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A switching control strategy based on alkalinity to optimize biogas outflow in the start-up of an anaerobic digester

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Abstract

This paper deals with the control of the start-up phase in anaerobic digestion systems by using monitoring parameters already implemented that have been coupled to the control law. Methane yield, as well as methane flow rate, and the ratio of intermediate over total alkalinity have been used as control parameters. These measurements have been included in a switching control strategy to drive the process toward a steady state in which biogas production is optimized avoiding accumulation of volatile fatty acids. Experimental validation of this control strategy has been performed from the results obtained using a 358 liter fixed bed anaerobic digester treating industrial winery wastewater.

Keywords: Switching control; alkalinity ratio; methane flow rate, anaerobic digestion.

INTRODUCTION

It is well known that anaerobic digestion (AD) is a very well adapted biological process for treating agricultural wastewater. AD indeed has several benefits: (i) capability of reducing organic matter; (ii) low operational costs; (iii) small space requirements; and (iv) low sludge production. These features offer widespread opportunities for nutrient and energy recovery. Several monitoring and automatic control strategies have been proposed over the years to optimize AD processes. They include, for example, fuzzy logic (Estabén *et al.*, 1997), robust adaptive control by using interval observers (Alcaraz-González *et al.*, 2005), total alkalinity control (Mendez-Acosta *et al.*, 2010) and adaptive control with unknown kinetics (Mailleret *et al.*, 2004). Steyer *et al.*, (2006) have described different control configurations that are directly linked to data, models, and knowledge of the process. Moreover, in those configurations their performance were analyzed regarding their efficiency in rejecting disturbances, changes of set-points, and their capability of managing non linearities and uncertainties.

Most of the control strategies have been validated for AD processes operated in continuous mode for a long time, but only few of them have been applied to the start-up phase. The typical start-up phase has been shown to be very long (several weeks or even months, depending on what process technology is used) with a strong impact on the performance and stability of the reactor (Michaud *et al.*, 2002). In order to monitor the optimal operation of the start-up phase, methane yield has been suggested as a good indicator. Some values of methane yield can be found for soft drinks (Borja and Banks, 1994), and wine distillery wastewater in different conditions (Balaguer *et al.*, 1997).

Regarding the start-up phase, Sbarciog *et al.*, (2012) have proposed a simple control strategy by switching the dilution rate between a maximum and a minimum value to optimize the biogas production. This approach implies the use of the model AM2

proposed by Bernard *et al.*, (2001a) to calculate an optimal dilution rate (D_{opt}) which is reached at the equilibrium point.

Other control parameters that have been used to monitor AD processes are the ratio of total alkalinity (TA), partial alkalinity (PA) or intermediate alkalinity (IA) over volatile fatty acids (VFA) concentration. The control of these parameters enable to guarantee the buffer capacity of the system due to bicarbonate concentration and to maintain the pH close to neutral (Boe, *et al.*, 2010). Different ratios have been considered in the literature. For instance, the ratio VFA/TA has been established to take values of 0.1 to 0.35 (Zickefoose and Hayes, 1976); the ratio IA/PA has been established as $IA/PA < 0.3$ (Ripley *et al.*, 1986); and the ratio IA/TA as $IA/TA \leq 0.3$ (Bernard *et al.*, 2001b). Hence, following the control law proposed by Sbarciog *et al.*, (2012) and taking into account that in the start-up phase there is a low production of CO_2 , this work proposes a higher but more conservative value of the ratio IA/TA as another control parameter to optimize the biogas outflow and avoid accumulation of volatile fatty acids.

MATERIALS AND METHODS

Anaerobic digestion system

The pilot plant used in this study consisted in a continuous anaerobic fixed-bed reactor with a total volume of 0.358 m³. The anaerobic digester is jacketed and connected to a heating system allowing temperature control. A recirculation system going from the bottom to the top was used to improve stirring conditions and to avoid gas accumulation inside the digester. The pilot plant is instrumented and automated using ODIN software (INRIA, Sophia-Antipolis, France). Raw industrial winery wastewater was used to feed the system. The operation conditions were set to a controlled temperature of 35°C and a pH of 6.8. Volatile fatty acid concentrations were measured by AnasenseTM titrimeter sensor.

Design of the control law

The aim of the control law proposed in this paper is to reach a stable steady state in which the coexistence of the two bacterial populations is possible together with high COD removal efficiency levels and a high biogas production. High dilution rates help to achieve this purpose, but the start-up of a bioreactor at this condition can lead the system to VFA accumulation. Hence, low dilution rates must be used to operate the start-up, which can lead to a low biogas production. In this work we propose the use of the ratio $\alpha=IA/TA$ as a measurement of the operational stability in order to prevent accumulation of VFA.

Three values of dilution rates (D) have been predetermined as follows: $D_{minTA}=0.15$, $D_{min}=0.3$, and $D_{max}=0.5$, where the first one represents a low dilution rate to avoid VFA accumulation due to the maximum ratio $\alpha_{max}=(IA/TA)_{max}$; and the other two are the ones proposed by Sbarciog *et al.*, (2012).

The switching strategy is based on the two following conditions:

- [1] The ratio α must be maintained below α_{max} ($\alpha < \alpha_{max}$).
- [2] Methane flow rate must not decrease more than 10% when [1] is fulfilled.

In order to avoid the wash out of the methanogenic bacteria at the early start-up, the bioreactor is initially operated at D_{min} until [1] or [2] faults. It is important to remark that this control law is based mainly on the ratio IA/TA. Therefore, if condition [1] is not fulfilled, the dilution rate is reduced to D_{minTA} and the system is operated under

this condition until [1] is reached again. Thus, the control law is only based on methane flow rate (condition [2]) by switching D between D_{\max} and D_{\min} .

The success of this strategy depends on the proper choice of the predetermined dilution rates, the value of α_{\max} , and the threshold fixed in condition [2]. Moreover, a moving mean was used to filter the maximum methane flow rate when switching from D_{\max} to D_{\min} in order to prevent a high frequency bang-bang behaviour.

RESULTS AND DISCUSSION

The control law was implemented in the digester start-up for a time period of 49 days. The ratio α_{\max} was set to 0.4 at the beginning. This value is close to the one proposed by Ripley *et al.*, 1986 for normal operating conditions. However, it was changed to 0.6 in day 6 in order to compensate the effect of the low production of CO_2 (see Figure 1, days 9 to 24). In this figure, there are 2 maintenance periods identified as M1 and M2.

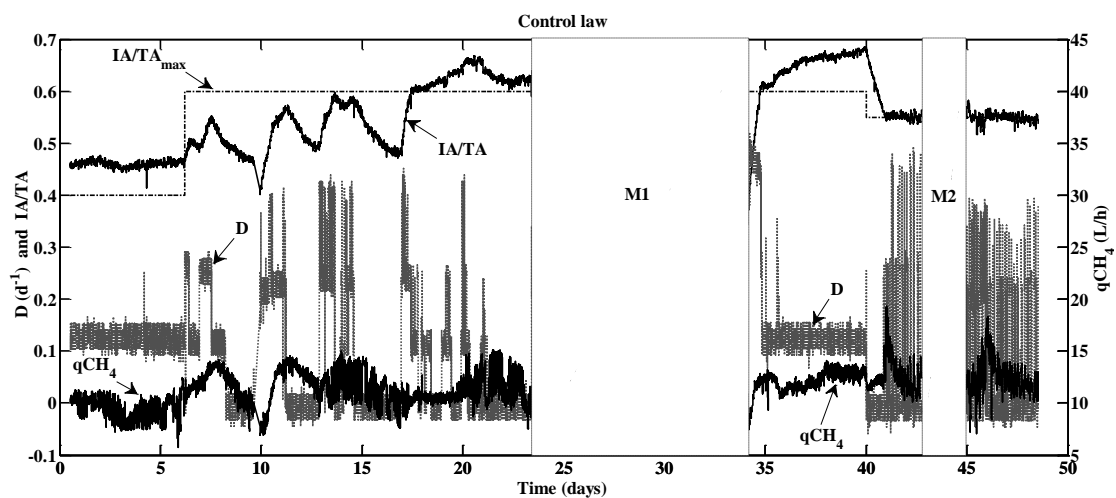


Figure 1 Controller effort on dilution rate.

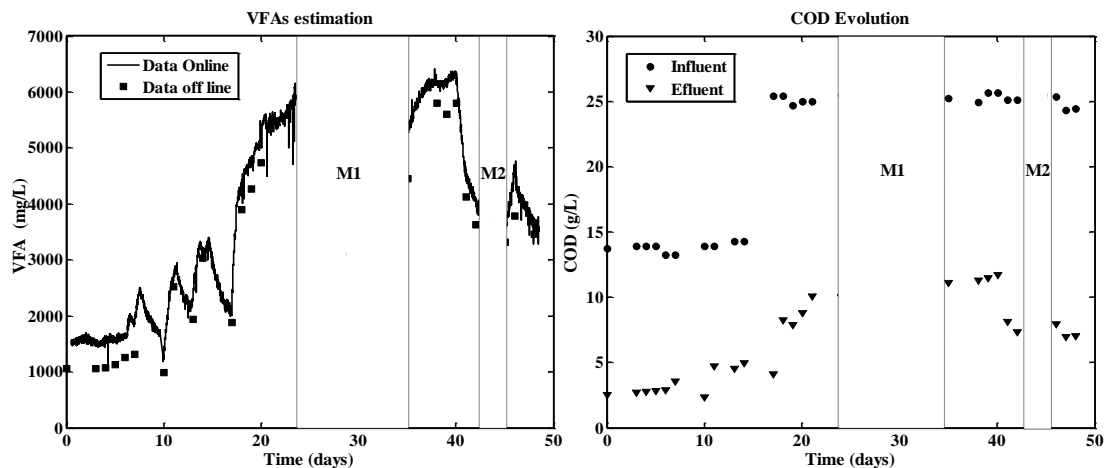


Figure 2 (a) VFA concentration through the action of control law. (b) Input and output conditions of organic matter (COD).

After M1, the control law was evaluated regarding the parameter α . Even though the system was operated with $D_{\min TA}$, VFA concentration increased (see Figure 2 (a)). Thus, $D_{\min TA}$ was set to zero and α was changed to 0.55 in order to guarantee a value below 5000 mEq/L of VFA. The switching strategy was tested changing the inflow concentration of COD. The combined effect of both control variables is shown from day 41 to 49. These results show that methane outflow was not increased to a maximum because the average dilution rate was maintained in low values.

Furthermore, when pH was regulated and a ratio of $\alpha = 0.55$ was considered, the system was stabilized giving high efficiencies of COD removal of 70%.

CONCLUSIONS

The switching strategy shows that it is possible to use free model control laws to guarantee stability in the start-up of anaerobic digesters. An optimal value for IA/TA was found to be $IA/TA \leq 0.55$ when pH is controlled and low dilution rates are used. Besides, it was demonstrated that the chosen monitoring parameters are efficient, but their capability can be optimized combining them in experimental implementation. For this control law it was observed that methane flow rate is robust instead of maximized when it is subjected to disturbances.

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