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Dynamical Modelling and Simulation of Wastewater Filtration Process by Submerged Membrane Bioreactors

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Dynamical Modelling and Simulation of Wastewater Filtration Process by Submerged Membrane Bioreactors*

Alain Zarragoitia, Sylvie Schetrite, Ulises J. Jauregui-Haza, and Claire Albasi

Abstract

A mathematical model was developed for the filtration process and the influence of aeration on Submerged Membrane Bioreactors. The dynamics of sludge attachment to and detachment from the membrane, in relation to the filtration and a strong intermittent aeration, were included in the model. The influence on the membrane fouling of intermittent aeration injected on the membrane surface, and its synchronization with intermittent filtration, were studied numerically and experimentally. For the evaluation of filtration cake development, the assumption of the presence of two cake layers (one dynamic and the other stable) was considered. The model development and simulation focused on the description of existing relationships among important system variables like mixed liquor suspended solids concentration, aeration, temperature of the sludge suspension, transmembrane pressure, and the fouling increase during the filtration process. The model obtained offers the possibility of improving the design configuration and operation strategies of Submerged Membrane Bioreactors in wastewater treatment, and it allows the of aeration-filtration cycles to be optimized.

KEYWORDS: wastewater treatment, filtration, submerged membrane bioreactor, modelling

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1- Introduction

The Submerged Membrane Bioreactor (SMBR) is an emerging type of biological treatment technology that is increasingly applied for municipal wastewater treatment. It offers a number of advantages over the conventional activated sludge process, such as excellent effluent quality, compact footprint, more concentrated biomass, and reduced sludge yield. Nevertheless, the filtration process is disturbed by the influence of complex factors that cause membrane fouling. This is still a major problem that hinders their more widespread and large-scale application (Judd, 2004). From the point of view of running costs, fouling is even more expensive, as the power requirement comes mainly from aeration. In hollow-fiber SMBRs, the aeration is used: 1- to supply the oxygen needed for degradation processes, 2- to clean the membrane while maintaining solids in suspension. Turbulent shear and the agitation of fibers are brought about by coarse bubbles that attenuate the accumulation of sludge cake on the membrane during filtration. Membrane fouling is strongly linked to 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 product concentrations, temperature of sludge suspension, and aeration intensity (Cho, 2002, Cho, 2005; Judd, 2004; Shin, 2003).

Mathematical modeling and simulation are powerful tools that allow specialists to predict system performance under different operating conditions. Formulating better dynamic models for the SMBR systems could help to develop more cost-effective strategies for minimizing the fouling problem. The aeration process forms an important part of the model and the simulation process enables the filtration-aeration cycles to be optimized and, consequently, the running cost due to aeration to be reduced. Interactions are very numerous and predicting fouling in SMBR systems is very complicated. For these reasons, a complete general mathematical model for SMBR has not yet been established (Aileen, 2007).

Many researchers have proposed dynamic models based on various concepts and hypotheses. A recent model, proposed by Li and Wang (Li, 2006), is a comprehensive mathematical model for membrane fouling in an SMBR. A sectional approach is 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 to 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 is decomposed into the individual components of pore fouling resistance, sludge cake accumulation, and dynamic sludge film formation. In its present form, this model is only able to describe general trends and it is not suitable for applications requiring accurate modeling of membrane fouling phenomena (Aileen, 2007). In addition, during the calculation of the TMP increase, the influence of the temperature on the filtrate and the sludge suspension rheology is not considered. This aspect plays an important role in the fouling problem. However, despite the model's limitations, it is a significant approach that provides a valuable tool for improving the design configuration and operation strategies of SMBRs in wastewater treatment. Therefore, some of its components were used as a foundation for the present work.

The aim of this work is to develop a dynamic model in order to simulate and optimize the filtration process in SMBRs, taking into consideration 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. The model development and simulation focused on the description of existing relationships among main variables like Total Suspended Solids (TSS) concentration, aeration, TMP, temperature and the fouling increase during the filtration process.

2- Experimental part

2.1- Experimental set-up

The experimental study was performed using an 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 0.1 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 at an influent flow rate 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 also used. The pH was maintained between 6.5 and 7.5 by adding Na_2SO_4 solution (10 g/L). PC-based real time data acquisition hardware (IOTECK) and the software DASYLAB were used for acquiring all data.

2.2- Operating conditions

The bioreactor was operated with two types of aeration flows: an intermittent coarse bubble flow injected close to the fibers, providing tangential liquid movement to avoid membrane fouling by reducing cake formation (reversible fouling), and a constant fine bubble flow injected through a perforated membrane at the bottom of the reactor, providing mixing and biomass oxygenation. The membrane module was isolated from contact with the fine bubbles; thus, membrane fiber movement was only produced by the flow of coarse bubbles.

The operation was stopped when the TMP reached 60 kPa under atmospheric pressure. Then, chemical cleaning was applied using 2 M chlorine solutions for 2 h, and 0.1 M NaOH for 24 h. Various operating conditions (idle-filtration time, aeration intensity, Solid Retention Time (SRT), Hydraulic Retention Time (HRT), coarse bubble injection cycles, and TSS concentration were tested.

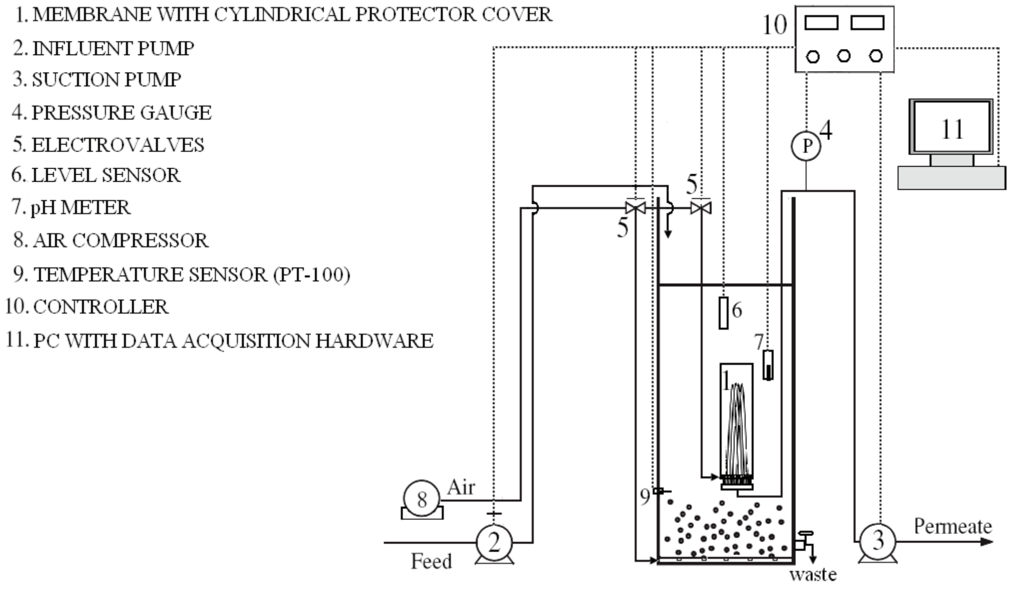

Figure 1. Schematic diagram of the submerged membrane bioreactor used in this study.

2.3- Analytical methods

2.3.1- TSS *concentration and particle size distribution*

The 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 floc size distribution was estimated with a laser granulometer (Mastersizer 2000, Malvern Instruments).

2.3.2- Dead-end filtration tests

Dead-end filtration tests were performed to estimate the specific filtration resistances (α=rsc=rdc). The filtration index measurements were performed in a special cell. The experimental filtration device was a Sartorius filtration pressurized 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 for the characterization of the cake fouling ability. For a given pressure ΔP, the specific filtration resistance of the sludge was calculated using Eq. (1) (dead-end filtration law) (Ognier, 2002).

$$\frac{t}{V}=\left(\frac{\mu\alpha C}{2TMP\Omega^{2}}\right)V+\frac{\mu R_{m}}{TMP\Omega} \tag{1}$$

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

3- Modeling

The proposed model was developed following the essence of Li and Wang’s model (Li, 2006). In our work, several modifications were made in order to improve the applicability of the results and to model the filtration process considering the influence of aeration on the SMBR. The model development and the simulation focused on describing the relationships existing among important system variables like TSS, aeration flow, TMP, sludge viscosity, temperature of the bulk phase and the fouling increase.

The modified model calculates the increase of the TMP, simultaneously evaluating the influence on fouling control of an intermittent aeration of coarse bubbles, synchronized with the filtration cycles. This procedure also analyzes the effect of shear intensity on sludge cake removal. In addition, during the calculation of the TMP increase, the influence of the temperature of the filtrate and the sludge suspension rheology was considered, as well as an estimation of the sludge density as a function of the sludge concentration. These aspects are new in the calculation and were included because we considered they played a major role in the description of fouling. The conceptual schematic of the developed model is shown in figure 2. It shows the main relations that exist during simulation and, also, the information flow established among the different parts of the model during calculation.

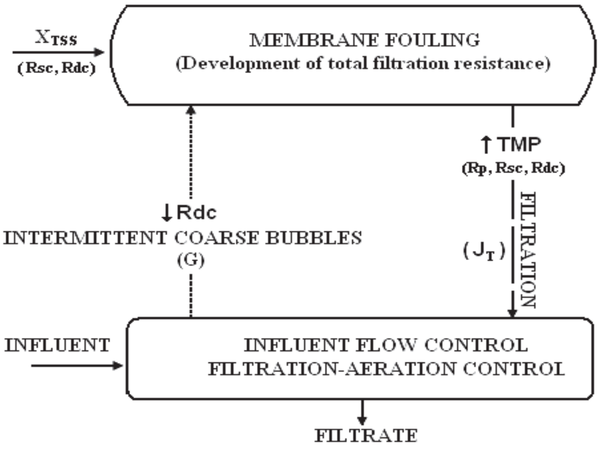

Figure 2. Conceptual schematic of developed model

3.1 Modeling of the fouling process

The sectional approach proposed by Li and Wang (Li, 2006) for determining total filtration resistance was also used. It divides the membrane surface into equal fractional areas and then calculates the total resistances, R, for each section separately. The total resistance for a membrane surface section comprises four resistance components: the intrinsic resistance of the membrane (Rm); the pore fouling resistance caused by solute deposition inside the membrane pores (Rp), which is proportional to the amount of permeate produced; the resistance of the dynamic sludge film (Rdc); and the resistance of the stable sludge cake (Rsc) attached to the membrane surface. The resistances Rdc and Rsc 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.

$$R_{TS_{(i)}} = R_m + R_p + R_{dc} + R_{sc} \tag{2}$$

where:

$$R_m = cte\,;\, R_p = r_p \sum Jt_f\,;\, R_{sc} = r_{sc} M_{sc}\,;\;\; R_{dc} = r_{dc} M_{dc} \tag{3}$$

The transmembrane pressure, considering all the sections, was estimated by the equation:

$$TMP = \mu J_T R_T \tag{4}$$

where:

$$\frac{1}{R_T} = \sum_{i=1}^{n} \left(\frac{S_{(i)}}{R_{TS(i)}} \right) \tag{5}$$

The following sections 3.1.1 - 3.1.4 summarize the models used to describe intermittent processes and membrane fouling estimation.

3.1.1 Actual rate of sludge accumulation forming the dynamic sludge film

An analytic approach was used to develop the basic differential equations considered to estimate the actual rate of sludge deposition on the membrane and the sludge detachment rate (eq. 6). The main characteristics of these equations are presented and discussed by Li and Wang (Li, 2006).

During SMBR filtration, the biomass sludge approaches the membrane surface for each section. However, aeration turbulence reduces the rate of sludge deposition on the membrane by altering the trajectory of the sludge particles that move towards the membrane surface and by scouring the deposited sludge off the membrane. Taking into account the experimental set-up and the characteristics of the coarse bubble injection system, an irregular shear distribution on the membrane surface was considered, due to the membrane effect on the shear intensity distribution. Consequently, the sine function expression (equation 7) used to calculate the shear profile by Li and Wang, for a given aeration intensity, was considered.

$$\frac{dM_{sc}}{dt} = \frac{24TSSJ^2}{24J + C_d d_p G} - \frac{\beta(1 - K_{ST})GM_{dc}{}^2}{\gamma V_f + M_{dc}} \tag{6}$$

where:

$$G = \begin{cases} \left[0.1 + 0.45\left(1 + \sin\frac{(2\varepsilon_i - \varepsilon_a)\pi}{2\varepsilon_a}\right)\right] \cdot \sqrt{\left(\frac{\rho_S g q_a}{\mu_S}\right)} & ;\varepsilon_\mathrm{i} < \varepsilon_\mathrm{a} \\ \sqrt{\left(\frac{\rho_S g q_a}{\mu_S}\right)} & ;\varepsilon_i \geq \varepsilon_a \end{cases} \tag{7}$$

$$\mathrm{q_a} = \left[\frac{Q_{CB}}{A}\right] \tag{8}$$

3.1.2 Sludge detachment rate due to intermittent aeration during the idle-cleaning period

We take advantage of a period without filtration, named the idle period, to remove adhered particles or to expand the deposit, as the scouring effect of the bubbles is enhanced. During this period, the dynamic sludge film is not further compressed because of the lack of permeate suction. The compression coefficient is presumably reduced to its lowest value, calculated by $\psi\gamma$. At this moment, the dynamic sludge film can be more easily removed by aeration turbulence. Hence, the rate of detachment of biomass from the sludge film becomes:

$$\frac{dM_{dc}}{dt} = -\frac{\beta(1 - K_{ST})GM^2{}_{dc}}{\psi\gamma V_f + M_{dc}} \tag{9}$$

3.1.3 Intermittent processes

Most SMBRs are operated in a filtration/idle-cleaning switch mode. Periodic equations are proposed in this work to describe the intermittence of coarse bubble aeration and the filtration process and in order to study the effects of aeration-filtration synchronization on the rate of sludge cake formation. Eq. (10) describes the intermittent filtration process and Eq. (11) represents the intermittent aeration with coarse bubbles.

$$J(t) = \begin{cases} 0 & ; tf + m(tf + t_{id}) < t < m(tf + t_{id}) \\ J_{\mathrm{T}} & ; m(tf + t_{id}) \leq t \leq tf + m(tf + t_{id}) \end{cases} \quad \forall \mathrm{m}: \mathrm{m} \in \mathsf{N} \tag{10}$$

$$Q_{CB}(t) = \begin{cases} 0 & ; t_{CB} + m(t_{CB} + Int_{CB}) < t < m(t_{CB} + Int_{CB}) \\ Q_{\mathrm{CB}} & ; m(t_{CB} + Int_{CB}) \leq t \leq t_{CB} + m(t_{CB} + Int_{CB}) \end{cases} \quad \forall \mathrm{m}: \mathrm{m} \in \mathsf{N} \tag{11}$$

3.1.4 Properties of the bulk phase

During the simulation, it is very important to work with adequate values for the properties of the bulk phase, specifically viscosities and densities. Many approaches are reported concerning how to calculate these properties depending on the TSS (Krauth, 1993; Lübbecke, 1995; Ohle, 1999; Shimizu, 1996; Ueda, 1996; Xing, 2001). Because of the temperatures and concentrations considered in this work, the correlations of Ohle (Ohle, 1999) and Krauth (Krauth, 1993) were chosen. Frequently, the effect of the temperature on the filtration process using SMBR is not included in models. These systems are very sensitive to the influent and bulk phase temperature. Thus, including this variable in the calculation of water viscosity (eq. 12), which is linked to the sludge viscosity (eq. 13), even if the temperature influence on biological behavior is not considered, allows a better estimation of the variation of resistances during filtration and, consequently, a more accurate calculation of TMP.

$$\mu_W = 0.001[1.78e^{(-0.041(T_S)0.875)}] \tag{12}$$

$$\mu_S = \mu_W[1.05e^{(0.08TSS)}] \tag{13}$$

$$\rho_S = \rho_W[0.99959e^{(0.0004397TSS)}] \tag{14}$$

3.2 Parameter values

A set of values for the model coefficients and parameters were selected based on previous reports and laboratory tests (Table 1). For practical reasons, some parameters were taken from previous studies of similar systems. The values of parameters related to the membrane characteristics and the specific filtration resistances were estimated from our own experimental results. An accurate process prediction by simulation is only possible after the parameters have been tuned for a given plant, so this work suggests a set of reasonable parameter values that allow the model to be run and its features to be presented.

3.3- Simulation conditions

A numerical simulation of the membrane fouling was performed using a program written in the Berkeley Madonna programming language, run on a PC in the Windows XP environment. The membrane fouling development was simulated by numerical iterations, which produced 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 bubble injection were simulated by means of periodic functions implemented in Berkeley Madonna V 8.3.9. All these modifications and the integration of the new equations were validated experimentally.

Table 1. Nomenclature, parameters and coefficients used in the model and simulations

Symbol	Meaning and Unit	Value	Reference
Am	Unit floor area of the membrane (m^2)	0.0013	This work
Cd	Coefficient of the drag and lifting force (dimensionless)	0.04	This work
dp	Particle size (μm)	100	This work
G	Apparent shear intensity of the fluid turbulence (s^{-1})		
Int_{CB}	Time interval between two coarse bubble injections (s)		
J	Local filtration flux through the i-th membrane section ($m^3/(m^2$ day))		
J_T	Overall flux ($m^3/(m^2$ day))	0.25	This work
K_{ST}	Stickiness of the biomass particles (dimensionless)	0.6	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 sections of the membrane surface area	128	
qa	Aeration intensity (L/(m^2 s))		
Q	Filtration Flow (L/s)		
Q_{CB}	Coarse Bubble 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})	2.0×10^{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 i-th membrane section (m^{-1})		
t_{CB}	Coarse bubbles injection time (s)		
tf	Filtration time (s)		
tid	Idle time (s)		
TMP	Trans-membrane pressure (Pa)		
T_S	Temperature of the sludge suspension (°C)		
Vf	Water production within a filtration period of an operation cycle (m^3/m^2)		
TSS	Total suspended solids (g/L)		
β	Erosion rate coefficient of the dynamic sludge film (dimensionless)	3.5×10^{-4}	(Li, 2006)
ε_a	Fraction of the membrane surface area with a reduced shear intensity	2/3	(Li, 2006)
ε_i	Accumulated membrane area fractions to the i-th section		
γ	Compression coefficient for the dynamic sludge film (kg/(m^3 s))	2.5×10^{-5}	(Li, 2006)
ψ	Reduction index of compression coefficient	0.1	
μ	Viscosity of the permeate (Pa s)		
μs	Viscosity of the sludge suspension (Pa s)		
μw	Viscosity of water (Pa s)		
ρs	Density of the sludge suspension (kg/m^3)		

4- Results and discussion

4.1- Comparative simulation results with experimental data

Several variables were tested in order to study the model's capability to predict different operating conditions. A comparison between the measured data and simulation results is shown in figures. 3 to 5. Table 2 shows the input values used during simulations according to the experimental values. The TSS, rdc, and rsc values were chosen according to the average values of these variables obtained experimentally.

In its current form, 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. It can be seen that simulation results of TMP are in good agreement with the experimental data. However, a slight underestimation of the real values of the TMP was obtained during the simulation.

There are several possible reasons for this. The first one is that, because of the model simplicity, the biological behavior of biomass and the presence of metabolic substances in the sludge composition were not considered; this can lead to errors in the simulation.

On the other hand, in MBR filtration, the sludge concentration and the aeration intensity changed the size of the sludge flocs, which, in turn, affected the cake resistance and the related TMP increase. But the influence of the floc size on cake porosity was not considered in the model, even though it could disturb the specific values of the resistance and, consequently, the TMP.

Also, the relationship between the shear intensity (G) and the aeration intensity (qa) given in Eq. (7) was obtained in laminar flow regime because of lack of information on the turbulent regime. During the intermittent aeration, the strong aeration produces a turbulent environment, so using these equations there should cause a certain degree of error 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 by the model (Li, 2006).

Table 2. Input variables for comparative simulation with experimental results.

Variables	Values in the experiments		
	Exp-1	Exp-2	Exp-3
TSS (g/L)	8	4.3	7
rdc (m/kg)	5.5×10^{12}	5×10^{12}	3×10^{12}
rsc (m/kg)	5.5×10^{12}	5×10^{12}	3×10^{12}
J_T ($m^3/(m^2$ day))	0.25	0.25	0.25
qa ($L/(m^2$ s)	9	11	15
Int_{CB} (min)	8	6	8
t_{CB} (min)	2	1	2
tf (min)	12	6	12
tid (min)	4	3	4

The operating mode of the SMBR allowed a temporary accumulation of sludge on the membrane. All the aeration-filtration cycles used were set to values that allowed a fast increase in the filtration cake thickness. Most of the time, the coarse bubbles were injected during the filtration cycles. In this case, the aeration intensity was less effective because of the opposing effect of the suction force due to permeation through the membrane. Therefore, the increase of the sludge cake film was accelerated and its partial removal from the membrane surface was carried out later 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. This diminishes the aeration cost and minimizes the negative effects of the strong aeration on the floc sizes and the sludge rheology (Van Kaam, 2007). The effect of the aeration intensity was observed during experimentation and simulation. An elevated aeration rate reduces the membrane fouling rate, and enhances the removal of the dynamic sludge layer. In general, even using the high aeration intensity values, the fouling problem does not appear to be avoidable for SMBR, due to the presence of a variety of fouling mechanisms, such as pore fouling processes. Upon analyzing the comparative simulations, it can be observed that, even for different operational conditions, the model is able to suitably predict these intermittent processes and the TMP evolution.

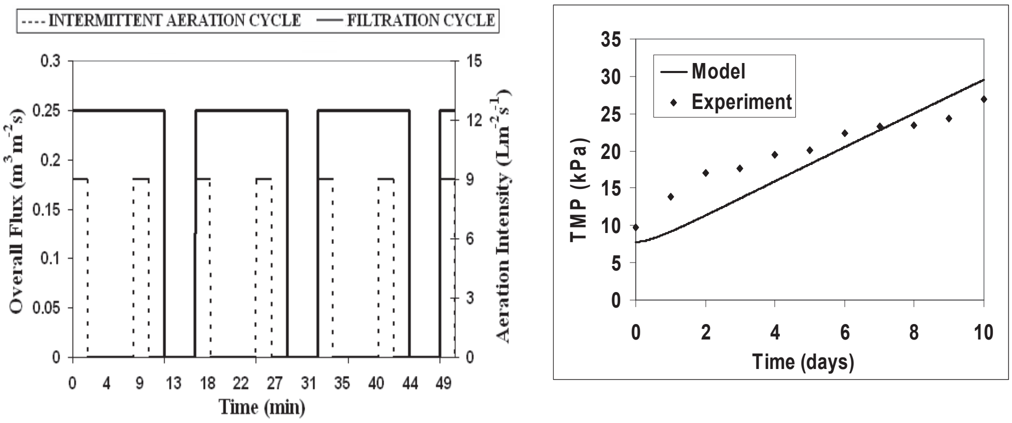

Figure 3. Simulation and experimental results corresponding to experiment 1. [qa= 9 L/(m^{2}s), tf= 12 min, tid= 4 min, Int$_{CB}$= 8 min, t$_{CB}$= 2min, TSS= 8 g/L, rdc= rsc= 5.5×10^{12} (m/kg), J$_T$=0.25 m^3/(m^{2}s)]

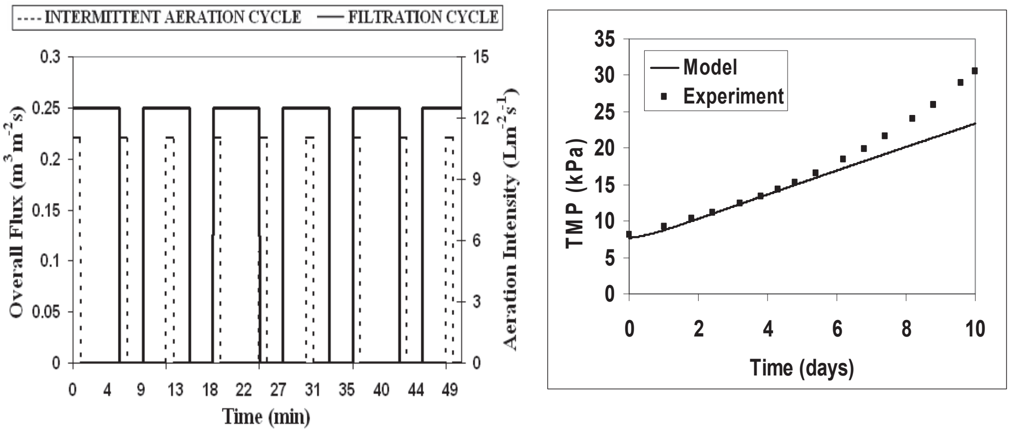

Figure 4. Simulation and experimental results corresponding to experiment 2. [qa= 11 L/(m^{2}s), tf= 6 min, tid= 3 min, Int$_{CB}$= 6 min, t$_{CB}$= 1 min, TSS= 4.3 g/L, rdc = rsc=5×10^{12} (m/kg), J$_T$=0.25 m^3/(m^{2}s)]

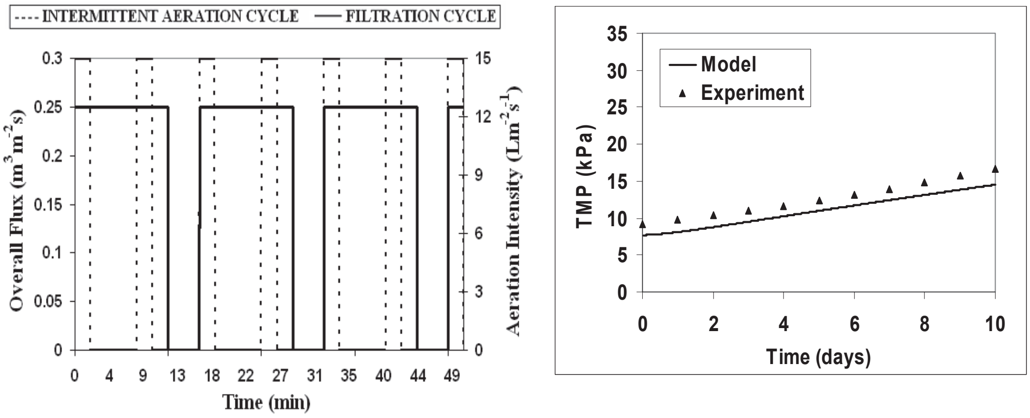

Figure 5. Simulation and experimental results corresponding to experiment 3. [qa= 15 L/(m^2s),tf= 12 min, tid= 4 min, Int_{CB}= 8 min, t_{CB}= 2 min, TSS= 7 g/L, rdc = rsc=3×10^{12} (m/kg), J_T=0.25 m^3/(m^2s)]

4.2- Influence of the SMBR process variables on TMP evolution

In order to evaluate the influence of the main process parameters on the TMP increase, different simulation cases were evaluated. Six strategies were designed in order to analyze the effect of each variable on the fouling evolution: (A) influence of the aeration intensity, (B) influence of the sludge stickiness, (C) influence of the TSS concentration, (D) influence of the flux, (E) influence of the temperature of the sludge suspension, and (F) influence of the specific filtration resistance. Table 3 shows the input parameters and the range of variation studied for each variable used during all simulations.

The simulation results are consistent with other research: Figure 6 shows that an elevated filtration flux, a high TSS concentration and low aeration intensity increase the TMP significantly (figures 6A, 6C, 6D). This behavior is consistent with the results of Germain *et al.* and Ueda *et al.* (Germain, 2005; Ueda, 1997), who demonstrated that an increase in the permeate flux and a reduction in the aeration rate would cause severe membrane fouling. Also, the filtration of a sticky sludge or a biomass with a high specific filtration resistance increases the fouling process (figures 6B, 6F).

Table.3- Common input parameters used during simulation

Variables	Values used during simulation					
	A	B	C	D	E	F
qa (L/(m^2 s)	5-15	11	11	11	11	11
K_{ST} (-)	0.6	0.3-0.7	0.6	0.6	0.6	0.6
TSS (g/L)	6.5	6.5	5-11	6.5	6.5	6.5
J_T (m^3/(m^2 day))	0.3	0.3	0.3	0.15-0.75	0.3	0.3
T_S (°C)	15	15	15	15	10-20	15
rdc (m/kg)	3×10^{13}	3×10^{13}	3×10^{13}	3×10^{13}	3×10^{13}	$1x10^{12}$-$1x10^{14}$
rsc (m/kg)	3×10^{13}	3×10^{13}	3×10^{13}	3×10^{13}	3×10^{13}	$1x10^{12}$-$1x10^{14}$

Int_{CB} = 6 min, t_{CB} = 1min, tf = 12 min, tid = 4 min

The stickiness of the sludge, one of the physicochemical properties of microbial cake layer deposited on the membrane surface, has a significant influence on membrane fouling. In the real system, the K_{ST} value varies during the filtration process but in the present model it is considered constant during the simulation process. Therefore, an incorrect estimation of this parameter could affect the rate of sludge adhesion on the membrane surface, the effect of the aeration intensity, and consequently the actual TMP value. This parameter is related to the microbial diversity inside the SBMR, because different populations have different stickiness (Ma, 2006; Zubair, 2007), and it is also a function of the concentration and composition of the Extracellular Polymeric Substances (EPS). Lee *et al*. (Lee, 2003) found that the SRT had a significant impact on membrane fouling, and believe that an unsuitable SRT produces a sticky suspended sludge. In consequence, developing techniques and operational conditions focused on growing a less sticky sludge could be interesting to minimize the fouling process.

Simulations show that TMP is highly sensitive and directly proportional to the specific filtration resistance of the sludge cake layer (figure 6F). This variable has a very important effect on the filtration process because, for the same amount of sludge accumulation on the membrane, a higher cake resistance leads to faster TMP increase. In our model, this parameter remained constant during the calculation. Nevertheless, several research works have shown that this variable depends on TMP, sludge concentration, floc size, sludge viscosity and bound EPS concentration (Cho, 2005; Ognier, 2002, Song, 2005). The sludge cake behaves like a compressible cake and it is logical to think that, during the filtration cycles, the cake properties may also vary from time to time.

The porosity of the stable cake will be reduced, increasing 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 considered as an approach. Thus, not considering this logical variation during simulation might introduce a certain degree of error in the calculations.

The effect of the temperature is also appreciable. High temperatures provide a better filtration and a lower TMP increase (figure 6E). This variable plays an important role on the biomass metabolism and the sludge composition. However, during modeling, only the influence of the temperature on the filtrate and sludge viscosities were considered. Taking account of the influence of temperature on the rheological characteristics of the sludge, even though it is a partial consideration of the temperature relevance, allows a better estimation of TMP evolution.

The simulation shows that the filtration flux, for the conditions evaluated, is the most important operating variable regulating the TMP increase (figure 6D). A high flux indirectly reduces the effectiveness of the aeration turbulence by removing the sludge from the dynamic sludge layer. In contrast, sludge cake deposition on the membrane can be minimized by decreasing the filtration flux and increasing the aeration rate. Also, for a lower sludge concentration; 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 (Li, 2006). But it sometimes has a negative economic impact on wastewater treatment cost.

On the other hand, a negative effect on the properties of the sludge flocs produced by excessive aeration has been reported (Van Kaam, 2007). The benefits of aeration in SMBR are well recognized (Chang, 2000). Nevertheless, it has been observed that, for these systems, an increase in cross-flow, as caused by the aeration, has two contradictory consequences. While the cake layer thickness decreases, a higher specific resistance due to a decrease in the average particle size is observed (Germain, 2005; Mackley, 1992; Shane, 2007; Wakeman, 1991).

This observable fact is not captured by the model, which assumes constant specific filtration resistances during simulation. Nevertheless, it is evident that choosing the best combination between aeration and flux seems to be an important key for the process as the model is able to quantitatively describe the effects of multiple variables involved in the SMBR filtration process. The model proposed here, even with the restrictions explained, can be employed to reproduce and investigate the influence of a large number of process variables on fouling development.

Finally, in the SBMR design process, the allocation of the membrane modules, and the distribution of the air-spargers, are very important aspects that influence the bubble flow pattern and the effectiveness of the aeration intensity. The possibility of quantitatively predicting the impact of the aeration intensity on the membrane fouling process helps decision making during the technological and geometric design of SMBR. On the other hand, the model could be used for the optimization of an SMBR system, acting on the operating variables that have a direct impact on the operation costs, which are frequently high for SMBR systems.

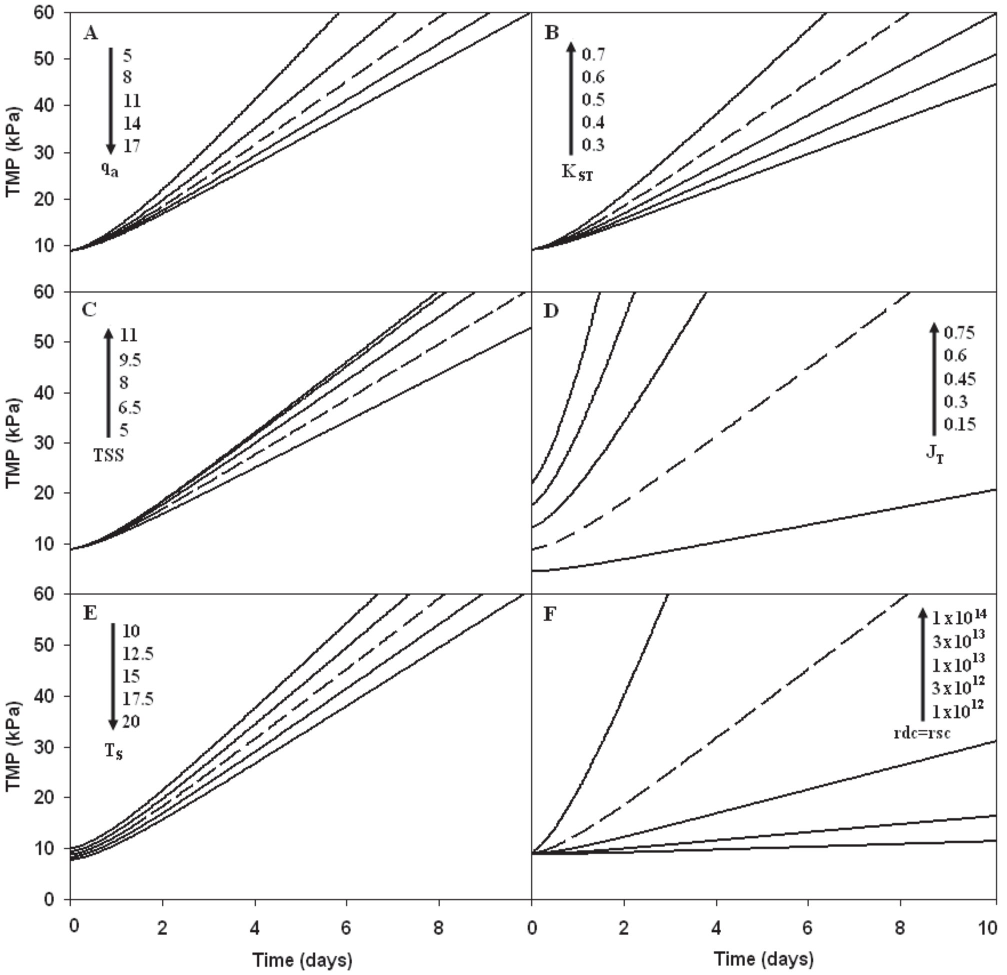

Figure 6. Effects of the process variables on the TMP increase in the SMBR. The discontinuous line represents the following conditions [qa = (L/m^2 s), KST = 0.6, TSS = 6.5 (g/L), J_T = 0.3 (m^3/m^2 day), T_S = 15 (°C), rdc = rsc= $3x10^{13}$(m/kg)]

5- Conclusions

A mathematical model that simulates the filtration process and the aeration influence on SMBRs has been developed. The dynamics of the sludge attachment to and detachment from the membrane, in relation to the filtration and strong intermittent coarse bubble aeration, are included in the model. The fouling components of pore clogging, sludge cake growth, and temporal sludge film coverage are considered in the calculation of the total membrane fouling resistance. With this model, membrane fouling under different SMBR running conditions can be simulated. The influences of a very large number of process variables on TMP increase, including the temperature of the sludge suspension, can be well quantified.

The model also describes the effect on fouling control of intermittent aeration of coarse bubbles synchronized with the filtration cycles, taking into account the effects of shear intensity on sludge cake removal.

The results of the numerical simulations fit the experimental data from the studied SMBR well. The new model provides an important tool for studying the SMBR membrane fouling problem and also offers the possibility to improve the operation strategies of SMBRs in wastewater treatment.

Future tasks will focus on system optimization and the improvement of model parameter estimation. Also, different operational strategies will be examined in order to find the optimal conditions for using the coarse bubble aeration flow. Some additional aspects, including a more rigorous consideration of the cake layer, the specific filtration resistances, the effect of floc size, and the cake porosity decrease, might be of the interest in future works.

References

Aileen N.L., Ng A. and Kim S., “A mini-review of modeling studies on membrane bioreactor (MBR) treatment for municipal wastewaters”, Desalination, 2007, 212, 261-281.

Chang S., Fane A. G., “Characteristics of microfiltration of suspensions with inter-fiber two phase flow”, J. Chem. Technol. Biot., 2000, 75, 533-540.

Cho B. D. and Fane A. G., “Fouling transients in nominally sub-critical flux operation of a membrane bioreactor”, J. Membr. Sci., 2002, 209, 391-403.

Cho J. K., Song G., Yun H., Ahn K. H., Kim J. Y. and Chung T. H., “Quantitative analysis of biological effect on membrane fouling in submerged membrane bioreactor”, Water Sci. Technol., 2005, 51, 9-18.

Cho J., Song K. G. and Ahn K. H., “The activated sludge and microbial substances influences on membrane fouling in submerged membrane bioreactor: unstirred batch cell test”, Desalination, 2005, 183, 425-429.

Germain E., Stephenson T. and Pearce P., “Biomass characteristics and membrane aeration: toward a better understanding of membrane fouling in submerged membrane bioreactors (MBRs)”, Biotechnol. Bioeng., 2005, 90, 316-322.

Germain E., Stephenson T., and Pearce P., “Biomass characteristics and membrane aeration: toward a better understanding of membrane fouling in submerged membrane bioreactors (MBRs)”, Biotechnol. Bioeng., 2005,90, 316-322.

Judd S. J., “A review of fouling of membrane bioreactors in sewage treatment”, Water Sci, Technol., 2004, 49, 2, 229-235.

Krauth K. and Staab K. F., “Pressurized bioreactor with membrane filtration for waste-water treatment”, Water Res., 1993, 27, 405-411.

Li X.-Y. and Wang X.-M., “Modelling of membrane fouling in a submerged membrane bioreactor”, J. Membr. Sci., 2006, 278, 151-161.

Lübbecke S. and Vogelpohl A., “Wastewater treatment in a biological high performance system with high biomass concentration”, Water Res., 1995, 29, 3, 793-802.

Ma B. C., Lee Y. N., Park J. S., Lee C. H., Lee S. H., Chang I. S. and Ahn T. S., “Correlation between dissolved oxygen concentration, microbial community and membrane permeability in a membrane bioreactor”, Process Biochemistry, 2006, 41, 1165-1172.

Mackley M. R. and Sherman N. E., “Crossflow filtration mechanisms and kinetics”, Chem. Eng. Sci. 1992, 47, 2085-3067.

Ognier S., Wisniewski A. and Grasmick A., “Influence of macromolecular adsorption during filtration of a membrane bioreactor mixed liquor suspension”. J. Membr. Sci., 2002, 209, 27-37.

Ohle P., “Bemessung von Membranbioreaktoren für die kommunale Abwasserreinigung”. PhD thesis. Insitut f¨ur Siedlungswasserwirtschaft, RWTH Aachen University, 1999.

Shane R., Merlo R. P., Hermanowiczc W. and Jenkins D., “Influence of mixed liquor properties and aeration intensity on membrane fouling in a submerged membrane bioreactor at high mixed liquor suspended solids concentrations”, Water Res., 2007, 41, 947-958.

Shimizu Y., Okuno Y., Uryu K., and Watanabe A., “Filtration characteristics of hollow fiber microfiltration membranes used in membrane bioreactor for domestic wastewater treatment”, Water Res., 1996, 30, 10, 2385-2392.

Shin H. S. and Kang S. T., “Characteristics and fates of soluble microbial products in ceramic membrane bioreactor at various sludge retention times”, Wat. Res., 2003, 37, 1, 121-127.

Ueda T. and Hata K., “Treatment of domestic sewage from rural settlements by a membrane bioreactor”, Water Sci. Technol., 1996, 34, 9, 186-196.

Ueda T., Hata K., Kikuoka Y. and Seino O., “Effects of aeration on suction pressure in a submerged membrane bioreactor”, Water Res., 1997, 31, 489-494.

Van Kaam R., Anne-Archard D., Alliet-Gaubert M. and Albasi C., “Rheological characterization of mixed liquor in a submerged membrane bioreactor: Interest for process management”, J. Membr. Sci., 2008), 317, 1-2, 26-33.

Wakeman R .J., Tarleton E. S., “Colloidal fouling of microfiltration membranes during the treatment of aqueous feed streams”, Desalination, 83, 1-3, 1991, 35-52.

Xing C. and Qian Y., “Physical and biological characteristics of a tangential flow MBR for municipal wastewater treatment”, J. Membr. Sci., 2001,191 ,1, 31-42.

Zubair A., Cho J., Lim B. R., Song K.G., and Ahn K. H., “Effects of sludge retention time on membrane fouling and microbial community structure in a membrane bioreactor”, J. Membr. Sci., 2007, 287, 211-218.