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Supervisory control applied to an anaerobic digestion process exposed to drastic feedstock changes

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INTRODUCTION

Anaerobic digestion plays a key role on circular bio-economy as a means to produce bioenergy and release nutrients trapped in organic matter, thereby enabling their recovery. Successful biogas production requires proper monitoring and control as an important tool for improving process stability and efficiency. The demand for a monitoring and control system is increasing along with the increasing number of large-scale biogas plants. During the last years, various indicators such as pH, alkalinity, volatile fatty acids (VFA) or biogas production have been used for online monitoring, and several control strategies have been proposed for controlling anaerobic digesters (Jimenez et al., 2015). The combination of the sensitive and reliable online indicators with a simple control system is more preferable than the use of low sensitivity indicators with a complex model control system. Biogas flow and pH are often the online indicators monitored in full-scale plants. However, for systems with high buffer capacity such as those treating manures, pH indicator becomes less sensitive and VFA is a more reliable indicator (Boe et al., 2010). VFA accumulation is known as a sensitive and reliable indicator for process imbalance in anaerobic digestion, which makes VFA an appropriate controlled variable. This work aims to extend and improve the extremum seeking control strategy previously developed (Boe and Angelidaki, 2012) to maximize biogas production in anaerobic digestion processes suffering radical changes in feedstock.

MATERIALS AND METHODS

Substrate and inoculum

Cattle manure was supplied from Hashøj full-scale biogas plant (Zealand, Denmark) and used as substrate in this study. The substrate was sieved and diluted with tap water to prevent clogging and to provide efficient mixing and pumping. Thermophilic inoculum was supplied from digestate of a well performing lab-scale reactor fed with cattle manure.

Experimental setup

The experimental set up consisted of a continuously stirred tank reactor (CSTR) with 9.0 L total and 7.5 L working volume operated at thermophilic condition (54 ± 1 °C). A 2-L gas trap (1.8 L working volume), containing 2.5% NaOH aqueous solution, was used to eliminate CO_2 and H_2S from produced gas. An automated displacement gas metering system with a 100 mL reversible cycle and registration was used to measure gas production (CH_4) (Angelidaki et al., 1992). A peristaltic pump was used to feed the reactor every 6 hours. The setup was equipped with a data acquisition (DAQ) hardware together with a PC to collect and record the produced gas data.

Moreover, a control algorithm was programmed in LabVIEW6i software (National Instruments) to change manipulated variable (i.e. organic loading rate) based on the control system.

Control system and disturbances

The control purpose is maximizing the methane production and reactor stability in presence of disturbances (i.e., glucose overload and ammonia inhibition). Minimum hydraulic retention time (HRT) is set as 5 days to prevent wash out of methanogens from the bioreactor. Organic loading rate (controlled by manipulating the influent pumping time) is the manipulated variable in control structure. The control strategy is based on a cascade structure (Fig. 1), where the slave loop is a feedback control using a proportional controller that manipulates the feed flow (FF) rate to achieve a specific biogas flow (GF – the set point). The master loop defines the set point using a rule based controller (Table 1) as function of the GF trend and the VFA content in the reactor.

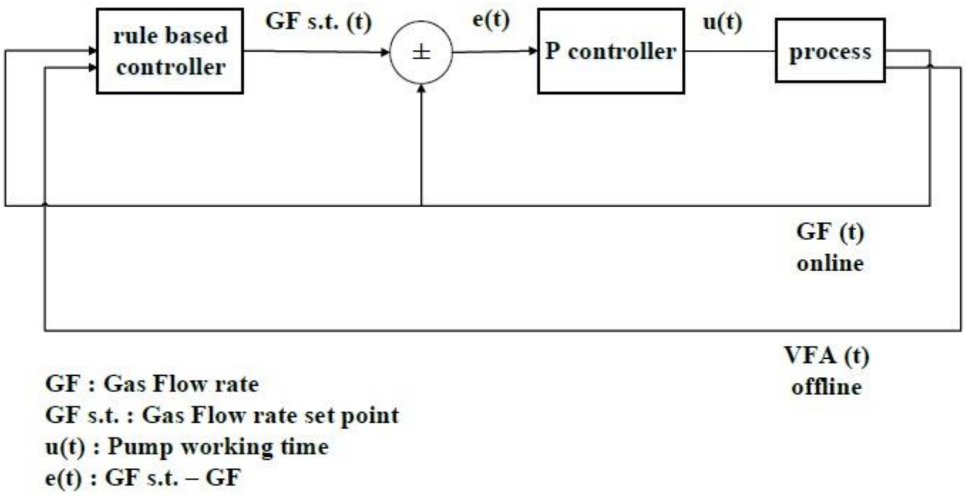

Figure 1. Control strategy block diagram

Table 1. Rules for set point optimization

State	Conditions	Control action	Exceptions
1	$if \quad GF_{real}(t) \geq GF_{set\ point}(t-1)$	$GF_{set\ point}(t) = GF_{set\ point}(t-1) + GF_{step}$	$if\ \ state\ 1 \quad and \quad e(t) < 0\ \ and \quad FF(t) < FF(t-1)$
			$FF(t) = FF(t-1)$
2	$if \quad GF_{min}(t-1) \leq GF(t) < GF_{set\ point}(t-1)$	$GF_{set\ point}(t) = GF_{set\ point}(t-1) + 0.5 \times GF_{step}$	No limitation
3	$if \quad GF(t) < GF_{min}(t-1)$ and $previously\ at\ state\ 1$ or $if \quad GF(t) < GF_{min}(t-1) \quad and$ $previously\ not\ at\ state\ 1\ and$ $VFA(t) \geq VFA(t-1) \quad and$ $VFA(t) < 2 \quad g/L$	$GF_{set\ point}(t) = GF_{set\ point}(t-1)$	$if\ state\ 3 \quad and \quad FF(t) > FF(t-1)$
			$FF(t) = FF(t-1)$

4	$if \quad GF(t) < GF_{min}(t-1)$ $and \quad previously\ not\ at\ state\ 1$ $and \quad VFA(t) \geq 2 \quad g/L$	$GF_{set\ point}(t) = GF_{set\ point}(t-1) - 0.5\ GF_{step}$	$if\ state\ 4 \quad and$ $FF(t) > FF(t-1)$
			$FF(t) = FF(t-1)$
5	$if \quad GF(t) < GF_{min}(t-1) \quad and$ $previously\ at\ state\ 4$ $and \quad VFA(t) < 2 \quad g/L$	$GF_{set\ point}(t) = GF_{set\ point}(t-1)$	$if\ state\ 5 \quad and$ $FF(t) > FF(t-1)$
			$FF(t) = FF(t-1)$
6	$if \quad GF(t) < GF_{min}(t-1)$ $and \quad previously\ not\ at\ state\ 1 \quad and$ $not\ at\ state\ 4$ $and \quad VFA(t) < VFA(t-1)$ $and \quad VFA(t) < 2 \quad g/L$	$GF_{set\ point}(t) = GF_{set\ point}(t-1) + 0.5\ GF_{step}$	$if\ state\ 6 \quad and$ $FF(t) < FF(t-1)$
			$GF(t) = GF(t-1)$

RESULTS AND DISCUSSION

Glucose step

The digester was fed with manure (2% TS) for 40 days (Fig 2). At day 40, the TS was increased from 2% to 6% adding glucose to the feed. Methane production quickly boosted. However, VFA started to accumulate right away acidifying the system, which is a typical case of substrate overload that leads to a process imbalance. The controller prevented that VFA accumulated above 2.7 g L^{-1} and in few days restored the VFA to the same level as before introducing glucose in the feed (Fig. 3). Biogas production was progressively increasing, probably as consequence of slow increase of methanogenic community.

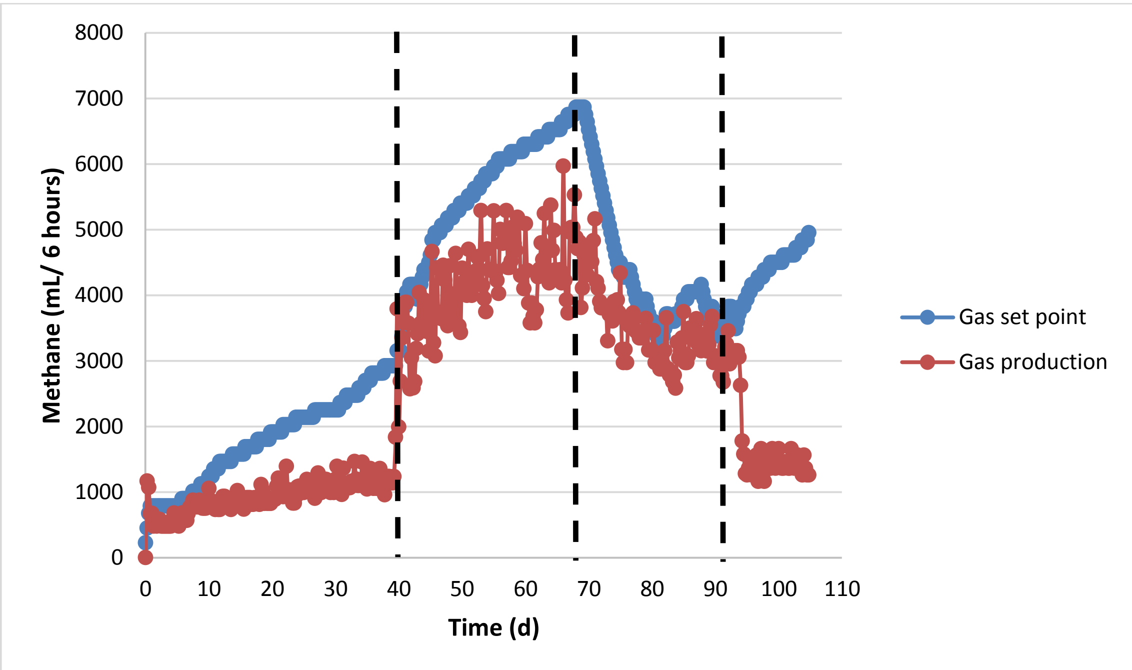

Figure 2. Methane production and set point during reactor operation. Vertical lines indicate when the substrate was changed: glucose addition (from 2 to 6 % TS), ammonia addition and back to TS 2%.

Ammonia step

At day 68 ammonia was increased up to 6 g L^{-1}, while keeping the same TS. VFA level quickly increased up to 3 g L^{-1}, probably due to methanogenesis inhibition. Once more, the controller prevented VFA accumulation and slowly was decreasing the OLR, thereby decreasing the ammonia load as well. Consequently the methane production barely reduced and was relatively stable during this operational period. From day 90 the reactor was fed with manure 2% TS and the controller drove the system to the initial conditions of the study, keeping the same methane production.

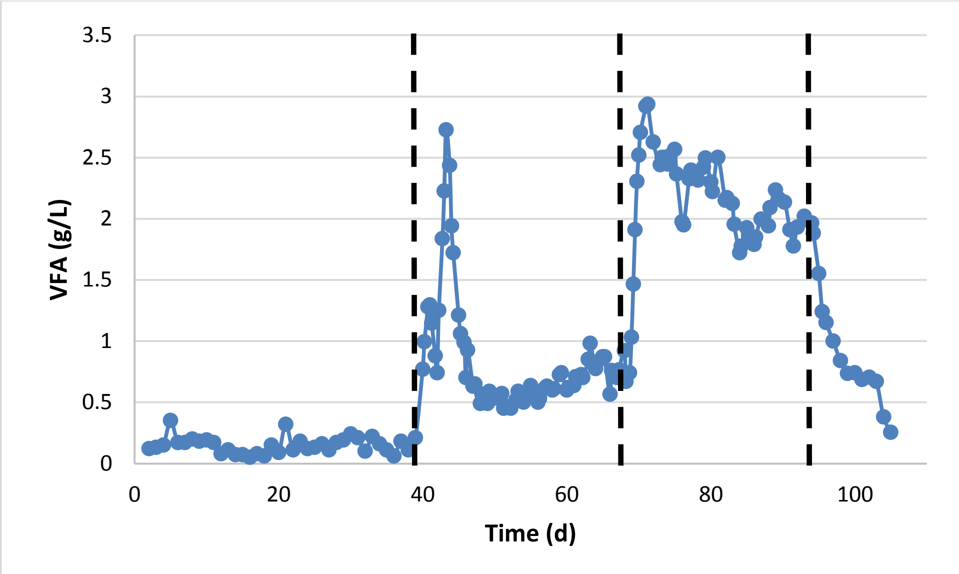

Figure 3. VFA concentrations during reactor operation. Vertical lines indicate when the substrate was changed: glucose addition (from 2 to 6 % TS), ammonia addition and back to TS 2%.

CONCLUSIONS

This study demonstrates the application of extremum seeking control to maximize biogas production while minimizing the risk of overload or inhibition. Ongoing research focuses on the application of the same control strategy to maximize biogas production during the transient from 2% TS manure to 6% TS biopulp, which will be included in the final paper.

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