

HF-MBR MODELLING. HOW IMPORTANT ARE THE SOLUBLE MICROBIAL PRODUCTS?

Pompilia BUZATU¹, Vasile LAVRIC²

Soluble microbial products (SMP) have been long time considered the major cause of membrane fouling when membrane bioreactors (MBR) are used for wastewater treatment. As a result, the formation and degradation of SMP have been incorporated in the conventional ASM models for a better prediction of MBR performance. This paper studies the impact of SMP modelling when optimizing the start-up of an MBR using ASM1; the results thus obtained are compared to those generated during the optimization of the same system using the ASM1-SMP.

Keywords: membrane bioreactor, MBR, SMP, wastewater treatment, ASM1

1. Introduction_Background

Membrane bioreactors (MBRs) can no longer be considered an incipient technology, as a high number of full-scale plants are already installed worldwide [1,2]. Their main advantage is the integration of the biological treatment process with ultra- and microfiltration membranes in a sole unit, thus removing the large settling tanks used in conventional activated sludge systems. The main drawback that hinders their wider utilization is the membrane fouling/clogging [1]. The most common practice to reduce the undesired process of clogging is the membrane scouring with air. However, this method is very energy intensive and efforts are being made to improve the operational conditions so as to reduce the aeration costs as much as possible [3,4]. Thus, efficient wastewater treatment in these systems relies on optimization of operational condition, the main purpose being the reduction of operational costs caused by aeration.

Experimental and computational efforts are made and the models developed for the conventional activated sludge (CAS) systems are usually used for MBRs modelling either in their original form (i.e. as they are used for CAS) or modified to take into account the MBR specificities: medium to very high sludge retention times (15-40 days compared with 3-15 for CAS), high mixed liquor concentration (MLSS, 7-14 g/l vs. 1.5-4 g/l), accumulation of soluble microbial products/extracellular polymeric substances (SMP/EPS) rejected by the membrane filtration step, and high aeration rates for scouring purposes [5]. The

¹ Ph.D. candidate, Chemical Engineering Department, University POLITEHNICA of Bucharest, Romania, e-mail: p_buzatu@chim.upb.ro

² Prof., Chemical Engineering Department, University POLITEHNICA of Bucharest, Romania

phase separation is the most important difference between CAS and MBRs, the membrane with a typical pore size of 0.02-0.2 μm being able to retain bacteria, flocs, and compounds with high molecular weight as polysaccharides and proteins inside the bioreactor. Therefore, the modified CAS model versions encountered in literature focus mainly on this aspect.

The activated sludge models (ASMs) are generally used *unmodified* when the purpose of modelling is a process design, effluent characterization, oxygen demand, and/or sludge production, and *modified* when the purpose is the prediction of soluble COD, the acknowledge of high SRTs and/or the better understanding of the treatment process dynamics, for example the link between the biology of the microorganisms and the fouling of the membrane. In the latter case new state variables are introduced either for improving the knowledge of some of the existing processes or for extending the mathematical model, including the description of those processes not present in the original ASMs, like the formation and degradation of SMP/EPS [5]. These are by-products of bacterial metabolism and are secreted when bacteria grow, when die or as response to changes in the environmental conditions. The SMP category lumps all the soluble organic matters (acids, proteins, lipids, DNA, humic acids, polysaccharides) produced by complex bacterial population in the bioreactor. They are believed to be of crucial importance for biological wastewater treatment systems because of their significant impact on both effluent quality and treatment efficiency [6-8]. They are formed as a result of both biological degradation of the initial substrate (the utilization associated products, UAP), and biomass decay (the biomass associated products, BAP) [9].

2. Aim of the study

The present study tries to establish whether the inclusion of SMP in ASM1 makes a significant difference when the model is used to optimally control the start-up of a hollow-fibre MBR (HF-MBR). The results of the optimally controlled HF-MBR obtained disregarding the contribution of SMP are analyzed against those obtained using ASM1-SMP in identical initial conditions. The start-up strategy consists of a discontinuous operation mode followed by a semi-continuous period (termed the “DC-SC policy”). This combination proved to be the best among three previously tested [10] and was chosen as the basis for this study.

3. Modelled system,

The modelled setup is schematically presented in Figure 1 and has been described in details elsewhere [10-12]. The wastewater passes from the storage tank (1) into the bioreactor (2), where the pollutants are removed while the

permeate is extracted through the HF membrane and stored in tank (3). The feeding and the filtration are stopped from time to time and the reversible fouling is removed through backwash. The filtration-backwash cycles continue until all the wastewater in tank (1) is subjected to the treatment process. The wasted sludge is extracted at the bottom of the reactor and stored in tank (4). Two fine bubble diffusers (5) ensure the air for the perfect mixing of the bioreactor and the oxygen for the biomass activity, while another diffuser, providing coarse bubbles, supplies the air for the scour of the membrane meant to delay the permanent fouling/clogging.

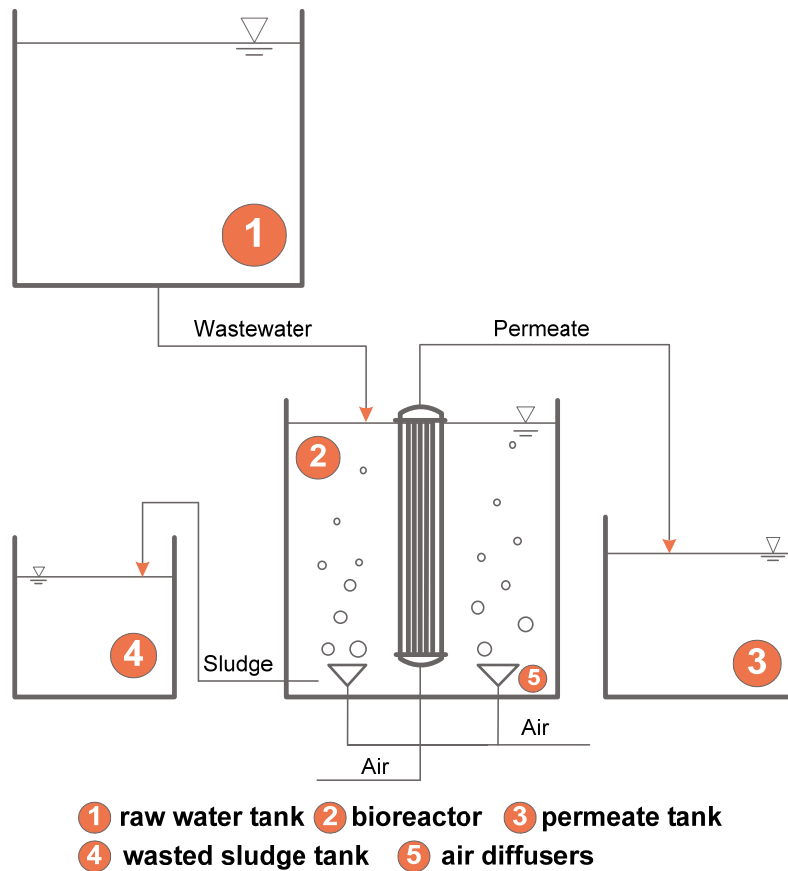


Fig. 1. Modelled system, schematic

4. Mathematical model and objective functions

The mathematical model comprises equations based on mass balances around the reactor and the permeate and waste tanks, which are detailed in Table 1 separately for filtration and backwash periods. The Petersen matrix for the complete ASM1-SMP is presented in Table 2. The highlighted cells represent the processes and compounds involved in SMP modelling that are, therefore, disregarded when the original ASM1 is utilized. This is done by setting to zero all the coefficients situated on the lines and columns involving SMP.

The optimization parameters considered were *a)* the filtration period, *b)* the air flow, *c)* the discontinuous period, and *d)* the inlet flowrate. The wastewater flow was fixed to the same value for both optimization cases and the permeate flow was calculated as the difference between the inlet and wastage line in order to keep the liquid level constant in the reactor.

The purpose of finding an optimally controlled inlet flow is to render the treated water dischargeable in the shortest time possible, and with the smallest volume of air passed through the bioreactor during the start-up.

Table 1

The mass balances for each vessel during filtration and backwash

Reactor, R	soluble components, S_i	Filtration	$\frac{dS_i^R}{dt} = [Q^{FEED} \quad -Q^{FEED} \quad Q^P] \cdot \begin{bmatrix} S_i^{FEED} \\ S_i^R \\ 0 \end{bmatrix} \cdot \frac{1}{V^R} + \sum_i r_i$
		Backwash	$\frac{dS_i^R}{dt} = [-Q^{BW} \quad Q^{BW}] \cdot \begin{bmatrix} S_i^R \\ S_i^P \end{bmatrix} \cdot \frac{1}{V^R} + \sum_i r_i$
	particulate components, X_i	Filtration	$\frac{dX_i^R}{dt} = [Q^{FEED} \quad -Q^{FEED} \quad Q^P] \cdot \begin{bmatrix} X_i^{FEED} \\ X_i^R \\ X_i^R \end{bmatrix} \cdot \frac{1}{V^R} + \sum_i r_i$
		Backwash	$\frac{dX_i^R}{dt} = [-Q^{BW} \quad Q^{BW}] \cdot \begin{bmatrix} X_i^R \\ 0 \end{bmatrix} \cdot \frac{1}{V^R} + \sum_i r_i$
Permeate, P	soluble components, S_i	Filtration	$\frac{dS_i^P}{dt} = [Q^P \quad -Q^P] \cdot \begin{bmatrix} S_i^R \\ S_i^P \end{bmatrix} \cdot \frac{1}{V^P}$
		Backwash	$\frac{dS_i^P}{dt} = 0$
Waste, W	all components, c_i	Filtration & backwash	$\frac{dc_i^W}{dt} = [Q^W \quad -Q^W] \cdot \begin{bmatrix} c_i^R \\ c_i^W \end{bmatrix} \cdot \frac{1}{V^W}$

The first objective function, derived from the former part of this intention, was the minimum between the conversion of the chemical oxygen demand (COD) and that of the total nitrogen (TN), as these two groups of pollutants usually make the subject of legal regulations when it comes to the discharge of the treated wastewater.

According to ASM1-SMP terminology, the COD concentration is calculated using equation (1):

$$c_{COD} = S_S + X_S + S_{UAP} + S_{BAP} + S_i + X_i \quad (1)$$

with the two middle terms, S_{UAP} and S_{BAP} , disappearing in the simple ASM1.

The TN concentration has the same expression in both models, as neither S_{UAP} nor S_{BAP} contain any nitrogen:

$$c_{TN} = S_{NO} + S_{NH} + S_{ND} + X_{ND} + i_{XP} \cdot X_i \quad (2)$$

The second objective function, derived from the latter part of the purpose and responsible for keeping the process time reasonable, was the productivity of the system with respect to the readily biodegradable substrates (S_S) and ammonia (S_{NH}).

Both objectives were evaluated at the end of the operating period.

As previously mentioned, the air flow was one of the considered commands but since a low air flow that is associated with a long pumping (operating) period can still lead to high energy costs, the overall air volume was used to differentiate between equally optimal solutions.

All optimizations were carried out using an in-house Matlab™ (MathWorks, Natick, MA) program implementing the genetic algorithms with 50 generations and 50 individuals per generation as default.

5. Results and discussions

Table 2

The Petersen matrix for ASM1-SMP

Processes		Components												
		S _S	X _S	X _H	X _A	S _{UAP}	S _{BAP}	S _O	S _{NO}	S _{NH}	S _{ND}	X _{ND}	S _I	X _I
Aerobic growth of X _H	on S _S	$-\frac{1}{Y_H}$		1		γ_{UAPH}		$1-\frac{1}{Y_H}$		$-i_{XB}$				
	on S _{SMP}			1		γ_{UAPH} $-\frac{1}{Y_{SMP}}$	$-\frac{1}{Y_{SMP}}$	$1-\frac{1}{Y_{SMP}}$		$-i_{XB}$				
Anoxic growth of X _H	on S _S	$-\frac{1}{Y_H}$		1		γ_{UAPH}			$\frac{Y_H-1}{2.86 \cdot Y_H}$	$-i_{XB}$				
	on S _{SMP}			1		γ_{UAPH} $-\frac{1}{Y_{SMP}}$	$-\frac{1}{Y_{SMP}}$		$\frac{Y_{SMP}-1}{2.86 \cdot Y_{SMP}}$	$-i_{XB}$				
Aerobic growth of X _A					1	γ_{UAPA}		$1-\frac{4.57}{Y_A}$	$\frac{1}{Y_A}$	$-i_{XB}$ $-\frac{1}{Y_A}$				
Particulate formation by decay of X _H			$1-f_p$	-1								i_{XB} $f_p \cdot i_{XP}$		f_p
BAP formation by decay of X _H				-1			$1-f_B$				i_{XB} $f_B \cdot i_{XP}$		f_B	
Particulate formation by decay of X _A			$1-f_p$		-1							i_{XB} $f_p \cdot i_{XP}$		f_p
BAP formation by decay of X _A					-1		$1-f_B$				i_{XB} $f_B \cdot i_{XP}$		f_B	
Ammonification of S _{ND}										1	-1			
Hydrolysis of X _S		1	-1											
Hydrolysis of X _{ND}											1	-1		

5.1. Optimal control using ASM1

The Pareto front obtained for the *DC-SC policy* using the ASM1 is presented in Figure 2 along with that generated by ASM1-SMP in identical conditions [12]. It can be noticed that disregarding SMP moves the front to the right, towards higher minimum conversions, while maintaining the productivities at approximately the same level or slightly increasing them. All the points now ensure the safe discharge of the treated water, unlike those obtained with ASM1-SMP, when the first three failed to comply.

Another interesting observation is related to the nature of the minimum conversion: when using the ASM1-SMP all conversions pertaining to the front belonged to COD, while those associated with TN were always higher. The situation is reversed with the ASM1 only model – all the conversion points on the front belong to TN and those of COD are always higher. This shows that when excluding SMP from the model, the COD becomes easier to be degraded than TN, as SMP represent some sort of internal substrate recirculation/reuse. On one hand there is less COD produced in the process (no UAP and BAP included in equation (1)) and on the other hand the SMP is not competing as substrate with the original ones, thus endowing bacteria to consume the latter (first two terms in equation (1)) and increasing COD conversion.

5.2. Air requirements

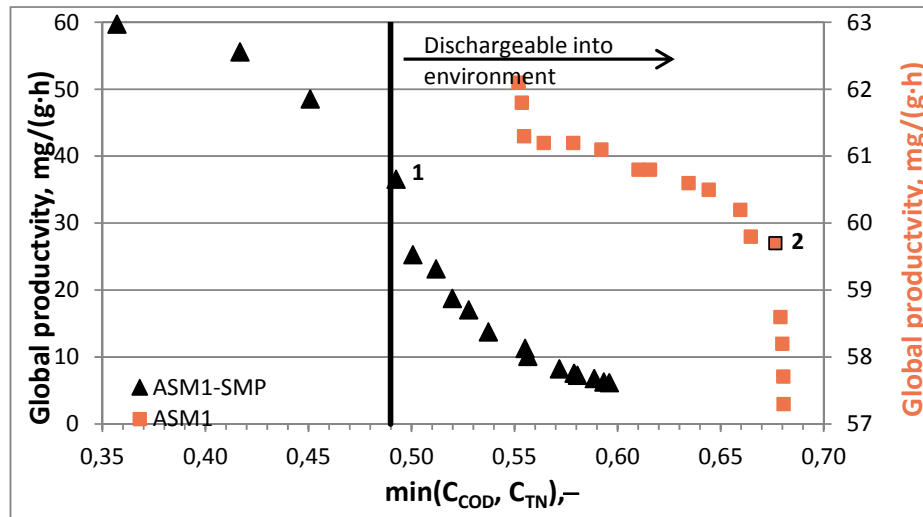


Fig. 2. Pareto front obtained using ASM1; comparison with the front generated by ASM1-SMP

When performing an optimization with two contradictory goals, like conversion and productivity, a Pareto front with equally optimal solutions is always obtained. The discrimination between these is made based on other criteria considered important from a technological or economical point of view, but not included amongst the objective functions. In this paper the extra-criterion used to differentiate the solutions is the air requirement expressed in terms of final overall volume passed through the bioreactor. The volumes associated with the Pareto front generated with ASM1 are presented in Figure 3, along with those generated using ASM1-SMP. When using the former model, the trend is reverted, as compared to latter model; high air volumes are now associated with high productivities. However, the highest air volumes required for biomass activity are now comparable with the lowest ones in ASM1-SMP, suggesting that by neglecting the SMP-associated processes significant air volumes could be overlooked.

Regarding the most appropriate set of parameters recommended for the start-up of the system, the first meeting the discharge conversion when using the complete model corresponds to the point labelled with “1” in Figure 2 and 3, for which we can guarantee that the discharged water complies with the environmental regulations. When using the simplified ASM1 model, the most appropriate set of parameters recommended for the start-up of the system corresponds to the point labelled with “2” in Figures 2 and 3: the productivity is still higher than that of the selected point for ASM1-SMP and the air consumption is one of the lowest. But this is a misleading result, since the unaccounted SMP,

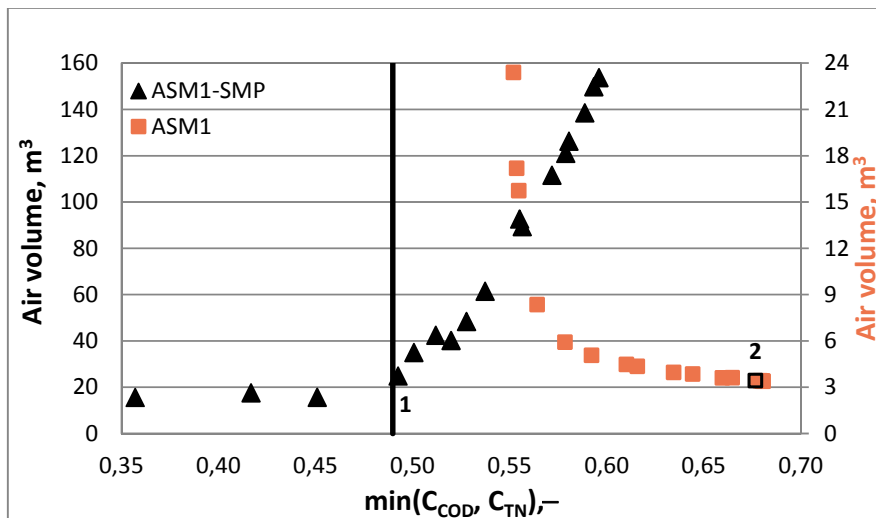


Fig. 3. Air volumes associated with ASM1; comparison with the volumes required by ASM1-SMP

which still exists in the discharged water, worsens its quality through a higher than regulated COD.

6. Conclusions

The conventional ASM1 has been applied to compute the optimum profile of the inlet wastewater flow during the start-up period of a membrane bioreactor used for wastewater treatment with the purpose of finding the set of operating parameters that ensures the safe discharge of water in the shortest time possible. The dichotomic objective functions used generated a Pareto front which was compared with that resulted using ASM1-SMP model for identical initial conditions.

The results thus obtained suggest that neglecting the SMP in the MBR optimal start-up (and, in fact, in any modelling/optimization application) generate false high conversions and productivities of COD, while severely underestimating the aeration demands. These render the ASM1 only model less applicable for real wastewater HF-MBR treatment applications. Still, for classic biological wastewater treatment systems, involving a bioreactor and an external gravitational separator system, this ASM1 only model remains useful.

The aforementioned results underline the importance of accurate SMP modelling when working with fined-tuned systems like HF-MBR, with implications upon kinetic and stoichiometric parameter estimation.

Acknowledgements

The work has been funded by the Sectorial Operational Programme Human Resources Development 2007-2013 of the Romanian Ministry of Labour, Family and Social Protection through the Financial Agreement POSDRU/88/1.5/S/60203.

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