7. Surface plot of the costs as function of the cleaning time and cleaning agent volume. The costs were capped at 0.25 EURO/m³.

Fig. 8. The operating window.

Fig. 9. Calculated values for filtration time, filtration flux, backwash time and coagulant concentration as function of the number of cleaning cycles for different cleaning agent costs: 50 EURO/ m^3 (dotted), 500 EURO/ m^3 (lines), 5000 EURO/ m^3 (dashed), it is noted that in some of the figures the lines coincide.

interval, (3) high costs for chemical cleaning and (4) low costs for chemical cleaning. It can be seen that N_C and W_C do not strongly influence the operational costs.

For the reference case, the chemical cleaning costs are less than 0.2% of the overall operating costs. Even if the number of chemical cleanings over the specified time interval is doubled, or the cleaning agent costs are 10 times more expensive, the cleaning costs hardly influence the operating costs, where

minor compensations are made with respect to energy costs or flocculant costs.

In Fig. 11 the division of the operational costs for the reference case are shown.

The time horizon t_H should not influence the results of the optimization.

If the time horizon is chosen too short, there is little space for the optimization to evaluate optimal settings for the num-

Fig. 10. Calculated values for cleaning time, cleaning agent volume, overall costs and number of filtration cycles as function of the number of cleaning cycles for different cleaning agent costs: 50 EURO/ m^3 (dotted), 500 EURO/ m^3 (lines), 5000 EURO/ m^3 (dashed), it is noted that in some of the figures the lines coincide.

Table 2
Summary of optimization results

	Reference	Low cleaning interval	High cleaning interval	Low cleaning costs	High cleaning costs
N_C	6	3	12	6	6
W_C (EURO/m ³)	500	500	500	50	5000
J_F (l/h/m ²)	67.1	67.3	67.8	67.3	67.3
t_F (s)	4074	4089	3862	4074	4074
t_B (s)	11.0	11.0	11.0	11.0	11.0
C_F (ppm)	1.14	1.14	1.14	1.14	1.12
V_C (m ³)	0.0039	0.0039	0.0039	0.0039	0.0027
t_C (s)	600	600	600	600	600
N_F	21	42	11	21	21
C_{tot} (EURO/m ³)	0.0660	0.0662	0.0659	0.0658	0.0660
R ($\times 10^{12}$ l/m)	2.50	2.60	2.35	2.50	2.50

Fig. 11. Pie chart of operational costs for the reference case.

ber of cleaning cycles (as cleaning normally is done every 12–24 h).

For example, if the time horizon is only 24 h, N_C can only assume a few realistic values leading to sequence durations of 6, 12 or 24 h. However, if the time horizon is for example 300 h, more realistic possibilities for N_C exist, for example, 21, 23 or 25 h.

Although a larger time horizon, will yield a wider range of possible values of N_C it also encompasses more calculations. In addition, feed water quality changes over time, and with that, also filtration, backwash and chemical cleaning model parameters change. Time horizons between 72 and 300 h are acceptable.

In Figs. 12 and 13 optimal settings for the control variables are shown for different time horizons. For larger time horizons, optimal profiles of t_F and J_F are relatively steep. The operational costs do not change significantly for different time horizons. The different dependencies of in V_C and N_F on N_C , as shown

Fig. 12. Calculated values for filtration time, filtration flux, backwash time and coagulant concentration as function of the number of cleaning cycles for different time horizons: 36 h (dotted), 72 h (lines), 144 h (dashed), it is noted that in upper left figure the lines coincide.

Fig. 13. Calculated values for cleaning time, cleaning agent volume, overall costs and number of filtration cycles as function of the number of cleaning cycles for different time horizons: 36 h (dotted), 72 h (lines), 144 h (dashed), it is noted that in upper left figure the lines coincide.

in Figs. 12 and 13 can be explained by the fact that a larger time horizon implies for a fixed value of N_C a larger production interval, resulting in more membrane fouling and consequently in more intensive chemical cleaning phases (higher volumes of V_C).

Although in this paper specifically dead-end ultrafiltration was addressed, it is expected that the conceptual structuring of such process, and the solution methodology can be effectively used for similar membrane processes, e.g. microfiltration or nanofiltration.

4. Conclusions

Computation of optimal operating settings (t_F , C_F , t_B , t_C , V_C , N_F) as function of the number of chemical cleaning cycles N_C for a fixed time horizon (t_{CS}) while producing a specified volume (V_{CS}), over that time horizon, was performed. The simulation results show that operational costs and optimal operating variables are not sensitive to the number of chemical cleaning cycles and the cleaning intensity. From these results it can be concluded that optimizing the number of chemical cleaning cycles will not reduce operating costs and hence optimization should try to accomplish other objectives such as, controlling membrane fouling. At a higher hierarchical level fouling control is an important issue with respect to membrane life time.

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Nomenclature

A_{mod}	membrane area (m^2)
$C_{E,CS}$	energy costs (EURO/ m^3)
C_F	coagulant dosing state (ppm)
$C_{I,CS}$	investment costs (EURO/ m^3)
$C_{M,CS}$	materials costs (EURO/ m^3)
C_{tot}	total costs (EURO/ m^3)
J	flux (m/s)
J_B	backwash flux ($l/h/m^2$)
J_C	chemical cleaning flux ($l/h/m^2$)
J_{CS}	net chemical cl. seq. flux ($l/h/m^2$)
J_F	filtration flux ($l/h/m^2$)
J_{FS}	net filtration seq. flux ($l/h/m^2$)
$\mathcal{J}$	performance index
k'	chemical cleaning flushing const. (m^{-1})
k''	chemical cleaning rate const. ($m^3/mol\ s$)
K	backwash parameter
n_c	stoichiometric cleaning param.
n_C	chemical cleaning cycle number
N_C	Total number of chemical cleaning cycles
n_F	filtration cycle number
N_F	Total number of filtration cycles
ΔP	trans membrane pressure (Pa)
R_f	membrane fouling resistance (m^{-1})
R_M	membrane resistance (m^{-1})
r_W	chemical cleaning rate (m/s)
t_B	backwash time (s)
t_C	cleaning time (s)
t_{CC}	chemical cleaning cycle duration (s)

t_{CS}	chemical cleaning sequence duration (s)
t_f	final time (s)
t_F	filtration time (s)
t_{FC}	filtration cycle duration (s)
t_{FS}	filtration seq. duration (s)
t_0	initial time (s)
V_B	backwash volume (m^3)
V_C	chemical cleaning volume (m^3)
V_{CS}	chemical cleaning seq. volume (m^3)
V_F	filtration volume (m^3)
V_{FS}	filtration seq. volume (m^3)
V_M	specific module volume (m)
V_{mod}	membrane module volume (m^3)
W_C	weight factor cleaning agents (EURO/ m^3)
W_E	weight factor energy costs (EURO/kWh)
W_{FI}	weight factor coagulant costs (EURO/ m^3 ppm)
W_I	weight factor investment costs (EURO/ m^2/y)
W_F	weight factor feed water costs (EURO/ m^3)
W_W	weight factor waste disposal costs (EURO/ m^3)
x_C	cleaning agent state (mol/m^3)
$x_{C,in}$	cleaning agent state at membrane inlet (mol/m^3)
x_W	overall fouling state (m)
$x_{W,f}$	fast fouling state (m)
$x_{W,i}$	irreversible fouling state (m)
$x_{W,s}$	slow fouling state (m)
y_f	filtration par. for fast fouling
y_i	filtration par. for irreversible fouling
y_s	filtration par. for slow fouling
<i>Greek letters</i>	
α	specific cake resistance (m^{-2})
η_P	pump efficiency
μ	viscosity (Pa s)

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