ANAEROBIC DIGESTION
Monitoring and Control

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1-Introduction

Anaerobic digestion is an old biological wastewater treatment process, having first been studied more than a century ago. It is a multistep process in which organic matter is degraded into a gas mixture of methane and carbon dioxide by microorganisms. It thus reduces the Chemical Oxygen Demand (COD) of the influent and produces valuable energy (methane). The biological scheme involves several multi-substrate multi-organism reactions that are performed both in series and in parallel
It has been experimentally demonstrated that the anaerobic digestion process is particularly adapted for concentrated wastes such as agricultural (e.g. plant residues, animal wastes) urban and industry wastewaters.
In addition, this process is able to operate under severe conditions : high-strength effluents and short hydraulic retention times. Last but not least, anaerobic digestion is also often used as a sludge treatment for the volume reduction and the stabilization of primary and secondary sludge.

For the past twenty years now, research has been carried out on the microbial ecosystem of the anaerobic digestion process, its kinetics and its mathematical modeling. This has allowed one to determine the different parameters involved in the process and the values necessary to perform good operating conditions.

2 - Why a monitoring and control ?

The microbial population in the anaerobic digesters are very complex. The physico-chemical parameters values in the bioreactor drive the metabolic pathways, the kinetics, and the microbial diversity.

The biological reaction have not real stable state even if they are in feed without any variations.

For good process operations, the organic loading rate should be adapted to the treatment capacity of the system.

However, as a variations of parameters are usual in the wastewater treatment processes (variations in the feed characteristics, temperature, pH, entrance of toxic matter, variation in the digesters of controlled parameters, problems with regulations) it is difficult to adjust the input flow of COD with the microbiological capacity of treatment.
In fine, the result is that the microbiological system could be generally overloaded or underloaded.

In the first case, the overload can generate the acidification of the system and it can stop the microbiological conversion. In the second case, the system is working under his capacity.

The automatic monitoring and control of the anaerobic digesters is a mandatory step for resolving this.

The basic problem is the choice of the parameters that should be monitored and the choice for an appropriate control strategy which will lead to good performance. The treatment of their values by an algorithm should give, at the end, an order to modify the working parameters in order to improve the characteristics of the process.

The loop for the control of processes is shown in the figure 1.

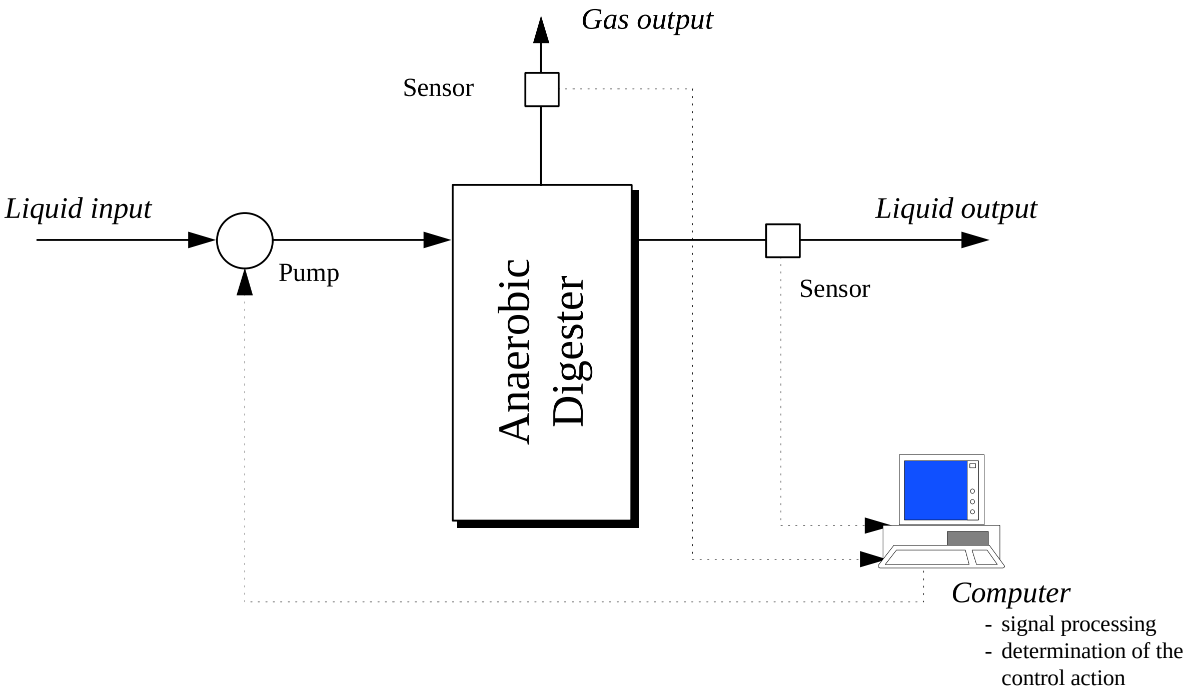

Figure 1 : Loop for the control of processes.

3 - Choice of the parameters

The choice of the parameters for monitoring and control will depend on several factors such as the origin of the wastewater, the technology of the digester used, the industrial sensors on the market, the knowledge available on the process, ...

In the literature, several parameters have been already used for monitoring and control of the digesters. For example, Switzenbaum et al. (1990) reviewed the parameters used for the characterisation of anaerobic digestion processes in solid, liquid or gas phases.

- For solid phase, these authors reported : solids, cell enumeration, Desoxyribonucleic acid (DNA), protein content, bacterial lipids, Adenosine triphosphate (ATP), enzyme activities, methanogenic activity measurement, microcalorimetry, co-enzymes and C1-carriers of methanogens, and immunology of methanogens.

- For the liquid phase : pH, volatile fatty acids, alkalinity, redox potential, sulphide.
- For gas phase : gas production, gas composition, hydrogen and carbon monoxide monitoring.

A this description, we will add the COD (Fell et al 1994) and the hydrogen in the liquid phase (Pauss and Guiot 1993) for example.

For some of these measurements, we can use an automatic analysis system but when the analysis could be only manual, the interest is very low.

The parameters of the solids phase are not often used for automatic control since they usually need manual operations. Generally, the parameters used are thus only based on liquids and gas phases measurements.

Volatile Fatty Acids concentrations has also been recognised for a long time to be an important parameter for the control of anaerobic digesters. Indeed, if the pH is high, the digesters can work with high VFA concentrations, up to several g/l. But in this case, the treatment efficiency will be low.

The use of bicarbonate alkalinity is another very popular parameter because it decreases when VFA accumulate. It should be at least 1000 mg $CaCO_3$/l for a successful operation of the process.

The hydrogen is also an important parameter. It has a very short relaxation time and the content in the gas phase could be between 20-30 ppm to 400-600 ppm with good operation of the process. These operational values will depend on the organic loading rate (i.e., high values are connected to the high organic loading rates). In the liquid phase for example, Pauss and Guiot (1993) reported values from 1.6 to 20 μM during operating conditions.

Substance	**Relaxation time**
H_2	15 s
Glucose	3 min
CO_2	1 h
Acetate	2 h
Propionate	4 h
Methane	2 days
CO	? [a]
Microbial Population	
Acidogens	30 min
Propionate consumers	5 days
Acetoclastic methanogens	10 days
Hydrogenotrophic methanogens	25 days

[a] Most likely controlled by H_2 relaxation time

Table 1. Theoretical relaxation times for different substances and microbial populations in anaerobic digestion (From Switzenbaum et al 1990)

Gas flow rate is also used widely, but it does not reflect the state of the process unless correlated with the influent amount of organic matter and methane and carbon dioxide percentage. An increase of CO_2 with a decrease of CH_4 contents are significative of disturbances and can be used as indicator for the beginning of the overload.
The response time of sensors and the system will depend of the time for relaxation of parameter but also where the sensor is located in the digester. The theoretical relaxation times for different substances and microbial populations in anaerobic digestion were reported in table 1 .

4- <u>Sensors used</u>

Of course, on line monitoring and control of anaerobic digesters need sensors. However, there are only few reliable sensors on the market available for industrial application.

Many sensors used chemical-physical properties. Nevertheless, the numbers of systems using mixte microbial populations as basic reaction is increasing.

Generally, the analysis of molecules in the liquid samples need first of all a filtration (micro or ultra filtration), a dilution and the samples are then processed by automatic lines.

For analysis in the gas phase, water removal or some specific treatment as H_2S removal for H_2 measurement are necessary.

The volatile fatty acid can be analysed by chromatography (liquid or gas), colorimetric methods or during alkalinity measurement. Recently Rozzi et al. (1997) proposed a VFA measuring biosensor based on nitrate reduction by mixte population. Other techniques are under evaluation as infra-red measurement for monitoring VFA in the digester at LBE of Narbonne.

The pH measurement is easy to do by actual probes. They are now very reliable.

The COD and TOC can be analysed on line by oxidation methods. They need also filtration before processing. Some industrials sensor are now available.

Specific sensors were built for alkalinity measurement (Rozzi et al 1985), (Hawkes et al, 1993). The analyser is based on the application of physico-chemical equilibrium. Concentrated acid is added to a sample of liquid in a sealed vessel, the bicarbonate is decomposed and the evolved CO_2 is partitioned between the liquid and the gas phases. The bicarbonate concentration in the sample is proportional to the equilibrium overpressure.

Membrane inlet mass spectrometry was used to directly measure the concentrations of CH_4 and H_2 in completely mixed anaerobic digester (Whitemore et al 1987).

Pauss and Guiot (1993) used one line measurement of dissolved hydrogen with an H_2-air fuel cell probe. This kind of probe was also used by for measurement of hydrogen in the gas phase (Moletta et al 1994).

Fluorescence at particular wavelengths was used for monitoring reduced forms of NAD(P)H or F 420 are used as biomass sensors (Peck and Chynoweth 1992). This sensor was built as immersion probes and can be subject to fouling of the optical surface.

The gas flow rate is easily monitored. The CH_4 and CO_2 percentage could be measured by Infra-Red techniques.

Biosensors using mixte microbial population can assess the concentration of biodegradable substrates but also the toxicity of wastewater. Such biosensors were developed like RODTOX by the university of Gent (Belgium) and RANTOX by the Polytechnical University of Milano (Italy).

Last but not least, software sensors were proposed for anaerobic wastewater treatment plant. They may be used to reduce the effect of noise on measurements as well as to reconstruct the variables that are not measured. Using a dynamic model, the state variables have been linked the on line measurement of gaseous flow rates and alkalinity (Bernard et al., 1998).

5 - Anaerobic digestion control.

The anaerobic digestion control needs models and automatic techniques for the conversion of the signal to a decision for modification operational parameters.
We can consider that there is two type of approach for control : models based and knowledge based controls (J. Harmand, personal communication).

For models based control, we have classical command as PID or advanced commands as optimal control, adaptive control, robust control for example.

For knowledge based control (or heuristic methods) , we have rule based control, expert system based control, fuzzy control, and artificial neural networks.

Different type of models have been already used for simulation and control of the anaerobic digestion.

Adaptive control was used by Dochain and Bastin (1985). Continuous time adaptive schemes are proposed for single step (methanization) and two steps (acidification plus methanization) plant. An important feature of the proposed algorithms is that they do not require any analytical description of the microbial specific grow rate.

Simple black box models predicting potential control parameters during disturbances to a fluidized bed anaerobic reactor was proposed by Premier et al. (1997).These black box models were used predicting over a limited horizon and relying on current and recent data values to refine the prediction.

Rules based control was used by Moletta et al. (1994) where the variation of three parameters were taken into account (pH in the liquid phase and hydrogen concentration and gas production on the gas phase) and used for monitoring the feeding pump. The organic load obtained with this approach was up to 147 Kg COD/m^3/day (Moletta - unpublished data).

Expert system was used by several authors. For example, Pullammanappallil et al. (1998) used expert systems strategy. In this work, the expert systems change the dilution rate according one of four possible strategies : a constrained conventional set point control law, a constant yield control law, batch operation or constant dilution rate.

The use of a neural network simulation for monitoring and control using data from an on line bicarbonate alkalinity sensor was publish by Wilcox et al. (1995). These authors suggest that a neural network is capable of rapid recognition of these disturbances.

Steyer et al. (1997) proposed the monitoring disturbances as a way to control highly load processes. This strategy is based on the analysis of disturbances added on purpose to the influent liquid flow rate. The control system then carefully overlooks the response of only two parameters : the output gas flow rate and the pH in order to determine whether or not the organic loading rate can be increased. An example of such response is graphically describe, showing typical experimental answer, on the following figure 2.

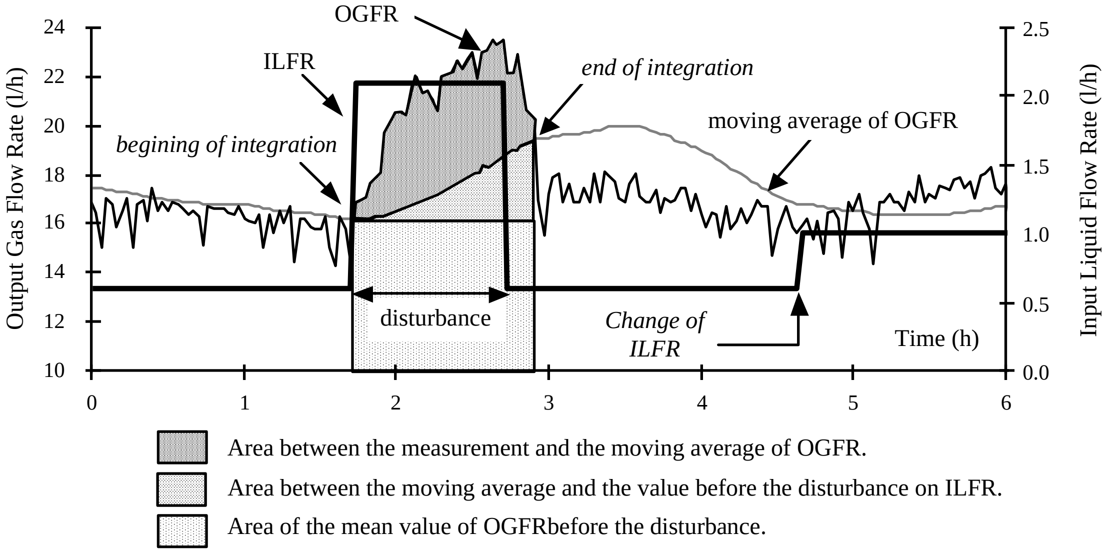

Figure 2- graphical response showing typical experimental answer

In this approach, the sensors (i.e., the gas flow rate and the pH) were selected for their potential for industrial applications, with the criteria of low maintenance effort. The Output Gas Flow Rate (OGFR) and the pH was the only two control variables. The control algorithm is then the following : a constant Input Liquid Flow Rate (ILFR) induce a certain OGFR (the value is call Q_{gmoy}) . By disturbing the IGFR (by α during δt hour), we would then expect that the Extra Gas Volume ($EGV_{expected}$) to be increase by $\alpha.\delta t.Q_{gmoy}$ liters. By integrating the OGFR response, we can determine the real EGV produced by the disturbance (EGV_{real}) . The integration lasts until the measured OGFR is lower than a moving average of its value. The different cases can then observed according the value of the response factor R defined as the ratio of EVG_{real} on $EVG_{expected}$. According the value of R, we can conclude that ILFR could be increased, decreased or kept at its value before the disturbance.

6- Action on the process

Generally, the controlled variable on the process is the feed pump speed.
(Moletta et al 1994) .

Guwy et al (1997) adjusted the digester buffering by addition of $NaHCO_3$. The control of bicarbonate alkalinity did not prevent changes in CO_2 and H_2 concentrations and gas flow rate.

Alatiqi et al (1990) used heat input and feed pump speed and Mindriany et al (1997) used the recirculation rate as process control in palm oil mill effluent degradation.

Several other strategies can be used as variation of the pH by addition of acid or soda, increase the amount of micro-organisms in anaerobic contact...

7 - Conclusion

By its very nature, the control of biological processes is a multidisciplinary subject and it has been demonstrated that only combined approaches (as opposed to a single approach) are able handle control objectives.

Monitoring and control is a powerful tool for of anaerobic digesters. Many approach have

been developed. However the first problem is the availability of sensors and specially at the industrial scale.
With monitoring and control, we might expected very high values of organic load with a good process operation.

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