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ARTICLE

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Application of a Fuzzy Logic Control System for Continuous Anaerobic Digestion of Low Buffered, Acidic Energy Crops as Mono-Substrate

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ABSTRACT: A fuzzy logic control (FLC) system was developed at the Hamburg University of Applied Sciences (HAW Hamburg) for operation of biogas reactors running on energy crops. Three commercially available measuring parameters, namely pH, the methane (CH_4) content, and the specific gas production rate (spec. GPR $= m^3$/kg VS/day) were included. The objective was to avoid stabilization of pH with use of buffering supplements, like lime or manure. The developed FLC system can cover most of all applications, such as a careful start-up process and a gentle recovery strategy after a severe reactor failure, also enabling a process with a high organic loading rate (OLR) and a low hydraulic retention time (HRT), that is, a high throughput anaerobic digestion process with a stable pH and CH_4 content. A precondition for a high load process was the concept of interval feeding, for example, with 8 h of interval. The FLC system was proved to be reliable during the long term fermentation studies over 3 years in one-stage, completely stirred tank reactors (CSTR) with acidic beet silage as mono-input (pH 3.3–3.4). During fermentation of the fodder beet silage (FBS), a stable HRT of 6.0 days with an OLR of up to 15 kg VS/m^3/day and a volumetric GPR of 9 m^3/m^3/day could be reached. The FLC enabled an automatic recovery of the digester after two induced severe reactor failures. In another attempt to prove the feasibility of the FLC, substrate FBS was changed to sugar beet silage (SBS), which had a substantially lower buffering capacity than that of the FBS. With SBS, the FLC accomplished a stable fermentation at a pH level between 6.5 and 6.6, and a volatile fatty acid level (VFA) below 500 mg/L, but the FLC had to interact and to change the substrate dosage permanently. In a further experiment, the reactor temperature was increased from 41 to 50°C. Concomitantly, the specific GPR, pH and CH_4 dropped down. Finally, the FLC automatically enabled a complete recovery in 16 days.

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KEYWORDS: anaerobic digestion; automation; beet silage; biogas; biomass; fuzzy logic control; monitoring

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Introduction

Ideal energy crops should be converted to biogas (methane) and fertilizer without use of chemicals or manure. A study of the Federal Agricultural Research Centre (FAL, Braunschweig) has shown that at the end of the year 2007 approximately 4,000 biogas plants with a total installed electrical capacity of almost 1,300 MW were in operation in Germany (Weiland, 2006; personal communication). It is assumed that nearly 15–20% of these biogas plants in Germany are operated without the addition of manure (Weiland, 2007). Acidic silage (pH 3.3–3.4) is a very poor buffered substrate, with an alkalinity range of 2,500 to 6,000 mg $CaCO_3$-equivalents/L. This could be regarded as a model for anaerobic digestion of other low buffered crops with a nitrogen content below 1%, like grain (wheat) or maize silage in the absence of manure. Manure is not only a source of nutrients (stabilizing the anaerobic digestion of energy crops with an extreme C/N ratio of >100), but it is also a good buffering agent with up to 21,000 mg $CaCO_3$-equivalents/L.

There also exists the assumption in literature that the anaerobic digestion with acidic substrates having an alkalinity below 6,000 mg $CaCO_3$/L should not be possible (Speece, 1996). Consequently, it was a great challenge to digest beet silage as a mono-substrate (Scherer, 2005, 2006; Scherer et al., 2003). It should be a precondition for extensive use of energy crops in areas without sufficient stock farming. A common approach to lower the need of manure is to use a recirculation of the effluent to improve the buffer capacity, as practiced in most of the two stage biogas plants of farmers in Germany with maize as mono-substrate (Banks and Humphreys, 1998; Jarvis et al., 1997). However, all these biogas plants still need additionally calcium oxide (lime) or occasionally intermittently manure as a buffering agent for continuous digestion (Barber, 1978).

The FLC technique has been validated as a control strategy for anaerobic treatment of industrial wastewaters (Carrasco et al., 2002; Estaben et al., 1997; Guwy et al., 1997; Holubar et al., 2003; Liu et al., 2004; Müller et al., 1997;

Murnleitner et al., 2002; Pullammanappallil et al., 1998; Punal et al., 2001; Steyer et al., 1997). However, there exists relatively less information about the applications of FLC to operate and monitor the anaerobic digestion of particulate organic wastes and/or energy crops (Boscolo et al., 1993; Holubar et al., 2003). Besides, lab-scale long-term applications of FLC for anaerobic digestion of solid matter lasting more than half a year are also seldom.

The objective of this study was to establish a reliable and simple FLC for anaerobic digestion of insufficiently buffered energy crops. As the most striking example, the acidic beet silage (pH ≈ 3.3–3.4) was chosen. Only 3 widespread process measuring parameters were applied; pH, CH_4 content and the spec. GPR. As a specialty, the spec. GPR was used instead of the vol. GPR. In this article, the presented FLC is used for the first time for a continuously driven long-term fermentation of renewable energy crops (beet silage) lasting for more than 560 days under this unique Fuzzy control strategy.

Materials and Methods

Reactors and Substrate

Laboratory-scale, single-stage continuous anaerobic digesters were used for the experiments, which were constructed in the Research Center of Lifetec Process Engineering at HAW Hamburg (Demirel and Scherer, 2008; Dobler et al., 2002; Scherer et al., 2003). Under different adjustments, the digesters were allowed to reach steady-state conditions, which meant that at least the threefold of the hypothetical, bacterial doubling time of 7 days was allowed for process performance, often more. The schematic configuration of the anaerobic biogas reactor is given in Figure 1. A separate, cooled substrate tank (at 4°C) was also included in the experimental set-up (not included in Fig. 1). Feeding was carried out using a substrate pump, which had a digital outlet and was directly connected with the process computer by a digital card under LabView (National Instruments, Austin, TX). Three simultaneous reactors were automatically fed from the same substrate tank, three times per day. Further details about the reactor configuration and the automation under LabView were previously reported (Dobler et al., 2002; Scherer et al., 2003).

Biogas production was continuously measured online, using a Milligascounter® type MGC-10 (Ritter GmbH, Bochum, Germany). Methane (CH_4) and carbon dioxide (CO_2) compositions (v/v) were measured online, using infrared sensors (BlueSens GmbH, Gaz Analyzer, Herten, Germany). The volume of gas was corrected for standard pressure and 0°C (STP, e.g., generally 9% lower values than measured). The temperature, pH and the redox potential (ORP) were also continuously measured online every 2 min (averaged per 8 h). A simultaneous, FLC processed fermentation was performed with the same cooled substrate tank, to simultaneously test different temperatures in parallel (Scherer et al., 2003, data not shown). Before each automatic feeding cycle, the reactor was completely stirred for about 5 min at 250 rpm. Therefore, the reactor was called as a completely stirred tank reactor (CSTR). By the way, viscosity problems, which have been solved by now, are quite serious during automatically feeding mode. Therefore, the feeding tubing was automatically washed by alternating the flow direction of the pump.

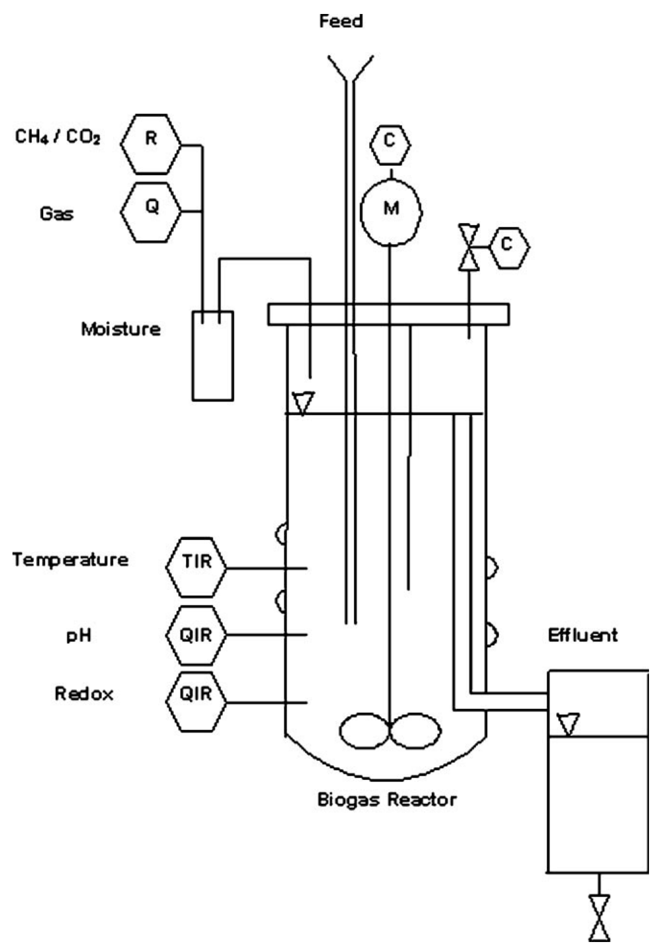

Figure 1. The scheme of the laboratory-scale anaerobic biogas digester. Q, quality of a measured value; M, motor; T, temperature; R, recorded values; I, instrument; C, controller.

The OLR was individually computed by the FLC program every 8 h/day, created by the fuzzy rules. A fuzzy tool of LabView was used to create the fuzzy rules. The fuzzy tool of LabView generated the new OLR_{added} into relative percentage, individually after each feeding cycle. The percentage of substrate addition was compared by the FLC with the substrate addition of the last cycle. The new addition was called the new OLR and was adjusted in a selected frame, for example, 10–120% of the last feeding. This adjustment influenced the velocity of adaptation to a feeding situation, fore example, the start-up period should be performed with another adjustment than the recovery after a reactor failure.

The SBS (without the leaves) and FBS (with the leaves and tops) were used as the mono-substrates. The general characteristics of the beet silages are given in Table I. The fodder and sugar beets were washed, smashed, and treated by natural lactic acid fermentation for 3–5 weeks after harvest in September and October, and left to stand outside at a temperature of 5–20°C. For further use, this suspension was diluted (1:1.5 or 1:2 for period 1,047–1,058 days) with water.

Analytical Methods

The volatile suspended solids (VSS) content was measured according to DIN Methods (DIN 38414-8, 1985). Alkalinity and ammonium (NH_4^+) were measured according to the Standard Methods (APHA, 1989). Lactate was determined using a Merck Lactic Acid Test (1.16127) (Merck, Darmstadt, Germany). Volatile fatty acids (VFA, C_2–C_6) and alcohols (C_1–C_3) were determined using an Agilent Technologies 6890 N (Agilent, Santa Clara, CA) with a flame ionization detector (FID).

Fuzzy Logic Control (FLC)

In order to make biogas plants for energy crops more reliable, a feedback controller for the whole process should be connected to the digester system. One of such a process controller is the Fuzzy based FLC as firstly proposed by Boscolo et al. (1993).

The FLC can be explained by a scheme in five different stages (Fig. 2). The first stage is used to record process values. The second stage reveals the fuzzification, to get a fuzzy set of fuzzy rules. The fuzzification means that inputs have to be converted by fuzzyfication into blurred linguistic terms, since the input parameters are too precise for the human logic (e.g. the linguistic terms high, medium and low for the temperature can be used). The rules of the FLC are formulated as a fuzzy set and this is the third stage after fuzzification. The numbers of the rules are determined as 3^x, and x represents the input number. The fourth stage is defuzzyfication, to obtain a result. Since the FLC provides the conclusion in linguistic terms, the result has to be converted to a number. The Centre of Maximum Method was used in this study as implemented in LabView (Ross, 2004). Finally, a numerical sum as output is obtained, which can be used by the FLC, to determine the feeding volume of the substrate pump of the biogas reactor. The Fuzzy rules could be programmed and the control range of the process parameters could be adapted to different types of biogas plants.

The FLC, which was developed at HAW Hamburg, determined the OLR, depending on the pH, the spec. GPR, together with CH_4 content (Scherer, 2006). The pH value is particularly an important input parameter for the FLC in the case of acidic, weakly buffered silage (pH between 3 and 4). The spec. GPR is the second input parameter, which describes the biogas production rate, in relation to feeding volume. The spec. GPR (m^3/kg VS/one day) is originally proposed here as a fuzzy control parameter, instead of the vol. GPR (m^3/m^3/day). The vol. GPR seems to be not suitable as it increases with increasing OLR and therefore can not support the pH control (or it responds too late). If an anaerobic reactor produces too much or too less biogas, with respect to the feeding volume, the FLC will then direct the OLR in the right direction. The CH_4 content is the third selected input parameter. If yeasts are present in the digester, the spec. GPR could lie within the right range, but the CH_4 content of the biogas can be too low (Scherer, 2006). The FLC should direct the OLR, enabling a stable process. Based on experience, the OLR is given in percentage of a preset minimum and maximum volume of the substrate, thereby adjusting the range of the coupled HRT. The FLC should be separately adjusted for each kind of substrate (maize silage, sugar beet silage, etc.), according to the parameters pH, spec. GPR and CH_4. Furthermore, during continuous run with the beet silage, the oxidation reduction potential (ORP) values were also measured, but the ORP was not found to be a reliable control parameter (Scherer, 2007). If oxidized VFA are enriched during fermentation of reduced sugars, the ORP reaches more positive values, but this signal is not reflected enough, and the signal is also often influenced by many sudden, unidentified perturbations. An early warning detector for hydrogen (H_2) or propionate or other VFA was also not considered due to the obtained successful experimental results of this study. The FLC has the advantage that a

Table I. The characteristics of the fodder and sugar beet silages.

Parameter	Unit	SBS value	FBS[a] value
pH		3.34	3.30
Volatile solids (VS)	%	18.44	14.03
Ammonium (NH_4^+)	mg/L	71	440
Phosphate (PO_4^{3-})	mg/L	15	190
Acetic acid	%	2.23	1.34
Propionic acid	mg/L	247	1,141
Isobutyric acid	mg/L	29	<10
Butyric acid	mg/L	146	308
Isovaleric acid	mg/L	63	11
Valeric acid	mg/L	70	12
Lactic acid	%	1.09	3.67
Alcohols (methanol, ethanol, propanol; primarily ethanol)	%	1.7	2.3

[a]Average values are reported here.

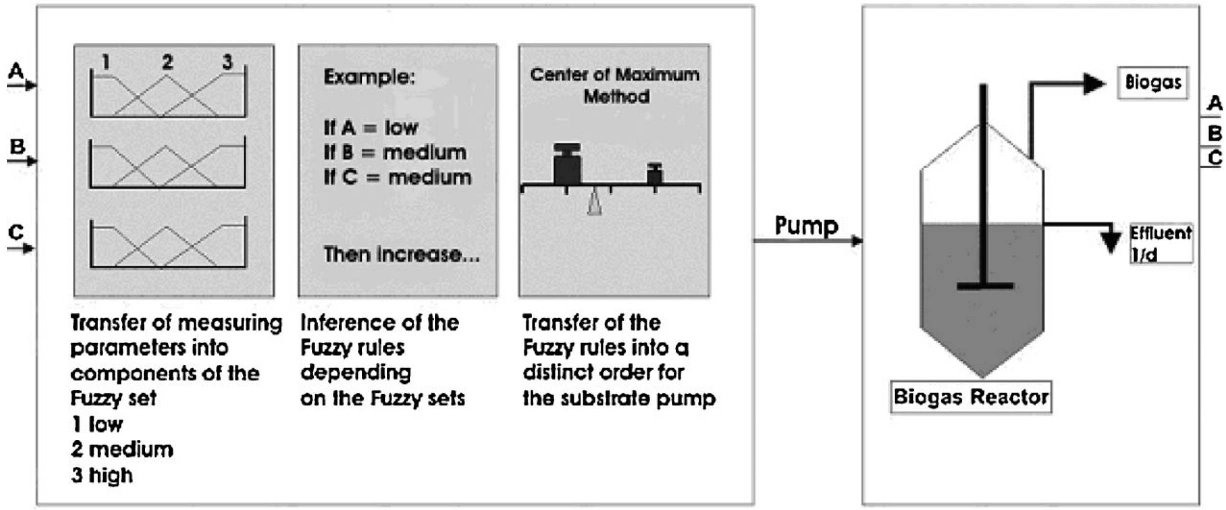

Figure 2. The scheme explaining the principle of a Fuzzy logic controller (FLC) for a biogas reactor. **A–C** are the three selected control parameters, CH_4, pH and the spec. GPR.

special mathematical model with kinetic data is not required for the anaerobic digestion process being difficult to obtain, for example, the ADM-1 (Batstone et al., 2002).

The Set of Ranges for the Beet Silage

Besides the fuzzy rules, the control ranges of the connected sensors (CH_4, pH, spec. GPR) should be separately set. The basic array of the control parameters should be provided by the FLC rules, but the range settings should additionally be achieved, which define the input areas against the linguistic terms and are part of the fuzzy tool of LabView. For example, the low range for the CH_4 content in biogas is defined to be between 0% and 60% (Fig. 3). In addition, a high critical and a less critical range for CH_4 should also be set. Thereby, the FLC increases or decreases the dosage of the substrate pump (Figs. 2 and 3). The high critical (HC) range of CH_4 lies between 75% and 85%, or even higher (normally not possible). Within this range, the FLC should increase the substrate dosage to its prefixed maximum value, which is related to the OLR of the last feeding rate in the previous feeding period. The CH_4 values from 0% to 60% also lie within a high critical range, but this range means the reverse of the high critical range between 75% and 85%. The substrate feeding has to be strongly reduced, if this range is reached. The medium ranges could be adjusted to be between 60% and 70% of CH_4, in which the OLR remains constant. The low critical control ranges for the CH_4 content in the biogas are a transient status between the high and the medium critical control ranges. In this case, the FLC should mildly decrease the OLR percentage, in relation to the previous substrate dosage.

In the same manner as shown for the CH_4 content, the control ranges for the spec. GPR and pH have to be also selected. The ranges can obviously be changed for every different experiment.

Results

The anaerobic mono-input digestion of FBS and SBS runs for more than 6 years, without any break, at both mesophilic (42°C) and thermophilic (60°C) conditions, at HAW Hamburg. After a yeast invasion the temperature of 42°C was selected instead of 37°C, which was also later recommended for anaerobic digestion of energy crops (Lindorfer et al., 2006). All parameters were monitored online and continuously recorded for the whole reactor operation periods,

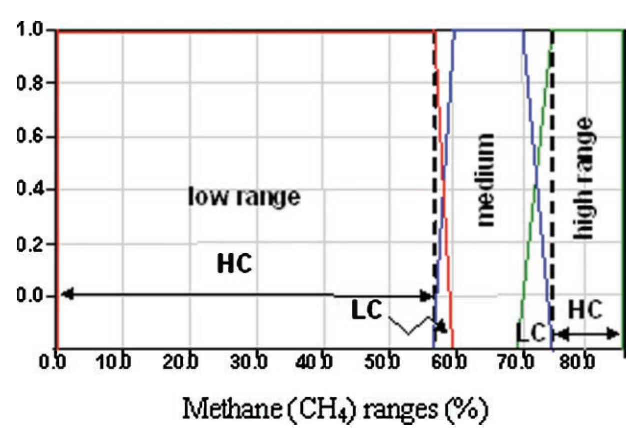

Figure 3. The adjustment of control ranges for the FLC-derived substrate feeding, according to the measured methane (CH_4) percentages in the produced biogas (HC, high critical; LC, low critical, related to the three ranges of low, medium, and high). [Color figure can be seen in the online version of this article, available at www.interscience.wiley.com.]

providing a deep insight into the anaerobic digestion process of this crop type.

During this long period of continuous fermentation, no manure or sewage sludge was added to the reactors, so that the initial ammonium level coming from the inoculum decreased from 2,000 to 250–300 mg/L. Thereby the direct influence of manure on the GPR could be excluded. This process of washing out the manure lasted nearly 2 years and led to a steady-state condition (Cobb and Hill, 1990). This was astonishing as the CSTR was completely mixed three times a day for 5 min at 250 rpm. The microbial population revealed a VSS of less than 2.5% in the stirred reactor, which was strictly related to the input and not to the inoculum, thereby providing true gas yields deriving only from the incoming substrate.

The history of biogas CSTR with automatically FLC is shown in Figure 4. Two time axes are shown at the bottom of the diagrams. The axis below shows the days after inoculating the reactor. The upper time scale refers to the start of the FLC. As there were a lot of automation problems to solve, the digester was continuously run for more than 2 years by manual feeding, until reactor day 757. The digester was fed once a day with an OLR of 2.7 kg VS/m^3/day, corresponding to a HRT of 26 days. After start of the

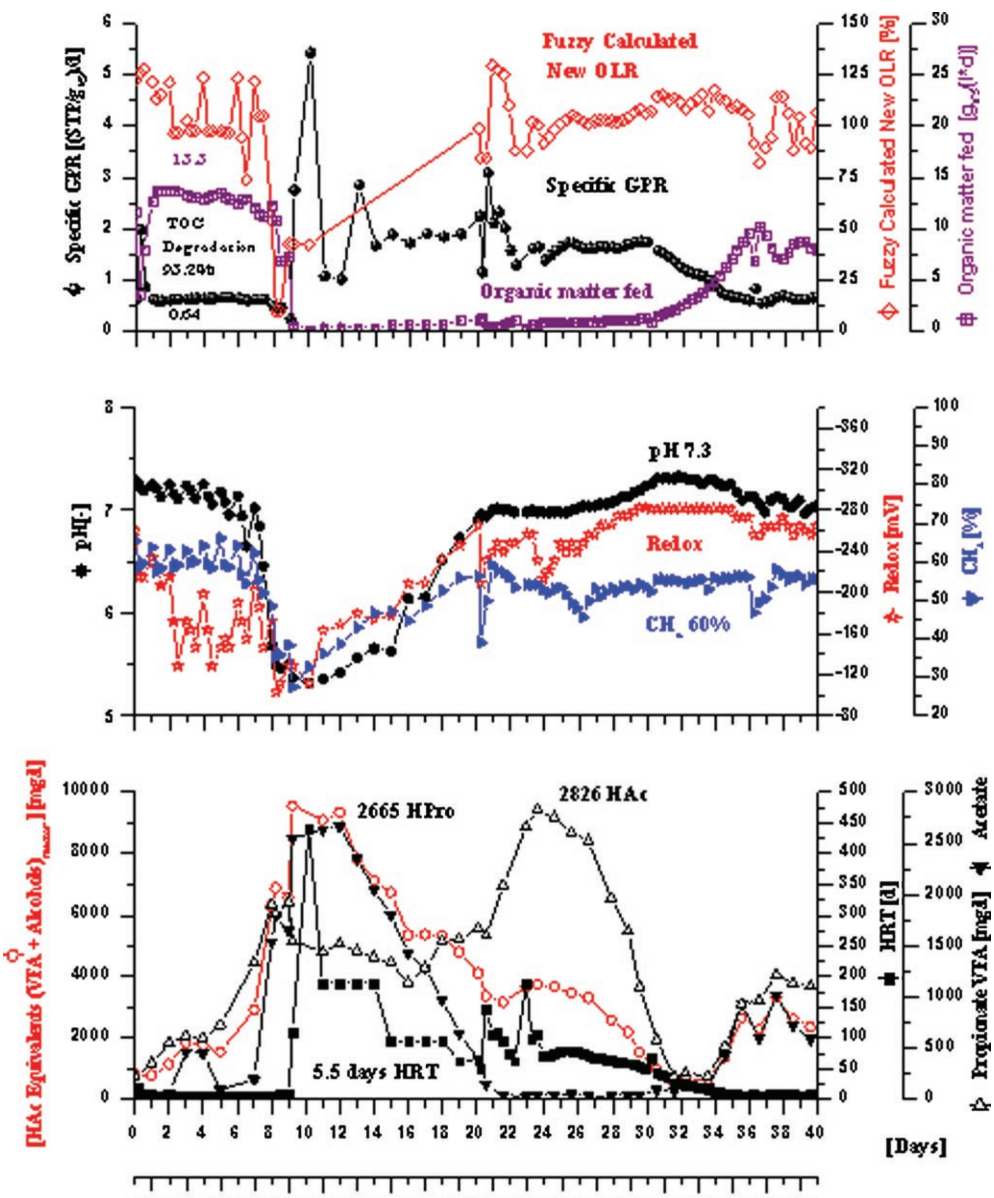

Figure 4. The history of a one-stage CSTR to demonstrate the usefulness of the automatic FLC. Two time axes are shown. The bottom axis shows the days after inoculating the reactor. The upper time scale above refers to the start of the FLC on day 757. Since the preset HRT of 5. 4 days was too short, and the corresponding OLR of 13. 8 g VS/L/day was too much, a severe reactor failure happened. The FLC automatically recovered this failure situation, without manual interaction. [Color figure can be seen in the online version of this article, available at www.interscience.wiley.com.]

FLC on reactor day 710, the substrate was still fed once a day by hand, but the automatic FLC was started on reactor day 757, feeding every 8 h a day. Firstly, the minimum HRT in the FLC was adjusted to be 5.4 days, corresponding to an OLR of 13.8 g VS/L/day. Promptly, this HRT was reached on day 758, but the change was too abrupt for the microbial population and caused a reactor failure. The minimum and maximum OLR adjustments were not in the right range. The pH decreased to 5.3 on reactor day 765, and the concentrations of acetic and propionic acids reached about 2,500 and 1,750 mg/L, respectively. Then, the feeding was automatically stopped by the FLC (upper diagram of Fig. 4), and the HRT increased to more than 400 days. Although no substrate was fed, the spec. GPR went further up, above 1.0 L/g VS/day, indicating that the previously accumulated VFA were consumed. For a 100% degradation, a spec. GPR of 0.75 L/g VS/day could be calculated (Scherer, 2007).

The history of the same digester for 84 days later is given in Figure 5. In the time between, the fuzzy rules and the frames of the sensor ranges were changed. Two completely unexpected

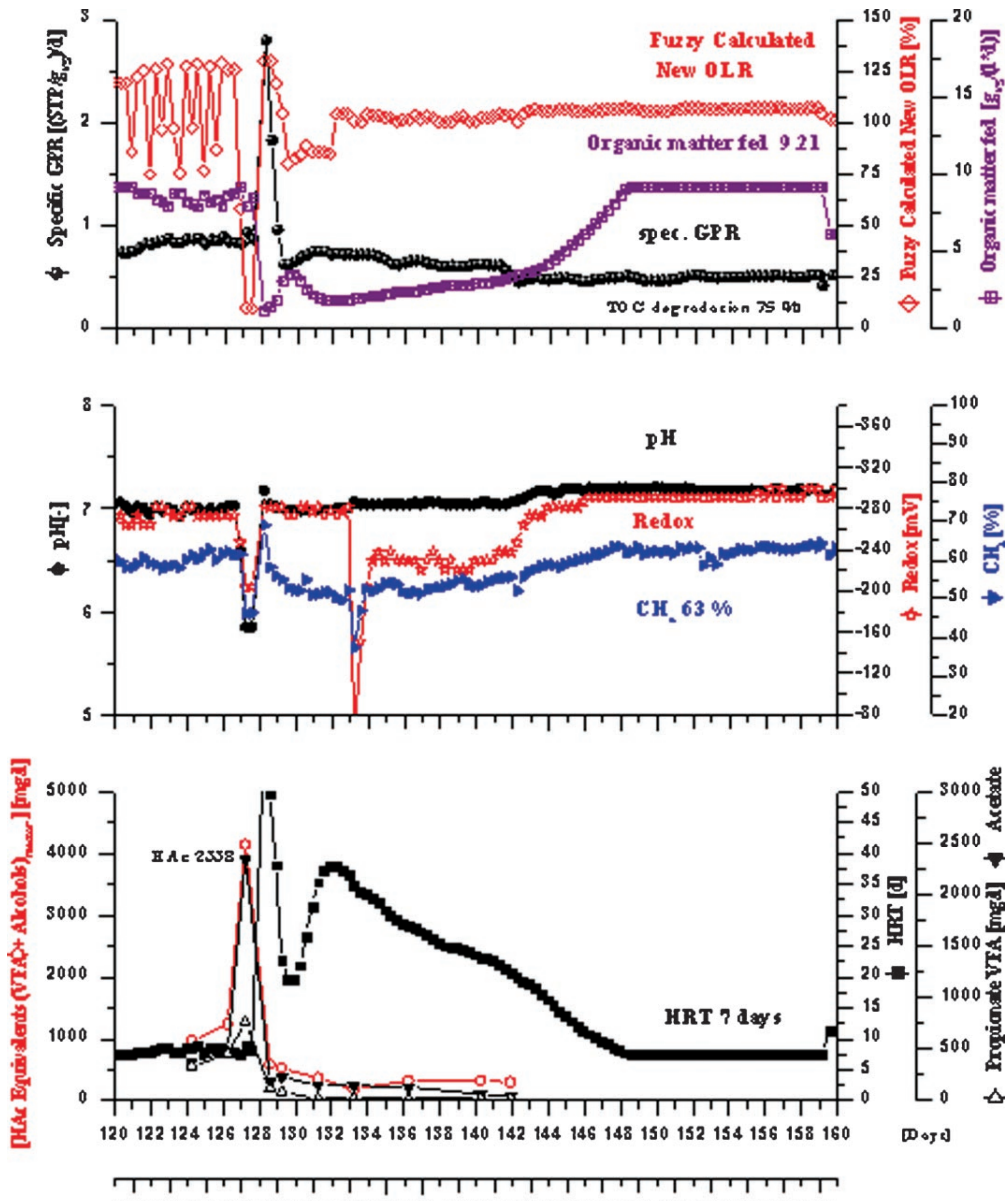

Figure 5. The history of a one-stage CSTR to demonstrate the usefulness of the automatic FLC. A reactor failure happened on day 883/884, as the electronic substrate balance was out of order and added too much substrate without control. The upper time scale refers to the FLC operation from 120 to 160 days, started on day 757. The FLC functioned perfectly, allowing an OLR of 13.8g VS/L/d and a VFA content below 50 ppm after reactor day 945. [Color figure can be seen in the online version of this article, available at www.interscience.wiley.com.]

events also occurred. Firstly, the substrate tube baked the electronic balance. Therefore, the pump dosed too much substrate into the digester, without any control. Unfortunately, the substrate was the residue in the substrate barrel. It came into contact with oxygen and apparently yeasts grew up (stored at 3°C). On reactor day 889, the spec. GPR seemed to be quite high about 0.60–0.75 L/g VS/day, but CH_4 dropped down below 50%. By the overdose, the pH decreased to 6.6 on reactor day 884. The acetate concentration increased to 2,338 mg/L. The ORP value also decreased, but the second decrease of the redox on day 890 could not be explained. The microscopic image exhibited a yeast invasion (pictures not shown). Therefore, since day 897 the reactor was operated at 42°C, to give the yeasts no chance to grow up again, as later recommended for digestion of energy crops at temperatures >41°C (Lindorfer et al., 2006). On reactor day 905, the digester was recovered, only 20 days after the reactor failure on reactor days 883–884. The FLC functioned completely automatic, without any manual interference.

Further history of the same digester is summarized in Figure 6. The scale on the bottom left refers to both VFA and alcohols being generally in the ratio of about 60:40.

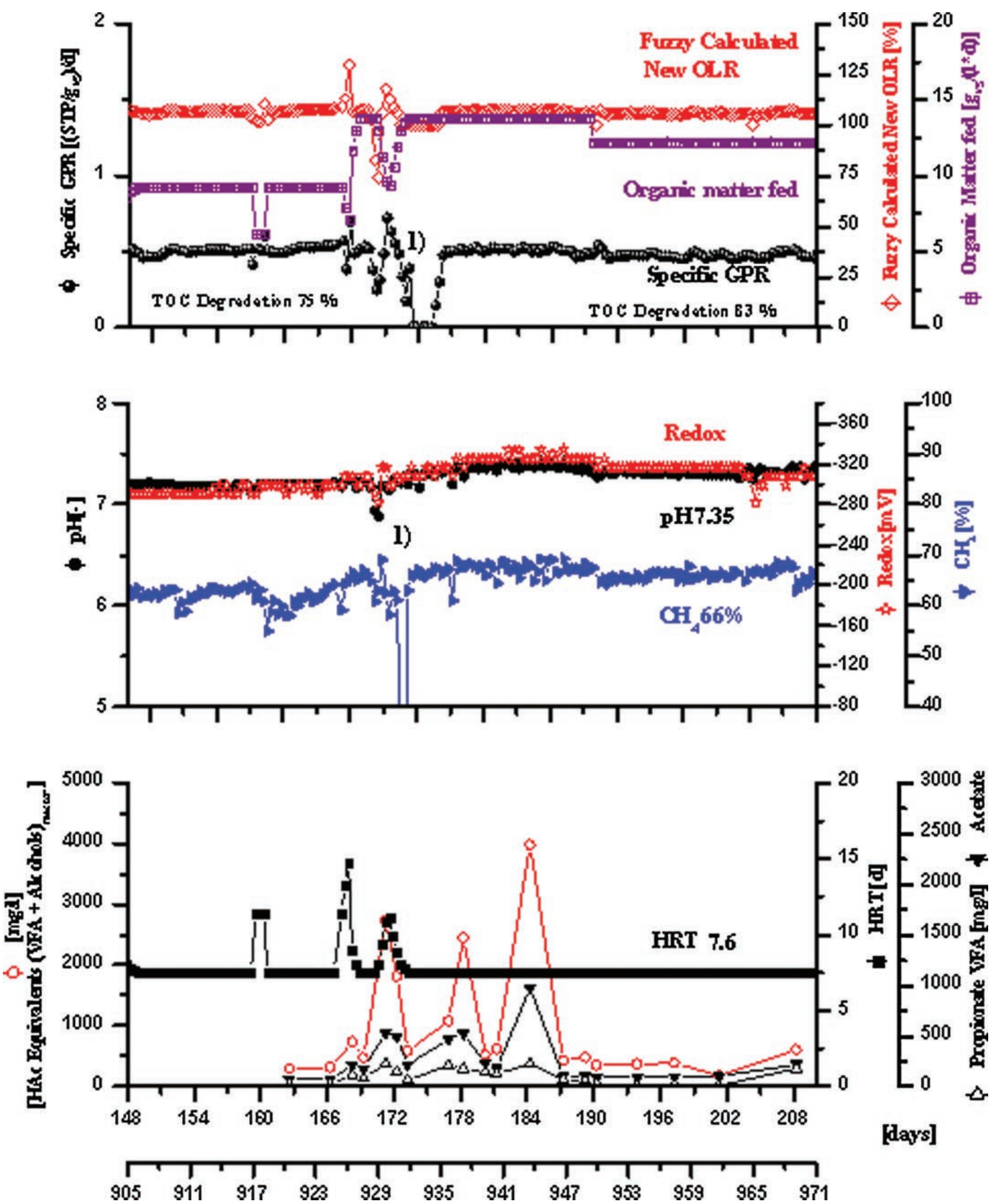

Figure 6. The history of a one-stage CSTR to demonstrate the usefulness of the FLC. The upper time scale presents the FLC operation from 148 to 208 days. (Arrow 1) refers to a singular technical problem. [Color figure can be seen in the online version of this article, available at www.interscience.wiley.com.]

The FBS was used without any supplements and the digester was operated at an OLR of 12.2–13.2 g VS/L/day, and a HRT of only 7.6 days. This resulted in a stable pH, CH_4, and spec. GPR levels, as indicated by VFA concentrations less than 500 mg/L. It must be mentioned that many agricultural biogas plants are running also stable, with tremendous high VFA levels of 3,000–5,000 ppm VFA, but alkalinities of more than 12,000 ppm $CaCO_3$-equivalents (Scherer, 2007).

A new critical reactor performance is displayed on reactor day 1,028 in Figure 7. The frames of the sensor ranges being integrated in the Fuzzy tool base were improved in the time between. The FLC reacted earlier on a pH change. The reactor was now 271 days later than day 757, as the automatic FLC started. The minimum HRT was set to 5.4 days and the reactor remained stable, without any failure. However, the FLC had to interfere permanently, as the pH and CH_4 values fluctuated. The VSS content of the reactor

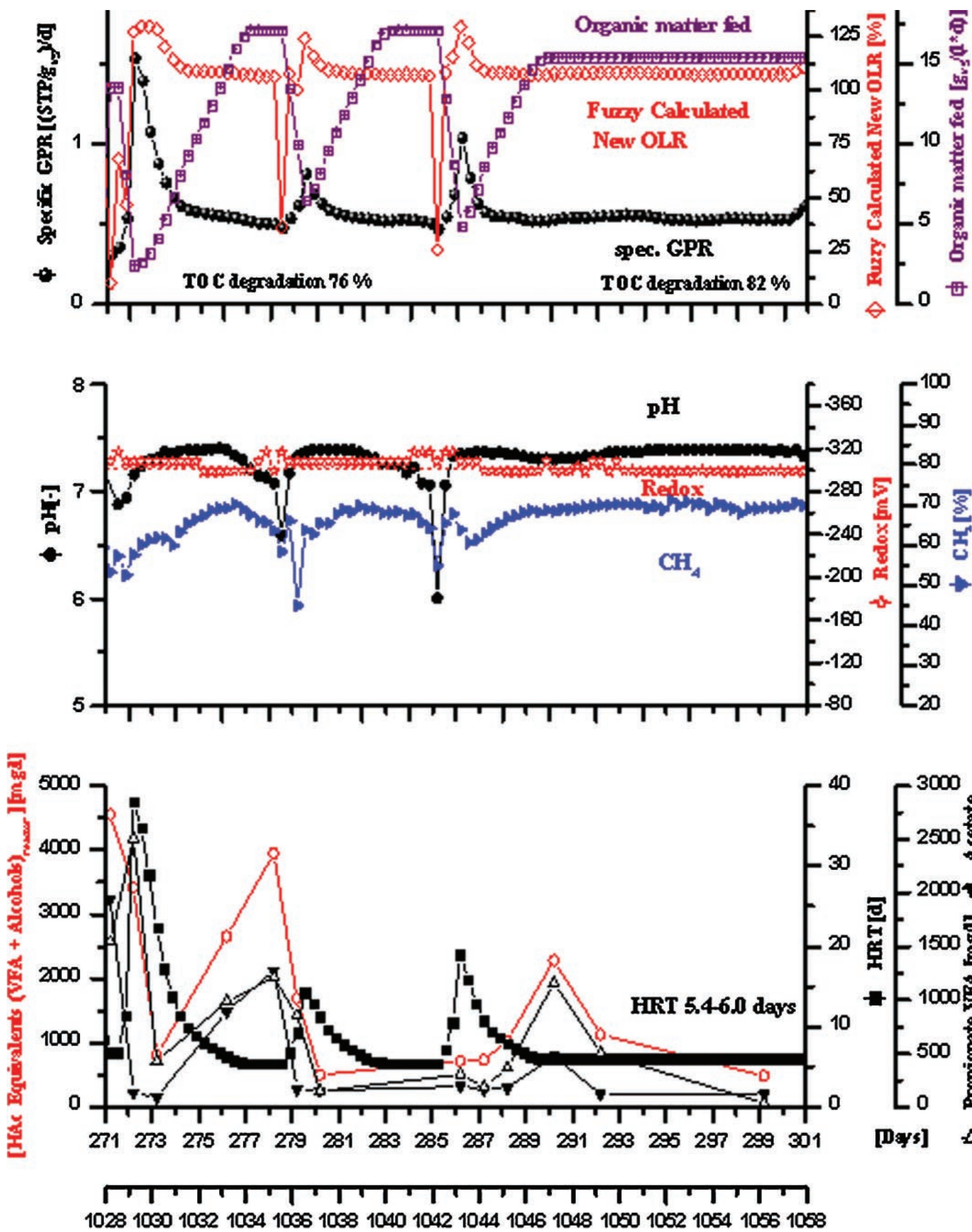

Figure 7. The history of a one-stage biogas digester to demonstrate the usefulness of an automatic FLC. After improving the ranges of the control parameters of the FLC, the reactor performance remained stable at retention times of 5.4 days (until 1,048d) and 6.0 days (until 1,058d). The upper time scale presents reactor operation with FLC from 271 and 301 days. [Color figure can be seen in the online version of this article, available at www.interscience.wiley.com.]

decreased below 1.5% in this period. However, these disturbances lasted only 2–3 days. The HRT was maintained by the FLC to 6.0 days as the minimum limit to avoid wash out of bacterial cells in the CSTR. The VFA concentration decreased below 500 mg/L, indicating stability of the digester. The FLC allowed a high throughput mode up to a maximum OLR of 15.6 kg VS/m^3/day in this period with a vol. GPR of 9 m^3/m^3/day (the substrate was less diluted for this limited period). The spec. GPR remained to be 0.56 L/g VS/day, and the degradation based on total organic carbon (TOC) was assumed to be 82% (Fig. 6). The real degradation rate could actually be higher, as a part of the incoming substrate could be washed out during feeding.

The recorded process parameters of the single-stage CSTR from the reactor operation period 1,102–1,142 days are shown in Figure 8. The substrate had to be changed from FBS to SBS on reactor day 1,069, which also had a low pH of around 3.4. This variation of substrate caused on the first glance only a minor change in the behavior of the fermentation. The pH of the reactor declined from 7.25 to 6.9 in 3 weeks (Fig. 8). This decrease of pH could be due to an error of the pH electrode, as the substrate change seemed to be minor. The new substrate (SBS) had nearly the same pH, but contained only 50–75% of the buffering capacity of the old substrate (FBS). The FBS had an alkalinity value of 4,000–6,000 mg $CaCO_3$ equivalents/L, while the SBS had only 2,500–3,500 mg $CaCO_3$/L. Therefore, the pH decreased permanently from 7.25 to 6.9, in spite of the FLC regulated feeding.

In Figure 9, reactor operation period from 1,259 to 1,295 days is displayed. The substrate change from FBS to SBS was already carried out 35 days before, but it was difficult to achieve steady-state conditions. The FLC stabilized the acidic (insufficiently buffered) fermentation without artificial pH buffering, only by decreasing the OLR and by increasing the HRT. The oscillating HRT increased from 7.6 days to between 30 and 50 days, by the FLC, in order to maintain automatically the process in a stable condition. The set point of HRT of 6 days could never be reached by the FLC and the new substrate SBS allowed only a very deep permanent pH of 6.5–6.6 (Fig. 6). This reactor behavior seemed to be quite unusual as no comparable stable biogas process could be encountered in literature. The FLC had to interfere enduringly. However, a stable situation was also reflected by the low level of VFA, below 500 ppm (right scale of the diagram at the bottom of Fig. 7). The redox values also remained smooth and were apparently not influenced by the pH disturbances of the digester. The methane level decreased from about 62–55%, at a HRT of 27 days.

In further experiments, it was observed that the declined CH_4 content of the produced biogas was typical for less ensilaged sugar beets (without the top and the leaves). The final pH of SBS was 3.4, nearly the same for FBS (pH 3.3), but the sugar content of the mono-substrate was nearly doubled from about 75 g/kg wet matter to 20–180 g/kg wet matter, limiting the silage process and reducing the concomitant CO_2 loss. Therefore, the SBS revealed significant lower methane content than fodder beets with the top. However, the HRT also influenced the CH_4 content of the biogas. With an HRT of 27 days (start–up phase), the methane content was about 58–60% in the reactor period until 710 days (Scherer et al., 2003). On reactor day 910, the CH_4 content of the biogas was about 62.5% at HRT 7.6 days, and even 69% at an HRT of 6.0 days (Figs. 5 and 6). Simultaneously, the spec. GPR decreased from 0.63 to 0.50–0.56 L/g VS/day. Therefore, the specific methane yield related both to the OLR and the converted organic matter behaved nearly constant. This observation was also made in another study, during anaerobic digestion of SBS at different HRTs under stationary conditions (Demirel and Scherer, 2008).

During the whole test period of more than 2,000 days, the content of the organic matter (VSS) of the CSTR was regularly measured. As the reactor was completely stirred, the organic matter content reflected the microbial biomass in the reactor. Although the HRT was drastically reduced from 26 to 5.4–7.6 days, by the automatic FLC starting on reactor day 757, the organic dry weight of the CSTR increased to 0.93% on reactor day 819, and later on, to 1.93% (reactor day 1,066, with the same substrate FBS).

In the last experiment, the reactor temperature was increased from 41 to 50°C, in 1°C steps per day (Fig. 10). As shown by the time axis of Figure 9, a new, separate reactor was set up with FBS as mono-input. The inoculum derived from the former reactor periods. Concomitantly with temperature increase, the spec. GPR, pH and the CH_4 decreased, and the FLC automatically decreased the substrate feeding (OLR). The OLR decreased to 1.5 g VS/L/day, but the HRT increased from 10 to 40 days, and on reactor day 502, the pH and the CH_4 content of the produced biogas declined below 50%. As the temperature shock came after a long period of stable and uniform fermentation, no real acclimatization was possible on reactor day 504. The FLC reacted directly and restricted the feeding severely. Thereby, the HRT increased sharply (in Fig. 10, the diagram at the bottom). Astonishingly, the period of disturbance lasted only 2 weeks. Further increase of the digester temperature to 60°C did not apparently influence the methanogenic population. Therefore, in the last period, the FLC regulated automatically down to a shorter HRT of 10–15 days (Fig. 10).

Discussion

The FLC, which was developed at HAW Hamburg, determined the OLR, only depending on pH, the spec. GPR (as m^3/kg VS/day) and the CH_4 content. The main previous work was to find out how many measuring parameters and fuzzy rules were necessary to obtain a stable and reliable fermentation (Scherer, 2006). The pH value was regarded as an important input parameter for the FLC, particularly in the case of acidic, weakly buffered silage (pH 3–4). The sensitivity of control was proved to be high enough. If the pH was too low (generally less than 7.0), then the reactor became sour, and generally the GPR and the CH_4 content dropped down severely.

The spec. GPR is the second input parameter, which outlines the biogas production rate in relation to feeding volume. For wastewater treatment it is difficult to relate the GPR to the input as generally the incoming water varies, but for more or less uniform fermentation of renewable

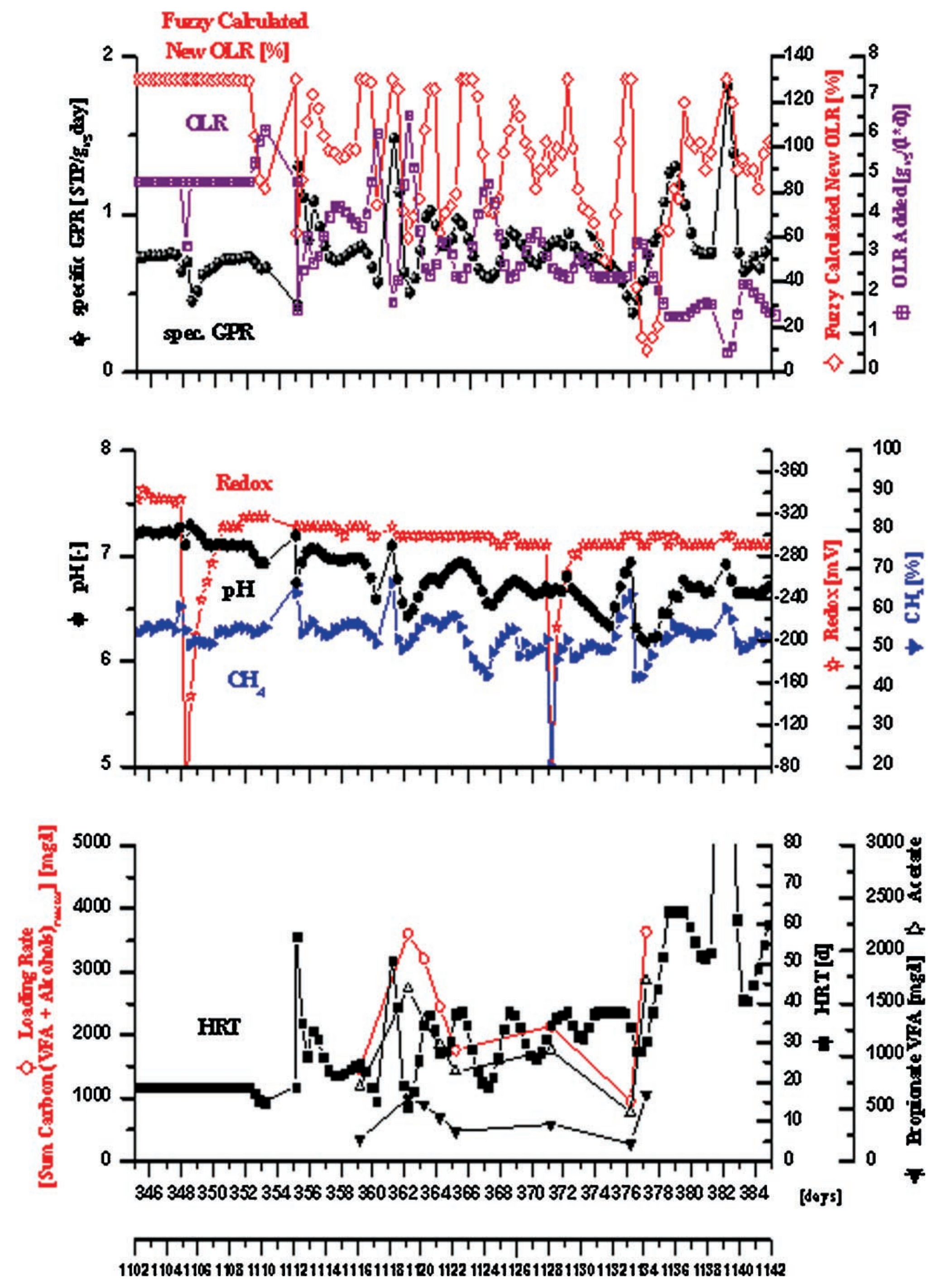

Figure 8. The history of a one-stage biogas digester to demonstrate the usefulness of an automatic FLC. On reactor day 1,069 (33 days before), the substrate FBS ran out and it was continued with the much less buffered SBS. The upper time scale refers to the FLC operation from 396 to 384 days. [Color figure can be seen in the online version of this article, available at www.interscience.wiley.com.]

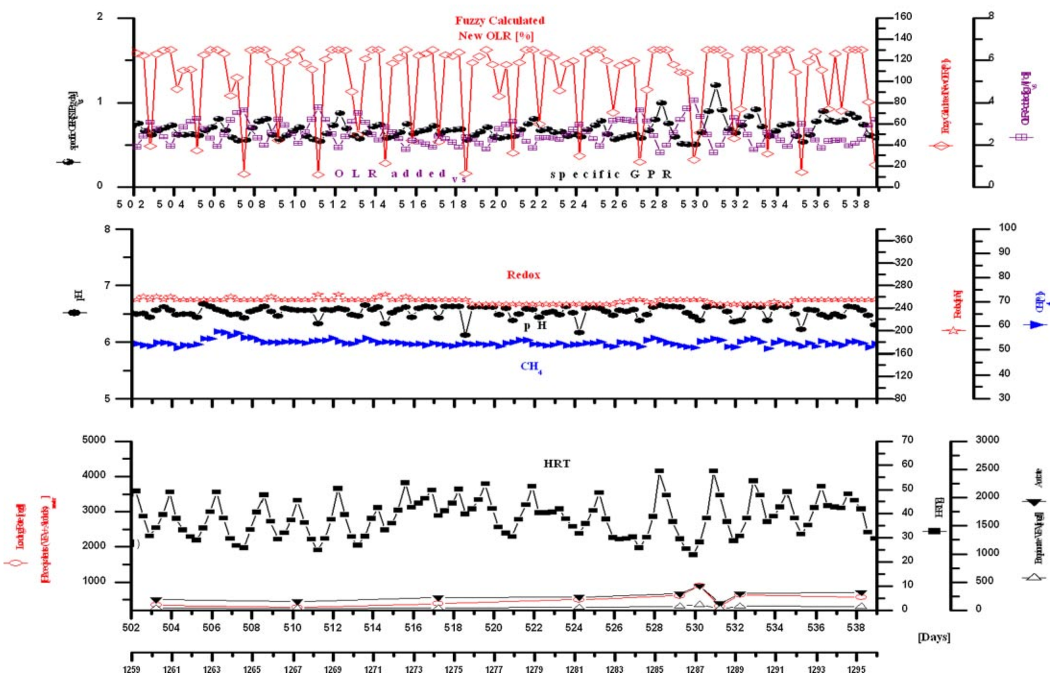

Figure 9. The history of a one-stage biogas digester to demonstrate the usefulness of an automatic FLC. The upper time axis indicates that the automatic mode of the FLC was in operation from 502 to 538 days. As pH fluctuated, the FLC interfered permanently, but the redox value and VFA levels remained stable (<500 mg/L). [Color figure can be seen in the online version of this article, available at www.interscience.wiley.com.]

biomass, the sum of dissolved volatile solids and volatile suspended solids can be determined as total organic carbon (TOC) of one charge or harvest for the input (Scherer, 2007). It was also found that only the spec. GPR was suitable instead of the vol. GPR. If the spec. GPR is too much or too less with respect to the feeding volume, the FLC will lead the OLR into the right direction.

The CH_4 content is the third input parameter of the developed FLC. Yeasts and methanogens should be differentiated, since both produce biogas. If yeasts are present, the GPR could lie in the right range, but the methane content can be too low (Fig. 4). Therefore, the CH_4 content is another important input parameter for the FLC. It can indicate invaded yeasts, which reduce the methane yield. Then, the FLC should correct the OLR.

Sometimes the redox value is supposed to be a controlling parameter (Pind et al., 2003). The redox value should be more positive after an increase of fatty acids in the reactor medium. During the continuous process with beet silage (>50,000 h), the redox value was also measured, but it was not observed to be a pronounced and reliable control parameter (Figs. 4–9).

A hydrogen sensor was used as an early warning system in a Fuzzy network for anaerobic wastewater treatment (Guwy et al., 1997; Müller et al., 1997; Murnleitner et al., 2002; Pind et al., 2003). Other used neuronal networks in addition (Holubar et al., 2003; Steyer et al., 1997, 2005). It was considered here that such a self-learning network is not applicable to a methanogenic long-term fermentation process, while there already exists too many abrupt technical problems superposing the real effects.

The FLC enabled a high throughput anaerobic digestion process for the used FBS (diluted). A maximum OLR of 15.6 kg VS/m^3/day, at a short HRT of 6.0 days, and with a GPR of 9 m^3/m^3/day could be reached (Fig. 7). The minimum HRT seemed to be around 5.3 days. A one-stage biogas system, which was manually fed with FBS once a day was operated by Maehnert and Linke (2006). It was found out that an abrupt inhibition occurred at an of OLR 4.5 kg VS/m^3/day under mesophilic conditions. The effect of increasing OLR was minor at 55°C, but an inhibition occurred at an OLR of 2.5 kg VS/m^3/day. Similar results were also obtained in another work, with a maximum OLR of 4.0 kg VS/m^3/day for sugar beet or fodder (=forage) beet silage under mesophilic conditions (Hassan, 2003).

Conclusions

This article presents for the first time a detailed long-term study about a FLC system developed for anaerobic digestion of energy crops with poor buffering capacity as mono-input. The lab-scale experiments were carried out with fully automated and completely mixed reactors, fed every 8 h a day with extremely sour beet silage (pH 3.3–3.4), to create a FLC strategy. Three commercially available measuring

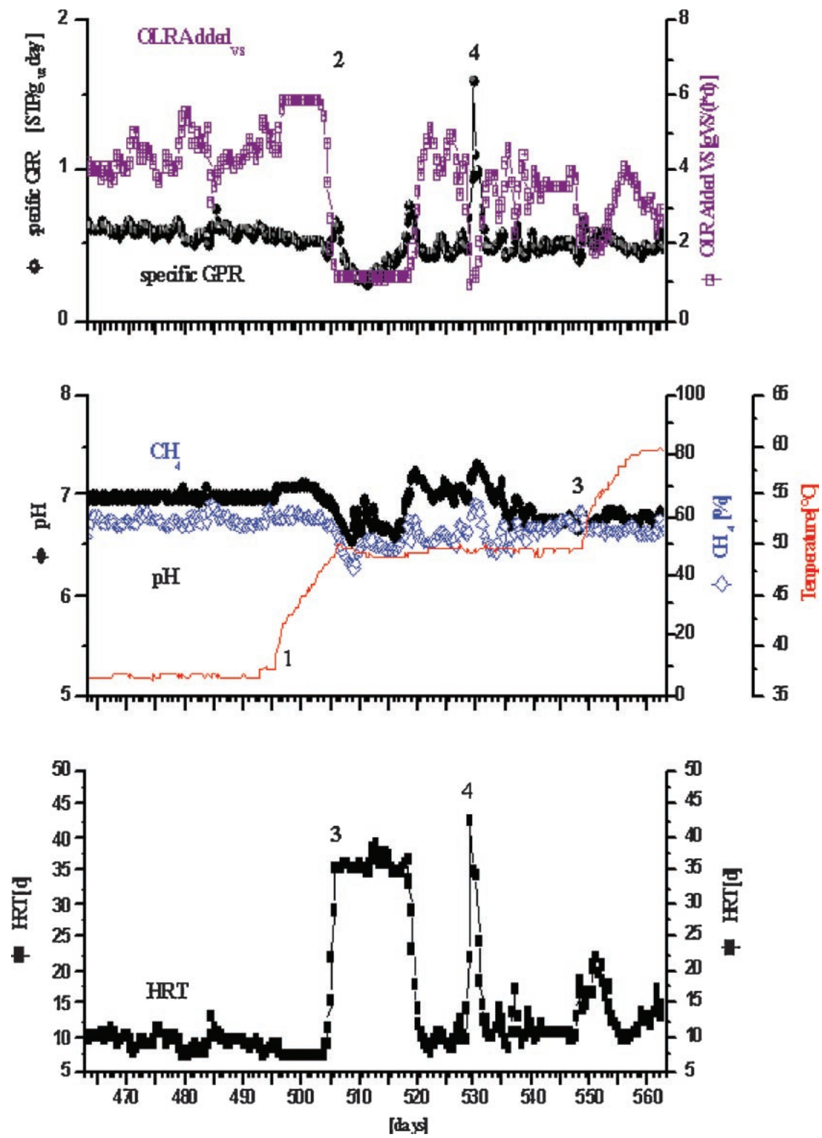

Figure 10. The history of a one-stage biogas digester demonstrating the usefulness of an automatic FLC. In contrast to the previous figures, a new lab-scale reactor was set up with FBS as mono-input, operated at 37°C instead of 42°C. Manually performed temperature increase (1, 3 in the middle diagram) led to a reduced OLR (2, upper diagram), corresponding to an increased HRT (3, lower diagram). This again revealed an artificially induced decrease of the spec. GPR (2, upper diagram). Arrow 4 refers to a singular technical problem (clogging of tubing). [Color figure can be seen in the online version of this article, available at www.interscience.wiley.com.]

parameters (pH, methane content-CH_4 and the spec. GPR) can cover most of all applications, including a careful start-up process and a gentle recovery strategy after a severe reactor fall, as shown in this paper for two reactor failures and an attempt to cause a third reactor fall. The feasibility of the FLC was also proved by an artificially induced temperature shock situation. The FLC with a feeding cycle of 3 times per day also enabled a process with a high OLR and a short HRT (high throughput anaerobic digestion process). The developed FLC system did not need any complicated detector (e.g. for propionate) or self-learning network or a special mathematical model. Similar to an alarm signal, it was found sufficient to preset and to limit the hydraulic retention time by minimum and maximum amounts of substrate per feeding cycle in the fuzzy tool base.

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