Development of instrumentation systems as a base for control of digestion process stability in full-scale agricultural and industrial biogas plants

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ABSTRACT

This article deals with the analysis of instrumentation from three modern German full-scale biogas plants with different inputs and typical process engineering concepts for German conditions. The measured results from each plant and the suitability of the instrumentation used are evaluated and assessed. Conclusions are also made about improving the use and architecture of the instrumentation. The analysis results show which benefits and optimum combination of on-line and off-line instrumentation could result for the control and automation of industrial and agricultural biogas plants.

Key words | anaerobic, biogas plants, energy crops, instrumentation, control and automation, renewable energy

INTRODUCTION

Energy production from biogas, which is manufactured using the fermentation of organic raw materials, has become more and more attractive over the last few years for economic, ecological (Lens et al. 2004, 2005) and also political reasons. Accordingly, biogas is becoming more important the world over. According to the prognosis issued by the German Biogas Association, around 4,000 industrial and agricultural biogas plants with a total capacity of 1,400 MWel. installed capacity were operated up to the end of 2008 in Germany alone.

Biogas plants are very complex items whose control and regulation is not a trivial task. Operators of most biogas plants are often overtaxed for this reason, and require support in the form of instrumentation, control and automation (ICA). The current state of ICA technology at biogas plants has already been extensively described in detail by Kujawski et al. (2007). Against the background of their instrumentation fittings, many biogas plants are referred to as so-called black box systems because they are often insufficiently transparent to be economically and efficiently operated.

In this context the instrumentation, which is the actual cornerstone for control and regulation, is often deficient. Off-line measurements (laboratory-based process monitoring) are seldom implemented or, often insufficiently documented. On-line measuring systems are only seldom installed at biogas plants. Even if a little data is available, it is seldom evaluated and analyzed with the result that such plants often have unreproducible operational problems. The measured data is seldom checked for plausibility, and is mostly used only for monitoring and not for control and/or regulation.

The economic efficiency of biogas plant operation is dependent on many factors. Optimum usage of the methane production potential of substrate used plays a central role in this case. This, however, is related to the stability of the anaerobic processes which in turn are dependent on (amongst others):

- the value and manner (e.g. continual or intermittent, regular or irregular) of digester organic load rate (in kg oDM (m³ d)⁻¹)
the characteristics of the substrates used, such as: composition (protein, fat and carbohydrate content); dynamics of substrate decomposition; content of potential inhibitors and/or toxins; content of trace elements; suitability for the formation of inhibitors and toxins (e.g. hydrogen sulphide, ammonia, organic acids) during the course of the anaerobic decomposition; suitability for the formation of effluent substrates, whose compounds ensure increases in the buffer capacity; physical processes/parameters such as efficiency of mixing, and the temperature which can be directly set by the operator with the help of ICA equipment.

The stability of processes in the biogas formation is assessed based on the knowledge of the condition of equilibrium in the anaerobic decomposition (hydrolysis, acidification, acetic acid formation and methane formation), alkalinity and the quantity of inhibitors and toxins in the digester. The first robust measuring equipment for investigating the stability of the anaerobic processes used at the early on a few full-scale biogas plants in recent years consists of:

- On-line: ORP potential, pH, EC, gas composition, gas quantity,
- Off-line: volatile fatty acids and alkalinity, ammonium nitrogen and hydrosulphide, which are normally determined in external laboratories using titrimetric, chromatographic or spectrometric methods.

There is, of course, a whole series of other measuring equipment such as fully automatic titrators, NIR spectrometers, electronic noses and tongues, gas chromatographs and ion chromatographs in addition to HPLCs (High-Performance Liquid Chromatograph) whose use in biogas plants is being investigated on site. Under certain conditions, they enable measurement of the required biogas parameters even at extremely high frequency and accuracy. The biggest challenges set by the use of this equipment are: development of the sample (biogas substrate is usually characterized by high TSS content of above 50 g/L) as well as decrease of purchasing and operating costs of this measurements on site.

The extent of the instrumentation equipment or measuring system and measuring program at a specific plant is dependent on the specific boundary conditions and the task in hand. Several factors therefore play an important role in the selection of optimum instrumentation technique/system: frequency of measurement, accuracy, representativeness of the sample, purchase and operational costs of the measuring equipment.

In a range of scientific projects, the instrumentation equipment for anaerobic technology has mostly been tested and investigated at lab/half-scale and/or for the anaerobic treatment of activated sludge (Steyer et al. 2005 and Spanjers & van Lier 2006), however up to now very few comparisons of the use of instrumentation and the overall instrumentation systems have been carried out on industrial and agricultural full-scale biogas plants.

The main goal of this study was the approach for optimal design of instrumentation systems and measurement techniques on the different biogas plants under special consideration of digestion process stability.

The subordinate goals were:

- Testing of available measurement techniques
- Statistical analysis of frequency of process instabilities
- Investigation of the best approach for measurement in:
  - “normal” operation—no visible process disturbances and constant composition and quality of input
  - “extraordinary” operation—start up of the plant, change of input composition or quality, visible disturbances of the process
- Consideration of instrumentation costs

MATERIALS AND METHODS

In this article, the three German full-scale biogas plants with varying inputs and typical procedural concepts (for German conditions) were analyzed:

- The Wambeln biogas plant (W BP) (max 560 kWel) was put into operation in spring 2006. The plant produces power and heat mainly from organic wastes such as waste foodstuff and organic fertilizers such as liquid pig manure and poultry dung.
- The Lelbach biogas plant (L BP) (max. 550 kWel) (also described by Wiese & Kujawski 2008; Wiese & König 2009) was put into operation in winter 2006. The plant produces power and heat mainly from maize silage,
cattle dung and also small quantities of fodder beet (only in spring and autumn 2007).

- The Nordholz biogas plant (N BP) (max. 550 kWel) was put into operation in winter 2007. The plant produces power and heat mainly from maize silage and cattle dung.

All the biogas plants investigated were designed and built in accordance with the following process engineering concepts:

- Two-stage process with primary digester and secondary digester to increase plant safety.
- Simultaneous wet fermentation: 7.3–7.8 pH, 5–9% total suspended solids (TSS) in digesters.
- Mesophilic conditions: approx. 40°C (resp. 313 K resp. 104°F).
- Hydraulic retention time (HRT): > 60 days for efficient use of biogas production potential.
- Automatic dosage system for biosolids: container with weighing machine, pushrod discharger and several vertical and horizontal screw conveyors.
- Central pumping station with automatically controlled slides and on-line measuring devices.

- Digester tanks covered with membranes for collection and storage of biogas.
- High level instrumentation and automation (see Table 1).
- Aerobic hydrogen sulphide removal: in order to reduce H₂S (< 250 ppm) in biogas, a little air (< 0.5% O₂) is injected into the digester and post-digester gas storage (only in BP Wambeln external hydrogen sulphide removal).
- Programmable logic controller (PLC) and a modern PC-based supervisory control and data acquisition system (SCADA).
- ICA on these biogas plants is mostly used for measurement and monitoring.
- The implemented control strategies are very simple e.g. exact dosage of the substrate to digesters regards their amount (weight or volume), time based mixing in the digesters, temperature control.

During the course of the measurement campaigns the following off-line instrumentation equipment was tested, which was used directly at the plants:

Table 1 | On-line instrumentation on the plants investigated

<table>
<thead>
<tr>
<th>Location</th>
<th>Measurement (method)</th>
<th>BP W</th>
<th>BP L</th>
<th>BP N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumping station:</td>
<td>Inductive flow meter</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Temperature meter (pt100)</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>pH (salt bridge)</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>ORP† (salt bridge)</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>EC† (inductive</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSS (optical)</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>NIRS‡</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Biogas pipeline</td>
<td>Gas flow rate (mass flow method)</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Gas analyzer: CH₄ (IR sensor), CO₂ (IR sensor), O₂ (electrochemical sensor), H₂S(electrochemical sensor)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Gateway</td>
<td>Heavy-load weighing machine</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>NIRS‡</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Anaerobic digester and post-digester</td>
<td>Level meters: gas/liquid phase</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Temperature meters: digesters, 2 x heating system (pt 100)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Video controller</td>
<td></td>
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</tbody>
</table>

†Oxidation-reduction potential, †Electrical conductivity sensor, ‡NIRS—near-infrared spectroscope—tested on the biogas plants—during the calibration phase good results were obtained (Wiese et al. 2008). Application for the real time prediction and control was not applied in measurement campaign.
Semi-automatic titrator and manual titrator for determination of VFA and alkalinity,

Quick tests for photometric determination of organic acids, acid buffer capacity and ammonia.

Indirect determination of acid buffer capacity using measurement of CO₂ amount after acidification of the sample with excess acid.

In addition, numerous off-line measurements were carried out by externally certified laboratories. The concentrations of organic acids in addition to alkalinity and ammonium nitrate were measured.

RESULTS AND DISCUSSION

The description and analysis of the results, and the resulting discussions, are presented separately for each plant investigated. Although each BP was provided with two digesters switched in series, the paper only presents the measured results from the primary digester because it was the one with the highest organic load rate. The figures show the data which played the largest role in the evaluation.

Wambeln BP

Figure 2 shows the 21 months of BP operation. The average performance over the entire period is only 439 kWₑₑ. The standard deviation of energy production is, at 71 kWₑₑ, extremely high. Hence it is obvious that the average monthly production of electrical energy at the plant, represented by the step curve, was very unstable and relatively low. BP had significant difficulties in operation over the period shown from February to September 2008.

Observations

At the Wambeln BP, the fermentation stability was mainly monitored with the help of a semi-automatic titrator for the determination of VFA and alkalinity. The external laboratory analyses were only intensified during critical operational phases. From Figure 2 it can easily be seen that the concentration of VFA determined by titration conforms well with the help of a gas chromatograph in external lab. An increasing tendency in the concentration of organic acids was noted between 23 August 2007 and 22 February 2008 (on 22.02.2008 the organic acid equivalent reached 13.9 g CH₃COOH/L). This had two causes: firstly, there was an inhibiting action caused by ammonium nitrogen (increased use of poultry dung as substrate during this period), which also caused an increase in the alkalinity, and secondly the fluctuating organic load rate in the digester.

The plant mainly uses easily degradable food waste which is delivered in batches. These batches have extremely varying qualities (for example with regard to biogas formation potential, TSS and its organic part). Up to March 2008, the source material batches were metered separately and successively into the digester. This led to considerable fluctuation of the digesters organic load rate. As a result of this, the concentrations of volatile organic acids and the alkalinity vary considerably up to March 2008 (see Figure 1). This negative effect could also have played its part in the increase of acid concentrations over this period.

Control and regulation strategies

The plant digester organic load rate was considerably reduced from March 2009 onwards. As a result of this, the organic acid concentration decreased considerably. Subsequently the organic load rate was slowly increased. The substrate dosage strategy was adapted so that batches of the input material were homogenised as far as possible in the plant buffer reservoirs before feeding into the digesters. As a result of the use of the strategy, the fluctuations in the VFA and alkalinity decreased considerably (see Figure 2 from 22.02.2008 onwards).

Conclusions

Analysis of the measurement data makes it clear that the measurement system used on the plant is insufficient in its current extent. Firstly, organic load rate of the digesters must be implemented through monitoring of the TSS and organic part of TSS concentration in the effluent substrate, especially since excellent linear relation between the TSS
content and the biogas production potential has been determined using differing samples of the effluent substrate. Secondly, more frequent monitoring of the ammonium concentration should be carried out.

The Lelbach BP

The plant produces electrical energy from renewable raw materials (mainly maize silage and cattle dung). In comparison to foodstuff waste such as was used at the Wambeln biogas plant, this substrate had a relatively stable composition (TSS and its organic part) and biogas formation potential. Figure 2 uses a step diagram to show the mean monthly installed electrical capacity of the plant, which is 517 kWel over the entire observed period, and has a standard deviation of 38 kWel. After a few months of start-up operation, the plant energy production was stable. Significant reduction of performance can only be observed at two locations (areas II and III). In December 2006 the energy production decreased due to a fault in the process biology, and in August 2007 due to an engine failure at the combined heat and power plant.

Observations and control strategies

Four periods in which significant changes took place are highlighted in Figure 2. During period I of the start-up phase, the biocenosis reacted extremely sensitively to the digester organic load rate. The digester content contained a relatively large quantity of oxidizing substances (increase of ORP potential), and the acid concentration was also partially increased. During phase II, a failure caused by the addition of an outside substrate (silage juice from the maize silo with high concentrations of organic acids) took place. This action was also indicated immediately by an increase in the ORP potential. As a result of this the digester was run with a reduced organic load rate over 4 months. This meant that the acid concentration decreased. In the case of fault IV, it can clearly be seen that an infrequently carried-out laboratory measurement of organic acids did not detect a peak in the acid concentration. The continuous ORP measurement, however, reacted and provided a warning. Over the entire observed period, the pH value was very stable and remained within the permissible range. The concentrations of reduced nitrogen compositions in combination with pH value at the plant were well below the inhibition limit for anaerobic processes.
Conclusions

Instabilities in the biological system were only observed over the period of investigation when the digester was in the start-up phase or when a new substrate was added. Even in these cases, the ORP measurement always indicated the unfavorable operating conditions. The pH measurement was shown to be less sensitive. One can recommend that the system alkalinity should be more detailed observed.

Nordholz BP

The primary digester was put into operation at the beginning of January 2008. In a similar manner to the Lelbach biogas plant, power was generated from maize silage and cattle dung. The energy production is stable (standard deviation is on average only 43 kWel.). Over the last three months of the period under investigation, the plant produced an average of 471 kWel.

Observations

The plant produced more than 80% (more than 400 kWel) of its planned capacity after only eight weeks of operation, but the acid concentration in the primary digester rose relatively quickly once the first batch of maize silage had been added (see Figure 3, phase 1). As a result of this, the acid concentration achieved values of 6.512 mg CH₃COOH/L (measured with a semi-automatic titrator) and 3.260 mg CH₃COOH/L (measured with the help of ion chromatograph in an external laboratory). The increase in acid concentration was also indicated in this case by the ORP sensor. During operation phases 1 and 2, the acid buffer capacity decreased continuously as a result of the maize silage in feed. This is a result of heavy organic load of the digester due to maize silage. On 29.01.2008 the alkalinity was 14.175 mg CaCO₃/L and on 01.04.2008 only 8.290 mg CaCO₃/L. On 01.04.2008, a large quantity of substrate from the secondary digester was recirculated into the primary digester.

This accounts for the considerable increase in alkalinity in the primary digester (see Figure 3, phase 3). Interesting relations between the alkalinity (measured by titration) and EC as well as between the ORP potential and the VFA (measured by titration) were observed over the period under investigation.

Control strategies

The digester organic load rate and the input composition were controlled depending on the development of acid

Figure 2 | Measurements at the Lelbach BP (LU—ext. lab, p.d.—primary digester).
concentration and alkalinity. The result of the balance have made it clear that considerable formation of alkalinity takes place during the process of anaerobic decomposition. As a result of this, the alkalinity in all the plants investigated was always higher in the downstream digester than in the upstream digester. This fact was used for dynamic control of the Nordholz plant. As a result of the circulation from the secondary to the primary digester, the alkalinity in the primary digester increased and acid concentration were diluted (see Figure 3, phase 3).

Conclusions

Detailed analysis of the measurement data obtained from the Nordholz biogas plant showed that the digestion of renewable raw materials can be characterized by high dynamics (with regard to acid formation, alkalinity) and especially during the start-up phase. These dynamics can be successfully observed by the on-line and off-line instrumentation used in this case. The measured results obtained are reliable, and can be very easily used for the purposes of control and automation.

Other interesting measured results

VFA and alkalinity appear to constitute very promising parameters for the control and regulation of biogas plants. During the measurement campaigns, other alternative measurement techniques such as manual titrators for the determination of VFA and alkalinity, cuvette tests for the photometric determination of organic acids, acid buffer capacity and ammonia, in addition to the indirect
determination of acid buffer capacity (using measurement of CO₂ amount after acidification of the sample with excess acid) were successfully used. The measured results obtained during the measurements are very promising, and show good correlation and compliance with the results of reliable laboratory measurements of the same parameters (see Figure 4). The laboratory VFA measurement was carried out with the help of ionic chromatography. The titration of VFAs was carried out with the usage of Nordmann’s method (Burchard et al. 2001) with reduced sample preparation. However, the reduced sample preparation caused a quite high TSS concentration in the sample. That is why between those both measurements there are some differences. However results are good correlated.

CONCLUSIONS

During the project, the measured results from three modern German full-scale biogas plants were investigated and evaluated. Only the instrumentation which has proven its use during use for the investigation of the stability of an aerobic processes at the plants was selected for the evaluation (robust, inexpensive and reliable).

Off-line instrumentation

Most of the off-line laboratory measurements were contracted out to external laboratories. This is the reason for the delayed (up to two weeks) results. Representative sampling was made very difficult because the digesters were extremely large (1.500 m³) and substrates were a long way away from the ideal mixture. Another disadvantage of laboratory measurement was the high cost (even 250 € per typical measurement for two samples). Extremely useful parameters such as VFA and alkalinity were able to be determined inexpensively and quickly on site at the plant with the aid of a semi-automatic titrator.

On-line instrumentation

Especially ORP, pH or EC measurement provided representative results with regard to sampling (instruments were installed at the pump station, and each of these enabled several cubic meters of substrate to be investigated at one time during pumping). The immediate availability of results using on-line instrumentation is a considerable advantage, especially in the case of plants with pronounced dynamics in the acid formation process (dangerous increase in acid concentration within one day!). Increases in the acid concentration or decreases in the alkalinity were able to be determined immediately through the use of on-line instrumentation. Disadvantage is, that this devices are only indirectly determine the required parameters (e.g. tendency of acid formation, or H⁺ ions concentration).

Optimal measuring systems

Both advantages and disadvantages were observed during the use of off-line and on-line measurements. It is, however, necessary that both types of measurement are carried out simultaneously at the plant, and that they work together in one measuring system. It is also important that off-line data is entered into the process control system and actively used for both control and regulation. The measuring system architecture must be adapted to the relevant requirements of the plant and the operator. In this case it is important that an adapted solution can save both money and time (a simple economic analysis has shown that up to 15,000 € of operational costs of instrumentation can be saved annually by optimizing the instrumentation at the plants investigated). The type and composition of the
input substrate appear to play a central role in the design of the measurement system.

During the analysis it was discovered that an increased use of robust and reliable on-line instrumentation is extremely necessary for both industrial and agricultural biogas plants, and that the consolation presented here can be sufficient in many cases (measuring equipment which is already in common use in sewage treatment plants was used in most cases). A measuring system should, however, be heavily adapted to the specific requirements and operating conditions of a specific plant. Statistical analysis of the data acquired has shown that one can do without many expensive laboratory measurements since the installed on-line instrumentation (e.g. pH, ORP and EC) was sufficient for monitoring the processes under normal conditions. An increased use of off-line instrumentation has, in contrast, considerable usefulness in critical situations.

Future work

During the analysis of measurement data from biogas plants, several interesting relations for individual measurement data (e.g. ORP and concentration of organic acids, or conductivity and alkalinity) have been found which is going to be developed and investigated more deeply as the next step of scientific work have to be done.

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