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Monitoring and control of the biogas process based on propionate concentration using online VFA measurement

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ABSTRACT

Simple logic control algorithms were tested for automatic control of a lab-scale CSTR manure digester. Using an online VFA monitoring system, propionate concentration in the reactor was used as parameter for control of the biogas process. The propionate concentration was kept below a threshold of 10 mM by manipulating the feed flow. Other online parameters such as pH, biogas production, total VFA, and other individual VFA were also measured to examine process performance. The experimental results showed that a simple logic control can successfully prevent the reactor from overload, but with fluctuations of the propionate level due to the nature of control approach. The fluctuation of propionate concentration could be reduced, by adding a lower feed flow limit into the control algorithm to prevent undershooting of propionate response. It was found that use of the biogas production as a main control parameter, rather than propionate can give a more stable process, since propionate was very persistent and only responded very slowly to the decrease of the feed flow which lead to high fluctuation of biogas production. Propionate, however, was still an excellent parameter to indicate process stress under gradual overload and thus recommended as an alarm in the control algorithm.

Key words | anaerobic digestion, propionate, simple control, volatile fatty acids

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INTRODUCTION

One of the topics that have been under focus in anaerobic digestion technology for more than one decade is monitoring and control of the process. The increasing number of large-scale biogas plants increases the demand for proper monitoring and control of these systems (Steyer *et al.* 2006). The control applications can be based on various monitoring parameters, such as pH, alkalinity, volatile fatty acids (VFA) or biogas production. Most of the control applications are based on feed flow manipulation while this requires an equalisation tank in the feeding line. There are several control strategies in combination with different monitoring parameters in the anaerobic process. Pretorius (1994) used a simple on/off control for startup and operation of a UASB reactor treating petrochemical wastes containing short chain fatty acids where the feed pump was turned on or off according to the pH set point. Denac *et al.* (1990) used empirical control approach to control the effluent quality expressed in total acids concentration by regulating feed rate and using alkaline addition (to maintain pH at 7) as the controlled variable. The PID controller has been used by Marsili-Libelli & Beni (1996) to maintain the bicarbonate alkalinity in an anaerobic filter by manipulating the bicarbonate dosing ($NaHCO_3$). Bernard *et al.* (2001) successfully tested a model-based adaptive linearising controller and a fuzzy logic controller, for controlling the ratio of intermediate alkalinity to total alkalinity and the level of total alkalinity, by regulating feed flow in a pilot-scale anaerobic filter treating distillery wastewater.

Other control parameters that have been suggested are biogas production and VFA (total or individual). The control applications that have been used for optimizing the biogas production were found in Steyer *et al.* (1999) and

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Liu et al. (2004). In Steyer et al. (1999), a probing control strategy was used by applying a disturbance (changing feed flow) on purpose and then analysing the gas production response to determine the reactor capability of handling the higher feed rate. Thereby, the pH was used as an alarm in the control algorithm. A similar strategy was used in Liu et al. (2004) where a cascade PID controller embedded into a rule-based supervisory system was used to maximize the biogas production using pH as an overload alarm. The biogas flow set point was automatically adapted according to the defined rules for optimizing the process performance where biogas is maximized without overloading and independently from the feed concentration. Control algorithms using VFA as controlled parameter have been tested by Renard et al. (1991) and Puñal et al. (2003). Puñal et al. (2003) used fuzzy control to control the VFA concentration by manipulation of the feed flow in a pilot-scale anaerobic filter treating winery wastewater. Renard et al. (1991) used a model-based adaptive control by regulating the dilution rate to keep the propionate concentration within a maximum limit during startup and steady-state running of a pilot-scale CSTR digester treating spent liquor from citric acid fermentation. In their experiment, the propionate concentration was manually measured every one or two days.

In this work, a basic automatic control strategy applied to a lab-scale CSTR manure digester was tested. A simple logic control strategy was applied based on online concentrations of individual VFA, i.e., propionate. A threshold concentration for propionate was set to 10 mM, and the feed flow was simply increased or decreased according to the measured propionate concentration compared to the set point. From the online individual VFA measurements, the process dynamics under different control strategies were studied for evaluation of different parameters suitability to be used as control parameters.

MATERIALS AND METHODS

The experiment was carried out in a 9-L CSTR reactor with 7.2 L working volume and 55°C operating temperature. The reactor was fed with cow manure four times per day. The gas production was measured every 6 hours by an automated displacement gas metering system with a 100 mL reversible cycle and registration (Angelidaki et al. 1992). The pH was measured every 10 min. by mini CHEM-pH Process Monitor (TPS Pty Ltd., Australia). The individual VFA concentrations were measured every 6 hours by an online VFA monitoring system based on ex-situ VFA extraction (Boe et al. 2007). The reactor had a liquid circulation loop connecting to the VFA measuring system where a 40 mL liquid sample was pumped into an equilibrium cell, acidified, added with salt and heated to extract VFA into gas phase before injecting automatically into a gas chromatograph (GC) for analysis. The signal output from the GC was then sent to the automatic control system for processing before the next feed started. Each feed started right after the VFA measurement data were obtained. Overall control was done by a programmable logic control (PLC) system (Versamax PLC, GE Fanuc Automation Europe S.A, Luxembourg), with computer interface. All calculations were managed within the PLC. The interface and data logging on the PLC were using GE Cimplicity HMI 6.1 (HMI, GE Fanuc Automation Europe S.A, Luxembourg). The experimental setup diagram is shown in Figure 1.

During control experiment, the feed volume was adjusted automatically according to propionate concentration while the organic content in the feed (feed concentration) was uncontrolled. Using a simple logic control approach, different tuning sets were tested as shown in Table 1. In the first period of experiment (day 7–16), the feed flow was set to increase by 5% if the measured propionate was lower than 5 mM, increase by 1% if it was between 5–10 mM, or decrease by 10% if it was higher than 10 mM. During the second period (day 17–28), the control was adjusted to accelerate the response by setting the feed flow to increase 20% if propionate was less than 5 mM, increase 5% if it was between 5–8 mM, increase 1% if it was between 8–10 mM, or decrease 20% if it was higher than the 10 mM. In the last period of the experiment, the feed flow was set to increase similarly to the second period. However, when the propionate was higher than maximum limit (10 mM), the feed flow was stopped and reset to the minimum feed flow limit of 480 mL/d (HRT 15 d), instead of decreasing flow rate in steps. The addition of a minimum feed flow limit was to prevent propionate undershoot and for the purpose of faster recovery when propionate was back to the level of 10 mM again. The control purpose in this

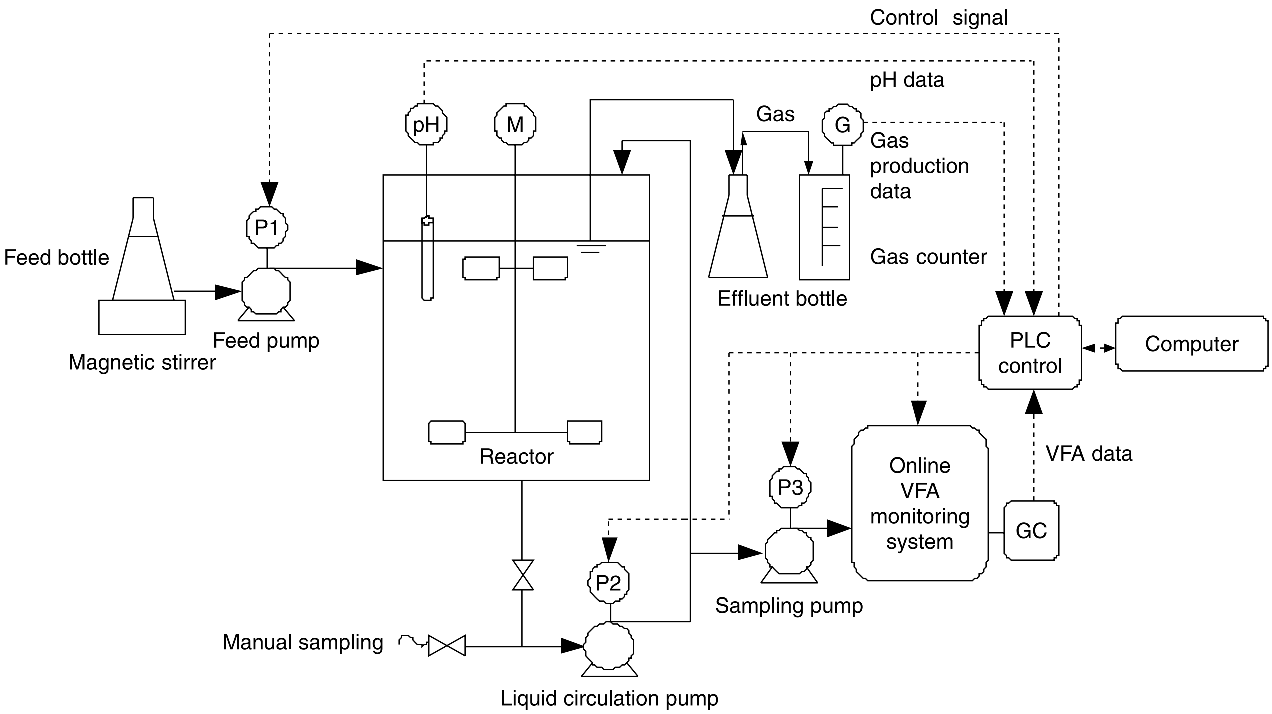

Figure 1 | Diagram of experimental setup.

experiment was to avoid propionate concentration above 10 mM for achieving reactor stability.

RESULTS AND DISCUSSIONS

At start up day 1, the feed pump flow was pulsed in order to test the dynamic response of the system, resulting in increase of all VFA until day 7. The slowest control setup was then used in the first period (day 7–16) with slowly increase of feed volume. At this stage, biogas production was gradually increasing together with increasing of acetate, while other individual VFA were still low, showing that the reactor was not overloaded. The pH was quite stable and only total VFA slowly increased. From day 11, propionate started to increase until day 14. When propionate reached 10 mM, the feed volume was then reduced by 10% according to the control algorithm. This caused a decrease in biogas production. Propionate and other VFA also decreased except acetate which increased probably due to its production from propionate degradation.

During the second control period (day 17–28), the increasing of feed rate was more aggressive (see Table 1).

Table 1 | Control algorithm used in the experiment

Day	Control argument
7–16	If (Pr < 5) then ($F_i = 1.05F_{i-1}$)
	Or if (5 ≤ Pr < 10) then ($F_i = 1.01F_{i-1}$)
	Else ($F_i = 0.9F_{i-1}$)
17–28	If (Pr < 5) then ($F_i = 1.2F_{i-1}$)
	Or if (5 ≤ Pr < 8) then ($F_i = 1.05F_{i-1}$)
	Or if (8 ≤ Pr <10) then ($F_i = 1.01F_{i-1}$)
	Else ($F_i = 0.8F_{i-1}$)
29–33	If (Pr < 5) then ($F_i = 1.2F_{i-1}$)
	Or if (5 ≤ Pr < 8) then ($F_i = 1.05F_{i-1}$)
	Or if (8 ≤ Pr < 10) then ($F_i = 1.01F_{i-1}$)
	Else ($F_i = F_{i,min.}$) where $F_{i,min.} = 480$ mL/d (HRT 15 d)

Pr = propionic acid (mM), F = feed volume (mL/d).

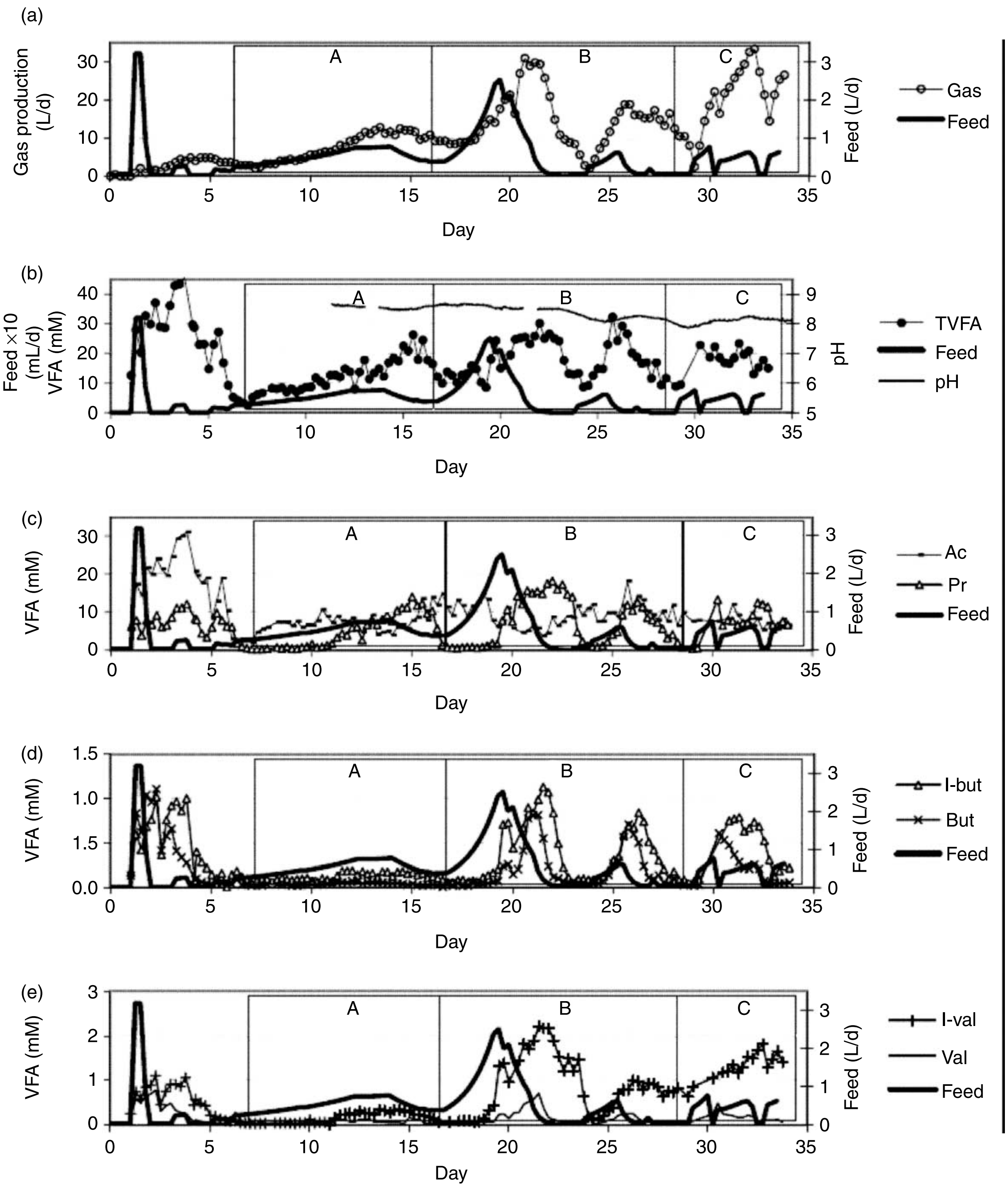

Figure 2 | Online measuring results from propionate control experiment by regulating the feed flow rate; (a) biogas production, (b) total VFA and pH, (c) acetate and propionate, (d) iso-butyrate and butyrate, (e) iso-valerate and valerate.

The gas production increased faster but still with lag time after the feed changes. The individual VFA did not show any significant response at the beginning, but began to accumulate very fast at day 18 when the feed was too high. The lag time response of VFA could be due to the change of process condition faster than change of hydrolysis rate which was believed to be the rate-limiting step in this case. After propionate exceeded the set point, the feed flow was sharply decreased (20% decrease per feeding). However, propionate concentration remained higher than the threshold value for a long time resulting in the feed being decreased automatically to nearly zero for long time before the concentration turned back within the control limit. Moreover, when the feed was decreased to nearly zero, it took some time before the feed turned back to the high level, which resulted in fluctuation of biogas production. Please note that at day 27 and 28 there was a technical problem with the feed control so there was no feed although propionate was below 10 mM. During the third period (day 29–33), the control setup was improved by introducing a lower feed flow limit which made the response to propionate recovery faster. This resulted in less fluctuation of propionate concentrations as shown in square C. However, the biogas production was still highly fluctuating.

Considering overall responses in Figure 2a,b,c, the biogas production, total VFA and propionate followed the trend of feed volume quite well but with some lag time as shown in square A and B. However, pH did not show significant change. The biogas production, total VFA and propionate concentration were kept increasing for a while after the feed had been reduced. The length of lag time depended on how fast the feed had been changed. Comparing square A and B in Figure 2a, the lag time of gas production was longer when feed was changed very fast, which means that the process dynamic was slower than the change in process operation. When comparing the responses of individual VFA (Figure 2c,d,e), it could be seen that the concentration of individual VFA, except acetate, followed the trend of propionate, which made the trend of total VFA similar to the trend of propionate, but not of acetate. When focusing on the sensitivity of iso-butyrate and butyrate (Figure 2d) compared to propionate, iso-butyrate and butyrate increased as fast as propionate when organic load was increased quickly (square B). However, propionate level remained low long after the organic load was decreased, which showed that iso-butyrate and butyrate were easier to degrade than propionate. It has also been reported that propionate had the slowest degradation rate of all VFAs (Wiegant *et al.* 1986; Pind *et al.* 2003).

An on-off control is simple but the results may be fluctuating since it does not take into account the offset between process output and the set point (Liu 2003). As the main purpose of this control was only based on propionate concentration, the biogas production was not included in the control algorithm and hence, it was not optimised. Moreover, the lag time of propionate response compared to the change in feed volume resulted in fluctuation of biogas production. Since propionate was shown to be most persistent of all VFA's in the reactor, reducing feed volume would decrease biogas production or other VFA, before propionate decreased to the set point level. As a result, this type of control was not sufficient to minimise overshooting (and undershooting) of the parameters which exhibit slow dynamics such as propionate. A more complex control technique might be preferable, for example, fuzzy logic (Puñal *et al.* 2003) or adaptive control algorithms (Renard *et al.* 1991). From our experiment, it is quite convincing that the better way to optimise biogas production is to use biogas production as a main control parameter, while using total or individual VFA such as propionate as an overriding alarm parameter in the control algorithm. This would be a good choice for the well-buffered anaerobic digester where pH does not change much during VFA accumulation. For the less-buffered system where pH is more sensitive to VFA accumulation, the control approach based on biogas production with pH as an alarm has proved to be enough for process optimisation by regulating feed flow (Steyer *et al.* 1999; Liu *et al.* 2004). Moreover, their control approach can also function independently from the feed composition.

CONCLUSIONS

A simple logic control based on propionate concentration can successfully prevent the reactor from overload. However, the propionate output was fluctuating due to the nature of the control approach which was unable to predict the rate of propionate change. The fluctuation of control output could thus be reduced by improving the control algorithm. In this experiment, the use of a lower feed flow limit decreased the undershooting of propionate output. However, propionate was very persistent in the reactor which required long duration of low feed before propionate decreased to the set point value, and this resulted in fluctuation of biogas production. Since biogas production is normally the target parameter to be maximised in the biogas process, it was concluded from this experiment that biogas production would be more appropriate as a main control parameter, rather than propionate or VFA. However, it was clear that the propionate parameter could indicate process stress under gradual overload where other parameters such as butyrate or valerate could not. So the propionate concentration would be most suitable as an alarm in a biogas production based control algorithm. Moreover, the controller could be largely improved as the online measurement is available.

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