ROBUST REGULATION OF ANAEROBIC DIGESTION PROCESSES

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Abstract:

In this paper we propose a simple controller to assess the Chemical Oxygen Demand of an anaerobic digester. We first present the model of the anaerobic digester based on two steps: acidogenesis and methanogenesis. Then we propose a simple output feedback controller for the model, that regulates a variable strongly related to the COD. The robustness of the control is illustrated by a simulation study assuming noisy measurements. We have implemented the controller on an anaerobic digestion process to validate its efficiency on a real life experiment.

Keywords:

Anaerobic wastewater treatment, continuous bioreactor, robust control.

1 Introduction

Control of biological wastewater treatment plants is a delicate problem since most of the time the available biological models are only rough approximations. Indeed, biological systems are known to be highly variable, difficult to measure so that no "strong" biological law is available. Thus, deterministic models of wastewater treatment especially suffer from modelling uncertainties: a very complex ecosystem composed by many different bacterial populations takes place in these processes. Thus, developping control systems based on simple measurements and able to guarantee the behavior of the process, in spite of modelling uncertainties, is of primary importance.

In the following, an anaerobic wastewater treatment process will be considered. Anaerobic digestion is a high yield biological process that reduces organic matter (Chemical Oxygen Demand, COD) of the influent to produce valuable energy (methane). The underlying model assumes that two main bacterial populations are present [2]. The first one, the acidogenic bacteria X_1, consumes the organic substrate S_1 (total soluble COD except Volatile Fatty Acids) and produces volatile fatty acids (VFA) S_2 through an acidogenesis step. The second population (methanogenic bacteria) X_2, uses the VFA in a methanogenesis step as substrate for growth and produces methane.

As the process is known to become unstable under sertain circumstances, it requires therefore a regulation procedure to ensure that the closed loop plant will be driven to the desired operating point and thus to avoid washout of biomasses.

In this work, a control law driving the model to the desired set point is proposed. Nonlinear system theory guarantees the behavior of the closed loop plant. Simulation and real life experiments validate this approach and achieve the contribution.

2 The Mass Balance Model

The dynamical model is based on the two following bioreactions:

- Acidogenesis: $k_1 S_1 \xrightarrow{r_1(.)} X_1 + k_2 S_2$
- Methanogenesis: $k_3 S_2 \xrightarrow{r_2(.)} X_2 + k_4 CH_4$

Reaction rates are given by: $r_i(.) = \mu_i(.)X_i$. According to [1], we obtain the following model:

$$\begin{cases} \dot{X}_1 = \mu_1(.)X_1 - \alpha D X_1 \\ \dot{S}_1 = -k_1\mu_1(.)X_1 + D(S_{1in} - S_1) \\ \dot{X}_2 = \mu_2(.)X_2 - \alpha D X_2 \\ \dot{S}_2 = -k_3\mu_2(.)X_2 + k_2\mu_1(.)X_1 + D(S_{2in} - S_2) \end{cases} \tag{1}$$

where D is the dilution rate, the terms S_{1in} and S_{2in} are the influent concentrations of S_1 and S_2 respectively. The k_i represent the yield coefficients associated with bacterial growth, $\mu_1(.)$ and $\mu_2(.)$ are the specific growth rates of X_1 and X_2. The parameter $\alpha \in]0\ 1[$ represents the proportion of bacteria that are not fixed on the bed, and therefore which are affected by the dilution effect: $\alpha = 0$ would correspond to an ideal fixed bed reactor, $\alpha = 1$ to an ideal continuous stirred tank reactor (CSTR).

Methane solubility is very low, therefore the methane produced by the methanogenesis step is not stored in the liquid phase. The methane flow rate (Q_{CH_4}) can then be written as a function of the state as follows:

$$Q_{CH_4} = k_4\mu_2(.)X_2$$

The methane flow rate is on-line measured, let us denote this output $y = \frac{Q_{CH_4}}{k_4} = \mu_2(.)X_2$.

Usually, the most crucial problem in solving equations (1) is the formulation of reasonable expressions for the corresponding specific growth rates: $\mu_1(.)$ and $\mu_2(.)$. *This work does not assume any analytical expression for the growth rates.*

3 Control Design

We propose a control law, using the output y for feedback, the dilution rate D as the manipulated variable, that achieves, independently of the kinetics, the global stabilisation of a process following model (1).

Such a controller does not exactly regulate the COD, but a biological equivalent of the total amount of organic substrate in the fermenter, denoted S_T. We have:

$$S_T = S_1 + \frac{k_1}{k_2}S_2$$

Classical pollution measurements (COD) are based on yield of *chemical* reactions involved in organic pollution degradation. Here we have the same reasoning, but we base our approach on yield of *biochemical* reactions involved in organic pollution degradation: here is the meaning of variable S_T. Thus, S_T regulation is equivalent to classical pollution (COD concentration) regulation.

We want to compute the control variable ($D(.)$) to be applied so that, with a chosen fixed positive $S_T^\star$, S_T has the following dynamics:

$$\dot{S}_T = D(.)(S_T^\star - S_T) \tag{2}$$

It is straightforward from system (1) that $D(.)$ must be computed from the output y as follows:

$$D(\xi) = \frac{k_3 k_1}{k_2(S_{Tin} - S_T^\star)}y \tag{3}$$

Hypothesis:

- *μ_i are functions of S_i only; $\mu_i(0) = 0$ and $\mu_i > 0$ when $S_i > 0$*
- *The initial conditions for the state variables, $S_{1,in}$ and $S_{2,in}$ are all positive*
- $0 < S_T^\star < S_{1,in}$
- *$\mu_1(.)$ is an increasing function on $[0 \;\; S_T^\star]$, $\mu_2(.)$ is an increasing function on $[0 \;\; \frac{k_2}{k_1} S_T^\star]$*

Theoretical considerations on the closed loop system show that there is only one equilibrium (corresponding to the set point $S_T^\star$); moreover, it is globally asymptotically stable provided that our hypotheses hold (see [3], [4]).

Key points of the demonstration are:

- First: we have to show that $\int_0^{+\infty} D(\xi(\tau))d\tau = +\infty$.
- Then, it is straightforward that S_T tends towards the set point $S_T^\star$ as $t$tends to infinity. Same conclusion hold for X_2 that tends to $X_2^\star = \frac{k_2(S_{Tin} - S_T^\star)}{\alpha k_3 k_1}$.
- We have still to consider the dynamical system in S_1 and X_1 on the manifold $S_T = S_T^\star$ and $X_2 = X_2^\star$. The study ensures that there is a single equilibrium point for this reduced system, moreover it is globally asymptotically stable.
- A local study of the jacobian matrix of the whole system ensures local exponential stability of the single equilibrium corresponding to $S_T = S_T^\star$.
- To conclude we apply a theorem from [6] on the stability of hierarchical systems that ensures that the single equilibrium point corresponding to $S_T = S_T^\star$ is globally asymptotically stable.

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4 Simulation Study

In this section, the parameter values given by [2] have been chosen to run the model. A multiplicative white noise (40%) has been added to the measurement of the methane flow rate.

We choose $S_T^\star = 2gCOD/l$ as the desired set point for S_T. With the kinetics expression of [2], ($\mu_1(S_1)$ follows Monod kinetics, $\mu_2(S_2)$ Haldane kinetics), our hypotheses are fullfiled. Thus, the closed loop system has a single equilibrium, globally asymptotically stable.

The simulated controller results can be seen on Figure 1. A simple linear filter in the feedback loop decreases the noise level for high frequencies. Despite the high level of noise, the controller action is efficient and turns out to be very robust towards variations of the influent concentration.

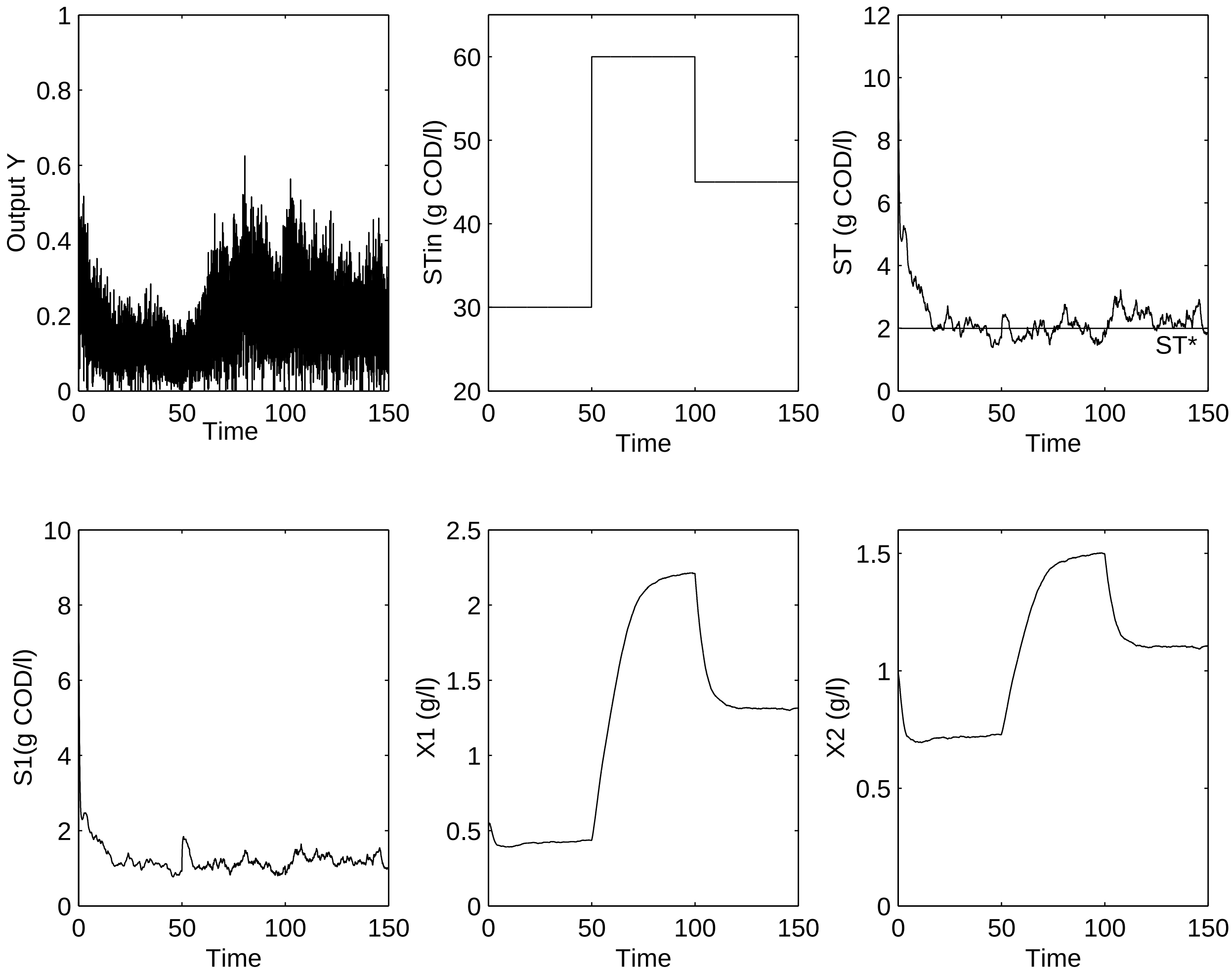

Figure 1: Simulation of the controlled plant, variations of the influent COD, 40% noise on output y.

5 Experimental Results

Experimental validation of the controller has been performed on the fully instrumented fix bed anaerobic digester [5], located in Narbonne (France), at the “Laboratoire de Biotechnologie de l’Environnement” (LBE) of the INRA.

The plant is a continuous upflow fixed-bed anaerobic digester. The digester is fed with raw industrial wine distillery vinasses obtained from local wineries and diluted in water by a factor 2. The plant is fully instrumented with sensors (online measurements of COD, VFA, gas outflows...) and actuators. All the sensors and actuators are connected to an input/output device that allows the acquisition, treatment and storage of data. Software’s device may perform advanced control law calculations and human operators can introduce and change some process parameters.

We show two transient behaviors for the input variable D and for the controlled variable S_T on figure 3. These experiments are in agreement with the predicted behavior of the closed loop plant (a first order with an unsettled positive gain).

Moreover, while experiments were carried out some failures happened and the closed loop plant had a safe behavior (see figure 4). Indeed for most failures, a decrease of the output methane flow

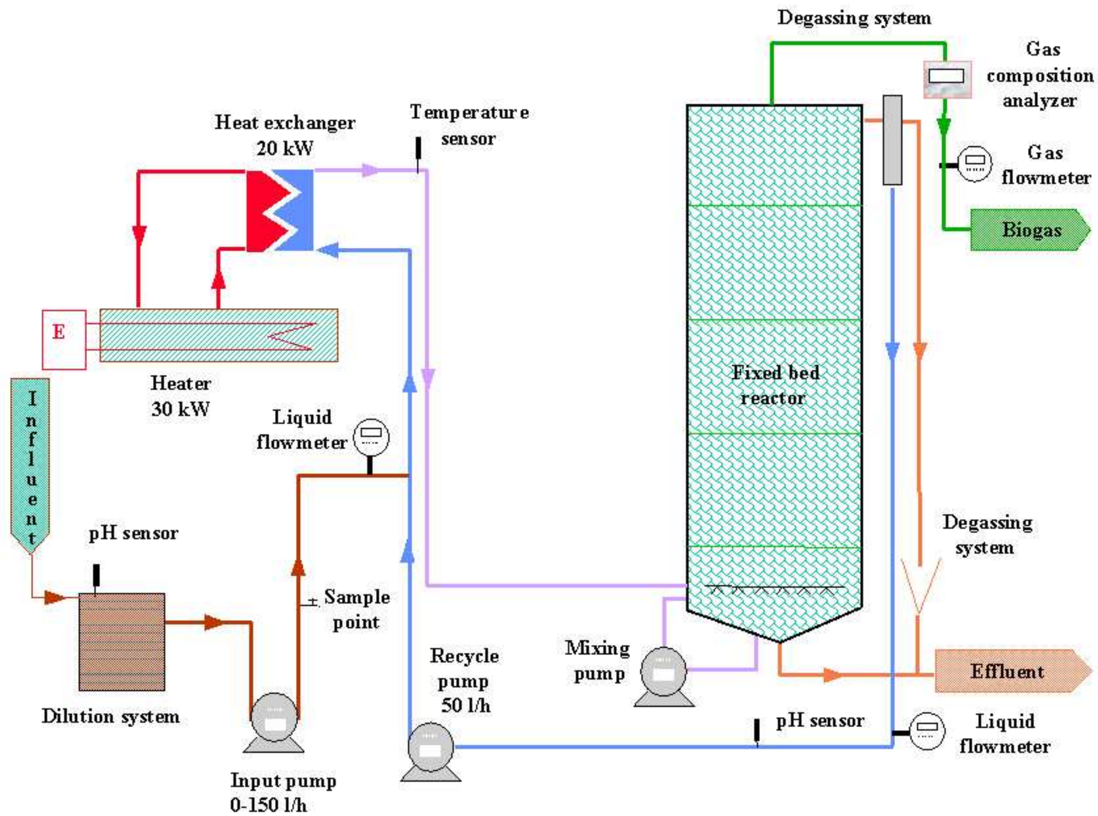

Figure 2: Schematic layout of the up-flow anaerobic fixed bed treatment plant.

rate was observed. In this case it is straightforward that the feedback loop leads the dilution rate to zero that is the safest situation (biomasses can not be washed out), at short term, for anaerobic digesters. Note that the action of PID-like controlers would be the opposite: increase dilution in order to increase methane production.

This phenomenom is highlighted on two kinds of failures. The first one (case A) is a misfunctioning in the gas analysing loop together with a problem in the dilution loop. The second (case B) essentially consists in feeding the digester with water. One can note that for both cases, the computed control law leads the dilution rate to its minimal value (5 l/h).Thus, human operators will have time to fix the problem.

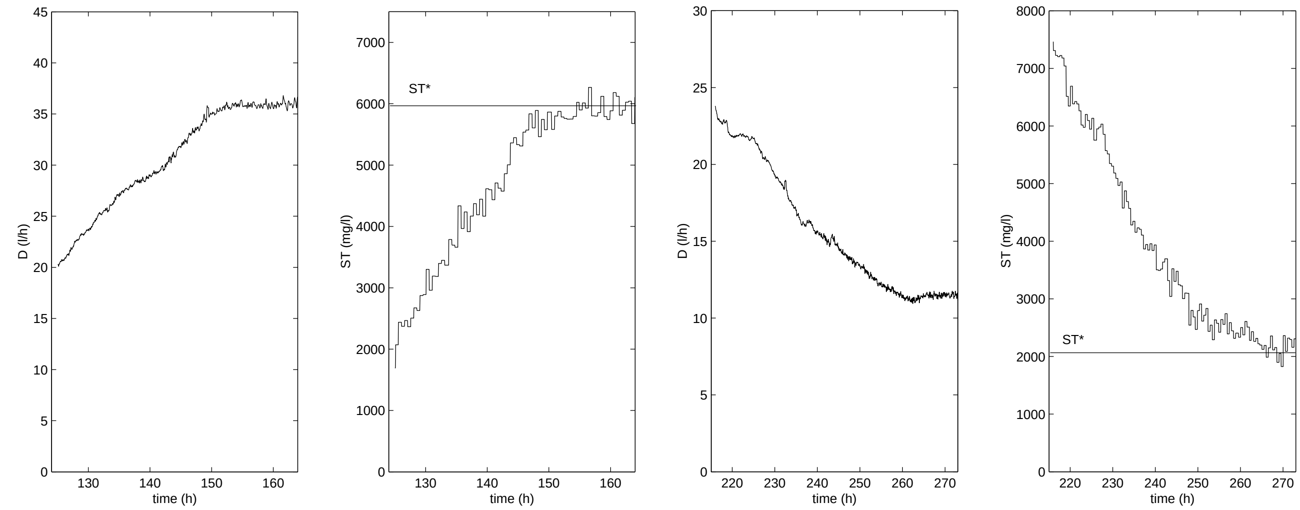

Figure 3: D and S_T behavior during two transients

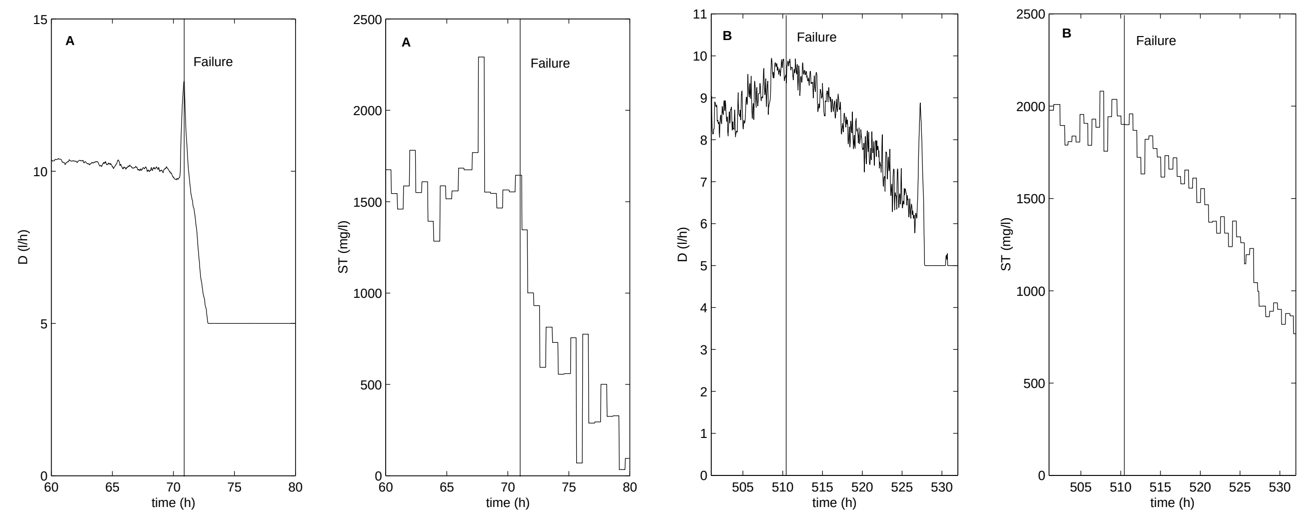

Figure 4: D and S_T behavior versus two kinds of plant failures

6 Conclusion

The proposed controller is very simple in its design: it is only an output feedback law. The only required parameter is the feedback gain, thus the controller can be tuned online just by changing the feedback gain in order to obtain the desired set point value for S_T (or COD). This control law turns out to be very robust to noise (even at high level) and to variations of the COD influent concentration.

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