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ADAPTIVE LINEARIZING CONTROL OF A DENITRIFYING BIOFILTER

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Abstract. Biological denitrification in a fixed bed reactor is a process gaining popularity in the area of water treatment. The advent of more stringent criteria on nitrate and nitrite concentrations of treated water make the use of efficient process control algorithms not only of interest but compulsory for process optimization. The paper is concerned with the design and real-life implementation of an adaptive linearizing controller of a pilot fixed bed biofilter.

Keywords : fixed bed reactor, adaptive linearizing control, distributed parameter systems

1 Introduction

Denitrification plays a key role in the treatment of drinkable water, and is largely motivated by the possibly high concentrations of nitrogen in drinkable water which may be particularly detrimental to human health. Indeed the quality of the presently available drinkable water is largely determined by the damaging effects of human activities, e.g. the intensive use of nitrogen based fertilizers not only in agriculture but also for domestic use. The regulations about the nitrogen content of drinkable water and their control tend to be more and more stringent. Fixed bed biofilters are destined to play an increasing role in the denitrification of drinkable water. The main advantages of fixed bed biofilters are the compactness of the process, their efficiency for biological water treatment, their good integration in the environment, and their low energy consumption.

The need of efficient controllers in order to optimize the operation of such processes is obvious. Strictly speaking, the dynamics of such processes are described by partial differential equations. In addition to the process nonlinearities, the distributed parameter dimension of the process makes the control problem even more difficult and requires a careful design. This paper is concerned with the design and application of an adaptive linearizing controller that intends to compensate for the lack of modelling accuracy (basically about the process kinetics) and of reliable on-line sensors for the key process variables (here, the biomass and the ethanol concentrations).

The paper is organised as follows. A description of the biofilter is given in section 2. Section 3 is devoted to the dynamical modelling. Section 4 is concerned with the control design. Real life experiments are presented in Section 5.

2 Description of the biofilter

The denitrification process under study is a submerged granular fixed bed biofilter (see Fig. 1); it is packed with pouzzolane, a very porous volcanic material which retains a big amount of microorganisms during the washing. Thus the initial biomass concentration is often very close to the maximum active biomass concentration. The substrates to be removed can freely move along the reactor. The inside temperature is kept almost constant via a double insulation enveloppe. An ethanol solution is mixed with the feeding nitrate in a tank at the inlet of the reactor. Eight measurement points are distributed at every thirty centimeters along the column for the measurement of nitrate and nitrite concentrations.

Preliminary hydraulic experiments showed that the axial dispersion is negligible, and that the biofilter is equivalent to a series of twenty to thirty stirred tank reactors and can be considered to be running in plug flow conditions.

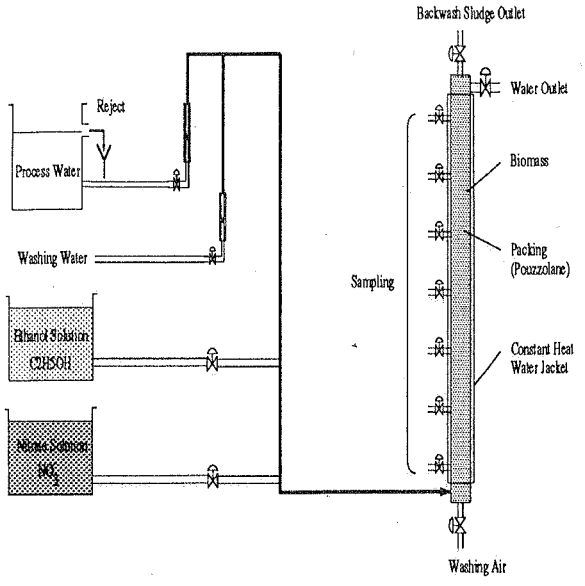

Figure 1: Experimental denitrification process

3 Modelling of the biofilter

3.1 The dynamical model

The denitrification processing is defined as being the reduction of nitrates (electron acceptor) NO_3^- into gaseous nitrogen N_2 by using organic carbon (electron donor) with production of intermediate compounds, namely nitrites NO_2^-. In order to dissociate nitrates and nitrites, two consecutive biological reactions are considered in the model, denitratation and denitritation :

$$NO3^- \xrightarrow{(1)} NO2^- \xrightarrow{(2)} N_2 \qquad (1)$$

The dynamics of the biofilter can be deduced from mass balance considerations for the different components : nitrate S_{NO_3}, nitrite S_{NO_2}, carbon S_C and active biomass X_a. In addition to the above two reactions of denitratation and denitritation, we have considered, in accordance with the experimental reality, a death/detachment reaction for the active biomass. The mass balances of the above components through an infinitesimal volume of Adz result in the following dynamical partial differential equations (PDE) :

$$\begin{aligned}
\frac{\partial S_{NO_3}(z,t)}{\partial t} &= -\frac{F}{A\varepsilon}\frac{\partial S_{NO_3}(z,t)}{\partial z} \\
&\quad -\frac{1-Y_{h_1}}{1.14Y_{h_1}\varepsilon}\mu_{NO_3}X_a(z,t) \qquad (2)\\
\frac{\partial S_{NO_2}(z,t)}{\partial t} &= -\frac{F}{A\varepsilon}\frac{\partial S_{NO_2}(z,t)}{\partial z} \\
&\quad +\frac{1-Y_{h_1}}{1.14Y_{h_1}\varepsilon}\mu_{NO_3}X_a(z,t) \\
&\quad -\frac{1-Y_{h_2}}{1.71Y_{h_2}\varepsilon}\mu_{NO_2}X_a(z,t) \qquad (3)
\end{aligned}$$

$$\begin{aligned}
\frac{\partial S_C(z,t)}{\partial t} &= -\frac{F}{A\varepsilon}\frac{\partial S_C(z,t)}{\partial z} \\
&\quad -\frac{1}{Y_{h_1}\varepsilon}\mu_{NO_3}X_a(z,t) \\
&\quad -\frac{1}{Y_{h_2}\varepsilon}\mu_{NO_2}X_a(z,t) \qquad (4)\\
\frac{\partial X_a(z,t)}{\partial t} &= (\mu_{NO_3}+\mu_{NO_2})X_a(z,t) \\
&\quad -k_dX_a(z,t) \qquad (5)
\end{aligned}$$

for $0 < z \leq L$. The boundary conditions, given at the input of the system, are written as follows : $S_{NO_3}(z=0,t) = S_{NO_{3,in}}(t)$, $S_{NO_2}(z=0,t) = S_{NO_{2,in}}(t)$, $S_C(z=0,t) = S_{C,in}(t)$. In the above equations, z represents the space variable. ε, Y_{h_1}, Y_{h_2}, μ_{NO_3} and μ_{NO_2} represent the porosity, the yield coefficients (g/g) and the specific growth rates (h^{-1}) of the denitratation and denitritation reactions, respectively. Concentrations of substrates and biomass are expressed in g/m^3, and the influent flow rate in m^3/h (or equivalently, the superficial velocity u in m/h). k_d is the death/detachment coefficient (h^{-1}). The specific growth rates are typically described with a double Monod-type model [8] :

$$\begin{aligned}
\mu_{NO_3} &= \mu_{NO_{3max}}\frac{S_{NO_3}}{S_{NO_3}+K_{NO_3}}\frac{S_C}{S_C+K_C}\\
\mu_{NO_2} &= \mu_{NO_{2max}}\frac{S_{NO_2}}{S_{NO_2}+K_{NO_2}}\frac{S_C}{S_C+K_C}
\end{aligned}$$

where $\mu_{NO_{3max}}$ and $\mu_{NO_{2max}}$ are the maximum specific growth rates of μ_{NO_3} and μ_{NO_2}, respectively. K_{NO_3}, K_{NO_2} and K_C are the affinity constants associated to nitrate, nitrite and carbon, respectively. The above kinetic expressions will be considered in the simulation model (used to test the performance of the control algorithm), and the identification procedure (performed to calibrate the model parameters)(see [2], [3]), but not in the control design, due to the large uncertainty associated to the process kinetics (e.g. [1]).

4 Control problem

4.1 Control problem statement

The objective is to control at the reactor output, the total concentration of nitrates and nitrites $y_L = y_{N+1}$ at some desired value y_d (defined in accordance with the regulations on drinkable water):

$$y_L = S_{NO_{3L}} + S_{NO_{2L}} \qquad (6)$$

each concentration being given in $g[N]/m^3$. The control input is the ethanol concentration $S_{C,in}(t)$ at the reactor input.

The design of the control algorithm takes the following assumptions into account :

1. the concentrations of nitrate and nitrite are measured at the reactor input and output;

2. the biomass concentration is not available for on-line measurement;
3. the ethanol concentration is known only at the reactor input;
4. the specific growth rates μ_{NO_2} and μ_{NO_3} are unknown;
5. the yield coefficients and the death/detachment coefficient are known.

The late lumping approach (see [4], [5]) will be used, i.e. the design of the control law is based on the distributed parameter model and the space-time discretization is used only for numerical implementation. By combining the first two equations of model (5) with expression (6), the dynamical equation of the variable to be controlled is as follows :

$$\frac{dy_L}{dt} = -\frac{F}{\varepsilon A}\frac{\partial y(z,t)}{\partial z}_{|_{z=L}} + \frac{k_2-1}{\alpha_2 \varepsilon}\mu_{NO_{2_L}} X_{a_L} \quad (7)$$

with $k_2 = \frac{1}{Y_{k_2}}$ and $\alpha_2 = 1.71$.

4.2 Controller design

The ethanol mass balance equation can be rewritten as follows :

$$\begin{aligned}\mu_{NO_{2_L}} X_{a_L} &= -\frac{k_1}{k_2}\mu_{NO_{3_L}} X_{a_L} - \frac{\varepsilon}{k_2}\frac{dS_{C_L}}{dt} \\ &\quad -\frac{F}{k_2 A}\frac{\partial S_C(z,t)}{\partial z}_{|_{z=L}}\end{aligned} \quad (8)$$

By combining equations (7) and (8), the dynamical output equation becomes :

$$\begin{aligned}\frac{dy_L}{dt} &= -\frac{F}{\varepsilon A}\frac{\partial y}{\partial z}_{|_{z=L}} + \frac{k_1}{k_2}\frac{k_2-1}{\alpha_2 \varepsilon}\mu_{NO_{3_L}} X_{a_L} \\ &\quad +\frac{1}{k_2}\frac{k_2-1}{\alpha_2}\frac{dS_{C_L}}{dt} \\ &\quad +\frac{1}{k_2}\frac{k_2-1}{\alpha_2}\frac{F}{\varepsilon A}\frac{\partial S_C(z,t)}{\partial z}_{|_{z=L}}\end{aligned} \quad (9)$$

Whatever the chosen discretization method, $\frac{\partial S_C(z,t)}{\partial z}_{|_{z=L}}$ can be approximated as follows :

$$\frac{\partial S_C(z,t)}{\partial z}_{|_{z=L}} \cong \Delta S_{C_L} + b_{0_{N+1}} S_{C,in}(t) \quad (10)$$

and the control input explicitely appears in the output equation. Let us define :

$$C_1 = \frac{k_1}{k_2}\frac{k_2-1}{\alpha_2 \varepsilon}, \quad C_2 = \frac{1}{k_2}\frac{k_2-1}{\alpha_2} \quad (11)$$

Then the output dynamical equation can be rewritten as follows :

$$\begin{aligned}\frac{dy_L}{dt} &= -\frac{F}{\varepsilon A}\left(\frac{\partial y(z,t)}{\partial z}_{|_{z=L}} - C_2 \Delta S_{C_L}\right) \\ &\quad +C_1 \mu_{NO_{3_L}} X_{a_L} + C_2 \frac{dS_{C_L}}{dt} \\ &\quad +C_2 \frac{F}{\varepsilon A} b_{0_{N+1}} S_{C,in}(t)\end{aligned} \quad (12)$$

Let us consider the following linear stable first-order closed loop dynamics:

$$\frac{dy_L}{dt} = \lambda(y_d - y_L) \text{ with } \lambda > 0 \quad (13)$$

The control is readily derived by combining equations (12) and (13) :

$$\begin{aligned}S_{C,in}(t) &= \frac{\varepsilon A}{C_2 F b_{0_{N+1}}}[\lambda(y_d - y_L) \\ &\quad +\frac{F}{\varepsilon A}\left(\frac{\partial y(z,t)}{\partial z}_{|_{z=L}} - C_2 \Delta \hat{S}_{C_L}\right) \\ &\quad -C_2 \frac{d\hat{S}_{C_L}}{dt} - C_1 \hat{\mu}_{NO_{3_L}} \hat{X}_{a_L}]\end{aligned} \quad (14)$$

This control law requires now estimated values of ethanol and biomass concentrations, and of the specific growth rate $\hat{\mu}_{NO_{3_L}}$ at the reactor output.

4.2.1 Ethanol and biomass concentrations' estimation

Let us consider an asymptotic observer (see [1], [6]). The auxiliary variable ζ is defined as a linear combination of the state variables (with $\alpha_1 = 1.14$ and $k_1 = \frac{1}{Y_{h_1}}$) :

$$\begin{aligned}\zeta &= \begin{bmatrix}\zeta_1 \\ \zeta_2\end{bmatrix} \\ &= \begin{bmatrix}S_c - h_1 S_{NO_2} - h_2 S_{NO_3} \\ X_a + h_3 S_{NO_2} + h_4 S_{NO_3}\end{bmatrix}\end{aligned} \quad (15)$$

with :

$$\begin{aligned}h_1 &= -\left(\frac{\alpha_1 k_1}{k_1 - 1} + \frac{\alpha_2 k_2}{k_2 - 1}\right), \; h_2 = -\frac{\alpha_2 k_2}{k_2 - 1} \\ h_3 &= \varepsilon\left(\frac{\alpha_1}{k_1 - 1} + \frac{\alpha_2}{k_2 - 1}\right), \; h_4 = \varepsilon\frac{\alpha_2}{k_2 - 1}\end{aligned}$$

The dynamics of the auxiliary variable ζ are given by the following equations :

$$\frac{\partial \zeta_1}{\partial t} = -\frac{F}{\varepsilon A}\frac{\partial \zeta_1}{\partial z} \quad (16)$$

$$\begin{aligned}\frac{\partial \zeta_2}{\partial t} &= -k_d \zeta_2 + h_3(k_d - \frac{F}{\varepsilon A}\frac{\partial}{\partial z})S_{NO_3} \\ &\quad +h_4(k_d - \frac{F}{\varepsilon A}\frac{\partial}{\partial z})S_{NO_2}\end{aligned} \quad (17)$$

The estimated values of biomass and ethanol concentrations are given by the following expressions from the on-line measurements of S_{NO_3} and S_{NO_2} and the computed values of $\zeta = [\zeta_1 \; \zeta_2]$:

$$\begin{aligned}\hat{S}_C(z,t) &= \zeta_1(z,t) - h_1 S_{NO_3}(z,t) \\ &\quad -h_2 S_{NO_2}(z,t)\end{aligned} \quad (18)$$

$$\begin{aligned}\hat{X}_a(z,t) &= \zeta_2(z,t) - h_3 S_{NO_3}(z,t) \\ &\quad -h_4 S_{NO_2}(z,t)\end{aligned} \quad (19)$$

4.2.2 Estimation of the specific growth rates

In the control law (14), only the specific growth rate for the denitratation is needed. We can apply the same method than previously. The growth rate can be written under the following form :

$$\mu_{NO_{3_L}} = \beta_{NO_{3_L}} S_{NO_{3_L}} \tag{20}$$

$\beta_{NO_{3_L}}$ will be estimated on the basis of the nitrate mass balance equation by using a recursive least square algorithm with a forgetting factor σ, which is written as follows in discrete time :

$$\hat{\beta}_{NO_{3_{L_{t+1}}}} = \hat{\beta}_{NO_{3_{L_t}}} - \gamma_t \phi_t e_t \tag{21}$$

$$\phi_t = C_1 S_{NO_{3_{L_t}}} \hat{X}_{a_{L_t}} \Delta t \tag{22}$$

$$\begin{aligned} e_t = {} & y_{L_{t+1}} - y_{L_t} + \Delta t \frac{u}{\varepsilon} (\Delta S_{NO_{3_{L_t}}} + \Delta S_{NO_{2_{L_t}}} \\ & + b_{0_{N+1}} (S_{NO_{3,in}} + S_{NO_{2,in}}) - C_2 (\Delta \hat{S}_{C_{L_t}} \\ & + b_{0_{N+1}} S_{C,in}(t))) - C_2 \Delta t \frac{d\hat{S}_{C_L}}{dt} \\ & - C_1 \Delta t S_{NO_{3_{L_t}}} \hat{\beta}_{NO_{3_{L_t}}} \hat{X}_{a_{L_t}} \end{aligned} \tag{23}$$

$$\gamma_t = \frac{\gamma_{t-1}}{\sigma + \gamma_{t-1}^2 \phi_t^2}, \quad 0 < \sigma \leq 1 \tag{24}$$

5 Experimental results

The experimental denitrification process is a fixed-bed biofilter of 2.1 m high (Fig. 1) as previously described. The polluting substrates (nitrite and nitrate) moved freely along the reactor, with a superficial velocity u of $6m/h$ or $9m/h$. The ethanol solution supplied at the reactor inlet is considered hereafter as the control variable.

5.1 Nitrite and nitrate measurements

Nitrite and nitrate concentrations are measured by molecular absorption spectrometry (Technicon sensor); the automatic determination method uses a process of nitrate and nitrite reduction by segmented continuous flow. A set of electromagnetic valves is controlled by the microcomputer, allowing to handle measurements of concentrations. The duration of a cycle of measurements depends on the number of sampling points (from ten to twenty minutes).

5.2 Computer system

A software package has been developed [9] to manage the different tasks relative to measurements, actions, parameter estimation, control action evaluation, graphic display, storage. This package has been implemented in C language on a PC compatible microcomputer (low equipment cost). An Advantech PC-LabCard PCL-812PG has been used for the communications between the microcomputer and the process.

5.3 Implementation form of space derivative

The numerical implementation of the control law requires the computation of space derivatives. This can be done by using either the orthogonal collocation method or a finite difference method. In both cases, several measurement points are needed ; from a practical point of view, this is a drawback for the implementation. It has been shown (through simulation runs and experiments on the biofilter) that it is possible to use the following (global finite difference) approximation :

$$\begin{aligned} \frac{\partial S_{NO_3}(z,t)}{\partial z}_{|_{z_L}} &\cong \frac{S_{NO_{3_L}} - S_{NO_{3,in}}}{L} \\ &= \underbrace{\frac{S_{NO_{3_L}}}{L}}_{\Delta S_{NO_3}(z_L,t)} + \underbrace{\frac{-1}{L}}_{b_{0_{N+1}}} S_{NO_{3,in}} \end{aligned}$$

$$\begin{aligned} \frac{\partial S_{NO_2}(z,t)}{\partial z}_{|_L} &\cong \frac{S_{NO_{2_L}} - S_{NO_{2,in}}}{L} \\ &= \underbrace{\frac{S_{NO_{2_L}}}{L}}_{\Delta S_{NO_2}(z=L,t)} + \underbrace{\frac{-1}{L}}_{b_{0_{N+1}}} S_{NO_{2,in}} \end{aligned}$$

The choice for global finite differences approximation for discretizing spatial derivatives of concentrations was didacted by two main reasons : the closed-loop simulation study showed that this kind of approximation lead to less sensitive results for regulation performances; in industrial plants, measurements are generally available only at the input and the output of the biofilter.

5.4 initial values and parameter values

Estimation and control algorithms have been initialized from eq. (14)-(19) as follows via numerical simulations :

$\zeta_1(L,0) = 11.80$, $(= S_C(L,0) + h_1 S_{NO_3}(L,0) + h_2 S_{NO_2}(L,0))$
$\zeta_2(L,0) = 666.43$, $(= (\delta X_a(L,0) + X_a(L,0)) + h_3 S_{NO_3} L, 0) + h_4 S_{NO_2}(L,0))$
$\hat{S}_{NO_3}(L,0) = 17.00$ g[N]$/m^3$, $\hat{S}_{NO_2}(L,0) = 0.00$ g[N]$/m^3$,
$S_C(L,0) = 101.5$ g[COD]$/m^3$, $X_a(L,0) = 625$ g[COD]$/m^3$,
$\hat{\beta}_{NO_3}(L,0) = 0.189$, $\sigma = 0.98$, $\gamma_0 = 20$, $\lambda = 4$ h^{-1}, $\Delta t = 0.25$ h.

The initial values of the auxiliary variables ζ_1 and ζ_2 have been chosen so as to correspond to the initial state of the reactor, plus some initial error (about 3 % : $\delta X_a(L,0) \simeq 20\ g[COD]/m^3$) on the value of the active biomass X_a. The values of the design parameters σ, λ and γ_0 have been chosen via numerous simulations so as to give a fair compromise between fast enough closed loop dynamics and good disturbance rejection. In particular, the value of λ corresponds to a closed loop time constant of 15 minutes.

The model parameters are equal to :

$$L = 2.1 \text{ m}, \epsilon = 0.52, Y_{h_1} = 0.51, Y_{h_2} = 0.42$$

The initial operating conditions are equal to :

$S_{NO_{2,in}} = 0$ g[N]$/m^3$, $S_{NO_{3,in}} = 17$ g[N]$/m^3$, $S_{C,in} = 101.5$ g[N]$/m^3$

The set point has been arbitrarily set to $2g[N]/m^3$ which is lower than the European standard ($5.65g[N]/m^3$).

5.5 Implementation of the control signal

The sampling period was equal to 15 minutes. The control variable, i.e. the influent ethanol concentration $S_{C,in}$, acted on the process by using a pump working at computer defined rates. It has been bounded from $10g[COD]/m^3$ to $189g[COD]/m^3$.

5.6 Results

Several experiments have been carried out to examine the response of the control scheme to various practical stimuli. The first experiment presented here has been done with the superficial fluid velocity $\frac{F}{A} = 9m/h$. Figure 4.1 shows the nitrate and nitrite concentrations at the outlet of the biofilter, the setpoint and the controlled output and the control variable respectively. The output has been converging towards the setpoint in two hours. At this time, a perturbation occurred, due to the breakdown of a pressure pump. Some other disturbances took place between four and five hours which have not been identified. In spite of these disturbances, the setpoint has been reached and tracked. The control input increased towards its maximal value to force the output variable to reach the setpoint.

The second experiment (see Figure 5) shows the closed-loop response after a load disturbance (the superficial fluid velocity increases from $6m/h$ to $9m/h$ after one hour) : the output converges towards the setpoint after a transient period of two hours. The control action remained smooth and slowly decreased.

Both figures 4.1 and 5 show the controlled output y_L, the control input $S_{C,in}$, and both components (nitrate and nitrite) of the controlled output. Figure 5.3 shows the values of the estimated biomass and ethanol concentration as well as the estimation of the "specific growth rate" $\beta_{NO_{3L}}$. Because of the use of a global finite difference for the space derivatives, bias can be introduced in the estimation of $\beta_{NO_{3L}}$. Because $\hat{\beta}_{NO_{3L}}$ is a physical parameter whose value can be interesting for process monitoring and diagnosis, it is interesting to recover values closer to the true ones. This can be done by considering better evaluation of the space derivatives of S_{NO_3}, S_{NO_2} and S_C.

One practical constraint is that the true on-line values of the space derivatives are unknown : that's why we have decided to consider a polynomial approximation for each concentration $S(z)$ on the basis of the steady-state data considered before : $S(z) = az^2 + bz + c$. The second step consists in changing each term of spatial derivative of nitrate, nitrite and carbon concentrations in eq. (21)(22)(23)(24) by the following approximations :

$$\begin{aligned}
\Delta S_{NO_{3_{L_t}}} + b_{0_{N+1}} S_{NO_{3,in}} &\simeq 2a_1 z_L + b_1 \\
\Delta S_{NO_{2_{L_t}}} + b_{0_{N+1}} S_{NO_{2,in}} &\simeq 2a_2 z_L + b_2 \\
\Delta \hat{S}_{C_{L_t}} + b_{0_{N+1}} S_{C,in}(t) &\simeq 2a_3 z_L + b_3
\end{aligned}$$

It has been found : $a_1 = 8.45$, $b_1 = -25.00$, $a_2 = -7.90$, $b_2 = 13.16$, $a_3 = 21.32$ and $b_3 = -93.04$.

As it is illustraten in ([3]), the second order polynomial approximation (derived from steady state concentration profiles) allows a rather fair estimation of the specific growth rate. As a matter of illustration we have added in Figure 5.3 (dotted line) the estimation of $\beta_{NO_{3L}}$ by using the polynomial interpolation for the space derivatives.

6 Conclusion

This paper was concerned with the control of a fixed bed denitrifying process (see also [2]). The purpose was to regulate the output total concentration of nitrates and nitrites by acting either on the superficial velocity or on the inlet ethanol concentration. An Adaptive linearizing controller has been designed and tested in simulation before the on-line implementation on the process. In the experiments, the inlet ethanol concentration has been chosen to regulate the residual sum of nitrate and nitrite concentration at the outlet of the biofilter.

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References

[1] Bastin G. and D. Dochain (1990). On-line Estimation and Adaptive Control of Bioreactors. *Elsevier*, Amsterdam.

[2] Bourrel S. (1996). Estimation et Commande d'un Procédé à Paramètres Répartis Utilisé pour le Traitement Biologique de l'Eau à Potabiliser. *Doctoral Dissertation, Université Paul Sabatier, Toulouse, France.*

[3] Bourrel S., D. Dochain, J.P. Babary and I. Queinnec (1998). Modelling, identification and control of a denitrifying biofilter. *Journal of Process Control* (to appear).

[4] Dochain D. (1994). Contribution to the Analysis and Control of Distributed Parameter Systems with Application to (Bio)chemical Processes and Robotics. *Thèse d'Agrégation de l'Enseignement Supérieur, UCL, Belgium.*

[5] Dochain D., N. Tali-Maamar and J.P. Babary (1997). On modelling, monitoring and control of fixed bed reactors. *Comp. Chem. Eng.*, **21/11**,1255-1266.

[6] Dochain D. and M. Perrier (1993). Asymptotic observers for fixed bed reactors. *Proc. ACC*, 1169-1183.

[7] Henze M., L. Grady Jr., W. Gujer, G.R. Marais and T. Matsuo (1987). Activated sludge model $N°1$. *Technical Report, IAWPRC Science and Technology Reports $N°1$, London.*

[8] Jacob J., H. Pingaud, J.M. Le Lann, S. Bourrel, J.P. Babary and B. Capdeville (1996). Dynamic simulation of biofilters. *SIMULATION - Practice and Theory*, Vol. 4, 335-348.

[9] Queinnec I., S. Bourrel and E. Paul (1996). Conduite en temps réel d'un réacteur de dénitrification. *LAAS/CNRS Report, n° 96076.*

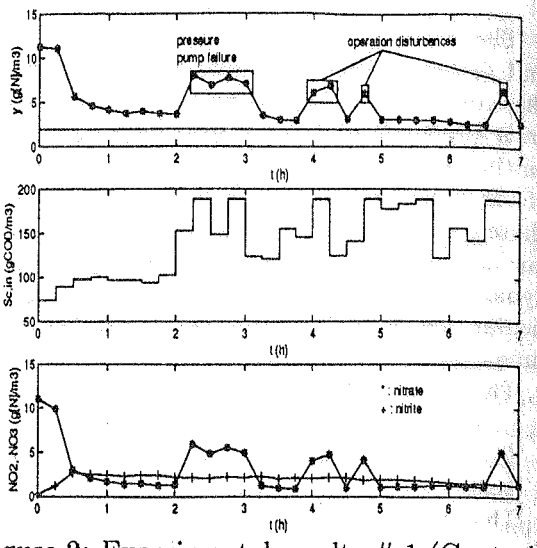

Figure 2: Experimental results # 1 (Control)

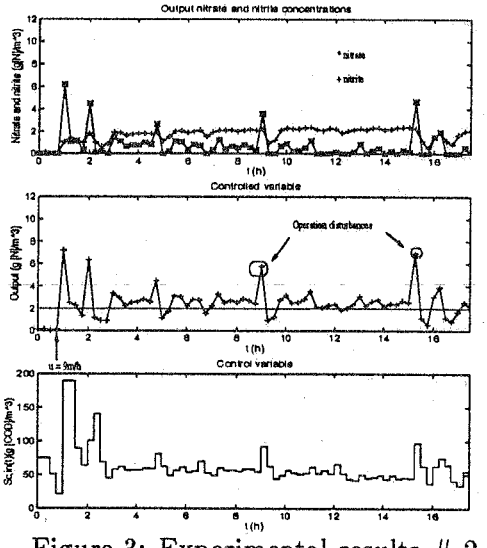

Figure 3: Experimental results # 2

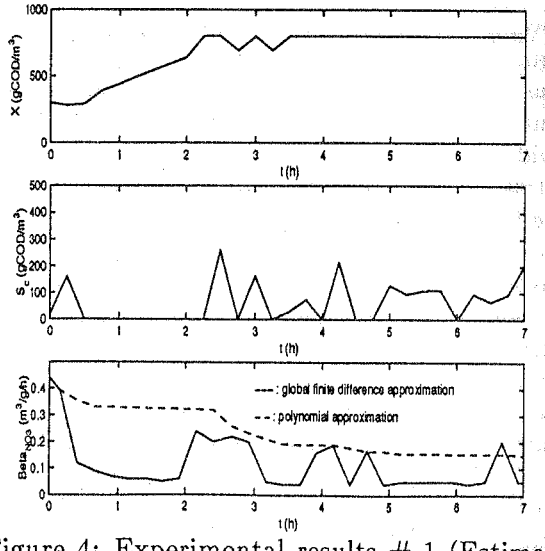

Figure 4: Experimental results # 1 (Estimation)