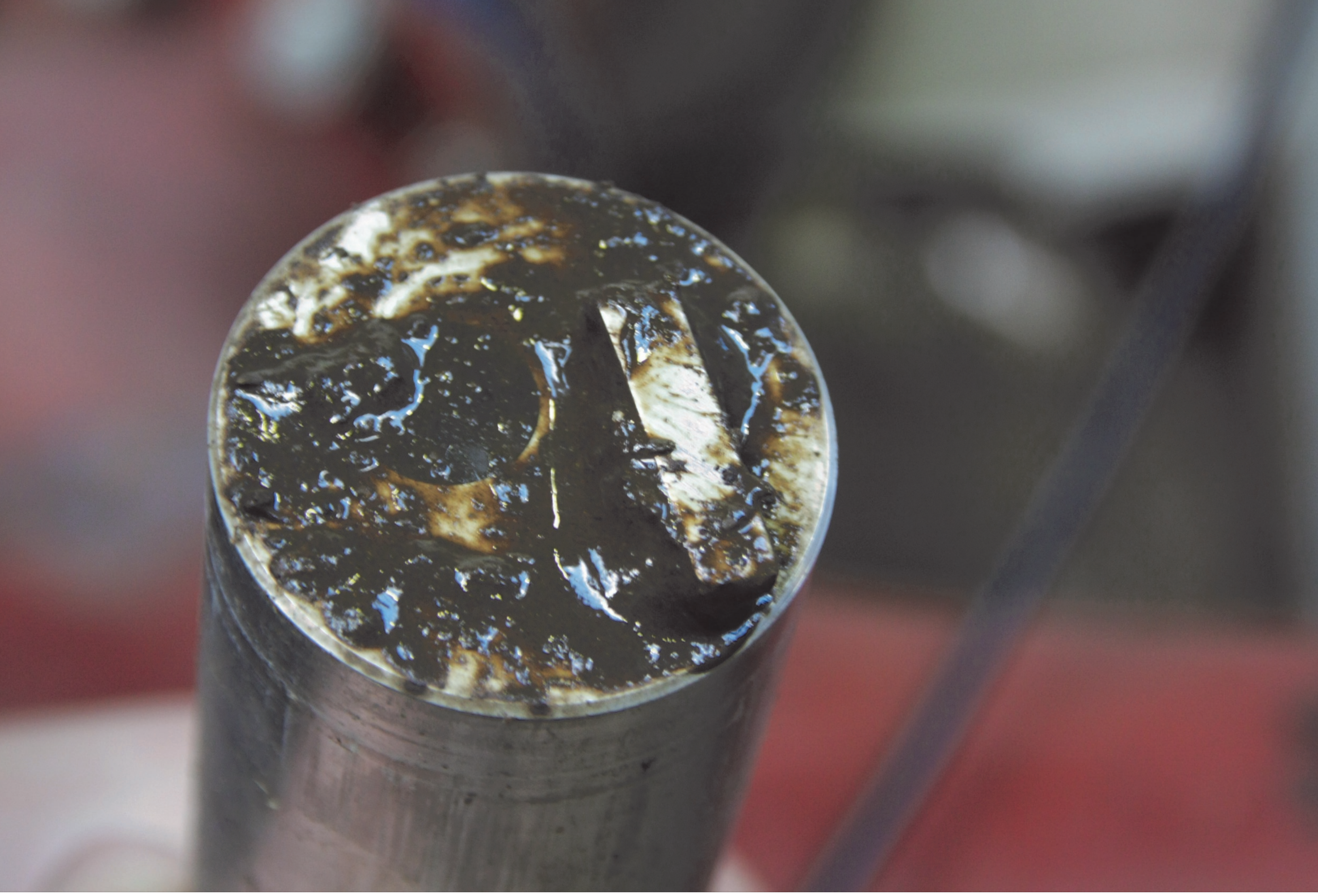

Online-measurement systems for agricultural and industrial AD plants – A review and practice test

Wolf, C.[1]; Gaida, D.[1]; Bongards, M.[1]

[1] Fachhochschule Köln, Campus Gummersbach, Institut für Automation & Industrial IT, Steinmüllerallee 1, 51643 Gummersbach

Abstract

Online-measurement systems for AD plants in general are crucial to allow for detailed and comprehensive process monitoring and provide a basis for the development and practical application of process optimisation and control strategies.

Nevertheless, the online measurement of key process variables such as Volatile Fatty Acids (VFA) and Total Alkalinity (TA) has proven to be difficult due to extreme process conditions. High Total Solids (TS) concentrations and extraneous material often damage the sensors or have a strong negative impact on measurement quality and long-term behaviour.

Consequently, there is a need for new robust and accurate online-measurement systems.

The purpose of this paper is to give an overview of existing online-measurement systems, to present the current state of research and to show the results of practice tests at an agricultural and industrial AD plant. It becomes obvious that a broad variety of measurement solutions have been developed over the past few years, but that the main problem is the upscaling from lab-scale to practical application at full-scale AD plants. Results from the practice tests show that an online-measurement of pH, ORP, TS is possible.

1 Introduction

The instrumentation of industrial plants in general is a key prerequisite to making efficient and continuous process monitoring and control possible in the first place (Lipták 2003). Looking at biogas plants, both agricultural and industrial, good instrumentation has proven to be essential to maintaining stable and efficient AD processes. In particular, the high volatility of AD processes due to their high sensitivity to varying process conditions such as temperature, pH, carbon buffer, acetic acid concentration, ammonia inhibition and substrate composition, requires close monitoring at all times (Kujawski & Steinmetz 2009a). This kind of process monitoring allows the setup of an early detection and warning system for process disturbances to prevent breakdowns and, as such, is of direct monetary benefit to the plant operator. Nevertheless, instrumentation at full-scale biogas plants is still in its infancy as shown by the recent biogas measurement program in Germany (FNR e.V. 2009). Currently 70 % of biogas plants in Germany possess measurement systems for biogas production while 60 % have systems for measuring biogas composition. Liquid and solid substrate feed are measured at 50 % and 80 % of the plants, respectively. In contrast, the more sophisticated measurement systems, such as online pH, ORP or even VFA analysis are available at less than 5 % of all plants. This leaves lots of potential for the application of innovative online measurements to improve plant performance and presents a huge market for manufacturers of online measurement systems. Furthermore, there is substantial research activity in this area aiming to provide new robust and feasible measurement systems.

However, the research conducted in the field of AD control and optimisation shows that in most cases sophisticated lab equipment (online gas chromatography, HPLC, spectrophotometric titration, etc.) is used for detailed process monitoring (Jantsch & Mattiasson 2004, Boe et al. 2007b, Méndez-Acosta et al. 2008, Ward et al. 2011), which delivers very good measurement accuracy but is very expensive and maintenance-intensive at the same time. Thus, transition of such methods and systems to full-scale applications is difficult, and mostly not feasible, due to high installation and maintenance costs. This concerns small and medium-sized agricultural plants in particular, where plant operators also have a lack of the required expert knowledge to operate these complex and sensitive systems. Nevertheless, current research in the area of online measurement systems for anaerobic digestion processes shows that the development of reliable, low-maintenance and feasible systems is far from trivial as the challenges are multifaceted (Spanjers & Lier 2006). On the one hand, high contents of dry matter with many sharp and hard objects render the use of sensitive electrodes nearly impossible and on the other hand calibration and maintenance procedures need to be simple so that they can be performed by the plant operators themselves (Wolf et al. 2011a).

This paper gives an overview of existing online-measurement systems, to present the current state of research and to show the results of practice tests at an agricultural and industrial AD plant. Section 2 is a literature review of the current state of research in the area of online instrumentation of AD plants. Furthermore, section 3 and section 4 present the setup and the results of the practice test of existing online-measurement systems at an agricultural and industrial AD plant respectively. The conclusion sums up achieved results and gives a final evaluation of the online-measurement systems.

2 Literature Review for Online Monitoring of AD plants

The large number of developments and research papers in the history of monitoring of AD processes illustrates the importance of reliable, low-maintenance and feasible online measurement systems. One of the first papers to consider the topic was McCarty (1982). In this paper McCarty gave a review of the developments in anaerobic digestion in the last century and pointed out that "recent advances in fundamental understanding of the [anaerobic] process have yet to be translated into practical application for process design, optimization and control."

Therefore, online-monitoring is crucial, but to choose the most viable process variables for online monitoring is even more important. In 2000 the variables pH, partial alkalinity (PA), gas production rate and composition as well as VFA concentration were compared under varying organic loading rates (pulse loads) at a lab-scale reactor to evaluate their suitability for monitoring purposes (Björnsson et al. 2000). The results showed significant change in PA and VFA concentration under the pulse loads, whereas a detected decrease in the pH could not be separated from normal operating conditions. Thus, pH was considered unreliable for early warning purposes as a significant drop in the pH only occurred under a heavy organic overload of the system. Results for gas composition and gas production rate monitoring were also delayed and merely significant in case of overload. These findings are confirmed by Ahring et al. (1995) and recently supported by Boe et al. (2010), all leading researchers in the AD community. In a substantial study the behaviour of pH, VFA and dissolved hydrogen was investigated under different kinds of disturbances. It became evident that pH is an important parameter in the case of AD systems with low buffering capacity and that the sum of VFA concentrations is less meaningful than the separate investigation of acetic, butyric and propionic acid. A fast response to disturbances was also detected in dissolved hydrogen, but an increase was not always related to process instability, which suggests a check against other parameters, such as VFA concentration, for the reliable detection of process instability. The use of pH and ORP online probes for process monitoring in combination with biogas production rate was investigated further in a research project by UTEC GmbH in Bremen, Germany (Zimmermann et al. 2003). It was shown at two full-scale biogas plants using co-digestion that a combination of these three process parameters allows a good assessment of process stability. In addition to alkalinity, VFA, pH and ORP, total and volatile solids have proven to be valid process parameters to predict biogas production and to monitor the substrate feed of biogas plants as well as significant indicators like volume load, volatile solids (VS) degradation or methane yield (FNR e.V. 2010). These publications as well as a summary of recent developments, online measurement methods and applications for AD were summarized clearly by Madsen et al. (2011), who concluded that the most important parameters for process monitoring are:

- VFA
- alkalinity (PA and TA)
- TS and VS
- biogas composition
- biogas yield
- pH
- ORP
- temperature

This list of process parameters can be divided into two classes according to the availability of online measurement systems, their reliability and their suitability for practical use at a biogas plant. On the one hand, biogas composition/yield, temperature, pH and ORP can be considered as state of the art for agricultural biogas plants as the existing technology is sufficiently robust and reliable. On the other hand, the online measurement of alkalinity, TS/VS and VFA is still subject to substantial research. Even though measurement systems for biogas plants already exist for these parameters, high prices and high maintenance efforts still pose a problem, reducing the acceptance of such technology in practice. Therefore the two classes of process parameters are state of the art parameters for process monitoring and new innovative parameters. Unfortunately, the state of the art parameters have proven to be less effective at determining the current process state of a biogas pant than the innovative parameters, which emphasizes the need for online measurement systems in the latter field. The following two sections describe the current state of research and practice for these two classes of process parameters.

2.1 State of research

Research in the field of online measurement systems for AD processes is mainly focused on a few parameters, such as biogas production and composition, pH, ORP, TS, VS as well as alkalinity and VFA. Of these parameters VS, alkalinity and VFA, which belong to the class of innovative parameters, have received lots of attention concerning the development of new measurement methods and systems (Table 1). In contrast, several long-term practice tests were conducted for the parameters biogas production/composition, pH, ORP and TS to prove their reliability and capability to detect process disturbances (Wiese & Kujawski 2008, Kujawski & Steinmetz 2009b). Looking at all the publications in this area, as summarized in Table 1, it becomes clear that there is a trend to go from direct biochemical measurement of process parameters to indirect measurement using spectroscopic methods in combination with powerful machine learning techniques. In particular, the indirect measurement of VS, alkalinity and VFA using UV/vis, near-infrared or even mid-infrared spectroscopy has proven to be a good alternative to expensive wet chemistry analyzers (Spanjers et al. 2006, Holm-Nielsen et al. 2008b, Wolf et al. 2010). These spectroscopic measurement systems analyse absorbance or reflection spectra over certain wavelengths using machine learning techniques (ANN, SVM, PLS, etc.) to indirectly measure biochemical parameters. The advantage of such systems is that they offer the possibility of measuring directly inside the measurement medium and to measure several parameters with one system using different basis calibrations. Due to the fact that the description of all published R&D results would be too long, only the most important and relevant developments are briefly described.

2.1.1 Biogas yield/composition

Research to-date on biogas quantity and quality measurements for AD processes primarily focuses on lab-scale applications, where measurement data needs to be as accurate as possible. For this reason the developments are mostly very expensive and their applicability to full-scale biogas plants is limited. Nevertheless the methods developed by Cadena Pereda et al. (2010b) and Keppler et al. (2010) are worth mentioning. Cadena Pereda used a volumetric cell, where the biogas is isolated from the displacement liquid, with an optical level detection allowing for a measurement range from 10 to 55.000 cm³.

Furthermore, the fill level data is automatically analysed using a FPGA board, which also controls the measurement system. Keppler investigated the measurement of carbon isotope ratios (13C/12C) of methane, which are considered a valuable process parameter to quickly detect changes in AD processes. The use of optical spectrometry in comparison to the conventional method using continuous-flow isotope ratio mass spectrometry was evaluated. Results show that these two methods deliver similar results, with the accuracy of the online spectrometry only varying by 0.7 % from the conventional method.

2.1.2 pH/ORP

The use of pH and ORP probes for online-monitoring of AD processes was strongly suggested by Zimmermann in 2003. It was shown that a combination of biogas production rate, pH and ORP measurements is well suited to the assessment of process stability. Due to the fact that absolute values for pH and ORP differ widely from plant to plant, the trends of pH and ORP measurements were used in this case. Based on this analysis, Wiese & König (2009b) and Wolf et al. (2011a) tested the application of pH and ORP probes of different manufacturers on full-scale agricultural biogas plants. Results indicate that available systems are reliable and sufficiently robust for agricultural plants, if calibration is carried out regularly every two or three weeks. Unfortunately, a correlation between process stability and pH/ORP measurement data could only be detected if process instability was imminent, which is in most cases too late. Nevertheless, long-time trends in AD processes can be properly monitored.

2.1.3 TS/VS

The most promising technologies for online TS/VS monitoring were introduced by Lomborg et al. (2009) and Nacke et al. (2010). The use of NIR spectroscopy for TS/VS measurement was introduced by Lomborg. Based on the pattern of reflected light in the NIR wavelength range (800 nm – 2.000 nm) by the measurement medium, an indirect measurement of TS and VS is possible.
Lomborg clearly showed that very good results can be achieved for low TS and VS concentrations (between 4.6 and 6.5), but that further investiga-

Table 1: List of developed and tested online measurement methods for AD processes in the past 20 years.

	Method	References
Biogas yield/composition	gas chromatography	(*Slater et al. 1990*)
	lab-scale fermentation tests	(*Scaglione et al. 2008*)
	volumetric gas flow meter	(*Cadena Pereda et al. 2010a*)
	near-infrared laser optical spectrometry/ CF-IRMS	(*Keppler et al. 2010*)
	pressure-based near-infrared analyzer	(*Bishop et al. 2010*)
pH/ORP	electro-chemical	(*Monzambe et al. 1988*)
		(*Zimmermann et al. 2003*)
		(*Wiese and Haeck 2006*)
		(*Wolf et al. 2011a*)
	calculation from bicarbonate and carbon dioxide concentration	(*Hawkes et al. 1994*)
TS/VS	microwave	(*Nacke et al. 2010*)
	backscattered light	(*Wiese and Haeck 2006*)
		(*Wolf et al. 2011a*)
	near-infrared spectroscopy	(*Lomborg et al. 2009*)
VFA/COD	titration	(*Powell and Archer 1989*)
PA/TA		(*Feitkenhauer et al. 2002*)
		(*Lahav and Morgan 2004*)
		(*de Neve and Lievens 2004*)
	ion-selective electrode arrays	(*Witkowska et al. 2010*)
	membrane-inlet mass spectrometry	(*Ward et al. 2011*)
	spectrophotometric	(*Jantsch and Mattiasson 2004*)
	multi-wavelength fluorometry	(*Morel et al. 2004*)
	spectrofluoremetric	(*Palacio-Barco et al. 2010*)
	headspace gas chromatography	(*Boe et al. 2007a*)
	saturation with CO_2 and acidification with sulfuric acid	(*Guwy et al. 1994*)
	UV/vis spectroscopy (UV/vis)	(*Wolf et al. 2011b*)
	near-infrared spectroscopy (NIR)	(*Tosi et al. 2003*)
		(*Holm-Nielsen et al. 2007*)
		(*Holm-Nielsen et al. 2008b*)
		(*Lomborg et al. 2009*)
		(*Jacobi et al. 2009b*)
		(*Wiese and König 2009b*)
	mid-infrared spectroscopy (MIR)	(*Steyer et al. 2002*)
		(*Spanjers et al. 2006*)

tions essential for higher concentrations, as the normal range at agricultural biogas plants goes from 6 to 10 % TS.
The measurement system introduced by Nacke uses a microwave sensor manufactured by hf-sensor GmbH (Leipzig, Germany). The absorption of microwave radiation is measured, because different materials such as polar molecules have very high absorption coefficients and non-polar molecules very low absorption coefficients. Based on these differences TS and VS content can be measured. Overall, TS concentrations between 6 and 13 % were successfully measured. Calibration of the microwave sensor was performed using PLS models.

2.1.4 VFA/COD and PA/TA

The most common methods for VFA and PA/TA measurement are titration, chromatography and spectroscopy. In 2002, Feitkenhauer (Feitkenhauer et al. 2002) developed a robust, online titration system for the two step titration defined by Anderson (Anderson & Yang 1992) for VFA measurement. Thereby, the measurement medium is titrated down to pH 5.1 in the first step and down to 3.5 in the second step, which yields the VFA and carbon buffer concentrations of the medium. In contrast to other titration methods, the titration cell was specifically designed to cope with the original measurement medium without previous biomass separation. A similar system for online titration of the measurement medium to measure VFA and PA/TA was developed by de Neve in 2004 (de Neve & Lievens 2004). It is called AnaSense® and has been distributed by the ProzessAnalysenInstrumente GmbH in Germany since 2004. Titration is performed using hydrochloric acid for titration after pH stabilization with sodium hydroxide in the case of very low initial pH values (< 5). The chemical dosage is added by peristaltic pumps. As the measurement system requires a particle size below 200 µm, an additional pre-processing unit is necessary for most applications, in particular for agricultural AD plants. Furthermore, regular maintenance (every week) of the pH probe, the peristaltic pumps and the pre-processing unit is necessary to guarantee reliable long-time operation. Looking at these titration based methods, it becomes evident that the pH measurement is not only the most important part of these systems but also one, which requires extensive maintenance. Thus, Jantsch & Mattiasson (2004) developed a system to measure PA in AD processes based on titration principles but without a pH probe. Instead, a pH indicator (Methylred) is added to the measurement medium, whose colour is detected by a spectrophotometer at the wavelengths 438 nm (protonated – red) and 516 nm (unprotonated – yellow). During titration, the ratio between absorptions at these two wavelengths indicates the pH value. If the pH reaches the desired level of 5.75 (titration according to Björnsson et al. 2000), acid consumption is measured and PA is calculated. To improve measurement quality, pre-filtering of the medium is also necessary. In this case, a nylon cloth with a mesh size of 20 µm was used.
Besides titration and chromatographic online measurement systems, spectroscopic methods, be it UV/vis, NIR or MIR spectroscopy, have proven to be very reliable, robust and low-maintenance.
Nevertheless, this technology is not widely accepted in practice due to high cost of spectrometers and fiber-optics. At the moment, NIR spectroscopy dominates the market of online measurement systems for AD processes because it has been applied to full-scale bioreactors in several cases as described by Wiese & König (2009a) and Jacobi et al. (2009a). It allows not only for online VFA measurement but also for PA/TA and VS measurement. One well-known system is the TENIRS probe (Transflexive Embedded Near Infra-Red Sensor) developed by Holm-Nielsen & Andrée in 2007 (Holm-Nielsen et al. 2007). The TENIRS probe measures reflection spectra in the wavelength range from 900 – 1600 nm. A first application study under laboratory conditions was published in 2008, showing that good measurement results (up to

69% accuracy) could be achieved for acetic acid, iso-butanoic acid and total VFA concentration (Holm-Nielsen et al. 2008a). Further investigation of the TENIRS system at a full-scale 1MW biogas plant in Germany took place in 2009 (Jacobi et al. 2009b). During thermophilic plant operation, calibration and online measurement of VFA, acetic acid and propionic acid in a bypass was successfully implemented and provided good measurement results for a period of 500 days. It was concluded that calibration for VFA and propionic acid yielded very good performance results with coefficients of determination of 0.95 and 0.89 respectively. Unfortunately, results for acetic acid were relatively poor with 0.69 compared to 0.89 achieved by Lomborg (Lomborg et al. 2009).

In comparison to UV/vis and NIR spectroscopy, MIR spectroscopy is the most anticipated alternative because reflection spectra of relevant AD process parameters have a highly distinctive fingerprint in the MIR wavelength range from 3 to 50 µm. Thus, measurability and selectivity is much higher in this wavelength range. Steyer was the first to evaluate applicability of MIR spectroscopic probes for the online monitoring of AD processes in 2002 (Steyer et al. 2002).

Using FT-IR spectroscopy (Fourier Transform IR) the absorbance patterns of raw wine distillery effluents which were treated in an AD-WWTP (wastewater treatment plant) were analysed for wavelengths in the range 2 µm to 10 µm. Parameters COD, TOC, VFA as well as PA and TA were successfully measured. Nevertheless, severe problems were caused by the coupling of the fiber-optics with the MIR spectrometer due to high signal losses depending on fiber length and bending. In 2002, production of fiber-optics suitable for online and on site operation was still in its infancy. A few years later, Spanjers et al. (2006) used these results and developed and tested an online MIR system for a full-scale AD process to measure COD, VFA, ammonium and TKN. These variables could be measured with sufficient accuracy. To assure reliable long-time operation of the system an automatic pre-processing unit for filtering was necessary. Furthermore, the observation window required regular cleaning once a day.

This overview of research developments in online monitoring of AD processes over the last decade shows that many different systems have been proposed but only a few have been fully developed and deployed in full-scale applications. The reasons for this are multifaceted: high costs, high maintenance, low reliability and very often the failure to develop industrially applicable prototypes. Thus, the development of industry-ready measurement systems is still necessary and highly anticipated due to rising substrate prices and continually reducing remuneration rates, in particular for older biogas plants. The following section will introduce a few available monitoring systems for biogas plants, which allow a more detailed process monitoring compared to common practice and which are already used at several plants in Germany.

3 pH, ORP and TS Practice Test at an agricultural AD plant

The probes installed at the Sunderhook ABP are manufactured by E+H. The pH and ORP probes from E+H, which were used in this case, are called “memosens”-probes because the connection between electrode and controller is an inductive plug connector. This connector allows for easy and fast calibration and replacement of the electrodes and helps to reduce maintenance time. To guarantee a stable long-term operation of the probes, probes and installation fittings are made out of stainless steel. Due to the fact that the immediate surroundings of the digesters are zone 0 or 1 according to the European ATEX guidelines for explosion prevention and prediction, installation of the probes directly into the digester wall is not possible. For this reason, the three probes were installed in a pump station, which is used to pump substrates into the first digester and digestate out of the first into the secondary digester.

The main advantages are that the installation fittings and measurement controllers do not need to be ATEX certified and that different material flows can be measured and logged with only one installation. Furthermore, the installation fittings are so-called quick-change fittings, which make it possible to pull the probes out of the process under operating conditions. The measurement data of the probes is sent to three small controllers (Liquisys M Endress+Hauser Messtechnik GmbH & Co. KG 2012), one for each probe, and from there sent as current signal (4-20 mA) to a PLC with an OPC server. An OPC client is running on the central computer with the software iPCOIN (intelligent Process Control Integration, Bongards et al. 2004) developed by the GECOC research group from Cologne University of Applied Sciences. iPCOIN reads the measurement values from the OPC server and stores them in a PostgreSQL database for further analysis.

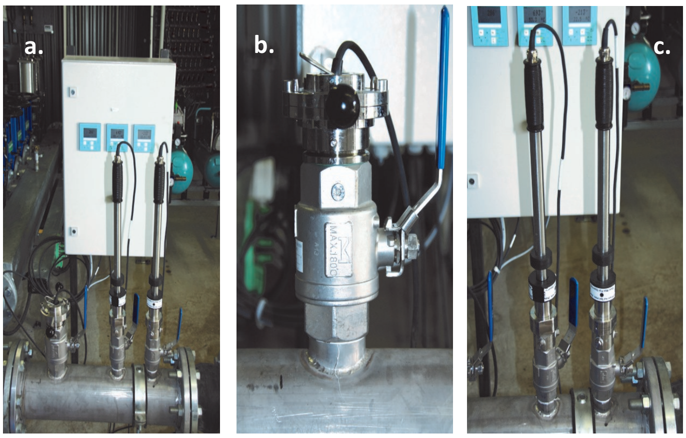

Figure 1: Installation of pH, ORP and TS probe at the Sunderhook ABP: a. complete installation, b. TS probe, c. pH and ORP probe.

A validation of the online measurement values was performed with regular laboratory samples. As the number of laboratory measurements is relatively small in comparison to the number of online measurement values, a t-test is used for an unbiased comparison.

The result of the t-test confirms that both values represent the same normally distributed signal with equal mean and standard deviation as $h=0$ and thus the hypothesis cannot be rejected at the 5 % significance level. The results for the f-test are different for the whole validation period and the one after the calibration of the probe.

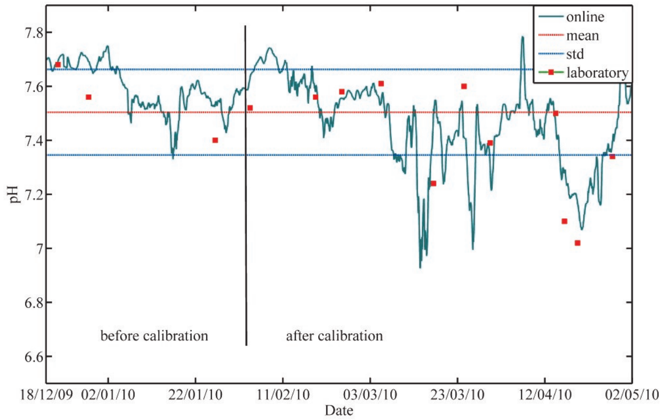

Figure 2: Comparison of pH online measurement values and laboratory samples.

The variance for the whole period is not equal according to the f-test as the hypothesis is rejected ($h=1$) at the 5 % significance level, whereas for the period after calibration the hypothesis cannot be rejected ($h=0$) and variances are equal.

The comparison of TS online and laboratory measurements clearly show that before the calibration TS values were too low and do not match with the laboratory measurements at all. This is also reflected by the results of the f-test, where the hypothesis that the variances of the two signals are equal is rejected ($h=1$) at the 5% significance level for the period before calibration.

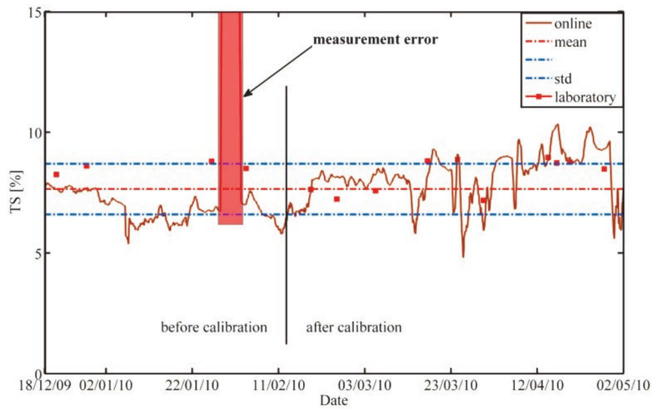

Figure 3: Comparison of TS online measurement values and laboratory samples.

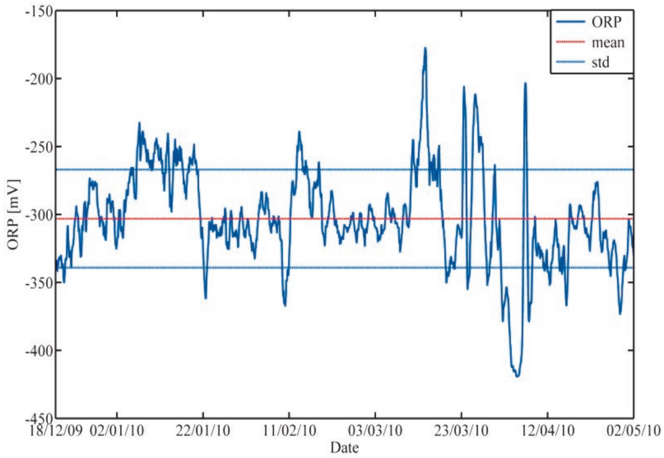

Figure 4: ORP online measurement values.

For the following period after calibration the hypothesis is confirmed with h being *0*. On the contrary, results from the t-test are the same for both periods. The hypothesis, that both signals possess the same mean and the same unknown variances, cannot be rejected ($h=0$).
For the ORP probe no laboratory samples were taken, because the exact measurement values do not have any significance in practice. Trends in the overall level of the ORP are much more important and indicative of operational problems (Zimmermann et al. 2003). Thus, a steady increase in ORP indicates that an organic overload is probable. The following figure shows the development of the ORP values for the investigated period.
All in all, it can be said that pH and TS monitoring with online probes seems to be a good additional way to monitor the AD process at the agricultural AD plant.
The ORP values do not provide any new knowledge of the process and thus is not deemed necessary. When it comes to long term operation of the probes, all three probes are very well suited for the use at agricultural AD plants if TS concentration of the digestate is not too high (>12%). The probes are very robust and relatively low maintenance products.
Furthermore, maintenance is fairly easy and does not require any expert knowledge, so that the plant operator can take care of the probes himself.

4 pH, ORP and TS Practice Test at an industrial AD Plant

The probes installed at the industrial AD plant are from Hach-Lange, which is one of the competitors of E+H on the market for online measurement systems for various environmental applications. Similar to the agricultural AD plant, the probes were installed in a bypass pipe, which is used to pump digestate out of the two digesters into the following screen drums. The probes were not installed inside the digester walls due to the prevailing ATEX regulations. To allow for as easy maintenance as possible, quick-change fittings were used for all three probes. In general, the test conditions are comparable to the ones at the agricultural AD plant, except for the extreme TS concentration of around 20 %, which is already considered to be dry digestion. Such high TS content is a big threat to the sensitive electrodes of the pH and ORP probes used in this case.

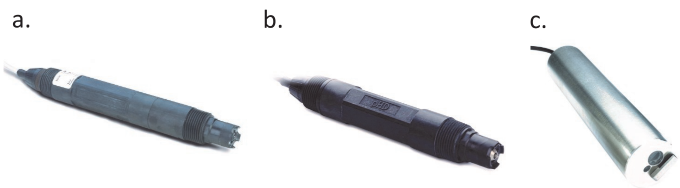

Figure 5: Probes used for the test installation at the industrial AD plant: a. pH , b. ORP , c. TS.

Control and data acquisition of the probes is managed by a SC1000 (Hach Lange GmbH 2012) controller using three 4 – 20 mA signals.
The controller itself is connected to a netbook PC, which is accessible over the internet using the remote monitoring software *Teamviewer*. An additional computer program accesses the gathered data once a week and sends it by email to the GECOC research group.
The online measurement results from the test period clearly show that pH and ORP probes of this kind are not suited for application in high *TS* environments at all. After several weeks, first the pH electrode was irreparably destroyed and a month later the ORP electrode was shorn off due to sharp particles in the digestate.

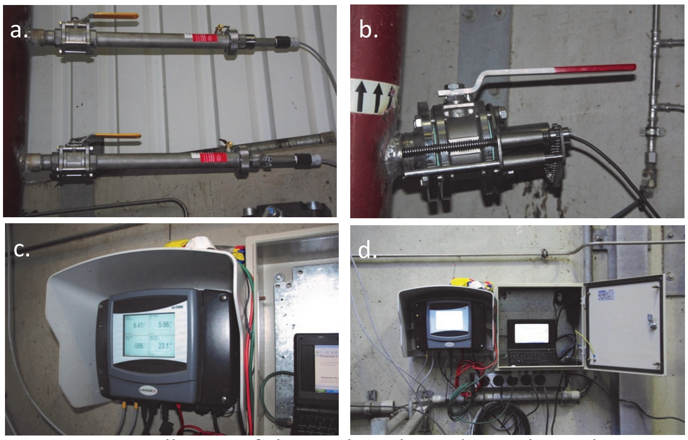

Figure 6: Installation of the probes the industrial AD plant. a. pH and ORP probes, b. TS probe, c. SC1000 controller, d. Overview of probe control and data acquisition.

The moment of destruction of the electrodes becomes obvious in the figures showing the curve progression of the two probes over the test period. The data after the break is meaningless and the electrodes were not replaced as the test proved that they are not robust enough for this environment.

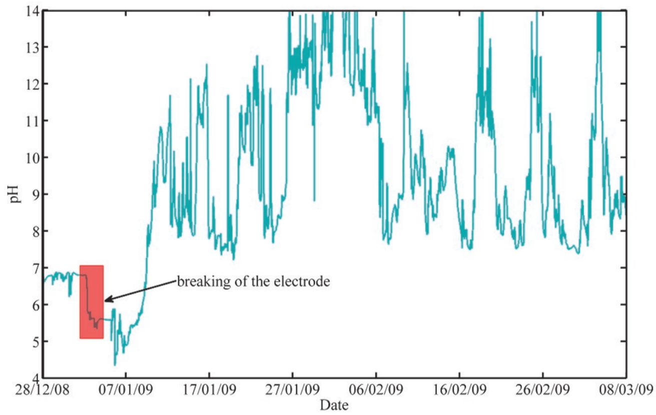

Figure 4: Online measurement data from the pH probe over the test period. Destruction of the electrode after one week of operation.

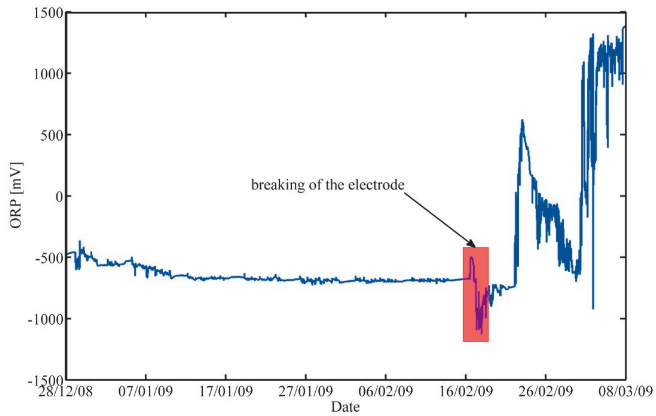

Figure 5: Online measurement data from the ORP probe over the test period. Destruction of the electrode after seven weeks of operation.

Only the TS probe was able to measure correctly over the whole test period, mainly because of the highly robust stainless steel casing and the scratch-resistant sapphire glass. Unfortunately, due to severe operational problems during the test period, the number of comparable laboratory TS measurements is very low (4 samples).

Thus, the validity and significance of the results is very doubtful, although laboratory samples and online measured TS values show a good match. The time period of the TS probe test is shorter compared to the ones for the pH and ORP probes as the installation of the quick-change fitting took longer than expected.

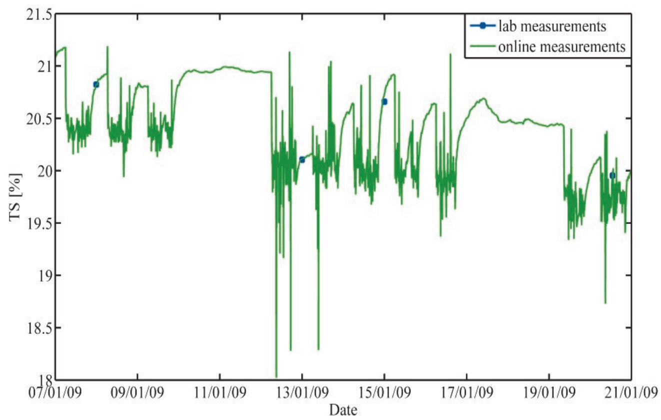

Figure 6: Comparison of TS online measurement values and laboratory samples.

4.1 Maintenance and robustness of the probes at the industrial AD plant

The pH and ORP probes used at Industrial I can definitely not be used in environments with high TS concentration. It is even doubtful whether more robust probe casings made of stainless steel would allow for a successful long time measurement of pH and ORP. The sensitive electrodes are the main problem because they come directly in touch with the process and can be easily damaged by sharp objects in the digestate. Without a proper protection no probe with a comparable design is likely to survive long in such a measurement medium. The following figure 7 makes it obvious that the electrode was shattered at both probes, whereas the TS probe was not damaged at all.

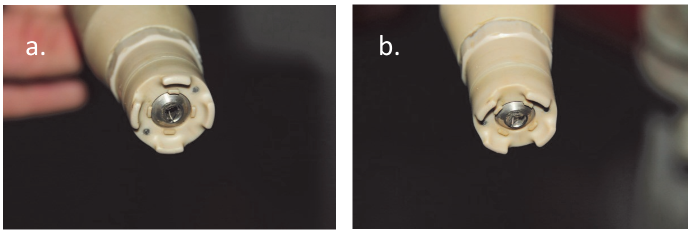

Figure 7: Damaged pH probe (a.) and damaged ORP probe (b.).

Maintenance of the TS probe was performed regularly every two weeks. The TS probe was properly cleaned and freed from small grains of sand and furring grains, which got stuck around the sapphire glass causing a clogging of the probe in the long run.

As the test period was very short with four weeks of operation, no recalibration of the probe was necessary during that time.

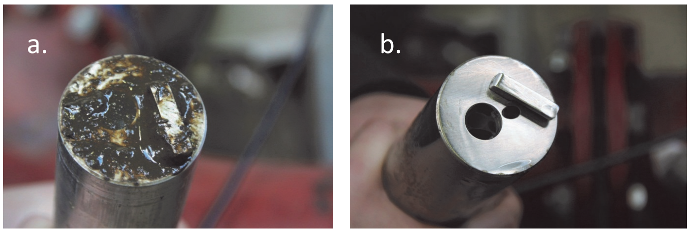

Figure 8: Damaged TS probe after one month of operation before and after cleaning.

5 Conclusions

This research paper has demonstrated that research on instrumentation of biogas plants is multifaceted with many significant advances being made, but that a substantial gap exists between the current state of research and practice as presented in the literature review. Thus, the demand for industry-driven research is huge and will continue to increase due to the rapid increase in the number of biogas plants across Europe. Sections 2, 3 and 4 have highlighted that the need for online measurement systems in particular, is great, because of the lack of robust and affordable online monitoring systems. These are needed to detect critical process conditions before the AD process collapses and to develop efficient optimisation and control strategies for biogas plants. The use of pH, ORP and TS probes can be considered state of the art for agricultural AD plants as the practical field trials described in sections 3 and 4 show that they are well suited for agricultural AD plants. In general, good agreement between laboratory and online measurement values could be achieved for these properties. Unfortunately, standard pH and ORP probes from manufacturers such as E+H and Hach-Lange cannot be used with biogas plants which have high TS concentration in their digesters, because the sensitive electrodes are quickly damaged.

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