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Improving the efficiency of membrane bioreactors by a novel model-based control of membrane filtration

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Abstract

In this work, a new model-based control strategy for membrane separation is presented which is based on an automated recognition of current dominant filtration mechanisms during the operation. For this purpose, a model-based optimization framework is proposed which includes parameter identifiability and estimation, as well as an enhanced model discrimination step. Based on the developed approach, it is now possible to identify time points, i.e., time intervals where a certain model is valid or more appropriate. Thus, suitable control actions can be carried out in order to increase the permeability respective to each mechanism improving the filtration performance in membrane bioreactors (MBR). The validation of the novel approach is demonstrated using experimental data from a test cell as well as from an MBR pilot plant.

Keywords

Membrane Bioreactor, Model Discrimination, Membrane Filtration Modelling

1. Introduction

Membrane bioreactors for wastewater treatment are becoming increasingly popular. Their more widespread application, however, is restricted by membrane fouling which reduces permeate yield and increases investment and operating costs. To maintain an economically feasible permeability, periodic back-flushing/relaxation (approx. every 10min), air scour and frequent maintenance cleanings (approx. once a week) are currently employed [1]. These measures are neither optimised nor controlled. I.e., they are often carried out before they are necessary, thereby wasting energy, permeate or chemicals, or too late [2]. This also leads to losses in productivity and to environmental hazards through formation of chemical cleaning by-products such as AOX. Mechanistic models which describe filtration and fouling mechanisms exist [3], but have not yet been used for process control. The aim of this work is to develop a model-based control strategy for membrane operation which reduces energetic expenditure and increases efficiency.

2. Problem Statement

In membrane filtration, permeability is influenced by membrane properties like pore size, porosity, hydrophobicity, and surface charge and by filtration conditions like transmembrane pressure, cross-flow velocity/aeration, and module geometry, as well as by sludge characteristics which depend on MBR operating conditions such as hydraulic and solids retention times, sludge age and loading rate [4]. A number of attempts have been made to correlate flux with biomass concentration, floc size, and sludge rheology [4], but due to the complex nature of the biological system and the difference in experimental methods applied these are often contradictory [1,4]. The biological diversity in the activated sludge offers indeed a great potential for the optimisation of MBR, but at the same time the presence of activated sludge limits the maximum hydraulic exploitation of the process by building a filter cake on the membrane surface or blocking pores (Fig. 1). The different possible locations of fouling necessitate different anti-fouling measures, e.g. internal blocking cannot be removed by increased shear on the surface as promoted by air scour.

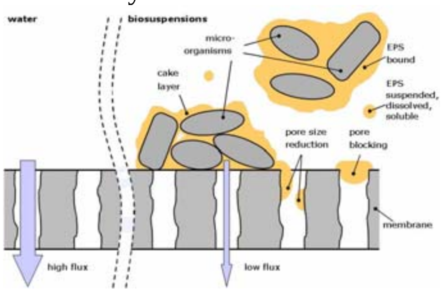

Figure 1: permeability reducing effects

The significant impact of membrane fouling is demonstrated in Fig. 2a, where the decrease of the transmembrane flux J in a lab-scale cross-flow test cell under constant pressure is shown. It should be noted that the flux diminishes to nearly 10% of the initial value in only a few minutes. Fig. 2b illustrates the initial fluxes of filtration intervals or sections (each lasting 4min, followed by 1min break) from a sequencing batch MBR plant. After process related filtration pauses of 90min, much higher initial fluxes were always achieved, i.e. relaxation during those periods resulted in a better removal of fouling than in the normal breaks. If fouling is always removed adequately, the efficiency of MBR plants will be enhanced if the steep flux decrement can be lowered. This will lead to smaller plants, lower chemical cleaning effort and energy demand.

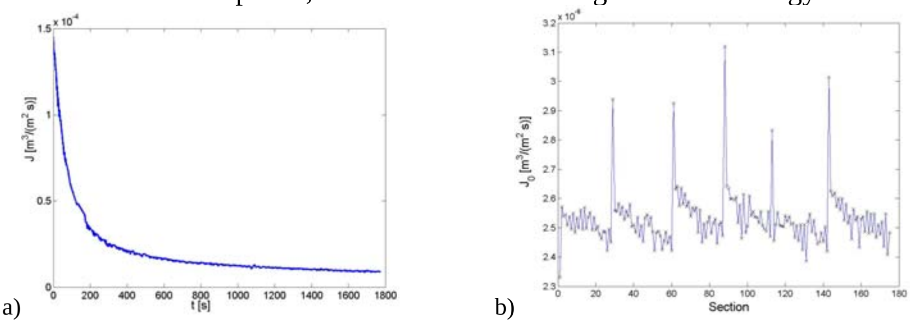

Figure 2: Decrease of flux over time/section: a) test cell experiments, b) MBR plant (initial J).

3. Solution approach

The proposed process control strategy is based on an automated recognition of current dominant filtration mechanisms during the operation. For this purpose, a model-based optimization framework is proposed which includes parameter estimation, as well as an enhanced model discrimination step. Based on the developed approach, it is now possible to identify time points, i.e., time intervals where a certain model is valid or more appropriate. The bounds of these sections are optimally positioned in order to find the best fitting. In this work, 5 different models describing the dynamic behaviour of the flux are used, which assume a constant transmembrane pressure difference (Table 1).

Table 1. Models used for the model discrimination

No.	Model	Effect	Ref.
1	Cake Layer Dead End Filtration	cake building	[5]
2	Standard Blocking	pore size reduction	[6]
3	Intermediate Blocking	pore blocking and cake building	[6]
4	Complete Blocking	pore blocking	[6]
5	Cake Layer Cross Flow Filtration	cake building until steady state	[7]

Each model in Table 1 corresponds to a different fouling effect. The application of a single model a priori is shown in Fig. 3a. In Fig. 3b it is demonstrated exemplarily how the models can be adapted to describing the different dominant filtration mechanisms during a typical filtration operation *a posteriori*. Thus, based on the knowledge of both the model in force and the time point (filtration section), it is possible to take control actions derived from the instantaneous situation on the membrane surface. This is particularly important for an optimal process operation of the MBR since, e.g., the short presence of a blocking model at the beginning of a cycle means irreversible membrane fouling. Following this idea, the main challenges are how to recognize the nature of the current prevailing mechanism as well as the times when the new mechanisms begin to dominate or when model parameters change quantitatively.

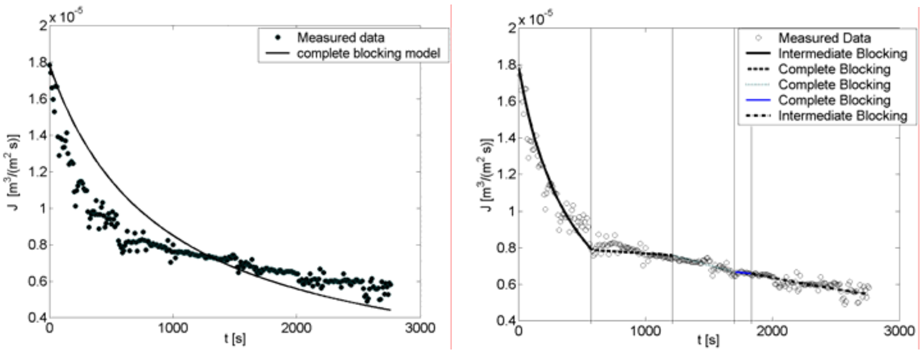

Figure 3: Comparison experiment/simulation using: a) just one model, b) various models

In order to detect the acting models and their switching points, a three-stage model-based optimization framework has been developed. Fig. 4 shows the structure of the solution approach. In an inner loop the parameters of all models have to be estimated at each interval of the considered filtration section. For the parameter estimation the maximum likelihood method is employed.

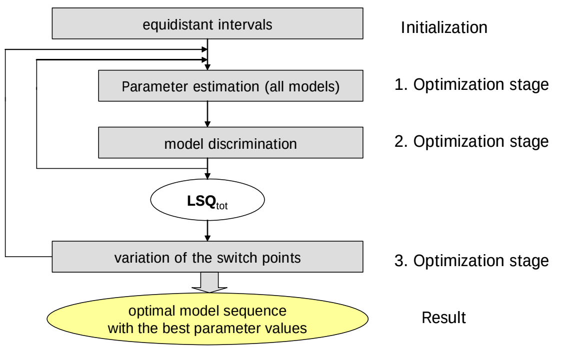

Figure 4: Computational strategy for the automated mechanism recognition (AMR)

The optimum can be found using gradient based methods for the models 1 to 4. Since model 5 is given by a nonlinear differential equation containing 3 parameters, which makes gradient based method quite slow, for the sake of reducing computing time for the online application the Nelder-Mead Simplex method [8] is used. Furthermore, each new interval is bounded to the previous one by its initial conditions. Here, it is assumed that the initial flux is equal to the terminating flux of the last model. Since the initial flux is a function of several process parameters including pressure, viscosity and membrane resistance, it is assumed that each interval begins with a virtually new membrane of a higher resistance than the previous membrane. The second optimization stage concerns the model discrimination, in which the best model for every interval is selected. Basically, the model discrimination can be carried out straightforward by searching the model with the least square error in the current interval. The third optimization stage is related to the variation of the model switching points, i.e. the length of the intervals in which a model acts. However, the objective function for this stage is highly discontinuous and randomly distributed. To find the optimal model switching points the PSO algorithm [9] is used.

4. Computation results

In this section, the applicability of the developed approach is demonstrated through experiments carried out in a test cell. Fig. 5 shows the intervals and models based on the AMR. In comparison with the one model fitting a priori, a better compliance can be reached. The mean square error is about the power of ten lower. In the Fig. 5 on the right, the model type distribution is illustrated for the considered experiment.

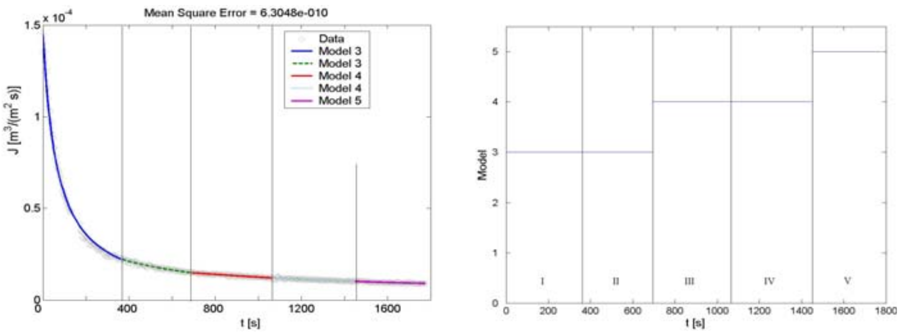

Figure 5: Comparison experiment/model fitting and its corresponding model switching

Based on the results, Fig. 5 can be interpreted as follows: at the beginning of the filtration process *intermediate blocking* is the dominant mechanism. This means that the membrane pores are blocked with substances but also a cake layer is formed. After nearly 700 seconds the mechanism changes to *complete blocking*.

From now on, the membrane pores cannot be blocked further. Instead, the pores of the previously built cake layer will be blocked. The last 300 seconds of the experiment are dominated by the *cake layer cross flow* mechanism. The process reaches a steady state point with a nearly constant but low flux. The question will be then: which decisions are necessary for the imminent pause and the next filtration step based on these results? The main conclusion is that the membrane medium was affected by pore blocking. The later complete blocking only affected the previously built cake layer. A cake layer can be eliminated by a simple filtration pause or increased aeration. In contrast, this will not work in the case of directly blocked membrane pores. If this is the case, a backward flushing should be initialized. Referring to the example, the backward flushing is the derived counter measure in order to bring back the membrane to a cross flow state with a higher flux.

In this work, 6 different data sets from the test cell were examined. This results in a pretty good agreement with the model switching by utilizing the AMR approach. With regard to the 24 hours cycle operation from a MBR plant, some deviations can be observed due to the measurement accuracy. Some extensions of the approach to consider this issue are underway. However, based on the developed concept, a first scheme of appropriate anti-fouling measures has been derived for the implementation on site.

5. Concluding remarks

The developed optimization-based framework represents a novel promising approach to counteract membrane fouling. With the help of the proposed framework, convenient control actions can be taken to increase the permeability respective to each mechanism. The resulting most suited strategies like higher aeration rates, increased back-flush frequency, cleaning or a combination, respectively, lead to an improved filtration performance. The validation and applicability of the approach has been demonstrated through experiments. The AMR is currently being extended to consider models for constant flux which is the more common operation in full-scale wastewater plants.

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