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OPTIMIZATION OF WASTEWATER FILTRATION PROCESS IN SUBMERGED MEMBRANE BIOREACTORS: APPLICABILITY OF A DYNAMIC MODEL TO SCALE UP.

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Abstract. The application of a hybrid mathematical model, which takes into account the effect of main variables in Submerged Membrane Bioreactor (SMBR) systems, was established in order to simulate and optimize the FILTRATION process into SMBR, on the base of experimental data performed on a bench and pilot scale bioreactors. The validity of the numerical process in the scale up of the water treatment process was checked. Numerical simulations of the wastewater treatment process were performed in order to find the optimal filtration conditions for both different scale bioreactors. Various operating conditions (idle-filtration time, aeration intensity, solids retention time, hydraulics retention time, and total suspended solids concentration) were tested. Different optimization criteria were considered to minimize the transmembrane pressure and energy consumption, and to maximize filtrate flow.

Keywords: Biological wastewater treatment; Submerged Membrane Bioreactor (SMBR); modelling; optimization

The wastewater treatment using a submerged membrane bioreactor (SMBR) allows obtaining a quite constant filtrate quality after biological degradation process and physical separation. The membrane bioreactor technology has been improved, and research on SMBR technology has increased significantly, particularly in the last 5 years¹. The advantages of the SMBR system over conventional biological treatment processes leads to a growing interest in MBR technology for water and wastewater treatment. MBR treatment of municipal wastewater yields high-quality water with reported removal percentages of 95%, 98%, and 99% (or greater) for chemical oxygen demand (COD), biochemical oxygen demand (BOD), and suspended solids (SS), respectively². Nevertheless, the filtration process is disturbed by the influence of complex factors that cause the membrane fouling.

On the other hand, mathematical modelling and simulation are powerful tools with which the specialists can predict the performances of potential systems under different operating conditions. For this reason, it is interesting to use models that can accurately describe the SMBR process for the design, and optimization of these systems.

The objective of this work is to show the practical application of a hybrid mathematical model, developed in a previous work³ for optimizing the operation of two SMBRs using different optimization criteria to minimize the transmembrane pressure and energy consumption, and to maximize filtrate flow. The model was established considering Soluble Microbial Products (SMP) formation-degradation kinetic based on modified published models⁴⁻⁶. A modification of Li and Wang's model⁷ allows to calculate the increase of the TMP evaluating, at the same time, the influence on fouling control of an intermittent

aeration of coarse bubbles synchronized with the filtration cycles, and to analyze the effects of shear intensity on sludge cake removal. In order to describe the biological system behaviour a modified ASM1 model was developed to estimate the optimal operating conditions related to a specific bioreactor condition. The validation of the model was carried out using the data from an experimental SMBR installed in a real domestic wastewater treatment plant.

EXPERIMENTAL PART

Two different SMBRs were studied. In the first (bench scale), a U-shaped, hollow-fiber membrane module with area of 0.3 m² (provided by Polymem, Toulouse, France), was immersed in a bioreactor of 10.5 L of working volume. Hollow fibres were made of polysulfone with a pore size of 0.1 µm, and internal/external diameter of 0.4/0.7 mm. The SMBR was initially filled with activated sludge from the Brax wastewater treatment plant (2000 eq inhabitants, only domestic wastewater). The municipal wastewater was continuously introduced. The influent flow rate was controlled by the liquid level in the reactor. Filtration was operated in an intermittent sequence of filtration-relaxation. The TMP was continuously monitored as an indicator of membrane fouling (Sensor Keller). Filtrate flow was measured with an electromagnetic flow meter (Rosemount), a temperature sensor (PT 100; -50 to 250 °C) and a Mettler Toledo pH meter were utilized. The pH was maintained between 6.5 and 7.5 by adding a Na₂SO₄ solution (10 g/L). PC-based real time data acquisition hardware (IOTECK) and the software DASYLAB have been used for acquiring all data.

The second bioreactor has four hollow-fibre membrane modules with an area of 2.5 m² (10 m² of total filtration area) and a bioreactor tank of 1 m³ (Polymem, Labège, France). The membrane material is the same as the previous one. This bioreactor is operated in a largest plant, collecting wastewater from domestic area as well as industrial one. In this case, different simulations were carried out in order to estimate the optimal values of the operating conditions using the approach of the experimental design. The model was established in order to simulate and optimize the filtration process into SMBR, on the base of experimental data performed on a laboratory scale bioreactor, with 10 litres of mixed liquor. Numerical simulations of the wastewater treatment process were performed in order to find the optimal filtration conditions for two different scale bioreactors.

The bench scale bioreactor was operated with two types of aeration flows. An intermittent coarse bubbles flow injected closed to the fibres, providing a tangential liquid movement, to avoid the membrane fouling by reduction of cake formation (reversible fouling), and a constant fine bubbles flow injected through a perforated membrane at the bottom of the reactor, providing mixing and biomass oxygenation. The membrane module was isolated to the contact with fine bubbles; thus, membrane fibers movement is only produced by the flow of coarse bubbles. The operation was stopped at 12 days of filtration or when the TMP reached 60 kPa under atmospheric pressure, and a chemical cleaning was applied, using solutions of 2 M chlorine for 2 h, and 0.1 N NaOH for 24 h.

Analytical methods

The Total Suspended Solids (TSS) concentration was determined by centrifugation at 5000 rpm for 10 min and drying at 105°C using a PRECISA HA60 moisture analyzer. The activated sludge flocs size distribution was estimated with a laser granulometer (Mastersizer 2000, Malvern Instruments). Dead-end filtration tests were performed to estimate the specific filtration resistance ($\alpha = r_{sc} = r_{dc}$). The filtration index measurements were performed in a special cell. The experimental filtration device was a Sartorius filtration pressured cell, with a working volume of 50 mL on a plane organic membrane of cellulose acetate (47 mm diameter, filtration area 0.17 cm² and pore size 0.2 µm). The quantification of Extracellular Polymeric Substances (EPS) was made on the sludge supernatant that had been obtained by centrifugation at 5000 rpm for 20 min, and on the suspended solid. The EPS from the suspended solid were extracted by addition of 2 N NaOH at 4°C for 4 h. The extracted solutions were then centrifuged at 20000 rpm for 20 min and filtrated on a 0.2 µm membrane. Soluble EPS were quantified in influent and permeate samples. Proteins and polysaccharides were measured by spectrophotometric methods. The Lowry method modified by Frolund was used for the quantification of proteins and humics with bovine serum albumin as standard⁸. For quantitative analysis of carbohydrates, the modification of the anthrone method described by Raunkjaer et al⁹ was used with glucose as standard.

The composition of municipal wastewater is highly variable. For this reason, average influent composition values were used during calculation. These estimated values were determined by different batch procedures. Respirometric measurements were used for the determination of readily and slowly biodegradable substrates considering $Y_H = 0.67$ gCOD / gCOD. The reactor of 1.5 L used for the oxygen uptake measurement was constantly aerated and stirred. A water bath was used to keep the temperature of

the liquid constant at 25 °C. Allylthiourea (ATU) (2 mg/l) was added to reactor to inhibit the nitrifying microorganisms. An S/X ratio of 1.2 was used, and these enabled the areas under the Oxygen Uptake Rate (OUR) curve to be distinguished. Dissolved oxygen was measured in the reactor by means of an oxygen meter (YSI-51). The readily biodegradable substrates (S_S) and the slowly biodegradable substrates (X_S) were estimated following a published procedure¹⁰.

Simulation conditions and optimization procedure

A numerical simulation of the membrane fouling was performed using a program that was written in Berkeley Madonna programming language, run on a PC in the Windows XP environment. Membrane fouling development was simulated by numerical iterations, which produces the overall TMP increase and the evolution in the distribution of the flux and the sludge cake layer across the membrane surface sections (time step = 1 s). The intermittent process of filtration and coarse bubbles injection were simulated by means of periodic functions implemented in Berkeley Madonna V 8.3.9. When the simulation results were compared with experimental data a good agreement was observed, thus, a D-Optimal Experimental Design (DOED) matrix was used for the optimization of the operating conditions for both SMBRs (Tables 1 and 2). The values of the response variables in each experiment were estimated “in-silico” using our model, then, the optimal values were founded using the mathematical tools included in the software Design-expert v7. This procedure allows a quickly estimation of the optimal values, that is important when the physical experiments are time-consuming, expensive and difficult to carry out¹¹. Finally, the predicted optimal operating conditions were validated by experimental way for bench scale SMBR. The validation of the optimum for the pilot scale SMBR is under study.

Table 1- Summary of the DOED used during the optimization of the operating conditions for the bench scale SMBR

	Factors considered in the design of experiments*				
	tf (min)	tid (min)	Int _{CB} (min)	t _{CB} (min)	SRT (days)
Low actual	5	2	4	1	20
High actual	15	5	10	3	70

* Design Model (quadratic), Experiments= 26, qa = 9 (L/(m² s)), J_T=0.24 (m³/(m² day)).

Where qa= aeration intensity, tf= filtration time, tid= idle time, Int_{CB}= time interval between two coarse bubbles injection, t_{CB}= coarse bubbles injection time, SRT=solids retention time, J_T= Overall flux

Table 2- Summary of the DOED used during the optimization of the operating conditions for the pilot scale SMBR

	Factors considered in the design of experiments*				
	tf (min)	tid (min)	Int _{CB} (min)	t _{CB} (min)	tbw (min)
Low actual	5	0.5	0.2	0.5	0.1
High actual	10	1.5	0.75	3	0.5

* Design Model (quadratic), Experiments= 30, qa = 1 (L/(m² s)), J_T = 0.24 (m³/(m² day))

Where qa= aeration intensity, tf= filtration time, tid= idle time, Int_{CB}= time interval between two coarse bubbles injection, t_{CB}= coarse bubbles injection time, tbw=backwashing time, J_T= Overall flux

RESULTS AND DISCUSSION

Optimization of the operating conditions for the bench scale SMBR

During the optimization, different criteria were considered, to minimize the transmembrane pressure and energy consumption, and to maximize filtrate flow (figs. 3-4). The equation 1 shows the objective function used to calculate and to minimize the energy consumption. On the other hand, Table 3 shows a summary of the measured influent characteristics and initial operating conditions used during simulation. The table 4 shows the optimization results estimated by simulation as well as the predicted values of the optimized response variables (after 12 days of filtration using the optimized operating conditions).

$$EC = \left[\frac{0.666(Q_{fil} * TMP * tf)}{FV * (tf + tid)} + \frac{0.666(Q_{air} * \Delta P_{air} * t_{CB})}{FV * (t_{CB} + Int_{CB})} \right] time \quad \langle kW/m^3 h \rangle \quad (eq. 1)$$

Where: EC= Energy consumption (kW/m³h), FV= Filtrate volume (l), TMP= Transmembrane pressure (kPa), Q_{air}= aeration flow (l/h), Q_{filt}= Filtration Flow (l/h), ΔP_{air}= aeration drop pressure (bar)

Table 3- Summary of the measured influent and initial conditions used during simulation.

Measured influent and initial conditions, values used during simulation							
Case	X _{TSS0}	X _{TSSR0}	X _{S0}	X _{I0}	S _{S0}	S _{I0}	S _{SMP0}
A	25	6000	100	25	155	30	65
B	30	8300	90	20	190	45	45

(Superscript 0, R0 expresses in “influent”, “initial value in the bioreactor” respectively), X_{TSS}= Total suspended solids in the mixed liquor (mg/l), X_S= slowly biodegradable products (mgCOD/l), X_I= inert organic materials (mgCOD/l), S_S= soluble biodegradable substrate (mgCOD/l), S_I= soluble inert matters (mgCOD/l), S_{SMP}=soluble microbial products (mgCOD/l)

Table 4- Optimization results calculated by simulation and the DOED for bench scale SBMR.

Case	Optimized values of the operating variables					Predicted values of the response variables		
	tf	tid	Int _{CB}	t _{CB}	SRT	FV (12 d)	TMP (12 d)	EC (12 d)
A	10 min	2 min	8 min	2 min	40 d	627 L	30 kPa	0.294 kW/m ³ h
B	15 min	2 min	8 min	2 min	30 d	762 L	37 kPa	0.262 kW/m ³ h

During the optimization, only five factors were considered in the DOE. Figures 1-2 show different examples of the optimization results, but considering only the values of tid and tf in the axis. The other factors values could be calculated in the same way, once a specific optimization criterion is chosen. Table 4 points out the existence of differences in the tf and SRT values for the case A and B, but it also suggests that different filtration-idle time cycles may lead in both cases to work in optimal conditions, this also change the synchronization between the filtration and the intermittent aeration. This result is reasonable and may find explanation in the fact that the cases A and B have different influent characteristics and biomass concentration (Table 3). These differences modify the behavior of the system due to the presence of different F/M ratios, different sludge viscosities (that are function of the X_{TSS} concentration), and biological variables.

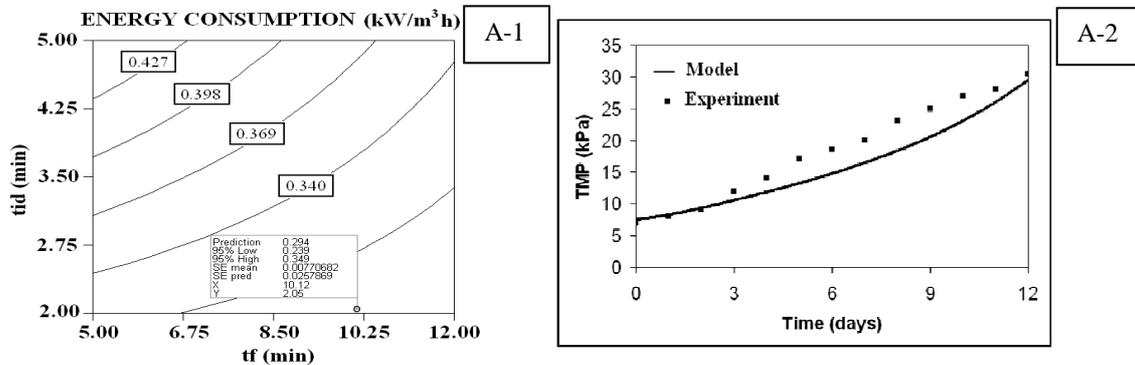


Figure 1- Optimization of operating conditions for the bench scale SBMR. Case A: Minimizing energy consumption [A-1: Contour graph obtained during the optimization of the operating conditions (minimizing the energy consumption). A-2: Experimental validation of the optimized values of the operating conditions].

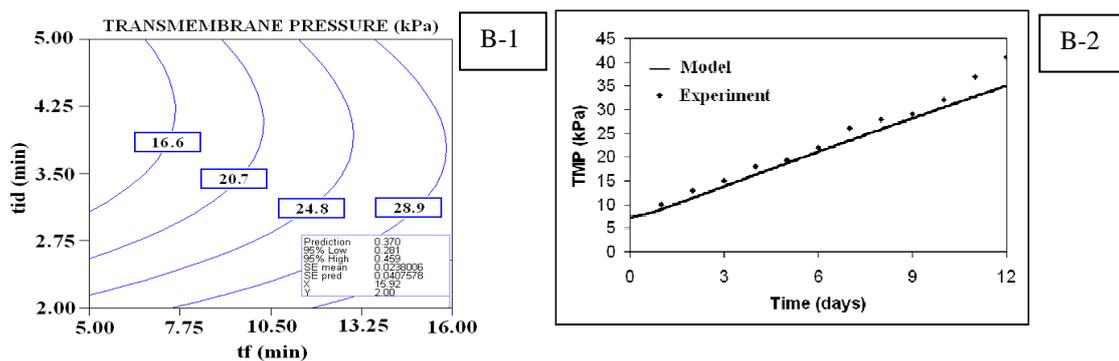


Figure 2- Optimization of operating conditions for the bench scale SMBR. Case B: Minimizing TMP [B-1: Contour graph obtained during the optimization of the operating conditions (minimizing the transmembrane pressure). B-2: Experimental validation of the optimized values of the operating conditions].

The same observations can be made for the composition of mixed liquors, which are not the same between case A and B, and modifying the value of the specific filtration resistance of the sludge cake layer, and consequently the fouling rate. In the experiments ran “in silico”, the EC values were found between 0.15-0.96 kW/m³h and the FV values between 432-800 l, therefore, the estimated optimal conditions facilitated, in both cases, to operate the bioreactor for an adequate volume of produced water with a reasonable energy consumption (Table 4).

Optimization of the operating conditions for the pilot scale SMBR

In the case of the pilot scale SMBR, the optimization study was carried out with the objective of modifying the usual values of the operating variables, in order to improve the operation efficiency of the SMBR. The results are shown in table 5. The analysis of the simulation-optimization results (Table 6) suggests that for a better utilization of the SMBR it would be convenient to increase the filtration time almost of 30% of its current value. In relation to the injection cycles of the coarse bubbles, the idle time between every injection could be increased in 80%, but at the same time, it is necessary to double the length of the aeration time. This operating way is more efficient because it decreases the energy consumption due to the aeration flow used to remove the sludge deposited on the membrane. Although, a higher idle time allows some temporary deposition of the sludge on the membrane, the simulation estimates that the increase of the injection time get possible to later efficiently the deposition of the sludge and the formation of the filtration cake on the membrane. On the other hand, a higher filtration time facilitates the production if a higher filtrate volume (increase of 11%) during the considered time, which decreases the estimated value of energy consumption by m³ of treated water (decrease of 56%).

Table 5- Current and optimized values of the studied operating values for the pilot scale SMBR.

Operating variables	Current value	Optimized value
tf (min)	5	7.61 (7.5)*
tid (min)	0.5	0.5
Int _{CB} (min)	0.25	0.5
t _{CB} (min)	0.25	1.76 (1.75)
tbw (min)	0.5	0.5

() * In brackets are shown the values used during the simulation with the optimized values of the operational variables.

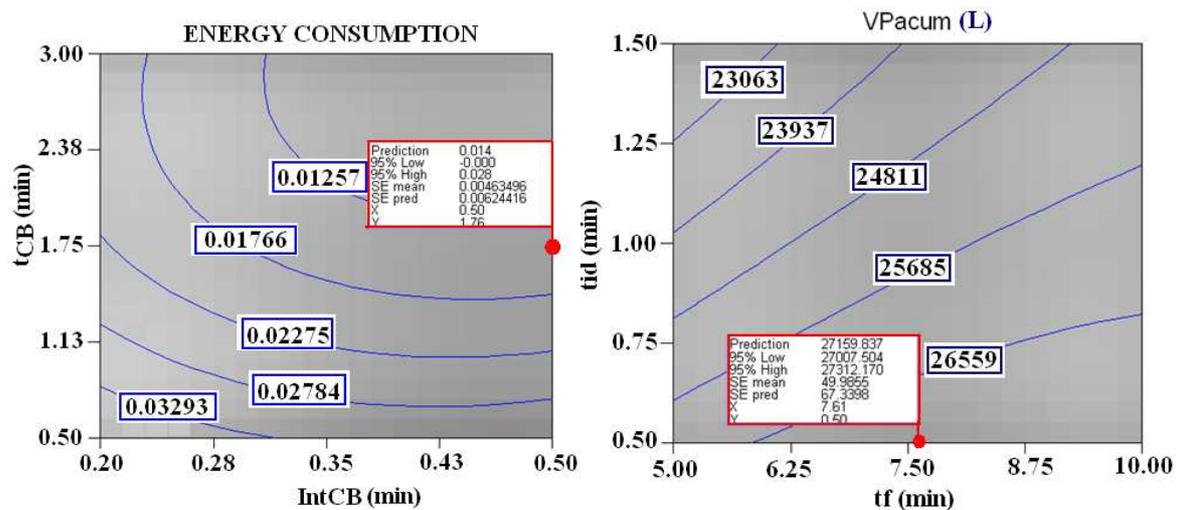


Figure 3- Examples of the contour graphs obtained during the optimization of the operating conditions for the pilot scale SMBR.

In relation to the value of the backwashing time, the model considers that the current value is correct (0.5 min). To evaluate the validity of the simulations and the quality of the model prediction, all

results have still to be validated in the bench scale SMBR. Some simplifications have been made during the modelling of the system; therefore, it is necessary to characterize the influence of the assumptions and the limitations of the model on the optimization results. The optimization procedure presupposes the existence of a model calibrated to the real system, an accurate process of prediction by simulation is only possible after tuning the parameters of the model to a given plant. Therefore, the more sensible parameters must be recalibrated if the influent conditions and the biomass characteristics change considerably. Before the optimization evaluation, the quality of the model prediction is a very important key to guarantee the quality of the optimization process.

Table 6- Influence of the optimized operating variables on the response variables for the pilot scale SMBR.

	Reponse variables (at 15 days)		
	TMP (kPa)	VPacum (L)	EC (kW/hm ³)
Results with the current values of the operating variables	43.6	24000	0.055
Results with the optimized values of the operating variables	25	27160	0.024
TMP reduction	42.6 %	-	-
Volume increase	-	11.6 %	-
Energy consumption reduction	-	-	56.4 %

CONCLUSIONS

An optimization study to improve the filtration process on two different SMBRs at different scales has been successfully developed. For this task, a recent developed model was used. A DOED was carried out "in silico" in order to optimize some operating variables. This simple optimization procedure improves the operating conditions for two different optimization criteria: minimizing energy consumption and minimizing TMP. Subsequently, the experimental verification process of the optimized operating conditions for the bench scale is in good agreement with the model predictions. Future tasks will focus on the system optimization, but, also including the aeration intensity and the filtration flux as factors to consider in the design of experiments. However, for better results a special attention is needed during parameters model calibration.

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