Software sensor monitoring and expert control of biogas production

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Abstract

The production of biogas by anaerobic digestion is subject to instability, mainly because of poor process monitoring and a lack of effective process control. Improving process control would lead to optimised feedstock inputs and digestate and biogas outputs and a more reliable process.

Two pilot scale two-stage anaerobic digesters, each with a total volume of 110 litres, were the subject of on-line monitoring and automation using National Instruments LabVIEW software. Monitoring was primarily in the liquid phase by pH, redox and conductivity probes mounted on the output of all vessels. The second vessel in each system provided data for use as inputs to a software sensor for estimation of bicarbonate alkalinity. All actuators were controlled *via* software, with the organic loading rate modulated by a rule based supervisory control.

The experiment was based on data obtained in a previous investigation with a four-stage digester of 220 litres total volume.

The system proved successful in maintaining predicted bicarbonate alkalinity at a set level and thus providing adequate process stability. The monitoring and control system provided a flexible basis from which to conduct further experiments into optimisation of methane production or yield. The system is also suitable for alternative methods of measuring key parameters as process control inputs, such as near infrared spectroscopy (NIRS).

Introduction

The anaerobic digestion process can be unstable, particularly when subjected to changes brought about by an increase in the organic loading rate. Shock loading of a feedstock which is rapidly hydrolysed will lead to an unstable reactor (Hills and Roberts, 1982; Knol et al., 1978), and unstable reactors have been shown to have lower methane production (Bull et al., 1983; Nachaiyasit and Stuckey, 1997; Robbins et al., 1989). It is therefore common to construct a digester that is larger than necessary to reduce the impact of overload situations by constantly running the reactor at an organic loading rate well below its optimum. This prevents instability but is at the expense of increased construction and maintenance costs. A more logical solution would be to monitor the internal state of the reactor and control the organic loading rate via an advanced supervisory control system. This would ensure optimal loading and methane production at all times.

Monitoring of anaerobic digestion is not a straightforward practice; the substrate is complex and there is potential for obscuring or even damaging the sensory devices. For these reasons, a software sensor to predict bicarbonate alkalinity was developed. A software sensor predicts an unknown parameter from the available data, in this case alkalinity from pH, redox and conductivity probes. These probes were chosen for their simple robust nature, the ease with which they are cleaned and calibrated, their familiarity with operatives and their relatively low cost.

Software sensors have been used in anaerobic digestion previously: For instance Alcaraz-González et al. (2002) used a wide variety of inputs including input flow rate, carbon dioxide exhaust flow rate, fatty acid concentration and total inorganic carbon to estimate the unknown parameters of microbial concentrations, alkalinity and chemical oxygen demand in a waste water treatment plant. Furthermore, Feitkenhauer and Meyer (2004) estimated substrate and biomass concentrations from inputs based on titrimetric techniques, and Bernard et al. (2000) used a mass balance based model and gaseous measurements to predict fatty acids and inorganic carbon, and a separate software sensor to estimate bacterial biomass.

The control system described here was a rule-based supervisory system with a feedback loop. This meant that the system operated by supervisory commands in the form of 'if → then' rules, and data from the process is fed back to the input feed pump. Rule based systems are considered better than conventional proportional integral derivative (PID) controllers in dealing with the non-linear and time-varying data often associated with bioreactors (Babuska et al., 2003). In Addition, they have previously been successfully used in anaerobic digestion, (Liu et al., 2004) with inputs of pH and biogas flow rate to control the organic loading rate *via* modulation of the feed flow rate.

Materials and methods

Two two-stage anaerobic digesters each of 110 litre total volume were constructed from 60 litre polyethylene containers. Heating was by water bath, pumping of feedstock into the primary tank was by Watson-Marlow peristaltic pump. Digestate removal from the primary tank to the secondary tank and from the secondary tank output was by simple weir overflow systems. Mixing was by mechanical propellers in the feed tank and by recycled biogas mixing in the primary and secondary digester tanks. The mechanical mixer was small but high speed, the intention being to assist hydrolysis through increasing shear forces. The biogas recycle mixing was chosen for the low shear forces associated with this mixing method, thus reducing disruption of aggregated microbial biomass. The biogas mixer pumped 10 litres of gas per minute through sparger tubes located near the base of the tanks. The two digesters differed in that one contained polyurethane foam as a microbial biomass support media for use in a separate study. However, the differences between the digesters did not have a significant effect on the monitoring and control system described here.

Tanks were continuously monitored for pH, redox and conductivity as well as temperature. All probe data was output to a personal computer running National Instruments LabVIEW software, from which data was stored in files and also used to calculate the predicted alkalinity. The software included an animated schematic view of the process (Figure 1) with a selection of control types: Automatic control with manual organic loading rate control, which switched the pump on a timed basis, the duration of the feed pump in this mode was controlled by the organic loading rate control. When in automatic control, the organic loading rate could be controlled dynamically by a rule based controllers from real time data obtained via the software sensor predicted alkalinity.

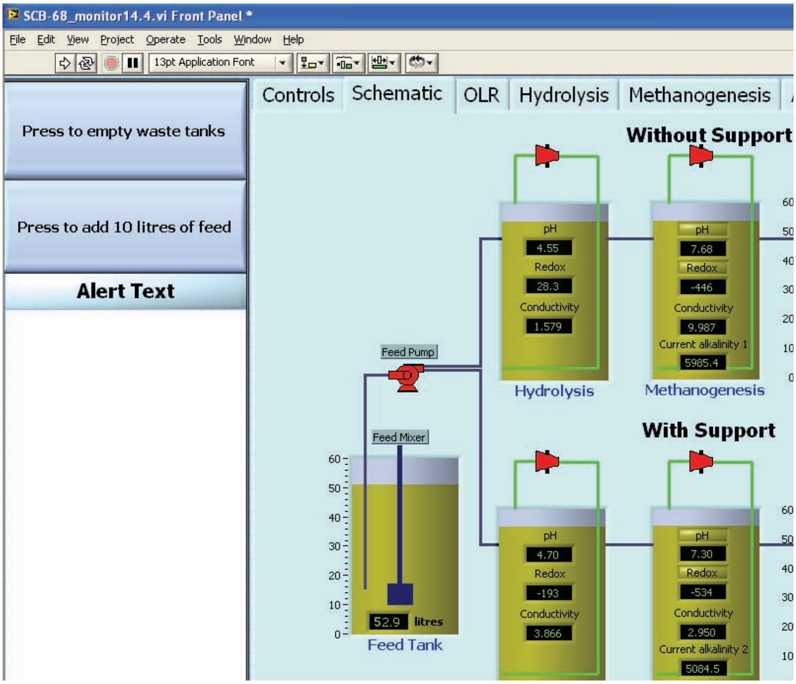
The software sensor was derived from a multiple linear regression model of data collected from a 220 litre four-stager anaerobic digester over a period of ten months. All digesters were fed on pig feed to maintain a constant input composition. The pig feed had a stated composition of 70 % non–fibre carbohydrate, 16 % protein, 7.5 % fibre and 4.5 % oil. The experimental period included a wide variety of organic loading rates and digester states including start-up, stable operation, failure and recovery to build a large dataset from which to construct the model. The resulting algorithm was incorporated into the LabVIEW software.

The algorithm is represented in LabVIEW as a set of constants for multiplying with the pH, redox and conductivity data. The constants are real time controls for modifying the algorithm without stopping the application, should a better model be found. The algorithm used is shown in Equation 1.

$$Alk_p = -8906 + (1678 \times V_p) + (1.998 \times V_r) + (384.2 \times V_c)$$

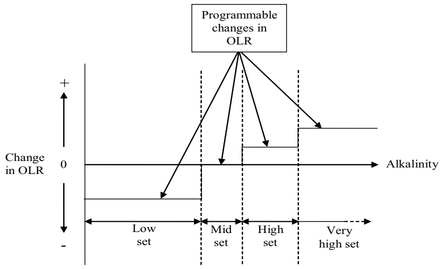
Where Alk_p = predicted alkalinity, V_p = pH value, V_r =redox value and V_c = conductivity value

Figure 1. Schematic front panel view of two-stage anaerobic digesters



The rule based supervisory control system was integrated into the LabVIEW interface. The controller consists of placing the predicted alkalinity into one of four linguistic sets: low, mid, high and very high. The boundaries of these sets were available for modification in real time to improve the control system, as were the amounts by which the organic loading rate was increased or decreased when predicted alkalinity was given membership to a specific set. Alkalinity that falls into the mid set would not change the organic loading rate, whereas alkalinity predicted to be in a higher or lower set than this would increase or a decrease (respectively) the organic loading rate, as shown in Figure 2. The control system also included a derivative component which detected upward or downward changes in alkalinity and suitably modified the organic loading rate to a degree set by both the rate of change and a control to weight the derivative component. The system was set to pump feedstock on an hourly basis and therefore the derivative control compared the current predicted alkalinity with that predicted one hour previously. The positive or negative derivative component was then added to the increase or decrease in OLR calculated from the set membership. This allowed the control system to respond quickly to sudden changes in alkalinity. For example when alkalinity was in the mid set, no change was made to the OLR from the set information, but if the alkalinity was beginning to fall the derivative component of the control system would respond by reducing the OLR. Initial set membership thresholds were decided upon by empirical data gained from the four-stage anaerobic digester experiment.

Figure 2. Rule based supervisory control set structure



Results and discussion

The software sensor gave a good prediction of alkalinity when validated with digester 1 data (Figure 3). The predicted (software sensor) and observed (titrated) alkalinities had a correlation of 0.819 ($p < 0.001$) for digester 1 (digester fitted with biomass support media). This was especially important when the predicted alkalinity fell to values below 3500 mg. l^{-1}, a value found to be the threshold of system failure in the four-stage digester.

Digester 2 (not fitted with biomass support media) suffered from problems with the redox probe and therefore the predicted alkalinity and titrated alkalinity had a correlation of only 0.198 ($p < 0.001$). This explains both the noisy response of the predicted data and the large error seen between 16/1/07 and 20/1/07 as shown in Figure 4.

The OLR of the 120 litre two-stage digester (1) controlled by the rule based control system is shown in Figure 5.

The oscillating nature of the organic loading rate demonstrates the difficulty associated with setting up a control system. The more stable organic loading rate seen after 24/01/2007 is the result of a decrease in the proportional (set based) component weighting and an increase in the derivative component weighting. These changes reduced the oscillations and improved the response respectively.

Figure 3. Predicted and titrated alkalinity data from laboratory scale 120 litre two-stage digester 1

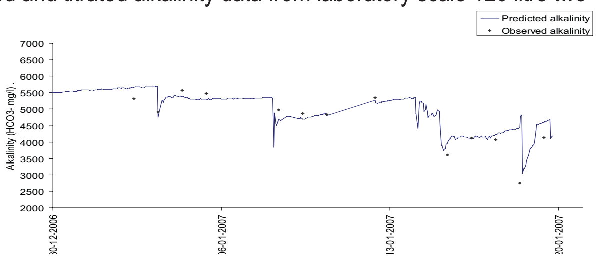


Figure 4. Predicted and titrated alkalinity data from laboratory scale 120 litre two-stage digester 2

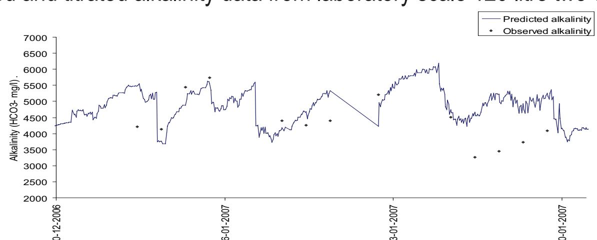
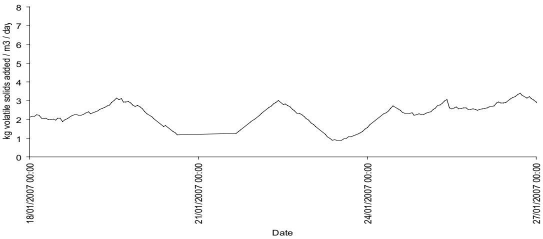


Figure 5. Organic loading rate controlled by the software sensor and a rule based supervisory control system on digester 1



Conclusion

The software sensor reliably predicted alkalinity in the second stage of two-stage anaerobic digester 1. The poor correlation between observed and predicted alkalinity in digester 2 demonstrated that monthly cleaning and calibration of the probes was necessary to ensure accurate prediction. The experiment did show that anaerobic digestion can be monitored efficiently and cheaply, and a system such as this would be simple to install on an existing full scale biogas plant.

The rule based supervisory control system produced a reasonably stable organic loading rate and emphasised the importance of the correct weighting of the various control parameters. Such a control system would allow optimal feeding of anaerobic digesters, thus maintaining stability and optimising output.

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