

A hydrogen-based variable-gain controller for anaerobic digestion processes

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Abstract An easy-to-implement controller based on gas phase measurements for anaerobic digestion processes was developed. The controller is based on the indirect control of COD in the effluent by means of controlling the hydrogen concentration in the biogas. The fast response of hydrogen under destabilizations, such as those caused by overloads, guarantees an early actuation on the system before it destabilizes. The controller is designed such that it brings the anaerobic digestion process to maximum capacity by pushing it to maximum methane production as long as hydrogen remains low. Experiments have been conducted to test the controller under organic over- and underload situations and promising performance was achieved. Further experiments must be carried out to validate the controller under a wider spectrum of situations to enable its robust industrial application.

Keywords Advanced control; anaerobic digestion; hydrogen; methane

Introduction

Anaerobic digestion is a stable process carried out by mixed microbial populations that convert substrates into intermediates (typically volatile fatty acids) and subsequently into methane. This is of great interest due to the conversion of wastes into a valuable product, as methane, with low operational costs and sludge generation (Lettinga, 1995).

Under certain circumstances stability of the anaerobic digestion can be endangered. Overloads where acid intermediates accumulate, can drive the system to unstable and inhibited situations (CordRuwisch *et al.*, 1997). The existing control techniques of anaerobic treatment plants are aimed at maintaining stable operation when disturbances in the influent composition occur (Olsson *et al.*, 2005). Currently control of anaerobic digestion plants is characterised by a large part of human expertise or by requiring complex systems with many sensors that are economically questionable when dealing with a waste treatment technology (Bernard *et al.*, 2005).

Hydrogen, due to its role as intermediate in anaerobic digestion, accumulates in the biogas when almost any type of destabilisation occurs and it is a well known indicator of imminent unstable situations such as overloads (Hickey *et al.*, 1987; Pauss and Guiot, 1993; Huang *et al.*, 2000; Bjornsson *et al.*, 2001; Archer *et al.*, 2002). Low concentrations of hydrogen in the biogas can indicate moreover underloaded performance of the process and that higher organic loading rates and methane productions could be achieved. This and the fast response of hydrogen makes it very suitable for control purposes avoiding system destabilizations (Dochain *et al.*, 1991). In addition to this, on-line hydrogen analysers are available at competitive cost, making more interesting its applicability.

In this work an easy-to-implement controller, based on the existence of a functional relation between the hydrogen in the biogas and the effluent COD concentration, is presented. The controller maintains the stable operation by monitoring the gas phase and brings the reactor to its maximum capacity in terms of methane production while keeping the effluent COD low.

Methodology

Theoretical relation between H_2 and COD

Theoretically it can be demonstrated that in steady state a functional relation exists between the COD concentration in the effluent and the hydrogen in the biogas when the effluent COD is due to VFA (Ruiz, 2005). This relation can be experimentally determined directly for a certain substrate, reactor configuration and operation condition, when the real system operates at steady state. This functional relation implies that setting a set-point for the hydrogen in the biogas is equivalent to setting a set-point for the COD in the effluent.

A modified version of the ADMI model (Batstone *et al.*, 2002) incorporating ethanol degradation pathways and calibrated for the UASB-UAF pilot-scale reactor was used to check this theoretical relation (Ruiz *et al.*, 2004; Rodríguez, 2006). The biogas hydrogen concentration and the COD in effluent were simulated in steady state for different OLRs to illustrate this functional relation between these two variables (see Figure 1).

Due to the high dependence of the steady-state hydrogen concentration on the different operational conditions, reactor configuration and type of substrate, it is strongly recommended that the adequate set-point value is selected experimentally. This functional relation exists under the assumption of true steady-state and this does not occur normally. Indeed the relation is expected to change with time and it is recommended to periodically recalibrate experimentally the hydrogen value corresponding to the desired effluent COD. This should not have a major effect on the controller performance because these changes in the H_2 /COD relation are expected to occur in large-scale time constants.

Experimental methodology

Experiments for testing the controller were conducted in a pilot-scale fully instrumented anaerobic treatment plant consisting of a hybrid UASB-UAF reactor of about 1 m^3 of liquid volume. The influent composition consisted of diluted wine, ethanol being the sole COD and carbon source. The wine dilution is done just before entering the reactor to avoid preacidification in the feeding tank. Required nutrients and alkalinity are added to the feeding stream before entering the reactor as well. The high recycling flow applied to the reactor guarantees a quasi-complete mixed reactor behaviour in the liquid phase. The on-line measurement devices available included feed and recycling flow meters, pH meter, inflow and reactor Pt100, gas flow meter, infrared gas analyser (CH_4 and CO), hydrogen gas analyser and on-line total organic and inorganic carbon (TOC, TIC) combustion analyser. Some variables, such as methane production rate (Q_{CH_4}), are

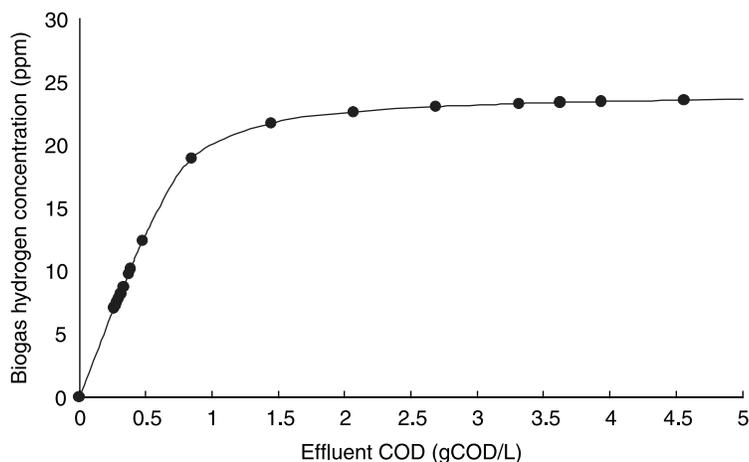


Figure 1 Simulation of the steady-state theoretical dependence of H_2 with effluent COD

calculated using the measured variables. Filtered on-line data were available every 15 min for all the variables provided by a monitoring and data acquisition system (Puñal *et al.*, 2001; Rodríguez, 2006).

Hydrogen-based controller

The controller is designed to maintain the hydrogen concentration in the biogas (and indirectly the COD concentration in the effluent) at a set-point value. This value corresponds to a COD concentration in the effluent in steady-state according to the steady-state H_2 /COD functional relation as explained above.

The control law is presented in Eq. 1. The dilution rate applied changes proportionally to its current value and to two factors: f_{H_2} and f_{CH_4} . The factor f_{H_2} is dependent on the current hydrogen concentration and the factor f_{CH_4} on the current methane production rate.

$$\frac{dD}{dt} = K \cdot D \cdot f_{H_2} \cdot f_{CH_4} \quad (1)$$

The controller modifies the dilution rate (D) according to the values of hydrogen concentration in the biogas ($ppmH_2$ in ppm) and methane productivity (Q_{CH_4} in $m^3_{CH_4}/m^3 \cdot d$). Thus only hydrogen concentration, methane concentration and biogas flow rate are required to be measured on-line.

The discrete implementation of the control action at a time t_i is presented in Eq. 2. The factors f_{H_2} and f_{CH_4} vary between $[-1, 1]$ and $[0, 1]$ respectively and K is a positive gain. Thus the range of change in the dilution rate remains within the interval $[-K \cdot D, K \cdot D]$. The controller performs effectively as a variable-gain hydrogen controller.

$$D(t_i) = D(t_{i-1}) + \Delta t \cdot K \cdot D \cdot f_{H_2} \cdot f_{CH_4} \quad \text{where } \Delta t = (t_i - t_{i-1}) \quad (2)$$

The hydrogen dependent factor is defined by an empirical non-linear function within the range $[-1, 1]$ and whose value must be zero when the current hydrogen concentration is equal to the set-point value ($ppmH_2^*$). Figure 2(a) shows the hydrogen factor function for a set-point value of 10 ppm. The empirical equation proposed (see Eq. 3) has two characteristic parameters m and n that are responsible for the slope of the curve when deviations of the set-point occur. Thus, the largest is the value of the parameter $m \in (0,1]$, the faster is the change in f_{H_2} for hydrogen concentrations below the set-point. The same applies for the parameter $n \in [1, \infty)$, the largest is its value, the faster is the change in f_{H_2} for hydrogen concentrations over the set-point.

$$f_{H_2} = \begin{cases} \left(1 - \frac{ppmH_2}{ppmH_2^*}\right)^{1/m} & \text{if } ppmH_2 \leq ppmH_2^* \\ \left(\frac{ppmH_2}{ppmH_2^*}\right)^n - 1 & \text{if } ppmH_2 > ppmH_2^* \end{cases} \quad (3)$$

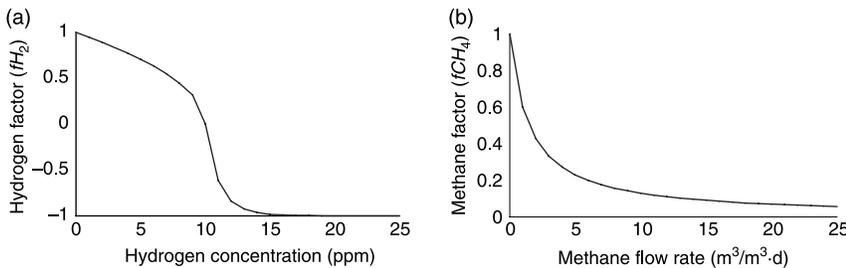


Figure 2 (a) Empirical function of the hydrogen factor for a $ppmH_2^*$ of 10 ppm, $m = 0.5$ and $n = 10$. (b) Empirical function of the methane factor for a $Q_{CH_4}^*$ of $15 m^3_{CH_4}/m^3 \cdot d$ and $\alpha = 0.1$

The hydrogen factor is therefore responsible for the direction of change in the dilution rate, correcting deviations from the hydrogen set-point and guaranteeing therefore for both the process stability and the effluent composition.

The methane dependent factor (Figure 2(b)) is dependent as an empirical saturation curve (Eq. 4) with two characteristic parameters namely the critical methane productivity ($Q_{CH_4}^*$) and a parameter α (named thrust factor). The meaning of α is approximately the value that the methane factor takes when the methane productivity reaches the critical value $Q_{CH_4}^*$. This factor allows the controller to push the system to higher OLR values as long as hydrogen remains below the set-point level.

$$f_{CH_4} = \frac{\alpha \cdot Q_{CH_4}^*}{Q_{CH_4} + \alpha \cdot Q_{CH_4}^*} \quad (4)$$

When a high methane productivity (Q_{CH_4}) close to the maximum of the reactor (defined by $Q_{CH_4}^*$) is achieved, the factor is decreased to a low value (depending on α) to make changes slow, to not exceed overload threshold and unnecessary underload. On the other hand when Q_{CH_4} is low f_{CH_4} is higher and allows the controller to make larger changes for faster recovery of the process.

Experimental validation of the controller

Experiments of subsequent increase and decrease of the total organic carbon in the influent TOC were carried out (see Figures 3 and 4). Prior to this experimental test the controller gain K was roughly tuned in simulation using the modified ADM1 incorporating ethanol degradation. K was fixed at a value ($6.66 \cdot 10^{-3} \text{ h}^{-1} \cdot \text{min}^{-1}$) allowing a maximum change of only 10% in the dilution rate (h^{-1}) in a 15 min interval.

The critical values, experimentally determined, were $11.33 \text{ (m}^3/\text{m}^3 \cdot \text{d)}$ for the methane productivity ($Q_{CH_4}^*$) and 45 ppm for the hydrogen set-point (ppmH_2^*), guaranteeing a low effluent COD. The values taken for the f_{H_2} empirical parameter factors were $m = 0.5$, $n = 10$ and $\alpha = 0.01$.

An increase in the influent TOC (Figure 3) from days 1 to 6 caused an increase in the hydrogen concentration in the biogas and the controller adjusted the feed flow rate (Figure 4) to bring back the hydrogen to the set-point and to maintain the effluent TOC low.

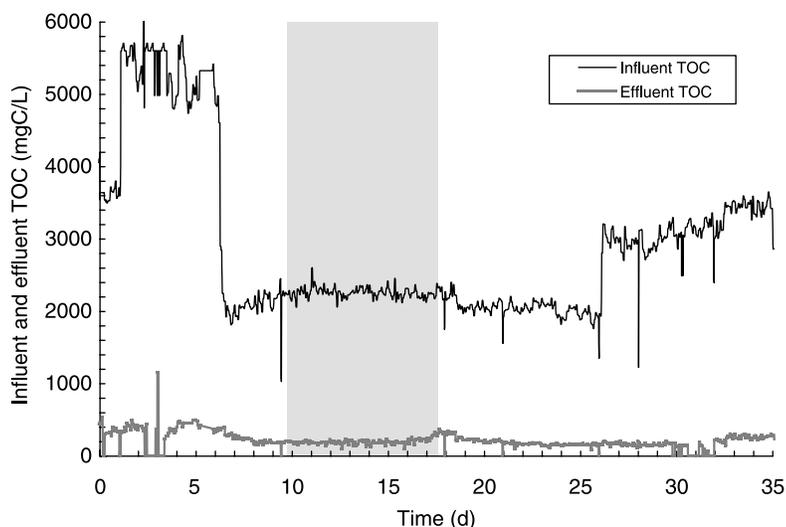


Figure 3 Influent and effluent TOC concentration during the experimental test of the controller

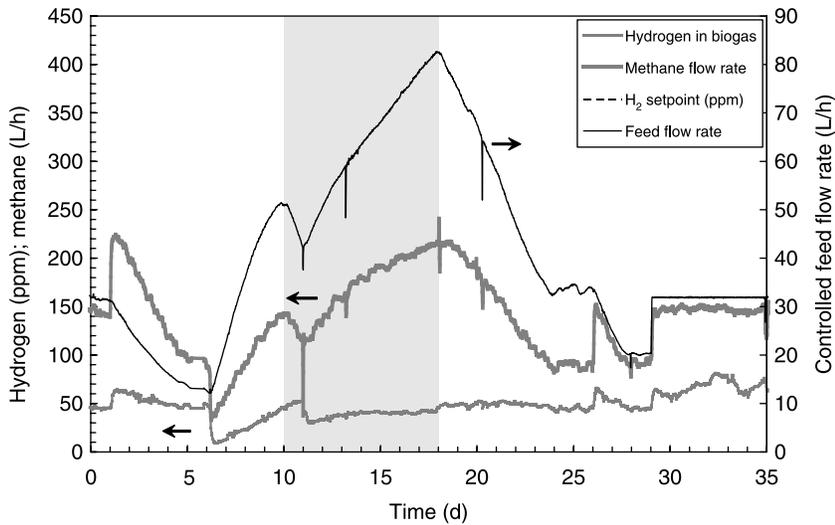


Figure 4 Controller and system responses during the test experiments

The influent concentration was reduced afterwards (from days 6 to 10) and a decrease in the hydrogen was detected, thus the controller increased the feed flow rate treating more wastewater and producing more methane.

The shadowed region in Figure 3, from days 10 to 18, corresponds to a period where the hydrogen sensor failed. It is shown how the controller brought back the system to the set-point and stable conditions as soon as the sensor had recovered.

Finally from days 26 to 29 the influent concentration was increased again and the control recovered the system successfully to the hydrogen set-point. After day 29 the control loop was opened and a constant feed flow rate was applied.

The good performance of the controller is highly dependent on the steady-state H_2 /COD relation that is expected to change with a much slower time constant than the controller scope. Several factors affect this H_2 /COD relation such as changes in the biomass of slow dynamics. Another important issue can be the changes in the stoichiometry of the acidification conversions depending on the environmental conditions as has been recently investigated (Rodríguez *et al.*, 2006a, b). This affects the products obtained during these conversions including hydrogen.

Conclusions

The easy-to-implement variable-gain controller based on biogas measurements (hydrogen concentration and biogas and methane flow rates) developed and tested provided good performance when correcting overloads. The controller maintains the anaerobic process under both stable and maximum capacity operation by acting on the dilution rate. The experimental tests of the controller conducted by both increasing and decreasing the COD concentration in the influent showed how under these conditions the controller is able to maintain both effluent quality and stable operation.

The low cost of the measurement devices required, make this controller very interesting for industrial application. Further calibration and tests under a wider range of situations are needed to assure the controller robustness in an industrial environment.

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