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ADVANCED CONTROL OF ANAEROBIC DIGESTION PROCESSES THROUGH DISTURBANCES MONITORING

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Abstract—This paper presents a new control strategy for highly loaded anaerobic digestion processes. This strategy is based on the analysis of disturbances added on purpose to the influent flow rate. The control system then carefully overlooks the response of only two parameters, the biogas output flow rate and the pH, in order to determine whether or not the load can be increased. The main advantages of this approach rely on its capability to automatically adapt the input flow rate to changes in the influent concentration, without any information on its concentration, and to optimize the biological treatment in relation to the influent degradability. Experiments have been carried out using two fluidized bed reactors of different sizes and they have demonstrated very good capability of this control strategy. In addition, since only very simple sensors are needed, industrial applications of this strategy can be expected. © 1999 Elsevier Science Ltd. All rights reserved

Key words—anaerobic digestion process, fluidized bed reactor, loading rate, control strategy, disturbance, monitoring

NOMENCLATURE AND NOTATIONS

COD = chemical oxygen demand ($g{\cdot}l^{-1}$)
EGV = expected biogas volume (l)
f_{max} = maximal percentage of variation of input flow rate
HRT = hydraulic retention time (h), (HRT $= \varepsilon V/Q$)
OLR = organic loading rate (kg $COD{\cdot}m^{-3}{\cdot}d^{-1}$), (OLR $= Q{\cdot}COD_{in}/V$)
Q = input flow rate ($l{\cdot}h^{-1}$)
Q_{old} = input flow rate before disturbance ($l{\cdot}h^{-1}$)
ΔQ = variation of input flow rate ($l{\cdot}h^{-1}$)
Q_g = biogas flow rate ($l{\cdot}h^{-1}$)
$Q_{g,av}$ = average biogas flow rate ($l{\cdot}h^{-1}$)
α = increase of input flow rate during a disturbance (% of previous flow rate)
δt = duration of a disturbance (h)
R = response factor (see in text)
R_{min} = tuning parameter: minimal value of R below which input flow rate is decreased
R_{max} = tuning parameter: maximal value of R over which input flow rate is increased
TOC = total organic carbon ($g{\cdot}l^{-1}$)
V = expanded bed volume (m^3)
VFA = volatile fatty acids ($g{\cdot}l^{-1}$)
ε = bed porosity

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INTRODUCTION

Anaerobic digestion, a process where organic matter is degraded into biogas (i.e. a gas mixture of methane and carbon dioxide), is particularly adapted for the treatment of food industry wastewater because it reduces the chemical oxygen demand (COD) of the influent and produces valuable energy (methane). In addition, this process is able to operate under severe conditions: high-strength effluents and short hydraulic retention times.

Several processes have been developed to operate anaerobic digestion processes. Concerning immobilized biocatalyst, for example, the anaerobic filter is a fixed bed process that provides high biomass concentration (Switzenbaum, 1983). However, low liquid velocity may lead to mixing problems and clogging in such systems (Henze and Harremoes, 1983; Bolle *et al.*, 1986). On the other hand, the upflow anaerobic sludge bed reactor (UASB) provides high biomass retention in bacterial granules ranging from 1 to 5 mm in diameter and admissible load can reach 40 kg $COD{\cdot}m^{-3}{\cdot}d^{-1}$ (Lettinga *et al.*, 1980; Pauss and Guiot, 1993). However, granule size control is quite difficult in these reactors, all the more since granule formation seems to be affected by changes in the quality of the effluent (Heijnen *et al.*, 1989). In fluidized bed biofilm reactors (FBBR), a higher biomass retention is achieved due to the large specific area of the support particles (Shieh and Keenan, 1986). Moreover, the fluidized state provides good mixing properties of the liquid phase. In fact, this system appears to be one of the most efficient for wastewater treatment.

In recent years, the development and the improvement of high performance bioreactors, on-line facilities and application of automatic control have brought evidence that bioprocesses can be optimized and efficient biological pollutant removal can be achieved. However, when dealing with anaerobic digestion processes, several problems are to be handled: slow methanogenic organisms growth, instability caused by toxic substrate or by overloading and, even though large progress has been made, bad understanding of the process. It is thus largely recognized that control of anaerobic digestion processes is a mandatory step because of the possible destabilization of the process due to disturbances such as overloading or accidental toxic feeding. However, applied control algorithms are mostly conventional PID type and there are only a few experimental results in the literature. A review of control studies applied to real processes can be found in the excellent paper by Heinzle *et al.* (1993).

As depicted before, one of the key issues to be addressed in controlling biological wastewater treatment processes is to reject the disturbances that can destabilize the reactor. In order to tackle this problem (i.e. insensitivity to unmodeled phenomena and parameter variations together with disturbance rejection), robust control strategies appear as a very promising option and significant improvements over conventional proportional integral (PI) controllers are evidenced (Pohlmeier, 1991; Steyer *et al.*, 1995; Harmand *et al.*, 1996). An adaptive control scheme could also be used because of its good disturbance rejection ability (Renard *et al.*, 1988; Dochain and Perrier, 1993; Ben Youssef *et al.*, 1995; Johnson *et al.*, 1995). In such a case, the parameters of the controller are continuously adapted to follow, and sometimes to estimate, the changes in the operating conditions. On the other hand, in a robust control scheme, the uncertainty is explicitly accounted for at the beginning of the design and no parameter adaptation is made over time. An adaptive control scheme can thus achieve better performance whereas a robust control scheme can handle more severe operating conditions. It is here to be noticed that many other control schemes can also be useful. For example, we mention the fuzzy control approach that appears to be capable of reducing the maximum extent of COD overload by 50% (Marsili-Libelli, 1992; Müller *et al.*, 1995). Fuzzy approximate reasoning was also used by Boscolo *et al.* (1993) for the management of a pilot scale anaerobic digester in order to improve the treatment of municipal solid wastes and by Estaben *et al.* (1997) for the control of an anaerobic digestion fluidized bed reactor. Another approach, a case-based control strategy, has been demonstrated to be useful and reliable at both laboratory and industrial scales (Moletta *et al.*, 1995a).

THE CONTROL STRATEGY

The purpose of our study is to develop a control strategy for an anaerobic digestion process. However, compared to more conventional controllers, our study faces this problem all the way around: even though our goal is to maintain the organic loading rate as high as possible despite variations in the influent concentration and to keep low and stable the concentration of the treated effluent, the basic idea of our strategy is to add disturbance on purpose on the input flow rate. We then analyze the response of some key parameters in order to determine whether or not it is possible to increase the loading rate. In the case of a negative effect of the disturbance (e.g. the disturbance induces an overload of the reactor), the loading rate is decreased whereas, in the case of no negative effect of the disturbance, the loading rate is increased.

We furthermore intend to develop this control strategy without any information about the input concentration. The choice of appropriate sensors is then of crucial importance. However, as pointed out by Olsson (1993) and Vanrolleghem (1994), several reasons explain the lack of instrumentation, control and automation in the field of biological treatment processes. Among these reasons, the lack of appropriate and reliable sensor technology and the difficulty we have in acting correctly on such a process are paramount. In our application, sensors were selected according to their potentiality for further industrial applications with the additional criteria of low maintenance effort. Our choice, based on previous studies related to this topic (see, for example, Marsili-Libelli (1992) and Moletta *et al.* (1995a), where an organic overload was shown to be defined in terms of hydrogen content in the biogas produced), led us to select the overall output biogas flow rate and the pH as the only two measurements used in the control strategy. Methane composition in the biogas produced could have been also selected but, as shown in the following, the two selected sensors were enough to perform our control objectives.

The control algorithm is then the following: a constant influent liquid flow rate with a constant influent concentration induces a certain output biogas flow rate (e.g. $Q_{g,av}$). But, by disturbing the input flow rate (i.e. by increasing the input liquid flow rate by α during δt hour) and by assuming the influent concentration to be constant during this time, we expect the total extra biogas volume ($EGV_{expected}$) to be increased by $\alpha \cdot \delta t \cdot Q_{g,av}$ liters. By integrating the biogas flow rate response, we can then determine the real EGV produced by the disturbance (i.e. EGV_{real}). The integration lasts until the measured biogas flow rate is lower than a moving average of its values (the width of the moving average is equal to the duration of the disturbance). Three different cases can then be observed, according to the value of the response factor R, defined as the ratio of $\mathrm{EVG_{real}}$ on $\mathrm{EGV_{expected}}$ (R = $\mathrm{EGV_{real}}$/$\mathrm{EGV_{expected}}$):

1. If the measured EGV is almost the expected one (i.e. $R \geq R_{\max}$), we can conclude that the microbial population is able to manage an increase of the loading rate. The input flow rate is then increased by a certain amount according to equation 1.
2. If the measured EGV is lower than the expected one (i.e. $R_{\min} \leq R < R_{\max}$), we conclude that the microbial population has reached its maximum treatment capacity and the input flow rate is kept constant at the value applied before the disturbance.
3. If the measured EGV is much lower than the expected one (i.e. $R < R_{\min}$), we conclude that the reactor is overloaded and the input flow rate is decreased by a certain amount (see equation 2).

Figure 1 graphically describes this strategy showing a typical experimental answer when $R \geq R_{\max}$.

$R_{\min}$ and $R_{\max}$ are two tuning parameters that are empirically chosen. The control law is thus defined as follows, ΔQ being the variation of input flow rate applied and Q_{old} the flow rate before the disturbance. $f_{\max}$ is the maximal percentage of admissible variation. After many tests with different values for $f_{\max}$, we decided to fix it to 0.2 (i.e. $f_{\max} = 20\%$). This means that with the best response (R = 1), the flow rate is increased by 20% and in the worst case (R = 0), it is reduced by 20%.

$$\text{If } R \geq R_{\max} \quad \text{then } \frac{\Delta Q}{Q_{\mathrm{old}}} = f_{\max} \cdot \left(\frac{R - R_{\max}}{1 - R_{\max}} \right) \qquad (1)$$

$$\begin{aligned} &\text{If } R_{\min} \leq R < R_{\max} \quad \text{then } \frac{\Delta Q}{Q_{\mathrm{old}}} = 0, \\ &\text{If } R < R_{\min} \quad \text{then } \frac{\Delta Q}{Q_{\mathrm{old}}} = f_{\max} \cdot \left(\frac{R - R_{\min}}{R_{\min}} \right) \end{aligned} \qquad (2)$$

It is to be noticed that both the increasing and decreasing quantities for the input flow rate are closely related to the value of the response factor R: the higher this ratio is (respectively lower), the more the input liquid flow rate is increased (respectively decreased).

Once the process has reached a new stable state after changing the input liquid flow rate, the same methodology is applied again (i.e. a new disturbance is performed and analyzed and the influent feed flow rate is changed according to the response of the output biogas flow rate). The pH is then used to stop this strategy if its value falls below a certain level, which may happen for instance in the case of volatile fatty acid accumulation or if sudden variations in the influent pH occur. In fact, the pH is used as an alarm in the control algorithm, which means that the disturbance analysis gives enough information to be able to take decisions.

This paper describes two phases in the development of this strategy. The first one is the validation phase on a lab-scale (15 l) fluidized bed reactor. The second phase concerns a 120 l pilot where this strategy was tested for the monitoring of the start-up period. We also validated this approach applying sudden disturbances on the input COD (overload and underload). The relationships between the answer factor R and the concentrations of volatile fatty acids were also investigated.

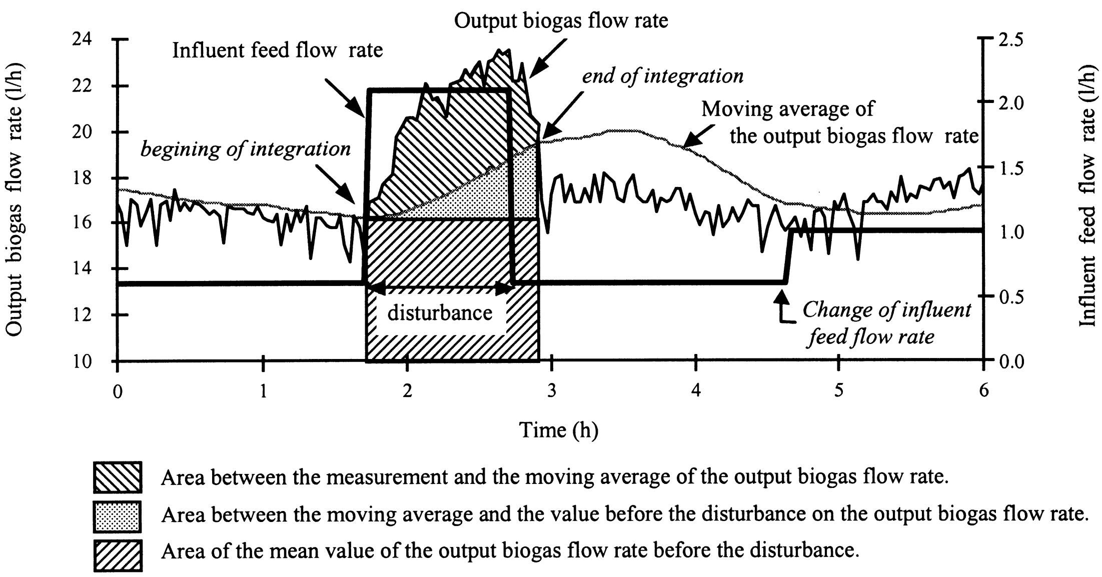

Fig. 1. Graphical description of the control strategy when $R \geq R_{\max}$.

We will see in the following that based only on these two simple on-line measurements (i.e. the output biogas flow rate and the pH), the control system is able to maintain high loading rates and to automatically adapt the loading rate to changes of the influent concentration. Finally, it is to be noticed that this controller has been applied using a fluidized bed reactor but the same strategy could have been used with other process technologies (Moletta *et al.*, 1995b).

MATERIALS AND METHODS

The influent to be treated is a raw wine distillery wastewater whose COD varies between 20 and 30 g/l. The pH of the influent was regulated at approximately 6.3 through alkali addition in the feeding tank. Additional characteristics of the wastewater are depicted in Table 1.

We used two fluidized bed reactors of different volumes (15 and 120 l working volumes) to test our control strategy. Their architecture is depicted in Fig. 2. The 15 l reactor (i.e. reactor I) consists of a cylindrical PVC column (0.115×1.5 m). A calming zone and a gas–liquid separation device are provided over the column. The 120 l reactor (i.e. reactor II) is a 0.2×3.85 m inox column. The temperature is maintained at $35 \pm 2°C$ by a heated water jacket in reactor I and by a variable power heat exchanger in reactor II. In both reactors, a settling device is provided in order to separate the off bioparticles from the liquid phase and to recycle it periodically into the reactor by means of a peristaltic pump. The support particles are made of a fine granular material (i.e. pouzzolane) with a specific density of 2 and a mean diameter of 300 μm. The expansion is provided by the combined effect of the input and recycling liquid flow rates. In reactor II, the overall liquid flow rate in the column is regulated at $0.7\ m^3 \cdot h^{-1}$ which results in an upflow velocity of $14\ m \cdot h^{-1}$. The initial bed height was 1.5 m. The expansion due to fluidisation was approximately 40%, but biomass growth led to an extra expansion resulting in 64% total expansion at equilibrium.

In both reactors, all main parameters (i.e. pH, temperature, liquid and biogas flow rates) are measured and stored on a personal computer using a monitoring software named Control-BUFFER we developed in our laboratory (Steyer, 1995). This software includes the strategy presented here and allows us to control the feeding peristaltic pump at the desired flow rate. It also adjusts the recycle flow in reactor II by monitoring an automatic valve when input flow rate is modified.

Table 1. Characteristics of the raw wine distillery wastewater

Component	Range
Volatile fatty acids (g/l)	1–8
Total organic carbon (g/l)	8–12
Phenol (mg/l)	120–1000
Total suspended solids (g/l)	1.2–7.7
Volatile suspended solids (g/l)	0.7–5
Alkalinity (meq/l)	6.0–62.4
pH	4.0–5.4

Total organic carbon (TOC) analysis are performed routinely using a TOC Dohrman-Carbon analyzer. COD measurements are performed routinely according to standard methods. Volatile fatty acids (VFA) are measured with a flame ionization detector gas chromatograph Chrompack CP 9000, nitrogen being the carrier gas (335 kPa). The column is a semi capillary Econocap FFAP (15 m length and 0.53 mm diameter). The injector and detector temperatures are 250 and 275°C, respectively. The temperature of the oven is programmed to rise from 80 to 120°C during the analysis with an elevation of 10°C/min. The chromatograms are recorded and integrated with a Shimadzu CR3-A integrator.

RESULTS

Validation phase on the 15 l reactor

The 15 l fluidized bed reactor has been controlled for more than a year using this strategy. Extensive experiments and analysis were conducted to check the ability of the control strategy in order to optimize the biological treatment of the wastewater. In particular, we determined disturbance profiles that are high enough to be detected but also low enough to be applied on the process without destabilizing it. In addition, we characterized the correlation between the biogas flow rate and pH responses in order to increase (or decrease when necessary) the

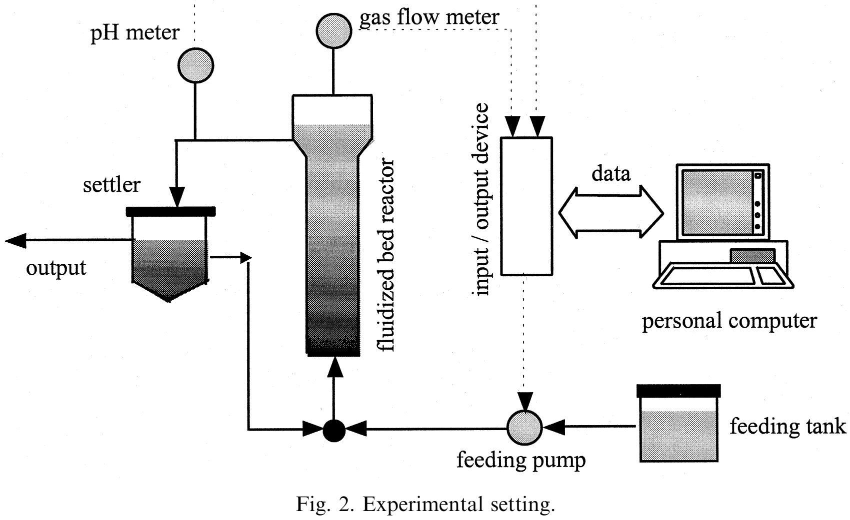

Fig. 2. Experimental setting.

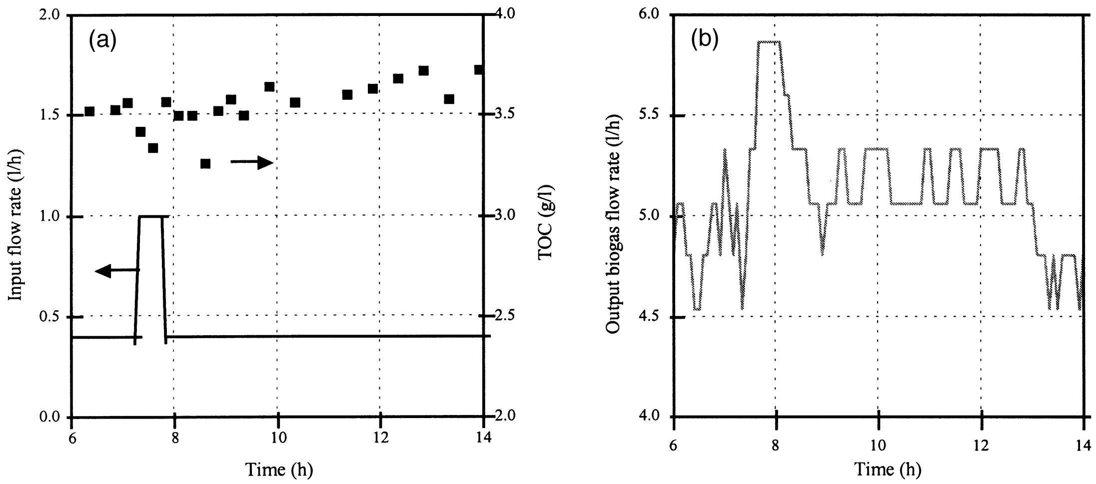

Fig. 3. Response to a disturbance with the following parameters: + 150% during 30 min.

input influent flow rate. An example of disturbance applied to the process is shown in Fig. 3. We can see in Fig. 3 that the disturbance does not induce noticeable changes in the output TOC concentration because of the small amount of carbon added in comparison with the reactor volume [Fig. 3(a)]. On the other hand, the biogas response is high enough to be detected and analysed [Fig. 3(b)].

The validation phase on the 15 l reactor also led to defining the optimal tuning parameters according to the range of hydraulic retention time and effluent concentration. In our case (HRT < 12 h and COD comprised between 15 and 35 g/l), the maximal increase of the load f_{max} is 20%, the R_{min} is 0.05 and the R_{max} 0.15.

An example of weekly profiles is shown in Fig. 4 for the 15 l reactor. It can be seen that the control algorithm increased the loading rate from 35 up to 90 kg COD$\cdot$m$^{-3}\cdot$d^{-1} within less than 5 days without destabilizing the anaerobic digestion process. Stopping of the feeding rate at t = 230 h was due to a change of the influent to be treated (COD in the influent = 18 g/l before t = 230 h and 35 g/l after). This change of the COD contents in the influent, together with the increase of the hydraulic retention time, explains the increase of the organic loading rate. In addition, if we take a closer look at the loading rate at the beginning of this example (See Fig. 5), we can see that the loading rate reaches a maximum after some time. This is a very interesting feature that we observed many times for this control strategy. In fact, whenever the concentration of the influent to be treated changes, the control strategy always tries to increase the loading rate as much as it can. In other words, it looks for

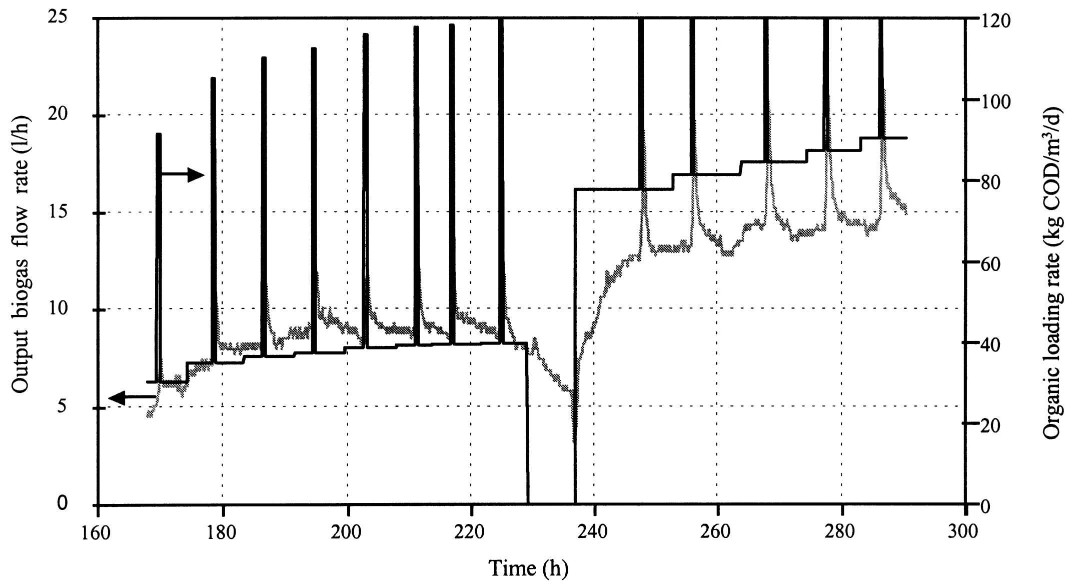

Fig. 4. Weekly profile of the loading rate together with the output biogas flow rate for the 15 l reactor.

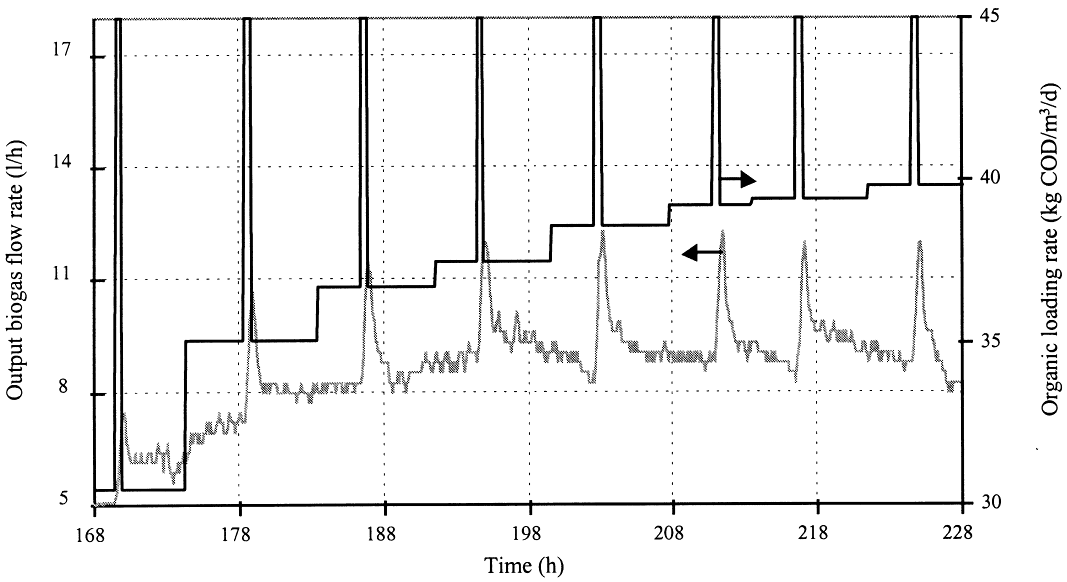

Fig. 5. Automatic adaptation of the increase of the loading rate to the characteristics of the effluent.

the maximum treatment capacity of the process and once it is reached, it follows the influent variations.

Tests on the 120 l reactor

Reactor performance. The start-up of reactor II was monitored over a period of 10 months approximately with the control system described here. The evolution of the organic loading rate (OLR) and the carbon removal during the period of May to November 1996 is shown in Fig. 6. At the very beginning of the operation, the loading rate is increased very rapidly. But at the same time, the carbon removal dramatically dropped down to 70%, showing thus an overload-like behavior. The system then automatically decreased the input flow rate and, consequently, the carbon removal increased. In June, the reactor seemed to have recovered a good removal potential and the OLR was increased slowly up to more than 100 kg $COD{\cdot}m^{-3}{\cdot}d^{-1}$ during the summer, the carbon removal being generally kept above 70%.

The hydraulic retention time seems also to be an important parameter for the overall carbon removal (see Fig. 7). The values presented here show that over a HRT of 2 h, there is no significant influence and the removal is closed to the maximal (over 90%). Below this value, the carbon removal drops very quickly down to 60% for the shortest retention times. That is to say that the reactor is more stable for long HRT and is more subject to instabilities for low HRT. This well-known result is an extra

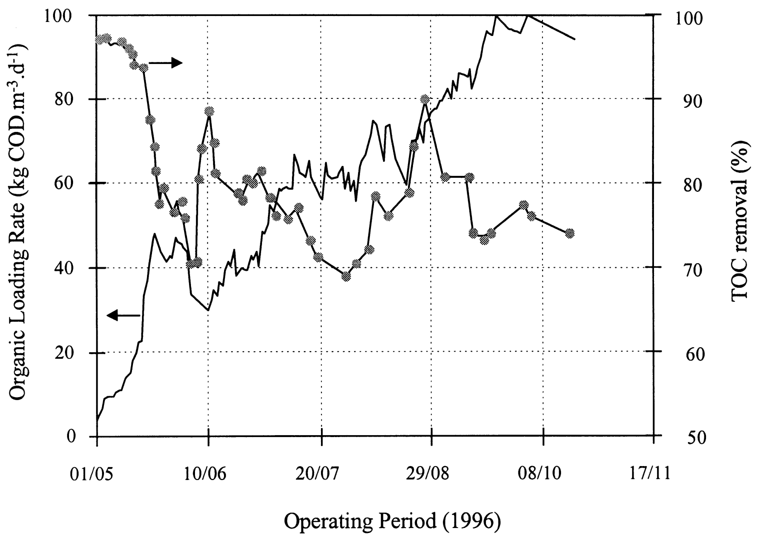

Fig. 6. Organic loading rate and carbon removal over the operating period.

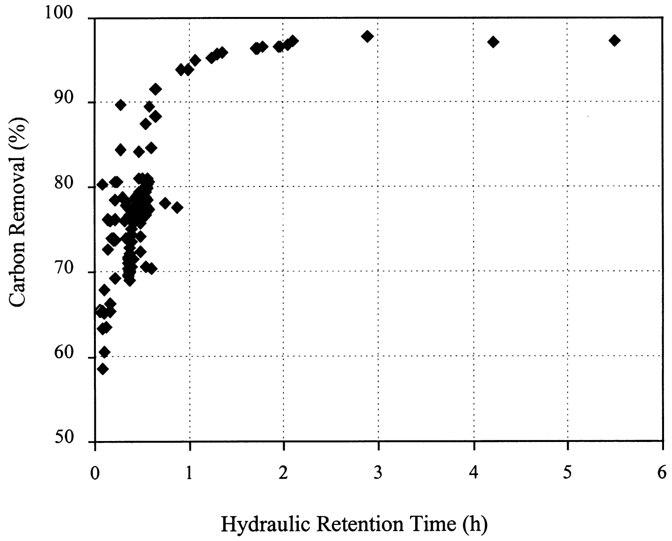

Fig. 7. Influence of the hydraulic retention time on carbon removal.

argument in favor of automatic control systems able to detect the limit of the process.

Changes in inlet COD. Many other tests were conducted to show the ability of the control strategy to handle changes in the influent concentration. For example, in Fig. 8, we can see the biogas response to two different perturbations: the first one is done using vinasses diluted twice as influent (i.e. input COD: $S_{in} = 15\ kg{\cdot}m^{-3}$ during the disturbance) and the second experiment is done using raw vinasses (i.e. input COD: $S_{in} = 30\ kg{\cdot}m^{-3}$). We can clearly see the difference in response from the comparison of these two perturbations: the absence of response during the first disturbance is normal since the combination of increasing the input flow rate together with decreasing the input influent concentration leads to a stable organic loading rate. On the other hand, using raw vinasses throughout the whole disturbance leads to double the organic loading rate and thus, to a significant response of the biogas flow rate.

The influence of a change of the influent COD concentration was also investigated over a long period of time. Our objective was here to analyse the reaction of the control system when facing a sudden underload or a sudden overload of the process. This has been done by diluting the influent by 2 over 60 h and then by returning it to its initial value. The evolution of the biogas and input flow rates are reported in Fig. 9. The underload applied at t = 163 h resulted in a sudden decrease of biogas flow. After the first disturbance, the response factor

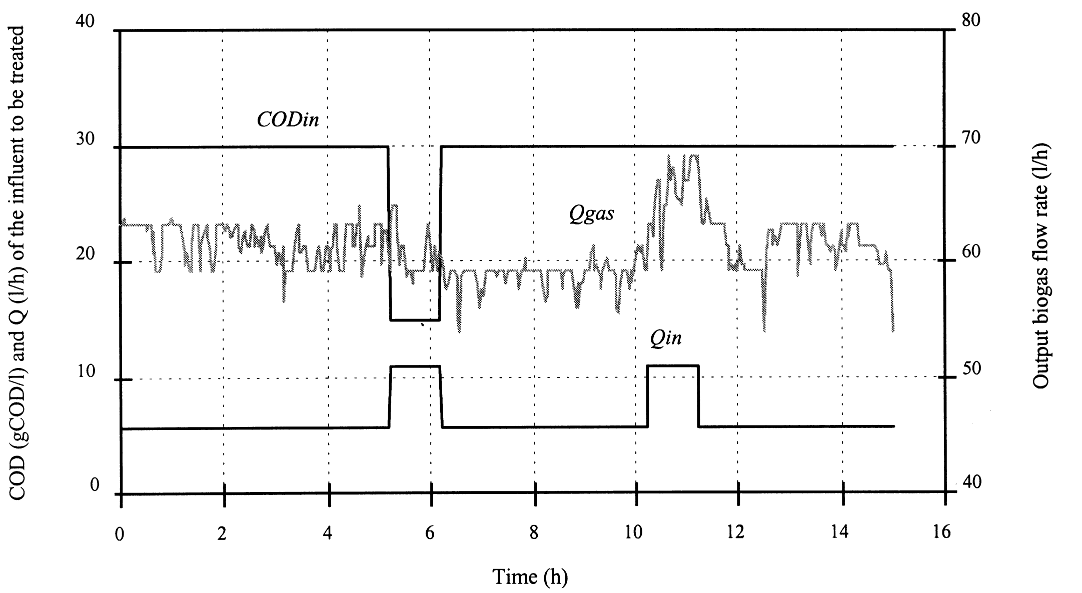

Fig. 8. Responses to the same disturbance using two different wastewater concentrations.

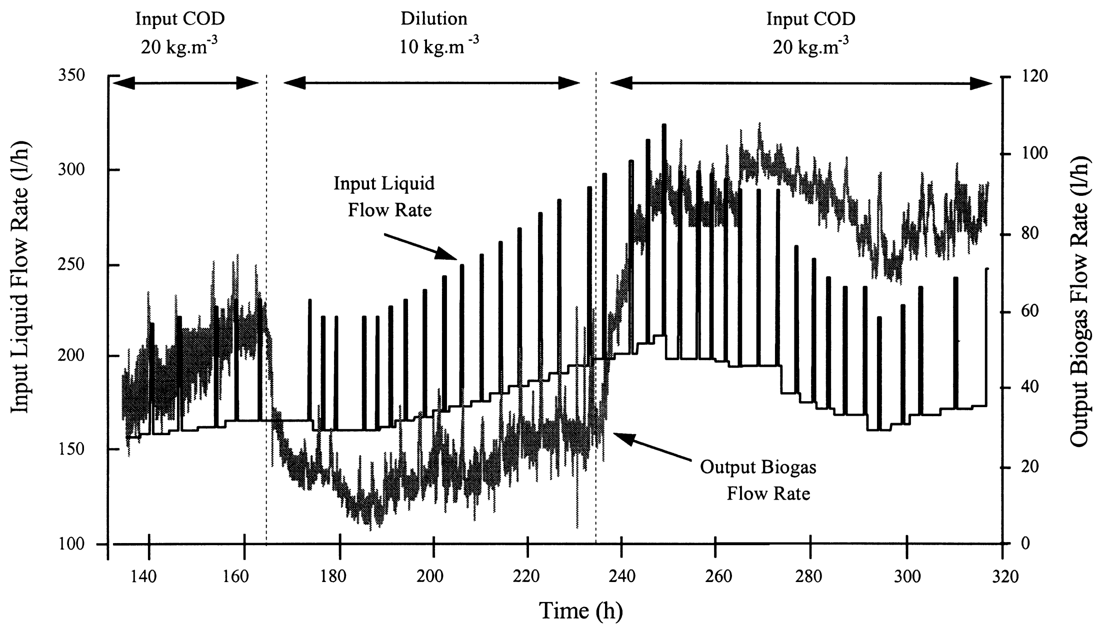

Fig. 9. Response of the control system to sudden changes in the inlet concentrations.

R was not sufficiently high because of the underload, as the concentration in the reactor decreased. However, after a few cycles, the system was adapted to the new conditions and regularly increased the input flow rate. At t = 234 h, the inlet concentration returned to its initial value. Over the first hours, the biogas flow rate increased considerably because of high values for the response factors. However, 10 h later the system was destabilized and the controller then reacted to this overload condition by decreasing the input flow rate stepwise back to the initial value before the underload. Then, at t = 290 h, the control system returned to normal operation by increasing slowly the input flow rate.

Another interesting feature of this control strategy is that the system waits for the stabilization of the process before taking a decision. This can be seen for example at time t = 162 h, where it waited about 10 h before changing the input flow rate. In fact, the time between two actions is another tuning parameter. In the case depicted by Fig. 9, this parameter was automatically monitored by the system (by looking at the stability of the output biogas flow rate). However, this could also be fixed at a low value to force the system to react as fast as possible. The choice here relies on the *a priori* knowledge we have concerning the disturbances that may occur on the process.

Relations between the response factor and traditional operating parameters

The influence of volatile fatty acid (VFA) concentration on the response factor was also investigated.

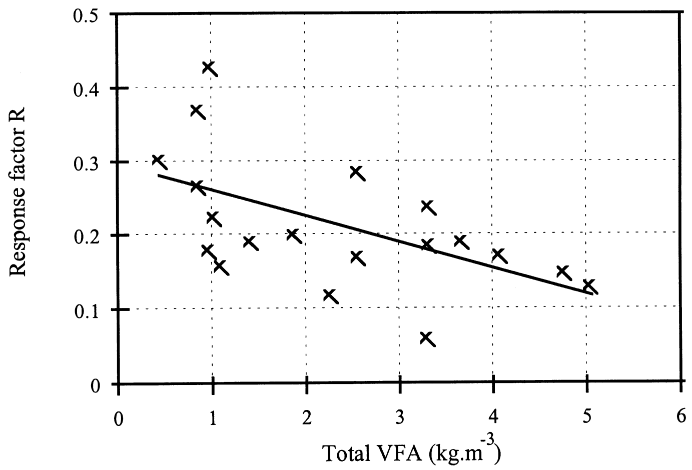

Fig. 10. Influence of volatile fatty acid concentration on the response factor R.

The VFA accumulation in a digester is generally considered as an indicator of malfunction of the process. Nevertheless, at high organic loading rates, it is not surprising to reach good removal performances with relatively high VFA amounts. The influence of total VFA on the response factor R is plotted on Fig. 10. It is obvious in this curve that it has a negative effect. This result indicates that, at VFA concentrations over $6\,kg{\cdot}m^{-3}$, the response of the system to the external disturbances will give a small value of R (below R_{min}) and results in a decrease of the inlet concentration. This confirms the validity of the approach used here by the confrontation of the response factor R to traditional operating parameters such as VFA concentration. The information drawn from the signal analysis of an easily measurable variable (biogas flow rate) is directly correlated to a more tedious measurement such as VFA concentration, which is indeed off line determined by gas chromatography.

CONCLUSION

In this paper, we presented a new control strategy for the monitoring and control of highly loaded anaerobic digestion processes.

The main advantages that are already recognized in this control strategy are the following: based on very simple and reliable sensors, that are extensively used at the industrial scale, the control system is able to automatically monitor an anaerobic digestion process and to prevent overloads. In addition, the controller is able to adapt its parameters to any change of the influent concentration and to force the process to reach its maximum treatment ability. The pertinence of the variables used in the control scheme has been checked by comparing them to more traditional operating parameters of anaerobic digesters such as VFA concentration. Adding disturbances on purpose and analysing the response of the system is undoubtedly adapted to biological reactors, all the more since mixed populations and variations in the influent quality are involved. This is the case for any wastewater treatment plant. Last but not least, this control system has been experimentally demonstrated to be useful in improving biological carbon removal but it is believed that the same approach could be used for other processes concerned with either carbon or nutrient removal.

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