Toward an operational dynamic model for tertiary nitrification by submerged biofiltration

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Abstract This work deals with the methodology put in place to fit and validate the parameters of a biofiltration model (BAF) in tertiary nitrification treatment and dynamic conditions. For an average loading rate of 0.65 kg NH_4-N/m^3 media/d, different time loading rates are applied inside a filtration-backwash run using a semi-industrial pilot. Comparisons between predicted and observed values on the NH_4-N, NO_3-N and TSS in treated water and the total head loss ΔP are carried out firstly using default values of BAF parameters. Model predictions overestimate values measured but trends are well reproduced. A sensitivity analysis is carried out and the hierarchy of BAF parameters has been set up classifying them into strong and low influence on the effluent concentrations. Among parameters revealing the strongest influence are those of the filtration module and the mean density of biofilm for the TSS effluent and the total ΔP, the specific autotrophic growth rate, the maximum biofilm thickness and the reduction coefficient of diffusivity in the biofilm for the NH_4-N, NO_3-N effluent. Finally, this classification leads to setting a calibration procedure, thanks to specific experimental tests directly measuring some BAF parameters.

Keywords Calibration procedure; modelling; sensitivity analysis; submerged biofilter; tertiary nitrification

Introduction

For about three decades, the submerged biofilter process has been used more and more for the treatment of municipal wastewater, especially for cities with strong land pressures. This technology, which has many advantages, such as its compactness, has gained in popularity lately in the wastewater field and become a reliable alternative to activated sludge systems. First installed for the carbonaceous removal, this process can be used for nitrogen removal (NH_4-N ≤ 5 mgN/L) in the tertiary stage (Tschui *et al.*, 1994; Pujol *et al.*, 1998; Payraudeau *et al.*, 2000; Jeong *et al.*, 2006), in particular to face seasonal peak-loads in tourist areas (Canler *et al.*, 2003). Biofiltration is a complex triphasic system in which water and air usually flow through the media in a co-current manner, while physical (biofilm diffusion, attachment/detachment of the biofilm, TSS filtration) and biological phenomena (soluble pollutants conversion by bacterial growth, biofilm space expansion) occur on the media.

In order to optimise their design and operation for tertiary nitrification, it is important to know the treatment performances in dynamic conditions. Consequently, the use of a modelling tool is essential. Several models describing biofilms exist (Wanner and Morgenroth, 2004; Perez *et al.*, 2005). Although interesting, two- and three-dimensional models (Picioreanu *et al.*, 1998, 2004) developed for biofilms at the microscopic level are not yet adapted to the needs of engineering practice. There are models that describe

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some of the mechanisms occurring in the biofilter. For example, Le Tallec *et al.* (1999) developed a filtration model establishing links between several parameters, such as TSS retention, water porosity, head loss and the filter coefficient without representation of biological processes. Two one-dimensional models considering only pollution in soluble form or the absence of diffusion phenomena in the biofilm have been developed recently (Viotti *et al.*, 2002; Hidaka and Tsuno, 2004).

Contrary to the above models, the submerged biofilter model (BAF – biological aerated filter) included in the GPS-X® V 4.1.2 software (Hydromantis, 1992–2003), integrates the physical and biological processes. The differential system equation implies 42 parameters and its resolution provides a dynamic representation of the process operation. Thus, this model is complex and the modification of the right parameter (calibration stage) is difficult.

No specific calibration procedure has been developed yet for such a model, contrary to those reported for activated sludge systems by Sin *et al.* (2005 – BIOMATH, HSG, STOWA and WERF). This work thus presents the means used to calibrate and validate parameters of the BAF model using experimental data in tertiary nitrification treatment.

Materials and methods

The procedure used to develop the protocol was carried out in three parts. The BAF model, as is in the software with the default parameters, was first tested by comparing simulated values with observed ones gathered during a sampling campaign of a pilot plant. Then, in order to better understand the weak points of the model based on the comparison and to get a better fit of effluent particulate and soluble variables with real measurements, a sensitivity analysis was carried out according to the same type of procedure described in Petersen *et al.* (2002). Finally, based on the sensitivity analysis and the preliminary results, a calibration protocol was set up.

Experimental data recorded in dynamic treatment

The experimental semi-industrial unit was located on the effluent of a highly loaded activated sludge plant in France (700,000 PE). The pilot consists of a submerged up-flow biofilter (height = 6.65 m; diameter = 0.907 m) filled with an organic inert spherical filtering media (diameter = 4 mm; average specific area = 955 m^2/m^3) at 3.5 meter height. Filtration runs were limited to 24 hours, non-limiting aeration conditions were applied (oxygen concentration >6 mg O_2/L in treated water) and the water temperature was approximately 13.5 °C.

Online data acquisition of several parameters (NO_3-N, temperature, O_2, total ΔP) was carried out. Analysis of classical inlet/outlet parameters (TSS, COD_{tot}, COD_{sol}) was carried out every day according to standard methods. Different magnitudes of hydraulic dynamic peak-loads of 3 hours were applied inside a filtration-backwash run, where a constant volumetric nitrogen loading rate of 0.65 kg NH_4-N/m^3 media/d was maintained (Table 1). The influent/effluent NH_4-N and NO_3-N concentrations were measured over an

Table 1 Successive increase of peak-loads coefficients for constant loading rate of 0.65 kg NH_4-N/m^3/d

Time (day)	Daily nitrogen loading rate (kg N/m^3/d)	Peak-load coefficient	Loading rate during 21 hours (kg N/m^3/d)	Loading rate during peak-load of 3 hours (kg N/m^3/d)
1	0.65	1.5	0.6	1
2		2	0.56	1.3
3		2.8	0.49	1.8
4		3	0.46	2

average 21-hour period and on each peak-load of 3 hours. The specific experiment presented here lasted four days.

Conceptual BAF model

This BAF model consists of four major components: hydraulics, biofilm, filter operations and filtration, and biological.

- *Hydraulic and spatial model* with "pseudo two dimensions" mass transport (Figure 1): the BAF is divided into n horizontal sections (six by default) considered as completely mixed reactor (CMR). The transfer of the state variables between each of theses horizontal sections is through liquid flow by advection. In the biofilm, the soluble and particular components are moving from the outside of the filtering colonised media towards the substratum (flat carrier) according to the concept of stratified layers (Beyenal *et al.*, 1998).
- *Biofilm model (20 parameters)* handles soluble biofilm diffusion, biofilm growth and particular attachment and detachment between each layers of the biofilm (Spengel and Dzombak, 1992). Furthermore, this model includes physical characteristics of the material support.
- *Filtration model – backwash/flush operations (three parameters)*: continuity equations and kinetics partial differential equations (Horner *et al.*, 1986) are combined. Head loss calculation is integrated in this model by Carmen-Kozeny equation (Reynolds and Richards, 1996).
- *Biological conversion of substrates (19 parameters)* by growth and decay model for heterotrophic and autotrophic biomass according to ASM1 concepts (Henze *et al.*, 1987).

Application of BAF model

First, the model was run with the default parameters found in the software, some however having been updated after a literature review on biofilm models (Vanhooren, 2002; Perez *et al.*, 2005) and the biological reactions ASM1 model (Petersen *et al.*, 2002; Marquot *et al.*, 2005). Analysis of the simulated/observed comparisons revealed some discrepancies.

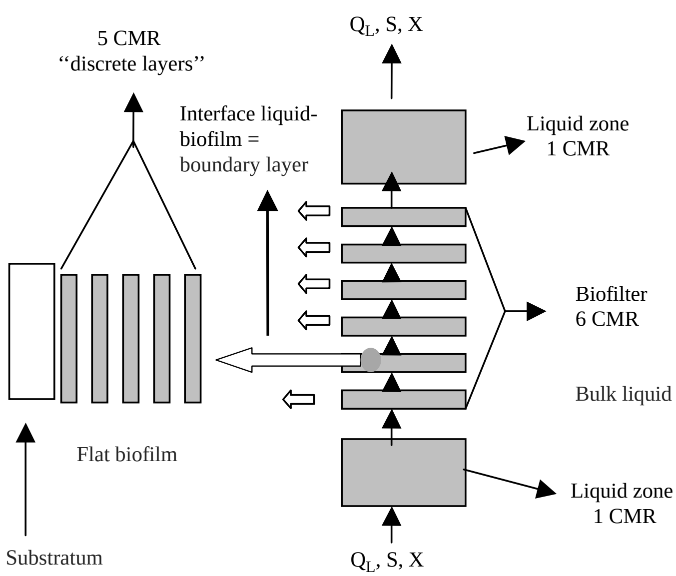

Figure 1 Hydraulic BAF representation

A critical analysis of the BAF model was thus carried out. The 42 parameters included in the model were gathered into four categories: physical characteristics of material and biofilm, mass transfer of the biofilm, biological conversion, and filtration/backwash. In each category, a distinction between the directly measurable parameters and those for which there is not a direct protocol of measurement but which are necessary to know was realised. A sensitivity analysis was then carried out in dynamic mode. This sensitivity study consisted of modifying the default value of each parameter by $\pm 25-50\%$. Thus, three different values were tested for each parameter: default, minimal and maximal values. The response of the system was displayed for NH_4-N, NO_3-N and TSS concentrations of the treated water and for the total head loss ΔP. It was carried out initially at steady state with the constant loading of 0.65 kg NH_4-N/m^3 media/d. All the simulations were realised with the following influent characteristics (according to a daily sampling of three months on the semi-industrial pilot): TSS = 50 mg/L; total COD = 120 mg/L; soluble COD = 50 mg/L; NH_4-N = 34 mg/L. The influent autotrophic biomass (X_{ba}) concentration was estimated from a nitrogen mass balance (Nowak *et al.*, 1994) on the activated sludge plant located upstream; the value found was approximately 0.2 mg COD/L.

Results and discussion

Comparison between predicted and observed results with the BAF model

The values measured by online sensor for NO_3-N and total ΔP, and the average daily values for TSS were confronted with the simulated values (Figures 2 and 3). NH_4-N concentration, obtained by chemical average measurements in the laboratory, was compared with the average values calculated from the simulated values every 5 minutes (Figure 2).

In Figure 2, the evolution of NO_3-N and NH_4-N are well reproduced, especially on day 4, where the fit is excellent. For nitrate a lag is observed for the first three days, which could be caused by some wrong initial conditions, in fact, very difficult to assess in a system such as a biofilter. The model is overestimating nitrate by approximately 15%, on average. Regarding ammonia, overestimation of approximately 60% during the hydraulic peak-load period (3 h) and 30% during the period of constant loading rate (21 h) is observed. Nitrification predicted by the BAF seems to be more important than the reality.

For TSS (Figure 3), a difference of approximately 30% between predicted and observed values is seen. The model simulates an increase of TSS with time for the four filtration runs, which is, in a sense, somewhat surprising. An incorrect regulation of the detachment phenomenon integrated in the biofilm and filtration models could explain this occurrence. For total head loss (ΔP), the behaviour is well reproduced although an overestimation between 30 and 40% compared with the measured values is observed

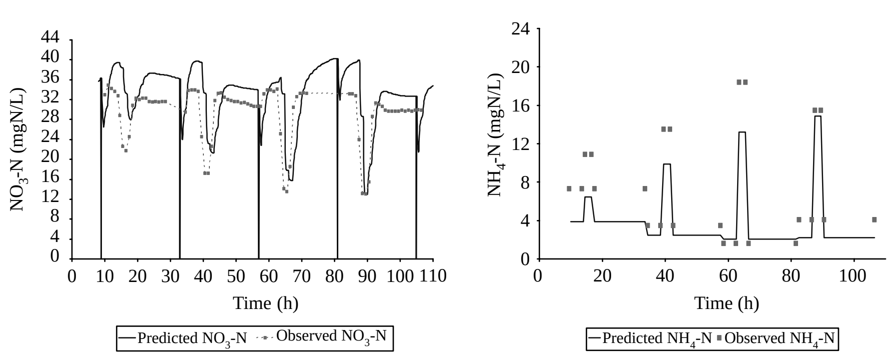

Figure 2 NO_3-N and NH_4-N effluent versus time: predicted and observed results

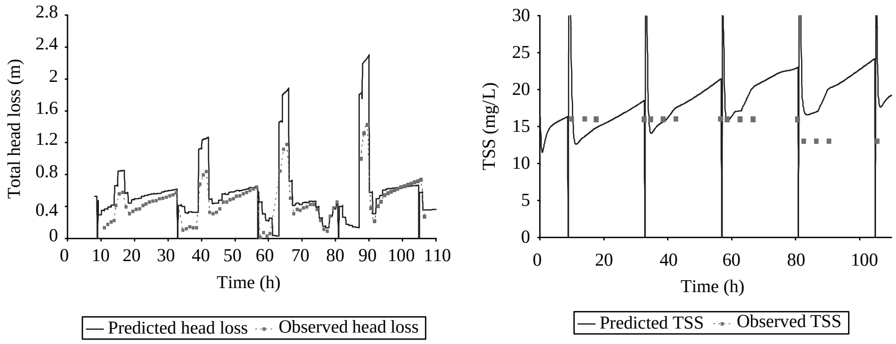

Figure 3 Total head loss ΔP and TSS effluent versus time: predicted and observed results

during hydraulic peak-loads period of 3 hours. Resetting to a good initial head loss value after backwash appears to be the main problem.

These preliminary results clearly show that the model describes relatively well the behaviour of the pilot plant. However, calibration of the parameters included in the model is necessary to be carried out in order to understand the implied mechanisms and to improve the fit between the observed and the simulated. However, the calibration of such models with many parameters needs to be realised following a clearly established protocol as described below.

Sensitivity analysis to BAF parameters

As stated before, the 42 parameters included in the model were gathered into four categories and a sensitivity analysis was performed. Table 2 presents the sensitivity

Table 2 Sensitivity of main BAF parameters

Modules	Parameters	Unit	Degree of sensibility (effluent water)	
			Particulates: TSS and total ΔP	Solubles: NH_4-N and NO_3-N
Physical characteristics of biofilm	Mean density of biofilm ρ_B	kg TSS/m^3 media	++	+
	Maximum biofilm thickness $L_{f,max}$	Mm	+	++
Mass transfer of biofilm	Reduction coefficient of diffusivity in the biofilm *f*	−	−	++
	Maximum attached liquid film thickness of biofilm	mm	−	−
	Surface solids detachment coefficient rate k_{detach}	kg/m^2 d	−	+
	Internal solids exchange coefficient rate	m/d	−	−
Filtration/Backwash	Clean bed filter coefficient λ_o	−	++	−
	Packing factor	−	+	−
	Solids removal rate during backwash	d^{-1}	++	+
Biological conversion ASM1	Autotrophic yield Y_A	gCOD/ gCOD	−	+
	Maximum specific autotrophic growth rate $\mu_{A,max}$	d^{-1}	−	++
	Autotrophic decay rate b_A	d^{-1}	−	+
	Maximum specific hydrolysis rate k_h	d^{-1}	−	+
	Ammonification rate k_a	m^3/gCOD/d	−	+
	Half-saturation coefficient K_{sat}	g/m^3	−	−

−, no influence; +, little influence; ++, strong influence degrees obtained on the soluble and particulate components for each parameter of the four modules constituting the BAF.

For the particulate components and head loss, the parameters of the filtration module exert a strong influence, especially the clean filter bed coefficient and the solids removal rate during backwash, as well as the mean density of biofilm ρ_B and the maximum biofilm thickness $L_{f,max}$. However, the surface solids detachment coefficient does not have any influence on the SS effluent, which is somewhat carryout surprising. All these parameters are very difficult to assess. It will thus be important to precise mass balances of suspended solids on several filtration-backwash runs, to try to evaluate precisely those parameters.

Concerning the soluble components, the tests show that the physical parameters of biofilm ($L_{f,max}$, ρ_B), the reduction coefficient of diffusivity in the biofilm f and the parameters of biological conversion ASM1 (particularly the maximum specific autotrophic growth rate $\mu_{A,max}$) influence effluent nitrogen concentrations.

Sensitivity tests were also carried out on the importance of influent fractionation. These tests revealed the significant influence of the autotrophic biomass concentration (X_{ba}) entering into the system. Thus, X_{ba} quantification has to be integrated within the framework of influent COD fractionation

Calibration procedure

The sensitivity tests led to a development, in the form of a protocol, of a calibration procedure to correctly modify the BAF parameters (Figure 4). Two stages were identified: (1) particular components; (2) soluble components.

This procedure indicates the information needed to characterise the filtering media along with the influent and effluent. Specific protocols will be adopted for determining some parameters. For example, the mean density and thickness of biofilm will be measured by the Horn and Hempel method (1997) initially adapted for a tubular reactor. In order to

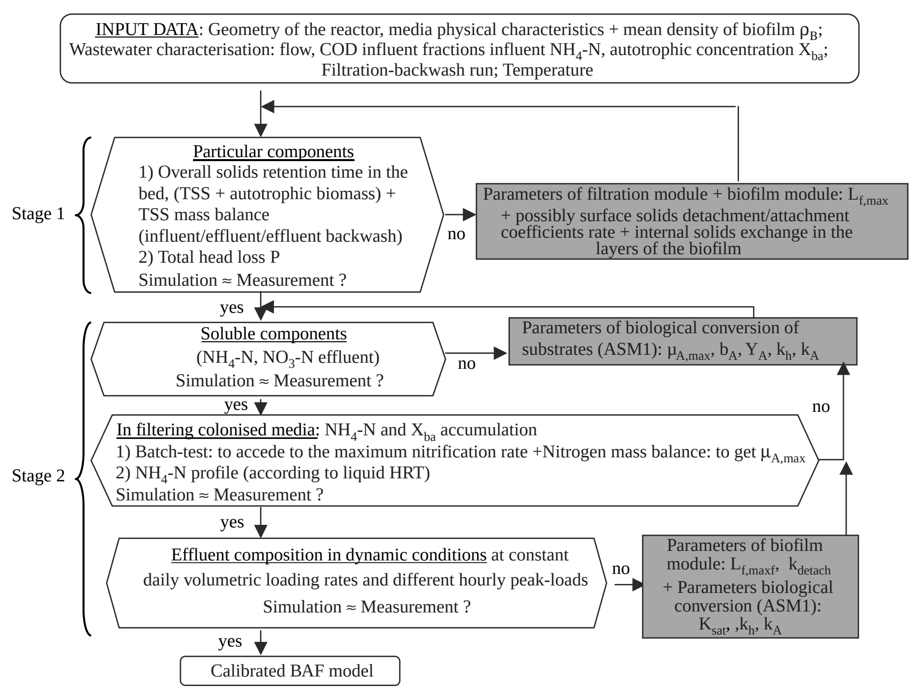

Figure 4 Calibration procedure

obtain a maximum nitrification rate of the nitrifying bacteria in the system for nitrogen loading rate and a given temperature, batch-tests will be carried out (Tschui *et al.*, 1994; Hidaka and Tsuno, 2004). At the same time, quantification of total biomass accumulating in the biofilter is possible from an influent/effluent nitrogen mass balance according to the methodology suggested by Nowak *et al.* (1994). These two methods allow the deduction of the maximum autotrophic growth rate $\mu_{A,max}$, parameter sensitive to the response of the system, in the filtering media and at a given temperature (Choubert *et al.*, 2005).

Finally, a standard protocol, more detailed than traditional measurements (COD, BOD, TKN) will be applied. This protocol is based on the fractionation of the organic matter on the influent system according to ASM1 definition and combines physical–chemical analysis (soluble COD) and a BOD analysis (biodegradable COD) proposed in Roeleveld and von Loosdrecht (2002).

Once these specific tests are completed, calibration of the remaining parameters, not directly measurable but, however, important, can be carried out. Thus, a set of parameters can be proposed in the case of a tertiary nitrification treatment in dynamic operation condition.

Conclusion

This work deals with the methodology proposed to fit and validate parameters of a BAF for tertiary nitrification treatment. First, this calibration procedure, with the help of continuous data acquisition from an experimental pilot plant, relies on comparisons between predicted/measured effluent soluble and particulate variables, which pinpointed some weaknesses of the model. From these results, a sensitivity analysis was carried out with BAF parameter values updated according to recent studies (bibliography). Then, a hierarchy of the whole BAF parameters was achieved. Finally, a dynamic calibration protocol was proposed. Its goal is to obtain a set of reliable parameters, based on specific experimental tests measuring directly some parameters of the model and whose protocols are under now development.

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