MODELLING OF SUBMERGED MEMBRANE BIOREACTOR: CONCEPTUAL STUDY ABOUT LINK BETWEEN ACTIVATED SLUGDE BIOKINETICS, AERATION AND FOULING PROCESS

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ABSTRACT

A mathematical model was developed to simulate filtration process and aeration influence on Submerged Membrane Bioreactor (SMBR) in aerobic conditions. The biological kinetics and the dynamic effect of the sludge attachment and detachment from the membrane, in relation to the filtration and a strong intermittent aeration, were included in the model. The model was established considering soluble microbial products (SMP) formation-degradation. The fouling components responsible of pore clogging, sludge cake growth, and temporal sludge film coverage were considered during calculation of the total membrane fouling resistance. The influence of SMP, trans-membrane pressure, and mixed liquor suspended solids on specific filtration resistance of the sludge cake was also included. With this model, the membrane fouling under different SMBR operational conditions can be simulated. The influence of a larger number of very important process variables on fouling development can be well quantified. The model was developed for evaluating the influence on fouling control of an intermittent aeration of bubbles synchronized or not with the filtration cycles, taking into account the effects of shear intensity on sludge cake removal.

Keywords: Biological wastewater treatment; Filtration resistance; Submerged Membrane Bioreactor (SMBR); Membrane fouling; MBR Modelling.

1- INTRODUCTION

Membrane bioreactor (MBR) has become a popular biological wastewater treatment technology because it offers numerous advantages over the conventional activated sludge process, such as excellent effluent quality, a compact footprint, a more concentrated biomass, and a reduced sludge yield. [1-4]. However, membrane fouling is still a major problem that hinders their more widespread and large-scale application [5]. On the point of view of functioning cost, they are even high, due to power requirement that comes mainly from aeration. In hollow fibers SMBR the aeration is used for: 1- the oxygen supply needed for degradation processes, 2- maintaining solids in suspension, 3 - to clean the membrane. A turbulent shear and the agitation of fibers are brought about by air bubbles that attenuate the accumulation of sludge cake on the membrane during filtration. The membrane fouling is highly linked to the sludge attachment on the membrane surface, but it is also dependent on the properties of the biomass and the process parameters, including the transmembrane pressure (TMP), filtration flux, sludge concentration, soluble and particulate microbial products concentration, and of course aeration intensity [4-7]. The researchers met difficulties to achieve a comprehensive understanding and description of the fouling phenomenon in SMBR. Due to the high number of interactions in the system the fouling prediction into the SMBR systems is very complicated. For these reasons a complete general mathematical model for SMBR has not been established yet [8].

Mathematical modelling and simulation are powerful tools with which the specialists can predict the performances of potential systems under different operating conditions. In particular, the dynamic models are very useful because they allow to study the evolution of membrane fouling and the biological system over time. To formulate better dynamic models for the SMBR systems could help to develop more cost-effective strategies for the minimization of the fouling problem. To include the aeration process as an important part in the model and to achieve the process simulation could allow to optimize the filtration-aeration cycles and, consequently, to reduce running cost due to aeration.

Many researchers have proposed dynamic models based upon different concepts and hypothesis. Most of them have been focused on the description of some specific parts of the system, such as the behavior of the biological population, the fouling process near the membrane surface. Generally, these models supposed many simplifications. On the other hand, a few models have been developed considering the relations that take place between the different parts of the system. The model proposed by Cho *et al* [9] describes the dynamic behaviour of the Extracellular Polymeric Substances (EPS) concentration with the change of the biological operating factors such as the organic loading rate, the Hydraulic Retention Time (HRT) and Solids Retention Time (SRT), calculating the effluent quality and membrane fouling simultaneously using a modified resistance-in-series model. This model does not consider the influence of the aeration on fouling control; therefore it is not capable to predict the influence of this process variable during filtration.

One more recent model proposed by Li and Wang [10] is a comprehensive mathematical model for membrane fouling in an SMBR. A sectional approach was used to describe the non-uniform distribution of the turbulent shear intensity and the fouling material coverage on the membrane surface. The dynamics of biomass attachment and detachment from the membrane, which are regulated by filtration suction and aeration cleaning, were considered in the model development. In this model the total fouling resistance was decomposed into the individual components of pore fouling resistance, sludge cake accumulation, and dynamic sludge film formation. The main limitations of this model consist in the assumption that all the biological parameters are constants. In its present form this model is only able to capturing general trends and may not be suitable for applications requiring accurate modeling in membrane fouling phenomena [8]. In addition, during calculation of filtration resistances of the different sludge films, the specific filtration resistance was assumed constant too. For these reasons, with this model it is not possible to analyze during simulation neither the influence of the aeration on biological system variables nor the long term modifications on sludge properties during filtration.

Previous works have demonstrated the effect of aeration intensity and mixed liquor properties on membrane permeability and the impacts of mixed liquor viscosity on the efficiency of coarse bubble aeration. Furthermore, research has also shown the impact of colloidal material, soluble chemical oxygen demand (COD), SMP, EPS and viscosity at different mixed liquor suspended solids (MLSS) concentration on membrane fouling [11]. Therefore, the objective of this study is to propose a hybrid mathematical model which takes into account the effect of all this variables in SMBRs systems. The model was established considering SMP formation-degradation kinetic based on previous published models [9, 12]. A modification of Li and Wang's model allows to calculate the increase of the TMP evaluating, at the same time, the influence on fouling control of an intermittent aeration of bubbles synchronized with the filtration cycles, and to analyze the effects of shear intensity on sludge cake removal. On the other hand, in order to describe the biological system behavior a modified ASM1 model was used. The final hybrid model was developed to calculate the sludge properties evolution, its relation with sludge cake growth, and their influence on membrane fouling. The proposed model was validated in an experimental SMBR installed in a real domestic wastewater treatment plant.

2- THEORY AND MODELS

2.1- Model development

The goal of this work was to develop an integrated model that allows to couple biomass transformation processes, membrane fouling and the effects of filtration cycles synchronized with intermittent coarse bubbles aeration, following previous efforts related to SMBR model integration [8]. The development of the model was focused on the description of the influence of mixed liquor properties and aeration on membrane fouling. It takes into account the most reliable theories and evidences, founded during recent researches, related to the existing relationships among the more important system variables, during SMBR operation [7, 11, 13- 15]. The SMBR system is based on biological degradation and physical separation using membranes. Thus, for describing the system it is necessary to model both sections. In order to facilitate the model evaluation, the selection of equations and biological processes considered during modelling was linked to the characteristics of the experimental reactor and its operational conditions. However, the final structure of the model offers the possibility of adding others process rates and stoichiometries. The conceptual schema of the developed model is shown in Fig. 1. It shows the main relations that take place during simulation and, also, the information flow established among the different parts of the model during calculation. The model is divided into three sections, the first considers the biological behavior (stoichiometry and process kinetics), the second one is related to membrane fouling evolution and the behaviour of all filtration resistances, and the last consists of a set of periodic equations that represents the process associated to coarse bubbles aeration, feeding and discontinuous filtration.

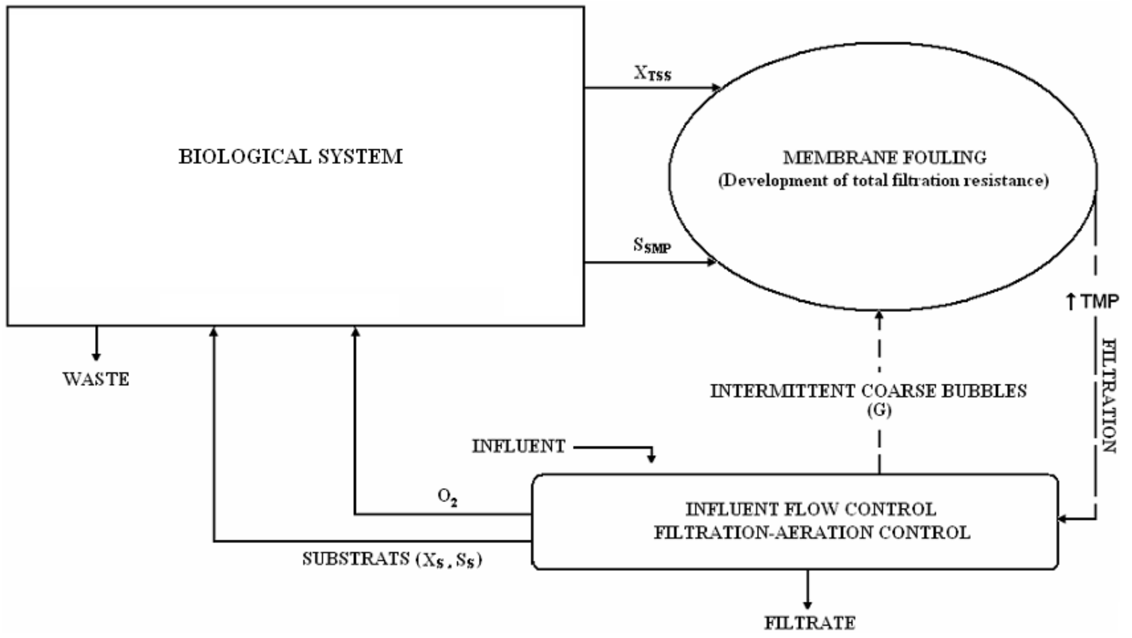

Fig.1- Conceptual schematic of developed model for SMBR

2.2- Components, processes, and biological pathway considered in the activated sludge model

To simulate the activated sludge process, a modified model based on previous works [9, 12, 16] was implemented. The model was established considering SMP formation-degradation kinetic proposed in the modification of ASMl developed by *Lu et al,* but adapting these equations to a strictly aerobic SMBR. Based on Lu's model, *Cho* has proposed a set of differential equations that include the MLSS estimation, the essence of this work was followed to estimate suspended solids concentration used in membrane fouling calculation. Other studies have shown that SMP comprise a considerable portion of soluble organic matter from the effluent of biological treatment processes, and the presence of SMP in the permeate is negative to the MBR process as well as to post-treatment processes [17]. While it is still unclear whether the accumulation of SMP in the activated sludge inhibits metabolic activity, (contradicting results have been reported [4, 18-21]), researchers agree that buildup of SMP can cause reduction in membrane permeability. Therefore, it is crucial to include SMP in the modeling of SMBR processes [8]. A preliminary biological pathway, on which the developed model is based, is shown in Fig. 2.

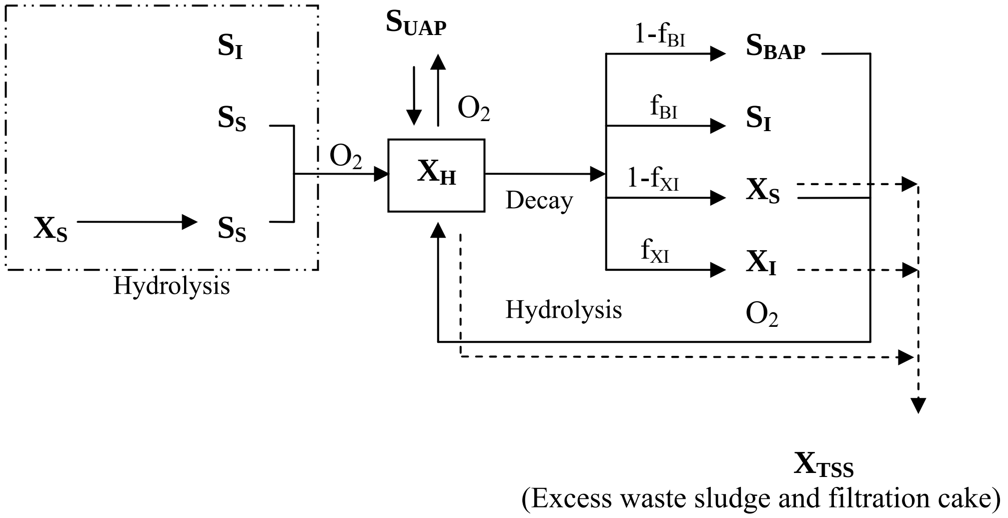

Fig.2- Conceptual schematic of biological pathway of model

The model assumes that heterotrophic organisms represent a variety of unknown species in the bioreactor. Only aerobic degradation was included taking into account the operating conditions and the characteristics of experimental SMBR. The considered biological steps are hydrolysis, growth on substrates and cell lysis. During hydrolysis process the slowly biodegradable substrate, Xs, must be acted first upon hydrolysis to convert into soluble biodegradable matters and then are degraded by heterotrophic biomass. In addition, a fraction of products of all hydrolysis processes is released as soluble inert organic matter, S_I. The soluble biodegradable substrate, S_S, can be directly degraded by heterotrophic biomass.

Utilization-associated product (UAP) and biomass-associated product (BAP) are showed in the biological pathway. UAP is produced directly by original substrate metabolism and BAP is derived from the decay of the active biomass. The formation rate of UAP is proportional to the substrate utilization rate. The BAP is controlled by the cell concentration and it is independent of cell growth rate. It can be then considered as products of endogenous respiration of cells mass. The total SMP is the sum of UAP and BAP. This pathway reflects that both UAP and BAP can be used as substrates by microorganisms.

During lysis process, the dead cells products are considered as inert organic materials (X_I), slowly biodegradable products (X_S), soluble inert matters (S_I), and biomass-associated products (S_{BAP}). While the hydrolysis process occurs, X_S produced by lysis are changed by hydrolysis into Ss and directly used by microorganisms as substrates. Similarly, the BAP derived from the decay of the active biomass can be degraded also by heterotrophs after hydrolysis. During wastewater treatment, the combination of all suspended solids components of the mixed liquor is X_{TSS}. A big fraction of the structural components in the dead-end cake filtration will be comprised of X_{TSS}. Peterson's matrix [16] of biological model including the process kinetics and stoichiometry is shown in Table 2. The biological reaction rate of a component (i), at time (t), r_i, is obtained according to Eq. (1).

$$r_i = \sum_{j=1}^{6} \nu_{i,j} \rho_j \tag{1}$$

Where, ν is the stoichiometric matrix, r is the reaction term, ρ is the kinetic rate and j, i are respectively referred to the biological processes and the components (or state variables). Considering the mass balance, the differential equations for all components are obtained using Eq. (2).

$$\frac{dCi}{dt} = \frac{Q_0 C_{i,0} - QC_i}{V} + r_i \tag{2}$$

Where, Q_0 = influent flow-rate; Q = effluent flow-rate; $C_{i,0}$ = the influent concentration of a component (i); C_i = the effluent concentration of a component (i); V = the volume of the bioreactor.

2.3- Modelling of the membrane fouling

In order to predict the effluent quality and membrane fouling simultaneously, a model that reflects the biological effects in the calculations was used. Most SMBR are operated in a filtration/idle-cleaning switch mode [22-24]. During the aeration process, some of the sludge film can be removed, but other part of the sludge amount is left on the membrane and became a new layer of sludge cake in the next cycle of operation. This mechanism of step by step resistance increase, due to stable sludge cake accumulation, was considered for modelling this kind of membrane fouling [10].

The biological system properties are changing along the time. Thus, the major limitation of Li and Wang's model [10] is to consider some important system variables as constants. In the present work, several changes were made allowing the inclusion of biological system variations during the calculation of TMP increase, specifically the evolution of sludge concentration and the specific filtration resistance of the cake (Eq. (4),(6)). The intermittence of coarse bubbles aeration, its effects on the rate of sludge cake formation, and the influence of the aeration-filtration synchronization were also incorporated by means of periodic equations that describe these processes. A partially analytic approach is used to develop the basis differential equations considered to estimate the actual rate of sludge deposition on membrane and the sludge detachment rate [10]. Taking into account the experimental set-up and the characteristics of the coarse bubble injection system, an uneven shear distribution on the membrane surface was considered, due to the membrane effect on the shear intensity distribution. Consequently, the sine curve expression used to calculate the shear profile by Li and Wang [10], for a given aeration intensity, was considered.

A sectional approach proposed by Li and Wang in determining total filtration resistance was also used. It divides the membrane surface into equal fractional areas and calculates separately the total resistances, R, for each section. The total resistance for a membrane surface section comprises four resistance components, including the intrinsic resistance of the membrane (R_m); the pore fouling resistance caused by solute deposition inside the membrane pores (R_p), that is proportional to the amount of permeate produced; the resistance of the dynamic sludge film (R_{dc}); and the resistance of the stable sludge cake (R_{sc}), attached to the membrane surface. The resistances R_{dc} and R_{sc} are the product of the specific resistance of the biomass in each specific cake fraction and the mass of the sludge attached in each film.

In our model, on the contrary to Li and Wang model, the specific resistance of the biomass is not a constant. Several works show that this variable is a function of TMP, sludge concentration, flocs size, sludge viscosity and bound EPS concentration. Therefore, a published empirical equation [7, 25] that takes into account the functional relationship among some of these variables was introduced. Non-dimensional analysis and different experiments were performed independently in order to establish the relations used to develop this equation. This modification allows a better estimation of resistances evolution during filtration and consequently a more accurate calculation of TMP.

Some authors consider that the SMP represent soluble EPS, and the SMP consist of proteins, polysaccharides, and some humic-like materials. But, other researchers think that the SMP is mainly composed of polysaccharides, some lipids, and certain amount of unsaturated compounds and nitrogen-containing substances (but not amides) [4, 12, 17, 26, 27]. On the other hand, the soluble EPS contains polysaccharides, lipids, and proteins. According to the unified theory proposed by Laspidou and Rittman [28], bound EPS are hydrolyzed to BAP, while active biomass undergoes endogenous decay to form residual dead cells. This theory proposed that the soluble EPS are identical to SMP in sludge liquor.

A recent work [26] compared the physicochemical characteristics of the SMP and soluble EPS from original and aerobically or anaerobically digested wastewater sludge. Analytical results revealed that the particles in SMP and soluble EPS fractions, extracted from original wastewater sludge, were not identical from the point of view of size, surface charge, and chemical compositions. But, even these results, the authors suggest that EPS could be considered are SMP in the microbial product fractions of sludge. Therefore, considering Laspidou and Rittman theory and Cho assumptions [7, 9, 25, 28], bound EPS in activated sludge floc is assumed to consist of both UAP and BAP. During evaluation of the empirical equation, the expression $S_{UAP}+S_{BAP}/0.8*X_{SST}$ is assumed to estimate the bound EPS amount in the activated sludge (expressed as mgEPS/gVSS). A summary of all this models is shown in table 3.

2.4- Sub-models connections

The links between the different sub-models are showed in Fig. 1. In general, the sub-models are interrelated through variables that are present in, at least, two sub-models. These variables play different roles in each part of the model. For example, in the biological part, a specific variable can take part of the biomass growth and participate in the degradation of the wastewater, while in the sub-model that characterizes the membrane fouling; the same variable could play an important role in the formation of the filtration cake. That is the case of X_{TSS}, which in the biological sub-model changes as function of the dynamics of the degradation process. This variable involves all the suspension solids inside the SMBR, including the biomass. At the same time, during the filtration process, a fraction of X_{TSS} passes to be a structural part of the sludge cake, acting on the actual rate of sludge accumulation in forming the dynamic and stable sludge films.

Another example is the coarse bubbles flow (Q_{CB}) that takes action on the intermittent aeration flow to the system. At the same time, this variable allows to estimate the aeration intensity, that help to remove, by means of the shear intensity, the temporary dynamic sludge film deposited on the membrane surface.

In the case of the S_{SMP}, these components are generated in the biological part of the system and participate in the dynamics relations that are established between the different processes of this level. Later, the S_{SMP} interacts with other structural components of the filtration cake and it will influence on the specific filtration resistance of the sludge cake layer, which is related directly with the increase of the membrane fouling. In both sub-models, the biological part and the membrane fouling estimation part, this variable will be present in the differential and semi-empiric equations that describe the different processes that take place in the SMBR.

2.5- Parameters values

The experimental determination of all the parameters values is an arduous and expensive task, for practical reasons for first estimations a set of coefficients and parameters based on previous reports and laboratory tests was used (Table 4). An accurate process of prediction by simulation is only possible after tuning the parameters to a certain plant, one of the goals of this work is to suggest a set of reasonable parameters values that permits to run the model and to present its features.

The values of the parameters related to the membrane characteristics were estimated from our laboratory results. The values previously published were mainly chosen from reports coming from comparable systems with municipal wastewater influent. From these sources, the methodologies that were used to estimate parameters values are different. Some stoichiometric coefficients were calculated by means of respirometric analysis and other were determined by non-linear regression, fitting the simulation results with data measured from lab-scale MBR. All this information is available in the cited papers presented in the Table 4.

However, in the case of the parameters highly linked to our system characteristics, e.g. K_La, or the empirical constants used to estimate the specific filtration resistances, we were careful at carrying out different experiments to obtain the most accurate values of the parameters used during the simulation.

The procedure to calculate the constants of the empirical equation was the same used by Cho et al [2, 3]: In our case, it was necessary to modify the range of TMP and the MLSS concentration, consequently the EPS concentration changed. Based on published dimensionless relationship, the empirical data were plotted and the non-linear regression was performed using the Chapman-4 parameters curve for describing the data plot. The bound EPS values were introduced as mgCOD/g(0.8XTSS) in order to adjust this equation to the units used in the integrated model. For this reason, the values of these empirical constants changed in comparison with the values presented by Cho et al [3]. Table 1 shows the experimental conditions used in the experiments:

Table.1- Experimental conditions used to evaluate the parameters of the semi-empirical equation.

	Exp-1	Exp-2	Exp-3
MLSS (g/L)	3,5,7,9,11	7	7
Bound EPS (mgCOD/gVSS)	210 ± 8	210 ± 8	Varied with time
TMP (kPa)	30	20,30,40,50,60	30

2.5.1- K_La estimation

For K_La estimation, the mixed liquor of the SMBR was aerated for 2.5 hours without influent flow in order to consume the remaining S_S in the reactor. Then, the aeration was stopped until the complete consumption of oxygen without influent flow. Later, the aeration was restarted without influent flow, and the dissolved oxygen was recorded until its saturation. The K_La value was obtained by curve fitting according to Eq. (3).

$$S_{O2}(t) = \left(S_{O2,Sat} - \frac{OCDB}{K_L a} \right)\left(1 - e^{-K_L a \cdot t}\right) + S_{O2,Ini} \cdot e^{-K_L a \cdot t} \qquad (3)$$

where, $S_{O2,Sat}$ is the saturation concentration for oxygen, $S_{O2,Ini}$ is the oxygen concentration at the beginning, t is time and OCDB is the oxygen consumption of decay of biomass.

2.6- Simulation conditions

A numerical simulation of the membrane fouling and activated sludge behavior was performed using a program in Berkeley Madonna programming language, run on a PC in the Windows XP environment. The activated sludge model simulation was performed solving simultaneously the set of differential equation obtained according Eq. (2). At the same time, membrane fouling development was simulated by numerical iterations, which produces the overall TMP increase and the evolution in the distributions 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 8.3.7.

Table.2- Peterson’s Matrix (Summary of stoichiometry and process kinetics).

Component, i Process, j	1 S_{02}	2 S_S	3 S_I	4^{UB} $S_{SMP} = S_{UAP}+S_{BAP}$ S_{UAP} S_{BAP}	5 X_I	6 X_S	7 X_H	8 X_{TSS}	Process Rate ρ_j
Hydrolysis									
1- Aerobic Hydrolysis		$1-f_{SI}$	f_{SI}	1		-1		$-i_{TSSXS}$	$K_h\left(\frac{S_{O2}}{K_{O2,h}+S_{O2}}\right)\left(\frac{X_S/X_H}{K_X+X_S/X_H}\right)X_H$
Heterotrophs									
2- Aerobic Growth on S_S	$1-\frac{1}{Y_H}$	$-\frac{1}{Y_H}$		$\gamma_{UAP,H}$			1	i_{TSSBM}	$\mu_H\left(\frac{S_{O2}}{K_{O2,H}+S_{O2}}\right)\left(\frac{S_S}{K_S+S_S}\right)X_H$
3- Aerobic Growth on S_{SMP}	$1-\frac{1}{Y_{SMP}}$			$\gamma_{UAP,H}-\frac{1}{Y_{SMP}}$			1	i_{TSSBM}	$\mu_{SMP}\left(\frac{S_{O2}}{K_{O2,H}+S_{O2}}\right)\left(\frac{S_{SMP}}{K_{SMP}+S_{SMP}}\right)X_H$
4- Lysis of X_H					f_{XI}	$1-f_{XI}$	-1	$f_{XI}\cdot i_{TSSXI}+(1-f_{XI})i_{TSSXS}-i_{TSSBM}$	$b_H X_H$
5- Lysis producing S_{SMP}			f_{BI}	$1-f_{BI}$			-1	$f_{XI}\cdot i_{TSSXI}+(1-f_{XI})i_{TSSXS}-i_{TSSBM}$	$b_{H,BAP}X_H$
6- Aeration	1								$K_{La}(S_{O2,sat}-S_{O2})$

Table.3- Summary of models used to describe intermittent processes and membrane fouling estimation.

Actual rate of sludge accumulation in forming the dynamic sludge film

$$\frac{dM_{sc}}{dt}=\frac{24X_{TSS}J^2}{24J+C_d d_p G}-\frac{\beta(1-K_{ST})GM_{dc}{}^2}{\gamma V_f+M_{dc}} \qquad (4)$$

Where: ,

$$G=\begin{cases}\left[0.1+0.45\left(1+\sin\frac{(2\varepsilon_i-\varepsilon_a)\pi}{2\varepsilon_a}\right)\right]\cdot\sqrt{\left(\frac{\rho_S g q_a}{\mu_W\left(1.05e^{(0.08X_{TSS})}\right)}\right)} & ;\varepsilon_\mathrm{i}<\varepsilon_\mathrm{a}\\ \sqrt{\left(\frac{\rho_S g q_a}{\mu_W\left(1.05e^{(0.08X_{TSS})}\right)}\right)} & ;\varepsilon_i\geq\varepsilon_a\end{cases}$$

$$\mathrm{q_a}=\left[\frac{Q_{CB}}{A}\right]$$

Sludge detachment rate due to intermittent aeration

$$\frac{dM_{dc}}{dt}=-\frac{\beta(1-K_{ST})GM^2{}_{dc}}{0.1\gamma V_f+M_{dc}} \qquad (5)$$

Development of total filtration resistance (for one section)

$$R_{TS_{(i)}}=R_m+R_p+R_{dc}+R_{sc} \qquad (6)$$

where : $R_m=\text{constant}$; $R_p=r_p\sum Jt_f$; $R_{sc}=r_{sc}M_{sc}$; $R_{dc}=r_{dc}M_{dc}$

$$r_{dc}=\frac{TMP^p}{\mu^2}\left(a+b\left(1-EXP\left(-c\left(\frac{S_{SMP}}{0.8X_{TSS}}\right)\right)\right)^d\right)\ ;\ r_{sc}=r_{dc}$$

Estimation of transmembrane pressure (considering all section)

$$TMP=\mu J_T R_T \quad \text{where:} \quad \frac{1}{R_T}=\sum_{i=1}^{n}\left(\frac{S_{(i)}}{R_{TS(i)}}\right) \qquad (7)$$

Intermittent filtration process

$$Q(t)=\begin{cases}0 & ;tf+m(tf+t_{id})<t<m(tf+t_{id})\\ Q & ;m(tf+t_{id})\leq t\leq tf+m(tf+t_{id})\end{cases} \qquad \forall\mathrm{m}:\mathrm{m}\in\mathbb{N} \qquad (8)$$

Intermittent aeration of coarse bubbles

$$Q_{CB}(t)=\begin{cases}0 & ;t_{CB}+m(t_{CB}+Int_{CB})<t<m(t_{CB}+Int_{CB})\\ Q_\mathrm{CB} & ;m(t_{CB}+Int_{CB})\leq t\leq t_{CB}+m(t_{CB}+Int_{CB})\end{cases} \qquad \forall\mathrm{m}:\mathrm{m}\in\mathbb{N} \qquad (9)$$

Table.4- Nomenclature, parameters and coefficients used in the model and simulations.

Symbol	Meaning and Unit	Value	Reference
Activated sludge			
f_{BI}	Fraction of soluble SMP generated in biomass (dimensionless)	0.005	[12]
fm	Permeating factor through membrane (dimensionless)	0.7	[29]
f_{SI}	Production of S_I in hydrolysis (dimensionless)	0.0	[9]
f_{XI}	Fraction of inert COD generated in biomass (dimensionless)	0.08	[16]
i_{TSSXI}	TSS to COD ratio for X_I (gTSS / gCOD)	0.75	[9]
i_{TSSBM}	TSS to COD ratio for biomass X_H (gTSS / gCOD)	1.24	[9]
i_{TSSXS}	TSS to COD ratio for X_S (gTSS / gCOD)	0.75	[9]
K_{La}	Overall oxygen transfer rate (day^{-1})	120	This work
K_h	Hydrolysis coefficient (day^{-1})	3.0	[16]
$K_{O2,H}$	Half-saturation coefficient for heterotrophic biomass (gO_2 / m^3)	0.2	[16]
K_S	Substrate half-saturation coefficient for heterotrophic (gCOD / m^3)	20.0	[16]
K_{SMP}	SMP half-saturation coefficient for heterotrophic biomass (gCOD / m^3)	30	[16]
K_X	Saturation/inhibition coefficient for particulate COD (dimensionless)	0.03	[16]
$S_{02,sat}$	Saturated oxygen concentration (gO_2 / m^3)	10	This work
Y_H	Heterotrophic yield coefficient for S_S (gCOD / gCOD)	0.67	[16]
Y_{SMP}	Heterotrophic yield coefficient for S_{SMP} (gCOD / gCOD)	0.50	[12]
$b_{H, BAP}$	Heterotrophic decay coefficient for formation of BAP (day^{-1})	0.22	[12]
b_H	Heterotrophic decay coefficient for formation of particulate (day^{-1})	0.4	[12]
μ_H	Maximum specific growth rate of substrate for Heterotrophs (day^{-1})	6.0	[16]
μ_{SMP}	Maximum specific growth rate of SMP for Heterotrophs (day^{-1})	0.7	[12]
$\gamma_{UAP:H}$	UAP formation constant of Heterotrophs (dimensionless)	0.38	[12]
Intermittent processes and membrane fouling			
Am	Unit floor area of the membrane(m^2)	0.0013	This work
a	Empirical constant	1156.2	This work
b	Empirical constant	1.36×10^4	This work
c	Empirical constant	172.4	This work
d	Empirical constant	150.9	This work
Cd	Coefficient of the drag and lifting force (dimensionless)	0.04	This work
dp	Particle size (m)	100 μm	This work
G	Apparent shear intensity of the fluid turbulence (s^{-1})		
Int_{CB}	Time interval between two coarse bubbles injection (s)		
J	Local filtration flux through the ith membrane section ($m^3/(m^2$ day))		
J_T	Overall flux ($m^3/(m^2$ day))	0.24	This work
K_{ST}	Stickiness of the biomass particles (dimensionless)	0.67	This work
Mdc	Mass of the sludge in the dynamic sludge film (kg/m^2)		
Msc	Mass of the sludge in the stable sludge cake attached to the membrane (kg/m^2)		
n	Total number of the sections of the membrane surface area	128	
qa	Aeration intensity (L/(m^2 s))		
Q	Filtration Flow (L/s)		
Q_{CB}	Coarse Bubbles Flow (L/s)		
Rdc	Resistance of the dynamic sludge film (m^{-1})		
Rm	Intrinsic resistance of the membrane (m^{-1})	1.2×10^{12}	This work
Rp	Pore fouling resistance (m^{-1})		
Rsc	Resistance of the stable sludge cake layer (m^{-1})		
rp	Specific pore fouling resistance in terms of the filtrate volume (m^{-2})	3.0×10^{11}	This work
rsc	Specific filtration resistance of the sludge cake layer (m/kg)		
rdc	Specific filtration resistance of the dynamic sludge film (m/kg)		
R_T	Overall filtration resistance (m^{-1})		
$R_{TS(i)}$	Filtration resistance for the ith membrane section (m^{-1})		
t_{CB}	Coarse bubbles injection time (s)		
tf	Filtration time (s)		
tid	Idle time (s)		
TMP	Trans-membrane pressure (Pa)		
Vf	Water production within a filtration period of an operation cycle (m^3/m^2)		
β	Erosion rate coefficient of the dynamic sludge film (dimensionless)	3.5×10^{-4}	[10]
ε_a	Fraction of the membrane surface area with a reduced shear intensity	2/3	[10]
ε_i	Accumulated membrane area fractions to the ith section		
γ	Compression coefficient for the dynamic sludge film (kg/(m^3 s))	2.5×10^{-5}	[10]
μ	Viscosity of the permeate (Pa s)	1.0×10^{-3}	This work
μs	Viscosity of the sludge suspension (Pa s)		
μw	Viscosity of water (Pa s)	1.0×10^{-3}	This work
ρs	Density of the sludge suspension (kg/m^3)	1.0×10^3	This work

3- EXPERIMENTAL PART

3.1- Experimental set-up

The experimental study was performed using a SMBR. A U-shaped, hollow-fiber membrane module with area of 0.3 m^2 (provided by POLYMEM, Toulouse, France), was immersed in a bioreactor of 10.5 L of working volume. Hollow fibers were made of polysulfone with a pore size of 0.1μm, 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). Two sensors, a PT 100 (-50 to 250 °C) and a Mettler Toledo pH meter, were utilized in order to measure the mixed liquor temperature and pH respectively. The pH was maintained between 6.5 and 7.5 by adding a Na_2SO_4 solution (10 g/L). PC-based real time data acquisition hardware (IOTECK) and the software DASYLAB have been used for acquiring and analyzing all data.

3.2- Operating conditions

The bioreactor was operated with two types of aeration flows. An intermittent coarse bubbles flow injected closed to the fibers, 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.

During the experiments, the overall flux was modified changing the volume of filtration acting on the speed of the suction pump, and the solids retention time was controlled by means of the sludge purge. The operation was stopped when the TMP reached 50 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. Various operating conditions (idle-filtration time, aeration intensity, SRT, HRT, coarse bubbles injection cycles, and MLSS concentration) were tested.

3.3- Analytical methods

Analysis of the influent, sludge, supernatant, and permeate were conducted, using the following procedures:

3.3.1- Solids concentration and particle size distribution

The MLSS concentration was determined by centrifugation at 5000 rpm for 10 min and drying at 105°C using a PRECISA HA60 moisture analyzer. The COD was measured by micro method COD 420, Odyssey, Hach. The activated sludge flocs size distribution was estimated with a laser granulometer (Mastersizer 2000, Malvern Instruments). Due to the utilization of membrane, no biomass was wasted from the effluent, and SRT was controlled directly by wastage of mixed liquor from the reactor.

3.3.2- EPS concentration

EPS quantification 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 standard [30]. For quantitative analysis of carbohydrates, the modification of the anthrone method described by Raunkjaer *et al* [31] was used with glucose as standard.

3.3.3- Influent composition

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 OUR curve to be distinguished. Dissolved oxygen was measured in the reactor by means of an oxygen meter (YSI-51). The parameters such as Dissolved Oxygen (DO) concentration and temperature were monitored continuously throughout the experiments. The respiration rate can be directly deduced by measuring the decrease in DO:

$$\frac{dO_2}{dt} = -OUR \tag{10}$$

where: O_2 = Dissolved Oxygen Concentration, OUR = Oxygen Uptake Rate, t = time.
The readily biodegradable substrates (S_S) and the slowly biodegradable substrates (X_S) were estimated by means of the equations following the published procedure [32].

$$S_S = \frac{1}{1-Y_H}\int_0^{t_1} OUR\, dt\, \frac{V_{MW} + V_B}{V_{MW}} \tag{11}$$

$$X_S = \frac{1}{1-Y_H}\int_0^{t_2} OUR\, dt\, \frac{V_{MW} + V_B}{V_{MW}} \tag{12}$$

where: V_{MW} = volume of wastewater, V_B= volume of biomass, t_l= duration time of fast respirometric response, t_2= final time of respirometric test, Y_H= Heterotrophic yield coefficient.
The results of measured parameters for influent wastewater are X_{SST}^0= 15-65 mg/L, S_S^0= 95-300 mgCOD/L, X_S^0= 80-190 mgCOD/L, X_I^0= 24-70 mgCOD/L, S_I^0= 20-58 mgCOD/L, S_{SMP}^0= 20-100 mgCOD/L.

3.3.4- Dead-end filtration tests

Dead-end filtration tests were performed to investigate the contribution of various components of the sludge for membrane fouling. The filterability of activated sludge is an important indicator for the fouling of SMBR, and thus 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 cm^2 and pore size 0.2 μm). Considering the filtration resistance as a deposit, the specific resistance was calculated characterizing the cake fouling ability. For a given pressure ΔP, the specific resistance,α, was calculated using Eq. (13) of dead-end filtration law [33].

$$\frac{t}{V}=\left(\frac{\mu\alpha C}{2TMP\Omega^2}\right)V+\frac{\mu R_m}{TMP\Omega} \tag{13}$$

Where μ is the viscosity of the sludge (Pa.s), C is the biomass concentration (kg/m^3), Ω is the membrane surface (m^2), V is the volume filtrated (m^3), TMP is transmembrane pressure (Pa); Rm is the membrane initial resistance (m^{-1}) and t is the time (s).

4- RESULTS AND DISCUSSION

4.1- Comparison of simulation results with measured data

The comparison between the measured data and simulation results are shown in Figs. 3 - 5. It can be seen that simulation results are in good agreement with the experimental data. During experimentation, several variables were tested in order to study the model ability to predict different operating conditions. The union of the biological modified model with the equations used to estimate the cake formation, allowed to study the influence of the biomass concentration evolution on the membrane fouling process, as well as the effect of this biomass increase on the other components present in the system. It can be observed that, even if different biomass concentrations and influent conditions were used, the model was able to predict suitably the measured values. However, it is necessary to consider some aspects and limitations.

All the evaluated aeration-filtration cycles were settled to values that allowed a fast increase of the TMP in a short time. In most of the cases the coarse bubbles were injected during the filtration cycles. In this case, the aeration intensity is less effective because of the opposed effect of the suction force due to permeation through the membrane. In all cases an underestimation of the real values of the TMP was obtained during the simulation. This might be due to several reasons. The first one, the SMBR was fed with municipal wastewater, which presents the disadvantage of a high variability in the characteristics of the feeding and the introduction of biological solids into the system. During calculations averages concentrations of the influent and the sludge, measured during the experimentation were used, this can be the origin of errors in the simulation.

On the other hand, the relationship between the shear intensity (G) and the aeration intensity (qa) given in Eq. (4) was obtained on laminar flow regime because of lack of information in turbulent regime. During the intermittent aeration the strong aeration produces a turbulent environment, so using these equations there should be a certain degree of errors in the simulation during calculation of the shear intensity from the aeration rate. Consequently, the actual turbulent shear intensity for a strong aeration flow should be lower than the one determined from Eq. (4) [10].

The sludge cake behaves like a compressible cake; it is logical to think that during the filtration cycles the cake properties varies over time. The porosity of the stable cake will reduce, increasing therefore the resistance to the filtration. This variation of porosity is not considered by the model, where the dynamic and stable layers have the same specific filtration resistance, which can be consider as an approach.

It is very important to know that, the empirical equation used to estimate the specific filtration resistances (r_{dc}, r_{sc}), that takes into account the functional relations existing between the X_{SST}, the SPE, and the TMP; it is not an universal equation for all SMBR systems. For this reason it is necessary to recalibrate the equation parameters, when the operating conditions are very different to those of the system where this equation was obtained. For a less rigorous calculation, this equation can be suppressed and it is possible to simulate with average values of specific filtration resistance. This allows calculating the trend of TMP under different operational conditions, mainly considering the dynamic effect of X_{SST} and coarse bubbles aeration.

Figure 3 shows two examples of the variability of the cake specific resistance. These values were measured at different times with dissimilar operating conditions following the procedure explained in 3.3.4. In these cases, the specific resistance values were found in a range of 1.0×10^{12}-3.5×10^{13} m/kg, but during experimentation higher values in the order of 1×10^{15} m/kg were found, mainly at low mixed liquor temperature (8-13 °C), or during the filtration of sludge with high SPE concentration (700-1000 mg/L) and sludge floc size lower than 70 mμ. This combination of sludge temperature-SPE concentration-floc size seems to have a very significant influence on the specific resistance values.

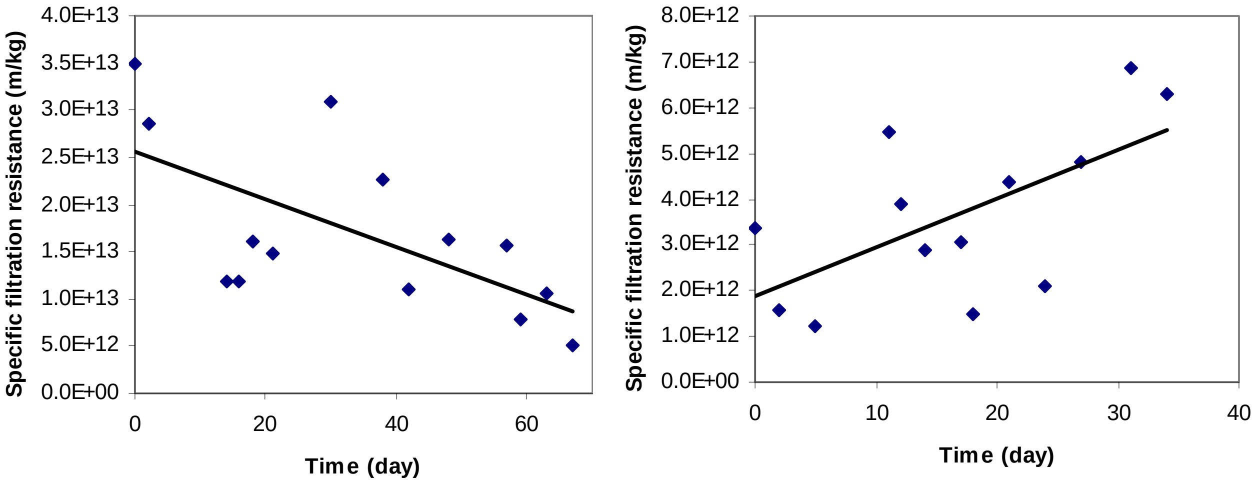

Fig. 3- Characterization of the cake fouling ability by means of the dead-end filtration, specific resistances values measured at different operation periods of the SMBR.

The operating mode of our SMBR allows a temporary sludge accumulation on the membrane, which elimination is later carried out by means of the strong aeration intensity. The values of aeration intensity are quite high, but the coarse bubbles are injected in short intermittent time intervals. It diminishes the aeration cost and minimizes the negative effects of the strong aeration on the flocs size and the sludge rheology [34]. The model allows, once the parameters have been calibrated to each specific system, to make the optimization of the synchronization between the aeration cycles and the filtration-idle cycles.

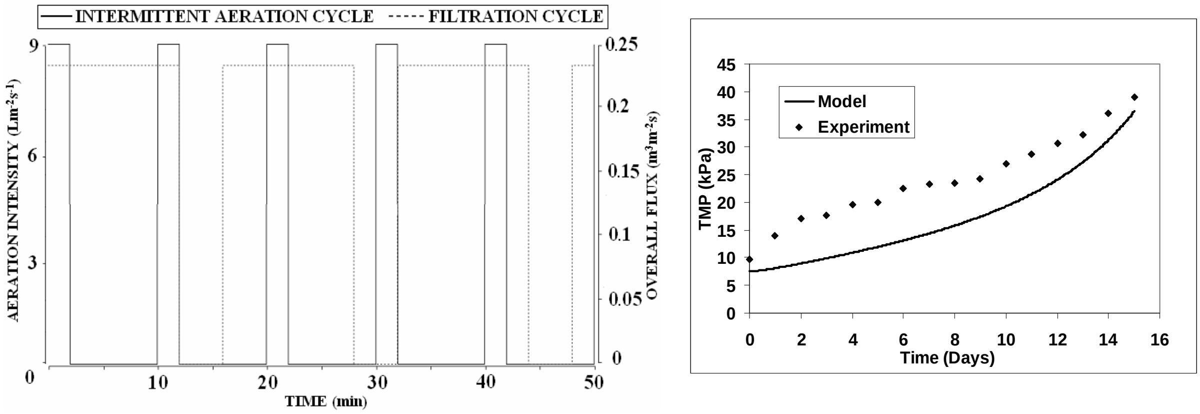

Fig. 4- Experiment A (superscript 0 expresses in influent): qa= 9 L/(m^{2}s), tf= 12 min, tid= 4 min, Int$_{CB}$= 8 min, t$_{CB}$= 2min, X_{SST}^0= 65 mg/L, X_{SST}= 6500-9500 mg/L, S_S^0= 230 mgCOD/L, X_S^0= 100 mgCOD/L, X_I^0= 28 mgCOD/L, S_I^0= 38 mgCOD/L, S_{SMP}^0= 50 mgCOD/L, SRT= 50 days.

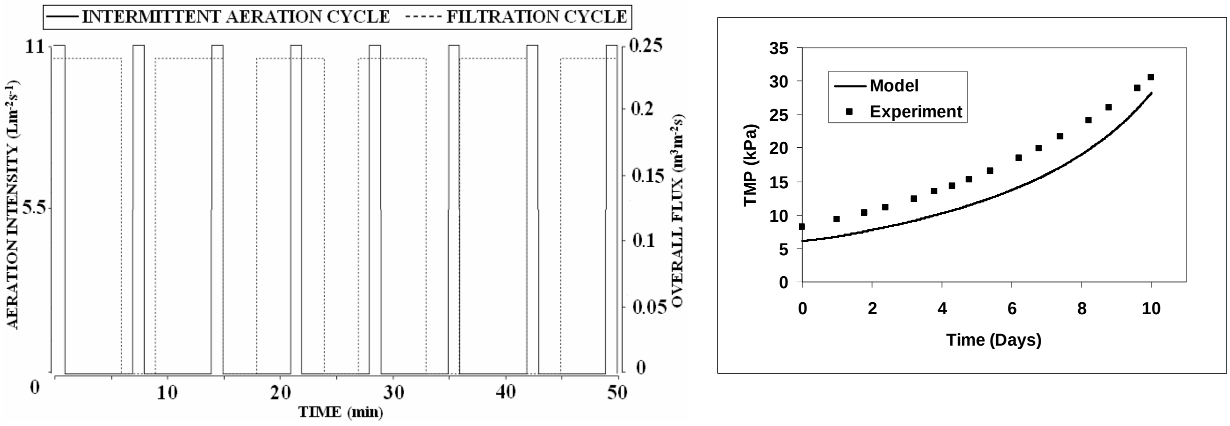

Fig. 5- Experiment B (superscript 0 expresses in influent): qa= 11 L/(m^2s), tf= 6 min, tid= 3 min, Int_{CB}= 6 min, t_{CB}= 1min, $X_{SST}{}^0$= 40 mg/L, X_{SST}= 4000-4600 mg/L, $S_S{}^0$= 110 mgCOD/L, $X_S{}^0$= 90 mgCOD/L, $X_I{}^0$= 28 mgCOD/L, $S_I{}^0$= 25 mgCOD/L, $S_{SMP}{}^0$= 23 mgCOD/L, SRT= 40 days.

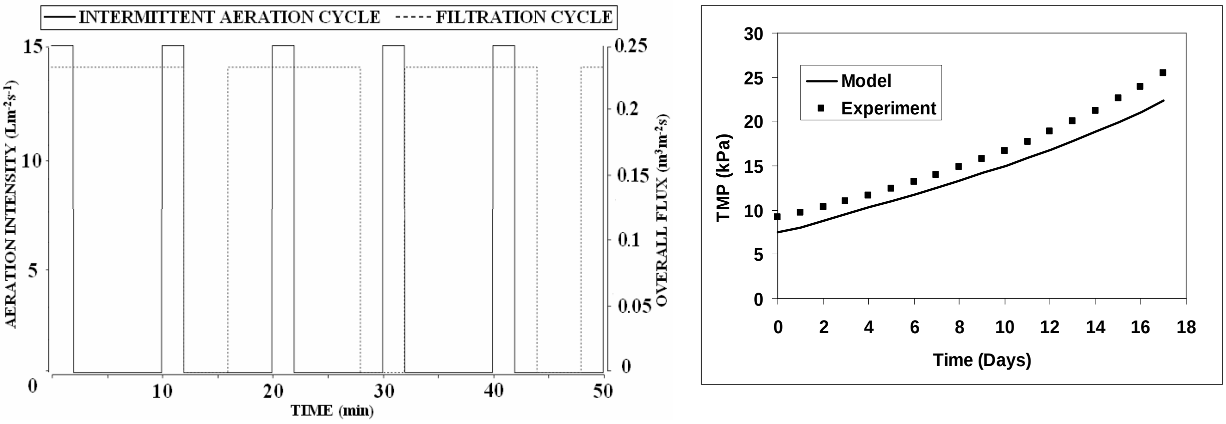

Fig. 6- Experiment C (superscript 0 expresses in influent): qa= 15 L/(m^2s), tf= 12 min, tid= 4 min, Int_{CB}= 8 min, t_{CB}= 2min, $X_{SST}{}^0$= 62 mg/L, X_{SST}= 6500-9300 mg/L, $S_S{}^0$= 130 mgCOD/L, $S_{SMP}{}^0$= 40 mgCOD/L, $X_S{}^0$= 80 mgCOD/L, $X_I{}^0$= 24 mgCOD/L, $S_I{}^0$= 22 mgCOD/L, SRT= 50 days.

4.2- Limitations of the model.

During the development of this work some criteria to which the integral model should respond were kept in mind. First, the model should be able to describe the influence of the operating and biological variables on the SMBR. The model has to achieve an acceptable grade of interrelation among a large quantity of system variables. The simulation with the model should offer quantitative and qualitative results in order to help, to the design of the SBMR systems like to the understanding of the process. However, it is necessary to point out the main model limitations:

In its current forms the model simulates the constant flux filtration processes. Thus, the TMP evolution can be predicted, but the change of flux at constant pressure cannot be calculated.

For practical reasons, some parameters were taken from previous studies of similar systems, or studies made in systems with activated sludge. These parameters were estimated at certain steady state and considered constant. Therefore, the more sensible bio-kinetic parameters must be recalibrated if the influent conditions and the organic loading rate change considerably.

The simulation using the empirical equation for the estimation of rdc and rsc should be restricted to the used range of TMP and MLSS during empirical parameters estimation (Table 1). Otherwise, it is advisable to simulate with average values of specific resistance measured by dead-end filtration. The parameters related to the membrane characteristics (Am, Rm, ε_a) were estimated for the membrane of our SMBR, these values need to be recalculated with the membrane change.

4.3- Influence of the SMBR process variables on the membrane fouling development

The simulation model was applied in order to evaluate, not in an exhaustive way, the influence of the main process parameters on the fouling development of an SMBR (Fig. 7-8). The simulation results are consistent with our system observations and those from other researches. It shows that, a high filtration flux and lower aeration intensity worsen the fouling problem significantly (Fig. 7A, 8D). This is consistent with the results of Germain *et al.* and Ueda *et al.* [35, 36], who demonstrated that an increase in the permeate flux and a reduction in the aeration rate would cause severe membrane fouling. The cake-removing efficiency could be improved by increasing the aeration intensity.

For a given SRT an increase in flux produces an increase in the X_{SST} concentration for several reasons (Fig. 7A, 7A'). The increase of the filtrate volume induces a similar increment of the influent flow, which produces a modification of the F/M ratio and, consequently, the biomass growth is favoured. Additionally, the cumulative effect on the system of the biomass added by the influent is more important for high flux values. Thus, the substrate-loading rate ratio is a significant factor on fouling process evolution and for the process control.

The figure 7A'' show the bound EPS concentration per unit biomass. At high flux values the increase of the biomass concentration is more important that the EPS augmentation, even when the EPS formation is favored with the flux, its formation rate is lower than the growth and accumulation rate of the biomass and, for these reasons, the ratio bound EPS/ biomass decreases.

It was demonstrated experimentally and estimated by simulation (Fig. 7A) that the filtration flux, for the evaluated conditions, is the most important factor that regulates the TMP increase. In the simulations, a high EPS concentration is related with the low fouling because the high EPS concentration per unit of biomass corresponds to the low values of filtration flux. So, even when the EPS concentration per unit of biomass is elevated the poor value of the flux do not permit a more important fouling rate. It is directly related to the biomass concentration increase and to the influence of the filtration cake on fouling process, which is highly linked with the biomass concentration in the SMBR.

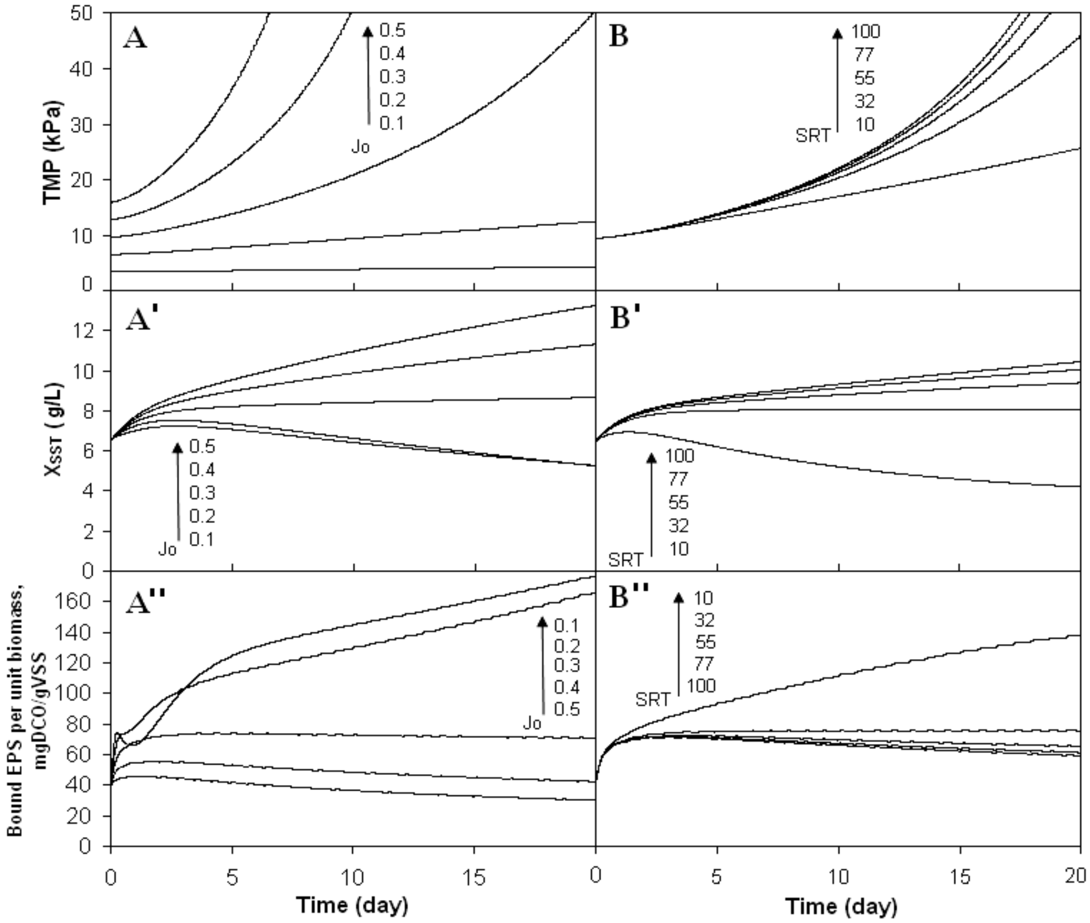

Fig. 7- Simulation Results (superscript 0, R0 expresses in “influent”, “initial value in the bioreactor” respectively). Effects of the process variables (J_0, SRT) on the TMP increase X_{SST} and bound EPS evolution in the SMBR. [A, A’, A”: qa= 6 L/(m^2s), tf= 14 min, tid= 3 min, Int_{CB}= 8 min, t_{CB}= 1min, $X_{SST}{}^{0}$= 35 mg/L, $X_{SST}{}^{R0}$= 6500 mg/L, $S_S{}^{0}$= 230 mgCOD/L, $X_S{}^{0}$= 100 mgCOD/L, $X_I{}^{0}$= 32 mgCOD/L, $S_I{}^{0}$= 38 mgCOD/L, $S_{SMP}{}^{0}$= 45 mgCOD/L, SRT= 40 days], [B, B’, B”: qa= 6 L/(m^2s), tf= 14 min, tid= 3 min, Int_{CB}= 8 min, t_{CB}= 1min, $X_{SST}{}^{0}$= 35 mg/L, $X_{SST}{}^{R0}$= 6500 mg/L, $S_S{}^{0}$= 230 mgCOD/L, $X_S{}^{0}$= 100 mgCOD/L, $X_I{}^{0}$= 32 mgCOD/L, $S_I{}^{0}$= 38 mgCOD/L, $S_{SMP}{}^{0}$= 45 mgCOD/L, J_0=0.3 m^3/(m^2 day)]

As it can see from Fig. 7B'', at the same flux value the highest value of the specific bound-EPS is related to the shortest SRT. This behaviour has been observed previously [4, 12, 37, 38]. Also, the specific bound-EPS content decreases at longer SRT. This reduction of bound-EPS might be due to a low formation rate of microbial substances or due an increase of EPS degradation as substrate by microorganisms at a low F/M condition. It is important to note that, at high level of biomass population, substrate in influent is quickly consumed and then, microorganisms may utilize the EPS bounded in the floc as well as released from a cell lysis for their metabolism. However, when SRT is over 55 days the effects on bound-EPS degradation have not significant variation. At higher SRT, not only active biomass, but particulate inert organic matters were also remained in the reactor simultaneously with some inhibiting substances. Thus, the active biomass increased slowly (Fig 7B') and the F/M ratio changes slightly [12, 39]. As a result, the effect of SRT on the fouling process will be less important at high SRT values over 55 days (Fig. 7B).

Before simulation, an adequate estimation of the Kst value is needed. On previous investigations [40, 41] the microbial cells of the MBR biomass are assumed to have an average stickiness around Kst= 0.5 for most simulation scenarios. The stickiness between the sludge and the membrane surface is considered much lower than the stickiness between the cells [10]. The Kst coefficient describes indirectly various physicochemical properties of the sludge that allows him to stick on the membrane surface, this coefficient has a significant influence on the calculation of membrane fouling. In the real system the Kst value varies logically during the filtration process, but it is considered constant during the simulation process. Therefore, an incorrect estimation of this parameter might affect the rate of sludge adhesion on the membrane surface, the effect of the aeration intensity and, consequently, the actual filtration resistances values (Fig. 8C). This parameter is related to the microbial diversity inside the SBMR, because different populations have different stickiness [42, 43], and it is also function of the concentration and composition of EPS. In consequence, to develop techniques and operational conditions focused to grow a less sticky sludge could be interesting to minimize the fouling process.

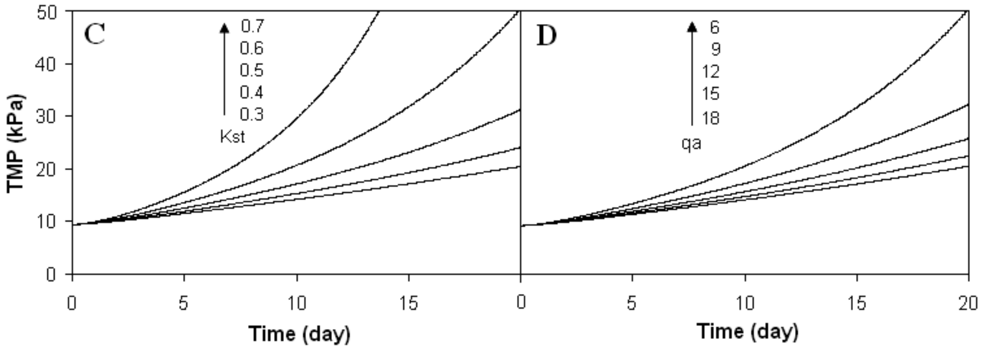

Fig. 8- Simulation results (superscript 0 and R expresses in influent and bioreactor respectively): Effects of the process variables (Kst, qa) on the TMP increase in the SMBR. [C: qa= 6 L/(m^{2}s), tf= 14 min, tid= 3 min, Int$_{CB}$= 8 min, t_{CB}= 1min, X_{SST}^{0}= 35 mg/L, X_{SST}^{R}= 6500 mg/L, S_S^{0}= 230 mgCOD/L, X_S^{0}= 100 mgCOD/L, X_I^{0}= 32 mgCOD/L, S_I^{0}= 38 mgCOD/L, S_{SMP}^{0}= 45 mgCOD/L, SRT= 40 days J_0=0.3 m^3/(m^2 day)], [D: Kst= 0.6, tf= 14 min, tid= 3 min, Int$_{CB}$= 8 min, t_{CB}= 1min, X_{SST}^{0}= 35 mg/L, X_{SST}^{R}= 6500 mg/L, S_S^{0}= 230 mgCOD/L, X_S^{0}= 100 mgCOD/L, X_I^{0}= 32 mgCOD/L, S_I^{0}= 38 mgCOD/L, S_{SMP}^{0}= 45 mgCOD/L, SRT= 40 days, J_0=0.3 m^3/(m^2 day)]

The effect of the aeration intensity was observed during experimentation and simulation (Fig. 8D). Furthermore, a higher flux indirectly reduces the effectiveness of the aeration turbulence in removing the sludge from the dynamic sludge layer.

An elevated aeration rate reduces the probability of sludge attaching to the membrane surface during filtration, and enhances the removal of the dynamic sludge layer during the idle-cleaning phase. In general, the fouling problem does not appear to be avoidable for SMBRs. However, sludge cake deposition on the membrane can be minimized by decreasing the filtration flux and increasing the aeration rate and for a lower sludge concentration [10]. But, sometimes it has a negative economic impact on wastewater treatment cost. Hence to choose the best combination between aeration and flux it seems to be an important key for the process.

During the simulations, it is possible to predict quantitatively the fouling rate through the TMP increase and quantifying the increase of the filtration resistances, the effect of different synchronisation cycles of filtration-idle time period and aeration on fouling evolution, and ,also, it is possible to estimate the development of the sludge cake coverage and thickness on the membrane surface (Fig. 9). It can be observed the non homogeneous distribution of the sludge on the filtration cake, due to the uneven distribution of the shear intensity along the membrane surface. In this figure 9 the only different parameter is idle time, 2 minutes in case

E, 6 minutes in case F. The example shows how the model can help to predict the behavior of the total system and o appreciate the impact of this parameter change.

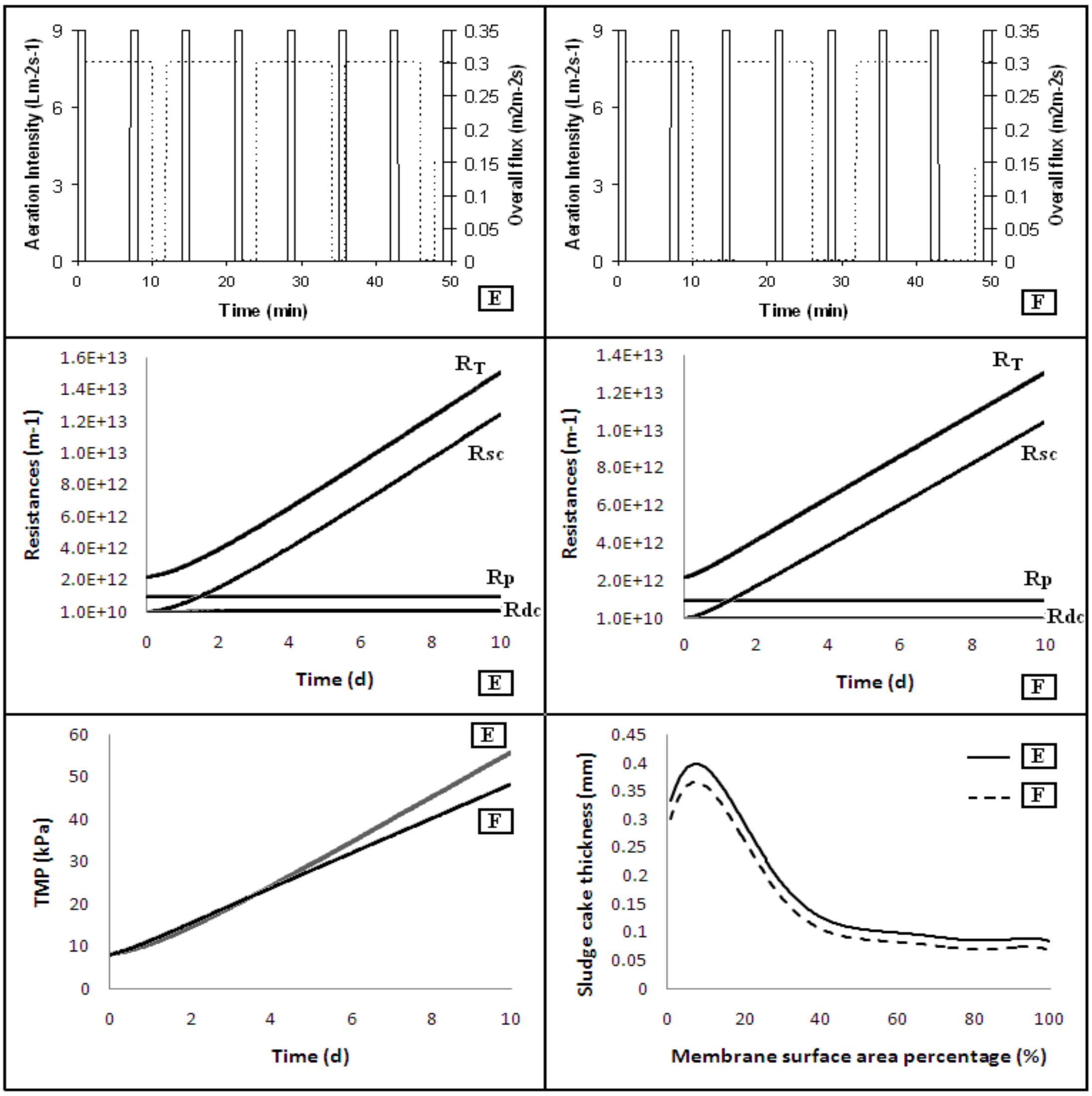

Fig. 9- Simulation results, effects of the synchronisation (filtration-idle time-coarse bubble injection) on filtration resistance evolution.

[E: qa= 9 L/(m^{2}s), tf= 10 min, tid= 2 min, Int_{CB}= 6 min, t_{CB}= 1min, X_{SST}^{R}= 8000 mg/L, SRT= 40 days, J_0=0.3 m^3/(m^2 day), rsc= rdc= 3.0×10^{13} (m/kg)],[F: qa= 9 L/(m^{2}s), tf= 10 min, tid= 6 min, Int_{CB}= 6 min, t_{CB}= 1min, X_{SST}^{R}= 8000 mg/L, SRT= 40 days, J_0=0.3 m^3/(m^2 day), rsc= rdc= 3.0×10^{13} (m/kg)]

In the SBMR design process, the allocation of the membranes modules, as well as the distribution of the air-sparker are very important aspects that influence on the bubbles flow patterns, and on the effective aeration intensity. The possibility to predict quantitatively the impact of the aeration intensity on the membrane fouling process helps to the taking of decisions during the technological and geometric design of SMBR. On the other hand, the model could be used for the multifactor optimization of SMBR system, acting on the variables that have a direct impact on the operation costs, frequently high for the SMBR systems.

Finally, the use of this model provided a rational and fundamental framework for designing experiments, interpreting results, and estimating overall process performance. The change of boundary condition such as influent quality, MLSS, HRT, SRT, EPS, the synchronization (filtration-idle time) and aeration intensity can be reflected on predicting the membrane fouling process.

5- CONCLUSIONS

A mathematical model has been successfully developed to simulate the filtration process and the aeration influence on Submerged Membrane Bioreactor in aerobic operational conditions. The biological process kinetics and the dynamics of the sludge attachment and detachment from the membrane, in relation to the filtration and strong intermittent coarse bubbles aeration, were included in the model. The model was established considering SMP formation-degradation and the existent relation between SMP and EPS, following the unified theory of Laspidou and Rittman.

The fouling components of pore clogging, sludge cake growth, and temporal sludge film coverage are considered during calculation of the total membrane fouling resistance. The influence of EPS, trans-membrane pressure, and MLSS on specific filtration resistance of the sludge cake was also included. With this model, membrane fouling under different SMBR operational conditions can be simulated. The influence of a very important number of process variables on fouling development can be well quantified. The model was developed for evaluating the effect on fouling control of an intermittent aeration of coarse bubbles synchronized with the filtration cycles, taking into account the effects of shear intensity on sludge cake removal.

The experiments were carried out considering several operational conditions, variation on the sludge concentrations, on the solids retention time, on the filtration and idle times, on aeration intensities and injection times of the coarse bubbles, relative variation of the influent characteristics and composition, and even using these dissimilar conditions the results of the numerical simulations fit well the experimental data from studied SMBR.

The new model provide an important tool for study the SMBR membrane fouling problem, but also offers the possibility to improve the design configuration and operation strategies of

SMBRs in wastewater treatment, and it allows the optimization of aeration-filtration cycles. However, for better results a special attention is needed during parameters model calibration. More precise equations for the calculation of the actual shear intensity and the estimation of the evolution of the sludge specific resistance are required. Also, to model aspects how the effect of the cake porosity evolution might be interesting in futures works.

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