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Mathematical modeling of fouling membrane in an anaerobic membrane bioreactor

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RÉSUMÉ. Dans ce travail, nous proposons un modèle mathématique simple de colmatage membranaire et nous le couplons à un modèle simple de digestion anaérobie (BioRéacteur Membranaire Anaérobie). Par simulation numérique, nous étudions le comportement qualitatif du modèle et nous montrons des résultats préliminaires sur des stratégies de contrôle possible pour limiter le colmatage.

ABSTRACT. This paper deals with the development of a simple model of membrane fouling and its integration with a simple anaerobic digestion model (Anaerobic Membrane BioReactor). Using numerical simulations, we investigate the qualitative behavior of the model and we show some preliminary results of possible control strategies to limit fouling.

MOTS-CLÉS : BioRéacteur Membranaire Anaérobie, Modélisation des MBRs, Colmatage de membrane, SMP, Traitement des eaux usées

KEYWORDS : Anaerobic Membrane BioReactor, MBR modeling, Membrane Fouling, SMP, Wastewater treatment

1. Introduction

Anaerobic Membrane BioReactor (AnMBR) is an interesting wastewater treatment technology, allowing to obtain a highly purified effluent. Such processes have integrated models : biological dynamics models coupled to membrane filtration models. In MBRs, specific components as Soluble Microbial Product (SMP) dynamics play an important role in membrane fouling [2] and they must be added to the process model, as it was proposed in [1], in order to properly describe the entire MBR dynamics. If a number of such integrated models have been proposed for aerobic MBRs (cf. for instance [3, 4]), very few have been proposed for AnMBRs for studying their behavior or control purpose ([5], [6], [7]). The aim of the present paper is to propose a simple and generic membrane fouling model which the usefulness is illustrated in coupling it with a simple anaerobic model [1], to completely describe an AnMBR for control design purposes. Qualitative behavior of the system is investigated and some control strategies are discussed.

2. Mathematical model

The idea is to adapt the model proposed in [8], which it is not suitable for control purposes since it is too complicated, in order to include a feedback of the decreasing flux due to membrane fouling into the actual output flow rate $Q_{out}(t)$ leaving the MBR. We propose to consider $Q_{out}(t)$ as a decreasing function of the total mass solids attached onto the membrane surface and of the solute (as SMP) deposited inside the pores, which are the two main membrane fouling mechanisms considered in this work. Under some realist assumptions used for building the membrane model, this later is given in the following for two functioning periods : filtration and relaxation.

2.1. Fouling model for the filtration phase ($\Delta P > 0$)

The filtration phase model is given by equations (1)-(5). It predicts the output flow rate Q_{out} as a decreasing function : when the permeate flux dramatically decreases, the process must be stopped and backwash or cleaning of the membrane must be realized.

$$\dot{m} = \delta Q_{out}(C_s S_T + C_x X_T + C_{smp} SMP), \quad [1]$$

$$\dot{S}_p = \delta' Q_{out}\Big(\beta.SMP + f(S_T)\Big), \quad [2]$$

$$R = \alpha\frac{m}{A} + \alpha'\frac{V_p S_p}{\epsilon A}, \quad [3]$$

$$A = \frac{A_0}{1 + \frac{m}{\sigma} + \frac{S_p}{\sigma'}}, \quad [4]$$

$$Q_{out} = J.A = \frac{\Delta P.A}{\mu\big(R_0 + R\big)}. \quad [5]$$

Where $m(t)$ the mass of solids attached onto the membrane surface, $S_p(t)$ the particles (as SMP) retained inside the membrane pores. Dynamics of these variables depend on soluble components $S_T(t)$, particulate components $X_T(t)$ and $SMP(t)$, all coming from reactional medium, with C_s, C_x and C_{smp} are weighting parameters used to model the contribution of each component to the membrane fouling, β the fraction of SMP leaving the MBR (see [1] for more details), $f(S_T)$ is a function used to model the contribution of S_T to the pores clogging, δ and δ' are weighting parameter used to calibrate the rate of the fouling (cake formation and pores clogging). $R(t)$ the total fouling resistance defined as the sum of the cake resistance ($R_m(t) = \alpha\frac{m}{A}$) depending essentially on $m(t)$, and the pores clogging resistance ($R_s(t) = \alpha'\frac{V_p S_p}{\epsilon A}$) which is assumed to be due mainly to $S_p(t)$, with $A(t)$ the total membrane area, ϵA the porous surface of A, V_p the total volume of the pores, α and α' the specific resistances, A_0 the initial membrane surface, σ and σ' parameters in appropriate units. $J(t)$ the permeate flux, $\Delta P(t)$ the transmembrane pressure, μ the permeate viscosity and R_0 the intrinsic membrane resistance.

We consider that the total filtering membrane surface $A(t)$, is not constant during a filtration period nor after several filtration/stop cycles : it is described in a very general way as a decreasing function of $m(t)$ and $S_p(t)$, as the possible function of (4). Here, $A(t)$ tends to zero as $m(t)$ and/or $S_p(t)$ tend to infinity. The function (4) is also able to model the fact that the initial filtering surface A_0 is not totally recovered after a backwash or a chemical cleaning, because it will be small remaining quantities of $m(t)$ and $S_p(t)$ which are not detached, causing an irreversible fouling effect, and thus $A(t) < A_0$.

2.2. Fouling model for the relaxation phase ($\Delta P = 0$)

The flux is simply stopped ($\Delta P = 0$) allowing the natural detachment of matters and particles. The model is simply given by :

$$\dot{m} = -f_m(m), \qquad [6]$$

$$\dot{S}_p = -f_s(S_p), \qquad [7]$$

For instance, we can choose $f_m(m) = \omega m(t)$ and $f_s(S_p) = \omega' S_p(t)$, with ω and ω' positive constants to be adjusted with respect to experimental data. The relaxation time is neglected compared to the filtration time and it is expected that one has always a certain percentage of attached matter which may remain onto the membrane surface and/or blocked inside the pores, yielding to irreversible fouling.

3. Investigating of qualitative behavior

To investigate the qualitative behavior of the system, we must integrate the fouling model (1)-(7) with a biological anaerobic model as illustrated in Fig. 1. For the biological compartment, we suggest to use the AM2b model which includes SMP dynamics and that has been precisely developed for control purposes [1]. Whatever the considered biological model, its output variables (soluble and particulate matters S_T, X_T, SMP, ...) are injected as inputs for the model (1)-(5).

We perform numerical simulations using parameters values given in Table 1, and we consider two functioning phases : filtration for $2h$ and relaxation for $5min$. Such sequence is probably not optimized and is quite far from an optimal adjustment, which remains an open problem of fouling control.

Simulation results are reported in Fig. 2, where we have plotted the dynamic evolution of the attached mass $m(t)$ on the membrane surface, the blocked soluble matter $S_p(t)$ (SMP in the majority) inside the pores, the fouling resistances $R_m(t)$, $R_s(t)$ and $R(t)$, the output flow rate $Q_{out}(t)$, the permeate flux $J(t)$ and the membrane surface $A(t)$. Dynamic responses are simulated for three different values of both parameters $\delta = (5; 25; 50)$ and $\delta' = (0.1; 0.75; 1.5)$, to emphasize effects of deposited and blocked matter rates on the

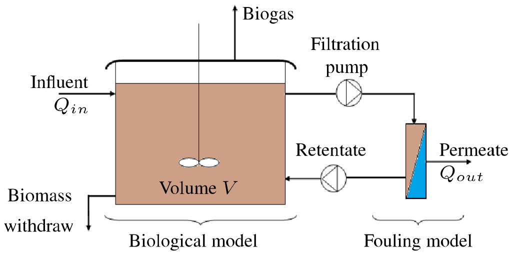

Figure 1. *Schematic representation of the proposed AnMBR model*

Table 1. *Parameter values used in simulations*

Parameter	value	Parameter	value	Parameter	value	Parameter	value
β	0.6	σ'	10	C_x	0.05	μ	0.001
V	50	α	1e10	C_{smp}	0.005	A_0	1
V_p	1.4	α'	1e10	δ	5,20,50	ΔP	0.25
σ	10	C_s	0.005	δ'	0.1,0.75,1.5	R_0	1.11e13

fouling dynamic. These rates depend on many parameters as concentrations of soluble and particulate matters, characteristics of mixed liquor and its viscosity or still temperature and matters specific capability to contribute to fouling.

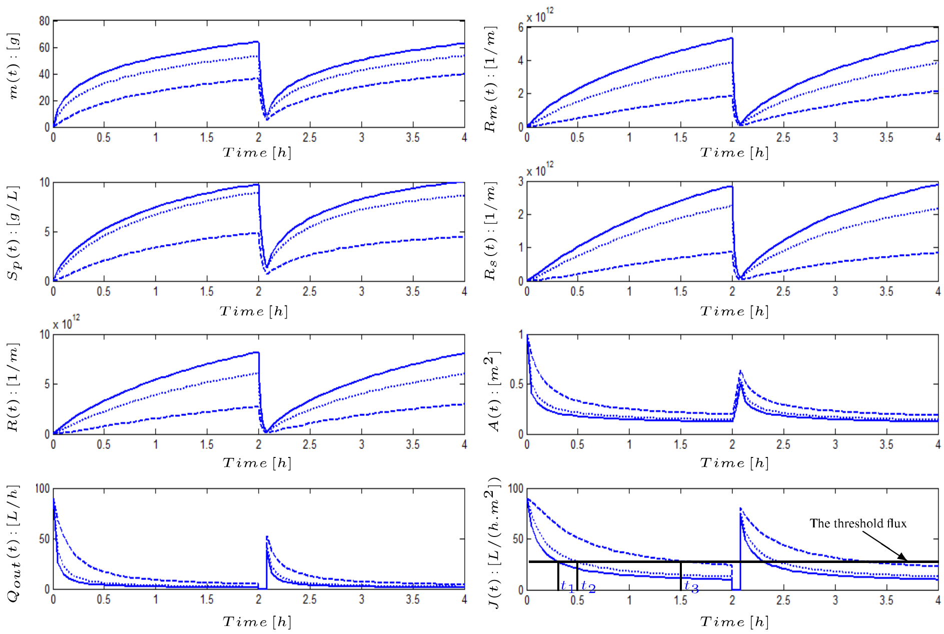

Figure 2. *Simulation results of the membrane fouling model for both phases (filtration and backwash).*

During the first minutes of the filtration process, the fouling is fast and significant. All variables have fast dynamics (increasing or decreasing) at the beginning and then attain progressively (with a decreasing rate) their equilibria (steady state). This can be explained by the fast clogging of pores which occurs firstly, before that the cake formation increases in a second time and prevents pores fouling (slow fouling phenomenon). We emphasize here that the useful filtering surface $A(t)$, the output flow $Q_{out}(t)$ and the permeate flux $J(t)$, decrease significantly, especially during first minutes of filtration as it is often the case in practice.

The trajectories of the main variables are plotted in the case of a slight and strong fouling. Solids plots correspond to a strong fouling due, for example, to a high concentration of solid matter. Dashed and doted plots correspond to a slower and softer fouling respectively : slower the fouling, longer the time period the process may operate without switching in a relaxation mode. For instance, if we define a threshold flux over which the process can operate (see sub-figure in bottom-right), then the process will be stopped very often and be switched in relaxation phase for strong fouling (t_1 is small, solids plots). In the case of slower fouling, the process will be switched less frequently to relaxation mode (t_3 is large, dashed plots). Such simulations show that δ and δ' may be adjusted to match a large range of experimental data.

4. Preliminary results on some control strategies

Membrane fouling is the major drawback of MBRs and one important challenge is to propose new control strategies to minimize fouling and improve treatment efficiency. Very often, the control strategies are tuned heuristically and use available process actuators : gas sparging, intermittent filtration and backwash (or relaxation). In the following, we investigate in simulation the influence of the previous filtering parameters on the flux production and process performances, by using the simple model (1)-(5) and (6)-(7).

4.1. Influence of the gas sparging

In this section, we investigate how gas sparging can be used for limiting membrane fouling. To do so, we need to modify the proposed model (1)-(5) in adding negative terms on the right sides of equations (1) and (2). This way, the fouling rates are reduced by gas sparging as illustrated by equations (8) and (9), where functions $f(m)$ and $g(S_p)$ are positive and depending on the intensity of gas sparging (parameter control).

$$\dot{m} = \delta Q_{out}(C_s S_T + C_x X_T + C_{smp} SMP) - f(m), \quad [8]$$

$$\dot{S}_p = \delta' Q_{out}\Big(\beta SMP + f(S_T)\Big) - g(S_p). \quad [9]$$

A first simple form of $f(m)$ and $g(S_p)$ which is already used in the literature is $k_m m$ and $k_{S_p} S_p$, which represent quantities of m and S_p detached by shear forces caused by membrane scouring, where k_m and k_{S_p} depend on the intensity of injected bubbles used to detach fouling [5]. Fig. 3, illustrates time evolution of the flux $J(t)$ with respect to different values of k_m (here $k_{S_p} = 0$, it is assumed that the irreversible fouling detachment is neglected, since it is not significantly affected by gas sparging). It can be seen that $m(t)$ and $R_m(t)$ are inversely proportional to the control parameter k_m, for higher values of this later, accumulated matter on the membrane surface and its corresponding resistance take small values. Output flow $Q_{out}(t)$ and permeate flux $J(t)$ are increasing proportionally to k_m during the first minutes of filtration (until *0.6h*). On the other hand, one sees on Fig. 3, that deposited matters $S_p(t)$ inside the pores and its relative resistance $R_s(S_p)$ are proportional to k_m and inversely proportional to $m(t)$. If the value of this parameter increases, then the quantity of $S_p(t)$ and the value of $R_s(S_p)$ increase likewise leading to a flux loss at the end of the filtration time (around steady-state). One can explain this result as follows : it is known in the literature that the cake layer formed by $m(t)$ represents a second biological membrane, preventing the pores fouling by $S_p(t)$ [4]. When this layer detaches, more particles of different sizes go through pores and cause further fouling. Which control strategy can favour the cake formation until acceptable level, to protect pores from fouling, but at the same time, without influencing permeate flux ? This question, actually, remains open.

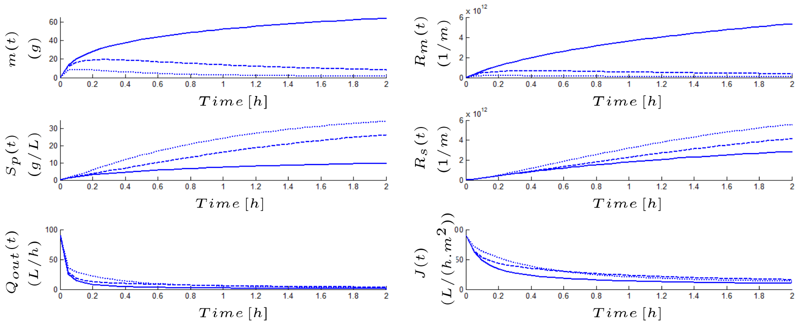

Figure 3. *Results simulation of the membrane fouling model with control terms using (8)-(9), solid :* $k_m = 0$*, dash :* $k_m = 5$*, dot :* $k_m = 25$*,* ($k_{S_p} = 0$)*.*

4.2. Influence of the number of filtration/relaxation (backwash) cycles per time unit

Given a sufficiently large time horizon, what is the optimal number of filtration/relaxation or backwash cycles allowing a higher mean value for the MBR output flux ? To illustrate the importance of this functioning mode, we are particularly interested by the mean value J_{mean} of the produced flux on the given period of $2h$ on which, we performed numerical simulations by changing the number of filtration/relaxation cycles with a constant ratio between filtration time and relaxation time $\alpha_t = \frac{T_{filtr}}{T_{Relax}} = 7$ for all cycles. On Fig. 4, results are given for :

– 1 cycle : $T_{filtr} = 105mn, T_{Relax} = 15mn \Rightarrow J_{mean} = 17.9\ L/(h.m^2)$,

– 2 cycles : $T_{filtr} = 52.2mn, T_{Relax} = 7.5mn \Rightarrow J_{mean} = 22.9\ L/(h.m^2)$:

– 5 cycles : $T_{filtr} = 21mn, T_{Relax} = 3mn \Rightarrow J_{mean} = 29\ L/(h.m^2)$,

– 10 cycles : $T_{filtr} = 10.5mn, T_{Relax} = 1.5mn \Rightarrow J_{mean} = 31.5\ L/(h.m^2)$.

It can be seen that higher the number of cycles, higher the produced mean flux on the given period. A functioning frequency of 10 filtration cycles appears to be the best strategy, since it produces the higher mean flux $J_{mean} = 31.5\ L/(h.m^2)$. But if the number of intermittent filtration cycles is too large on the considered functioning period, then it can damage the process by forcing it to operate very frequently in On/Off mode. It is thus suggested not to wait too long before proceeding to the membrane cleaning by relaxation (or backwash) and to find the best ratio for operated time by benefit in terms of flux produced.

4.3. Coupling sparging gas and intermittent filtration controls

Our idea here is to minimize the energy consumption when using gas sparging and the flux loss (resp. the permeate loss) when the process is in relaxation mode. In others words,

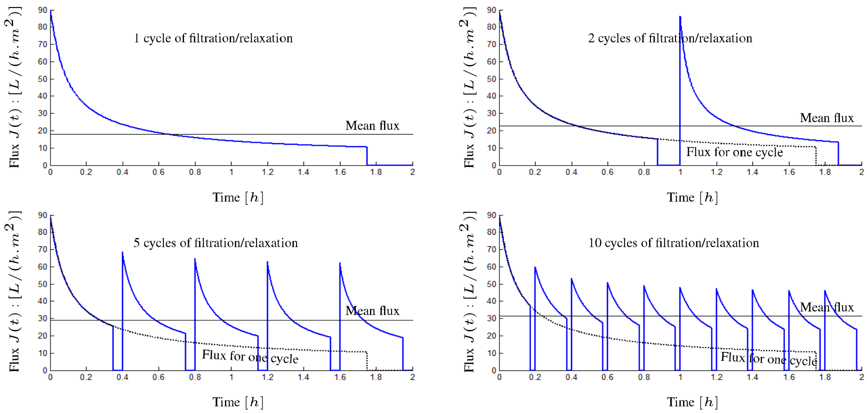

Figure 4. *Results simulation of different numbers of filtration/relaxation cycles.*

instead of using gas sparging and intermittent filtration simultaneously, we propose to use them sequentially for the following reasons :

– Gas sparging is used to detach the matter deposited on the membrane at the beginning of the filtration (fouling is soft and not yet dense).

– Intermittent relaxation is used to detach a denser fouling (strong), which can occur after an enough long functioning time.

To illustrate this idea, we performed numerical simulations plotted in Fig. 5. The system is first simulated without any control (black plot). Then this reference scenario is compared with the proposed coupled control (blue plot). It means that gas sparging is first applied until the flux reaches the threshold flux (here $J_s = 18\ L/(h.m^2)$). At this instant ($t = 0.64h$), we apply intermittent control with $k_m = 5$ in the equation (8), where $f(m) = k_m m$ with 4 cycles.

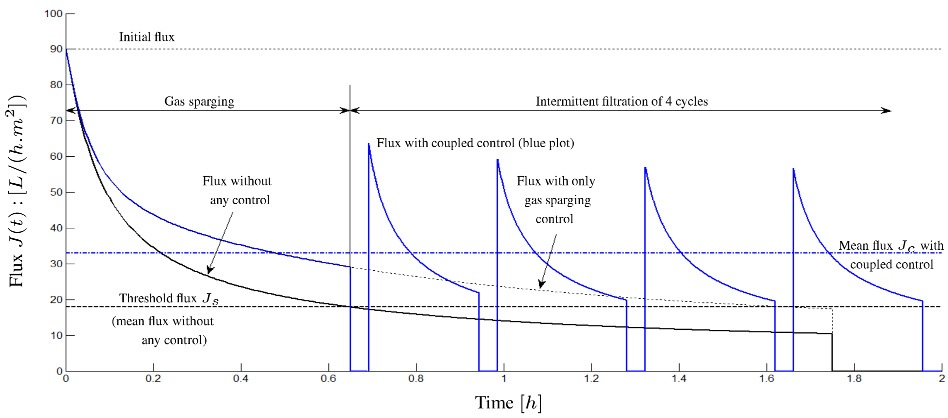

Figure 5. *Coupling control based on gas sparging and intermittent filtration.*

Simulations show that this control strategy allows one to increase the mean production flux to 33 $L/(h.m^2)$, whereas the mean flux without control was $18\ L/(h.m^2)$. As it is noticed in Fig. 5, when applying the gas sparging control, it has increased favorably the permeate flux on the control period (until $0.64h$). It should be noticed that even if we applied only the gas sparging all along the functioning period, without using intermittent filtration cycles (see black doted plot), the mean flux is $28.76\ L/(h.m^2)$, lower than the produced flux when the two techniques are used together (see blue dashed plot). Thus, intermittent filtration was an appropriate control strategy to obtain over the whole functioning period a maximum of flux, while optimizing the energy.

Our study on control strategy is obviously inline with other studies as the work presented in [7]. Their main purpose was to investigate and select the best operating conditions in terms of aeration intensity, duration of filtration/backwashing cycles and number of membrane cleaning to optimize energy demand and operational costs.

5. Conclusion

In this paper we proposed a simple fouling model of AnMBR. The model was developed under certain classical hypotheses on the membrane fouling phenomena, by taking into account two fouling mechanisms and, was coupled with a reduced order anaerobic digestion model. It was shown by simulation that the proposed model can predict quite well the fouling behavior for the considered AnMBR. In a second part of the paper, preliminary results were obtained about the results of different control strategies over a given time period : at the beginning stage of the process functioning, it appeared useful to use the gas sparging and the intermittent filtration at the end of the considered time period. Based on these results, we proposed to couple control benefits in order to produce the maximum mean flux over the total considered functioning period.

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