MONITORING THE PERFORMANCE OF ANAEROBIC DIGESTERS AT HIGH LOADING RATES FOR FAILURE CONTROL AND OPTIMIZATION

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Abstract---*The anaerobic digestion process is of world wide significance for the treatment of highly concentrated wastes such as industrial and rural effluents, and sewage sludge. As its by product, a renewable fuel is produced. However, this process is known to be relatively unstable. Especially when loaded with high concentrations of organic material, volatile fatty acids (VFA) are produced rather than methane (CH_4) gas resulting in severe ecological, hygienic, and economic problems. The performance of a 1-liter laboratory anaerobic digester (CSTR) under high loading rates was investigated. The changes in the conversion efficiency of the digester, volatile fatty acid concentrations, H_2 partial pressure and pH were monitored at every step increase in the loading rate to determine the behavior of the digester near the maximum sustainable loading rate and under overloaded conditions. Some microbiological and chemical principles which explain why anaerobic digesters fail and how to prevent failure are likewise discussed. The findings reported in this study may be useful in the design of a control technique for the safe operation of anaerobic digesters.*

INTRODUCTION

A general interest in anaerobic digestion as a waste treatment and an energy producing process was first seen during the 1970s when in the midst of an oil crisis, worldwide research on renewable energy sources was encouraged and promoted (Wheatley, 1991). Methane, the by-product of the anaerobic process, is a useful alternative energy source. The production of biogas (a mixture of CH_4 and CO_2) from the anaerobic digestion of wastes could offer developing countries a unique opportunity to become energy self-sufficient. Specifically in Asia, rural anaerobic digestion has become popular because of the growing fuelwood deficiency (Coombs, 1991). Biogas is also known to be a cleaner and a more environmentally friendly energy source than conventional energy (e.g coal and other forms of fossil fuels). Therefore, the use of biogas as an alternative energy source represents a sustainable solution to the present problem of fuel deficiency and environmental degradation.

In developed countries where oil and other fossil fuels can be used more economically than the methane gas, anaerobic digestion is increasingly used for waste treatment rather than for energy production. However, despite the reported success and wide application of anaerobic digestion, industries are still reluctant to employ this process for waste treatment. Instead, the wastes are treated aerobically, which means that a relatively expensive process (high energy cost due to aeration and sludge treatment) is preferred to one which can be operated at low cost (energy self-sufficient). The main reason for this is the reputation of the process for instability and the difficulty in failure control.

Several laboratory and pilot scale studies, as well as full-scale digester operations indicated that reduced performance and failure in anaerobic digesters are caused by organic overloading (Canovas-Diaz & Howell, 1988; Kennedy, 1985; Chynoweth, 1994). This problem has been demonstrated in several of the digesters at the Western Australia Headworks and Treatment Plant, Woodman Point, Perth, Western Australia. A number of digester failures in the treatment plant had been recorded from 1989 to 1994 resulting in long shutdown periods and severe economic loss. Instabilities in the operation of anaerobic digesters (biogas digesters) in the Philippines have been reported. The 1994 Non-conventional Energy System Census conducted by the Central Philippine University - Affiliated Non-conventional Energy Center (CPU-ANEC) in the provinces of Iloilo, Antique, Aklan, Capiz and Guimaras revealed that out of thirty four (34) biogas digesters installed in these provinces, twenty two (22) are inoperational.

To prevent digester failure due to organic overloading, the rate of feed addition is frequently applied well below the maximum sustainable

loading rate of the digester. Such an operation is not always desirable, especially when a process is expected to perform competitively and cost-effectively. To make the process more efficient and economical, the loading rate of the digester could be maximized. However, feeding the digester at high loading rates increases the risk of overloading and consequently results in digester failure.

In order to ensure successful operation of anaerobic digesters at high loading rates, constant monitoring of process parameters is necessary. Several studies have reported the importance of process indicators such as VFA, alkalinity, pH, gas production and composition, H_2, volatile solids and COD (chemical oxygen demand) in the monitoring of digester performance (Switzenbaum et al., 1990). However, few studies have investigated the changes in the above parameters at high loading rates and the behavior of the digester at its maximum sustainable loading rate.

Objectives of this study

This study was aimed at determining useful control parameters in the anaerobic digestion of organic wastes. The specific objectives were:

1. to monitor the changes in various process parameters (methane production rate, VFA concentrations, H_2 concentration and pH) during step increases in the loading rate.
2. to investigate digester behavior at high loading rates and at overloaded conditions.
3. evaluate digester performance at the maximum sustainable loading capacity of the digester.
4. To provide information on why anaerobic digesters fail and how to prevent failure.

REVIEW OF THE ANAEROBIC PROCESS

Stages of methane conversion

In anaerobic digestion, the organic substances in the waste are converted to methane (CH_4) and carbon dioxide (CO_2) by different groups of interacting bacteria. The methane conversion is a complex process involving several consecutive and parallel reactions (Fig 1).

The first stage is hydrolysis. Complex organic compounds (proteins, cellulose, lipids) are hydrolysed by extracellular enzymes into simpler compounds (sugars) small enough to allow their transport across the cell membrane of the bacteria. The enzymes can be produced by both facultative and strictly anaerobic bacteria.

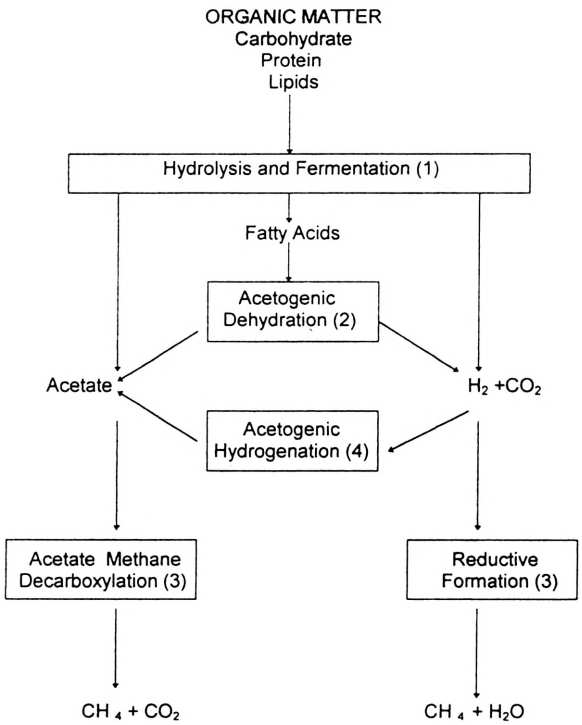

Figure 1. Schematic representation of the complete anaerobic degradation of organic matter showing the general pathways and the three major metabolic groups of bacteria: 1) fermentative bacteria; 2) obligate hydrogen producing acetogenic bacteria; 3) homoacetogenic bacteria (McInerbey & Bryant, 1981).

The second stage is acid fermentation or acidogenesis. The simpler compounds from the hydrolysis of polysaccharides are fermented to volatile fatty acids (VFAs) such as acetate, propionate, butyrate, alcohols , CO_2 and H_2 and some lactic acid by the fermentative bacteria.

The third stage is acetogenesis. The more reduced products such as propionate and butyrate are oxidized to acetate, CO_2 and H_2 by syntrophic bacteria called obligate proton-reducing (i.e. H_2-producing) acetogens or obligate proton-reducing (i.e. H_2-producing) organisms to acetate, CO_2 and H_2.

The final stage is methanogenesis. The methanogenic bacteria utilize the H_2 produced by acidogenic and acetogenic bacteria for the reduction of CO_2 to CH_4. Some species cleave acetate to CO_2 (known as aceticlastic methanogenesis) and CH_4.

In order for the digester to operate under stable and optimum performance, there must exist a balanced microbial population in the reactor. An imbalance in the activity of the acid forming bacteria

and the methane forming species can lead to the accumulation of the volatile fatty acids and eventually inhibition of the digestion process.

Thermodynamic effects on methane fermentation

According to thermodynamics, the spontaneity of a reaction is determined by its exergonicity ($-\Delta G$). Table 1 shows the equations and standard free energy changes involved in the anaerobic degradation of organic matter. It is shown that the H_2-consuming methanogens play a very important role in the the conversion of the acid products to CH_4. Studies on the metabolic interactions between the acid-producing bacteria and the H_2-consuming methanogenic bacteria indicate that the rate at which the H_2 concentration is kept low determines the stability of the digestion process (Wolin, 1975, Kaspar and Wurhmann, 1978, Mah and Boone, 1982). At high partial pressure, the production of propionate, butyrate and other reduced products are favored instead of acetate production and methane conversion.

The H_2 concentration also regulates the degradation of the reduced fermentation products by the obligate hydrogen producing bacteria (OHPB) to acetate, H_2 and CO_2. At standard partial pressure of H_2, the degradation of propionate and butyrate are inhibited (+ G, equations 2 and 3 Table 1.1). The degradation of butyrate or propionate is not energetically favorable until the partial pressure is lowered to about 2×10^{-3} or 9×10^{-5} atm, respectively (McInerney & Bryant, 1981). In order for the degradation to proceed, the low H_2 level must be maintained in the system through H_2 removal, a task accomplished by the H_2 consuming methanogenic bacteria. Therefore, in ecosystems where methanogens are effectively utilizing H_2, considerably less propionate and butyrate are produced.

Kinetic Factors Influencing Digester Efficiency

Process kinetics play a central role in the development and operation of anaerobic treatment plants. Since the anaerobic digestion process is composed of a sequence of reactions, one step usually proceeds at a rate lower than the other steps. Lawrence (1971) proposed that for anaerobic digestion processes, the rate limiting step is that step which will cause process failure to occur under conditions of kinetic stress. Methanogenesis is

Reactions	ΔG, (kJ/reaction)
(1) $C_6H_{12}O_6 + 2\ H_2O \rightarrow 2\ CH_3COOH + 2CO_2 + 4H_2$	- 342.0
(2) $CH_3CH_2CH_2COO^- + H_2O \Leftrightarrow 2\ CH_3COO^- + H^+ + H_2$	+ 48.1
(with methanogens)	- 102.4
(3) $CH_3CH_2COO^- + 3\ H_2O \Leftrightarrow CH_3COO^- + HCO_3^- + H^+ + 3\ H_2$	+ 76.1
(with methanogens)	- 39.4
(4) $4\ H_2 + 2HCO_3^- + H^+ \Leftrightarrow CH_3COO^- + 4\ H_2O$	- 104.6
(5) $CH_3COO^- + H_2O + \Leftrightarrow CH_4 + HCO_3^-$	- 30.0
(6) $4\ H_2 + CO_2 \rightarrow CH_4 + 2H_2O$	- 135.6

Table 1. Equations and Standard Free-Energy Changes Involved in the Anaerobic Degradation of Organic Matter (McInerney and Bryant 1979; Zeikus, 1980; Zehnder & Wurhmann, 1977)

considered the rate limiting step in the digestion of soluble organics (e.g. sucrose), (Ghosh and Poland, 1974; Novak and Carlson, 1970). For insoluble polymers, hydrolysis is regarded as the rate limiting step (Ghosh et al., 1974).

Hydraulic retention time (reactor volume/feed flow rate) is one of the most important operational factors affecting the efficiency of an anaerobic digester (McInerney and Bryant, 1981; Grady and Lim, 1980, Dague, et al, 1970). As the retention time is increased in a system fed with a substrate of constant concentration, a higher percentage of the organic matter is destroyed but less organic matter is available. Thus, the rate of methane production may decrease. Conversely, when the hydraulic retention time is shortened by increasing the feed flow rate, the CH_4 production rate may increase. However, the liquid throughput might exceed the growth rate of the bacteria and result in the washout of the slow growing methanogens (hydraulic overloading).

The organic loading rate is another important factor to consider in the operation of anaerobic digesters. The loading rate can be increased at a given RT by feeding more concentrated feed or by shortening the RT at a given feed concentration. High loading rates increase the methane production rate, but in effect, decrease the % solids destruction of the waste (McInerney & Bryant, 1981).

MATERIALS AND METHODS

Source of Biomass. The biomass used in this study was a granular sludge obtained from a hybrid anaerobic digester at Swan Brewery, Perth, Western Australia.

Synthetic substrate C-source (g/L): D-glucose, 24.5; yeast extract, 1.0; tryptone, 1.0; Basal nutrients: NH_4Cl, 1.07; $MgCl_2.6H_2O$, 1.02; $CaCl_2.2H_2O$, 0.01; KCl, 0.52; Na_2SO_4, KH_2PO_4, 0.30; $NaHCO_3$, 2.10; Trace metal solution (mM): HCl, $FeCl_2.4H_2O$ 0.2; $CoCl_2.6H_2O$, 0.006; $MnCl_2.4H_2O$, 0.0033; $ZnCl_2$, 0.006; H_3BO_3, 0.0016; $Na_2MoO_4.2H_2O$, 0.0049; $NiCl.6H_2O$, 0.0025; $CuCl_2.2H_2O$, 0.006. One liter stock solutions were prepared and autoclaved for one hour (15 psia, 110 °C) to maintain sterile condition in the feed medium. The trace elements (5 ml) and the $NaHCO_3$ buffer (25 ml) were added into the feed bottle through a 0.2 m sterile filter. In the case where a more concentrated feed was used, the amounts of basal nutrients, trace elements and buffer solution were increased proportionally with the feed concentration. The pH of the feed was adjusted to 7-7.5 by adding NaOH before the start of each experiment.

Experimental Set-up. A 1.3-L Braun Biolab anaerobic digester (Fig 2) was filled with 1.0 L of active anaerobic sludge (13 g/L of dry suspended solids) leaving a 0.3 L gas volume. The reactor temperature was maintained at 35 °C by immersing the reactor in a water bath thermostatically controlled by a Thermo Mix MM Braun heater. The sludge liquid was kept well mixed by a flat blade impeller stirring at 300 rpm.

The feed to the reactor was supplied by a two-channel peristaltic pump (EYELA Micro Tube Pump MP-3) calibrated at the commencement of the experiments. The loading rate was regulated by a digital timer. The on-time setting of the timer was varied according to the changes in the loading rate while the off-time setting was maintained constant. The amount of feed entering the reactor was measured by a Sartorius electronic balance (BA 4100 Goettingen, Germany).

The biogas produced during digestion passed over NaOH pellets and through concentrated solutions of NaOH to remove the CO_2 gas. The volume of the gas produced was measured continuously by weighing the equivalent mass of water displaced by the gas from the digester. The Sartorius balance was interfaced to an IBM-PC computer for continuous monitoring of the volume of gas produced.

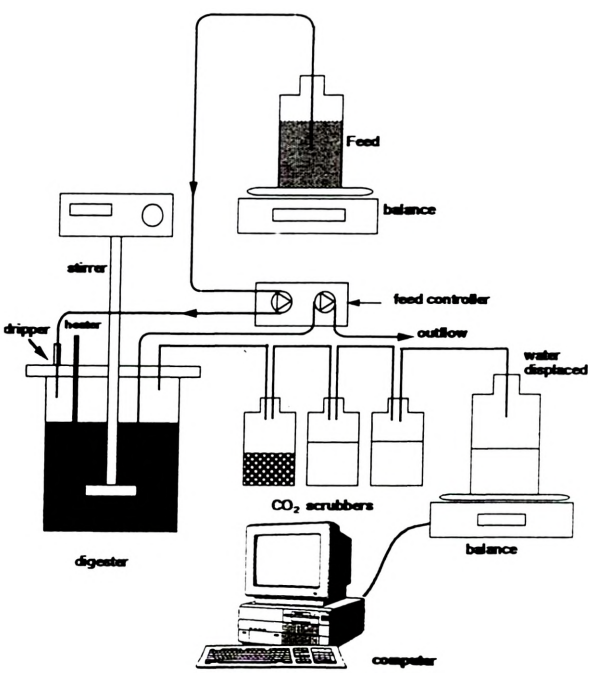

Figure 2. Schematic diagram of the experimental setup

pH. About 5 ml of sample was withdrawn from a sampling port on top of the digester and analysed for pH. The pH of the sludge and the feed were measured with Hanna HI 8424 Microcomputer pH meter.

Volatile Fatty Acid (VFA). Samples of reactor mixed liquor were prepared for volatile fatty acid determination by centrifuging (in a microfuge at 15,000 rpm) 1 ml of mixed liquor for 10 minutes to remove suspended solids. The supernatant was acidified by the addition of 0.5 % v/v concentrated phosphoric acid to extract all the free VFA as well as to suppress bacterial activity. The samples were analysed for the presence of volatile fatty acids by Varian 3300/3400 gas chromatography. The operating parameters for gas chromatograph were as follows: Column:Glass, 1.8 m x 2 mm ID, Packing: Poropack QS,80/100mesh, Column Temperature: 190°CarrierGas: N_2 carrier gas flow rate : 12 ml/min, Injection Temperature: 250 °C, Sample Volume: 1 l, Detector: Flame Ionisation Detector, Detector Temperature: 250 °C Detection Limit: 0.1 mM.

Standards with known concentrations of acetic acid, propionic acid, and butyric acid 0.5-20 mM were included at regular intervals during volatile fatty acid analysis to calibrate the instrument. The samples were stored frozen at -20 °C in cases where volatile fatty acid analysis could not be carried out at the time of sampling.

Hydrogen Concentration in the Biogas. The hydrogen content of the biogas was determined using a Trace Analytical, Reduction Gas (Stanford, CA) model RGA3. The analyser operated under the following conditions: Column Temperature: 106 °C, Detector Temperature : 228 °C, N_2 carrier gas flow rate: 10 ml/min, sample size: 0.5 ml. The H_2 detection was based on H_2 reduction of HgO to Hg vapour, which was measured through a UV light detector. The chromatograph was recorded using Omniscribe chart recorder and H_2 concentrations of both gas sample and the H_2 standard were determined from the chromatogram via peak height analysis. The detection limit is ± 10 ppb.

RESULTS AND DISCUSSION

Determination of the maximum sustainable loading rate of the digester

The loading rate of the digester was increased by step increments of 20 to 40% to allow the reactor to operate at high organic and hydraulic loading rates (Fig. 3a). The response of the digester towards the step increases was monitored in terms of gas production rate, VFA concentration, and H_2 partial pressure inorder to assess digester performance prior to and after reaching the maximum sustainable loading rate.

As expected, the increase in the loading rate was reflected by the increase in the methane production rate (Fig. 3b, 0 to 36h). This trend was observed until at 19 mmoles glucose/L d (HRT = 8 days), a maximum gas production rate of 52.7 mmoles CH_4/ L d (or 1.42 L CH_4/L d) was obtained. During this period, the acetic and propionic acids increased from concentrations below 1 mM to about 2 mM (Fig. 3d, 36h). This indicated that the balance between the acid production and methane formation reactions had been slightly disturbed. To determine whether the loading rate could be further increased without resulting in acid accumulation, the feed flow rate was raised to 22.9 mmoles of glucose/L d, (HRT=6 days). This time, the increase in the loading rate did not result in a further increase in the methane production rate but instead resulted in the drop of the conversion

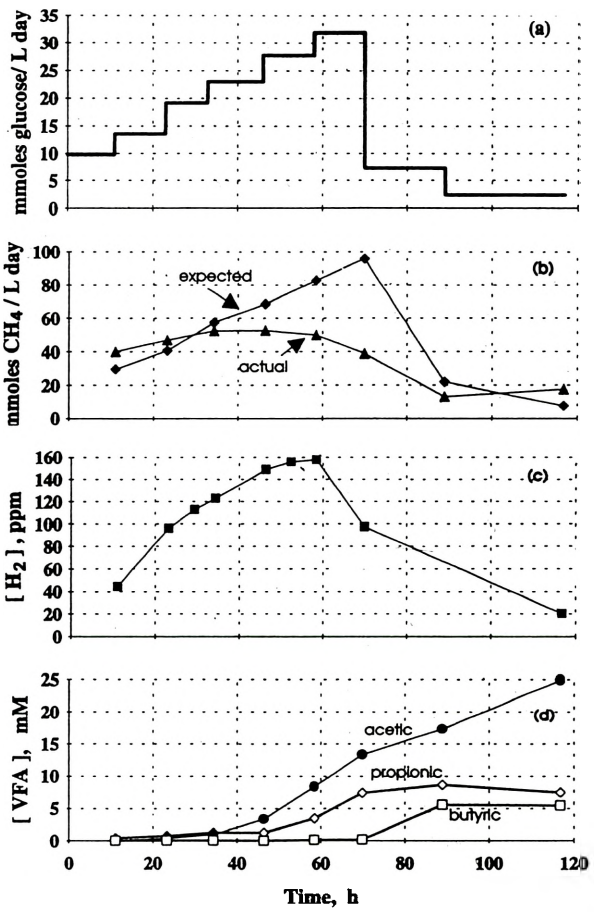

Figure 3. Response of the laboratory digester to continued increases in the loading rate using low feed concentration of 24.5 g/L d.

efficiency from 76% to 69% (Fig 3b, 48 h). This signified an accumulation of organic intermediates which was confirmed by an increase in the propionic acid concentration by almost threefold in twelve hours and small increrases in the acetic and butyric acids (Fig. 3d, 36h). Although the acid concentrations were still within the range reported for stable digesters, the fact that the VFA concentrations were increasing was a clear proof that digester imbalance had occurred and that the risk of failure had increased. The increase in the VFA concentration and the failure of the digester to increase the methane production rate proportionally with the loading rate indicated that the digester had reached its maximum sustainable loading rate at 19 mmoles glucose/L d.

Digester behavior above the maximum sustainable loading rate

The loading rate was increased above the maximum sustainable loading rate to 32 mmoles glucose/L day (HRT = 4 days) to determine the response of the digester to critical loading conditions (Fig 3b, 59 to 72 h). This increase in the loading rate resulted in a 36% decline in the rate of methane production. Within twelve hours after the increase in the loading rate, the propionic and acetic acid concentrations rose to 13 mM and 7 mM respectively.

Several authors reported that an imbalance in the microbial population during the anaerobic process is brought about by high concentrations of H_2 (Kaspar and Wuhrmann, 1978; McInerny and Bryant, 1981; Wolin, 1974). The glucose synthetic waste used in this experiment is a readily degradable substrate, thus the continued increases in the loading rate consequently resulted in the gradual increase in the H_2 concentration. The build up of H_2 from 40 ppm to 160 ppm within the 60 hours digester run (Fig 3c) is a result of a relative increase of the bacterial hydrogen production compared to the H_2 consumption.

According to the thermodynamics of the anaerobic process, the increase in the H_2 concentration would shift the electron flow during fermentation towards the formation of the more reduced products such as propionate and butyric acids rather than acetic acid. McInerney and Bryant (1981) reported that a hydrogen partial pressure of 95 ppm to 2000 ppm could inhibit propionate and butyrate degradation respectively. Due to the accumulation of the propionic, acetic and butyric acids in this experiment, the pH dropped from 6.5 to 5.1. Since the methanogenic bacteria were found to be very sensitive to high acidity (McCarty, 1964), the drop in pH resulted in the decline of the methane production rate.

The increase of the loading rate to 27 mmoles glucose/L day (HRT= 5 days) and further to 33 mmoles glucose/L day(HRT = 4 days) could have caused the washout of the slow growing methanogens (hydraulic overloading). Grady (1980) reported that for a constantly stirred tank reactor, a HRT < 10 days could cause hydraulic overloading. The perceived hydraulic overloading in this experiment resulted in the accumulation of mainly propionic, acetic and butyric acids, with propionic acid as the main acid constituent. This result agreed with the hydraulic overloading experiment undertaken without pH control by Canovas-Diaz and Howell (1988) in a downflow fixed film anaerobic reactor. He reported concentrations of 3000 mg/l of propionic, 2000 mg/l of acetic and 400 mg/L of butyric after a sharp hydraulic overloading.

The effect of increased feed concentration on digester performance

1) At a feed concentration of 48 g glucose/L.

The feed concentration was doubled to determine if the maximum sustainable loading rate is affected by the concentration of the waste(Fig 4a, 0 to 62h). As expected, the increase in the loading rate was reflected by the increase in the methane production rate. This trend was observed until the loading rate was increased to 19 mmoles glucose/L day (HRT=14 days). The loading rate of 19 mmoles glucose/L d could already have been high, for at this rate, acetic acid started to accumulate and the hydrogen concentration already increased above 100 ppm (Fig 4c and d, 45 to 62 h). It appeared therefore that the maximum sustainable loading rate was about 19 mmoles glucose / L d (HRT = 14 days). In contrast to the results from previous experiment, acetic acid showed a greater tendency to accumulate than propionic acid. Its concentration increased sharply from 1.9 mM to 6 mM within 20h whereas only small increases in the propionic and butyric acid concentrations were evident. Acetic acid predominated in this experiment because during anaerobic fermentation, the reducing equivalents are firstly channelled towards the formation of acetate, H_2 and CO_2 followed by the formation of propionic and butyric acids (Mah, 1980).

The increase of the loading rate to 24 mmoles glucose/L d (HRT=11 days) resulted in a decline in

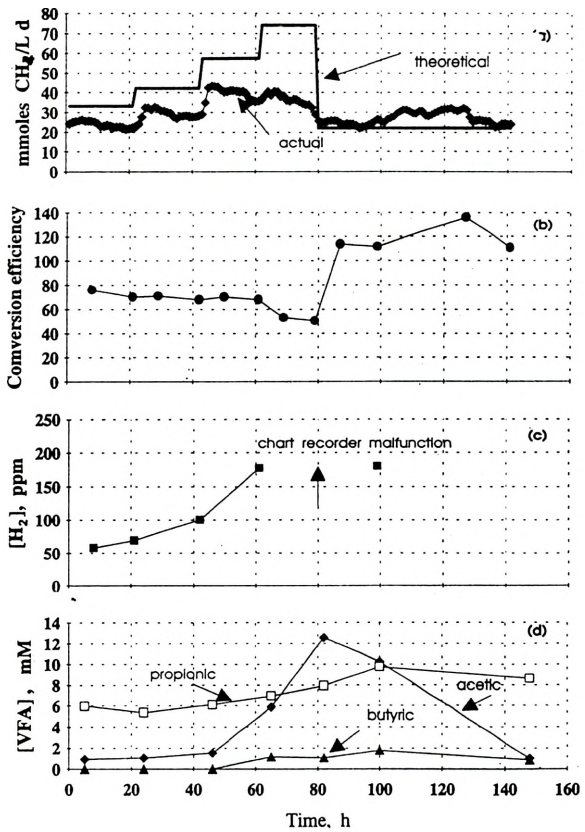

Figure 4. Response of the laboratory digester to continued step increases in the loading rate using medium feed concentration of 48 g/L.

the methane production rate (Fig. 4b, 62 - 80 h). This indicated that the maximum sustainable loading rate of the digester was exceeded at 24 mmoles glucose/l day. A clear overloading of the digester was evident at this rate for during this period, the hydrogen concentration rose from 100 to 179 ppm (Fig. 4c), indicating a higher bacterial H_2 production rate than the H_2 consumption rate. The increase in VFA concentrations resulted in the drop of pH from 6.5 to 6.0. Consequently, the methane production rate and the conversion efficiency decreased.

2) At an increased feed concentration of 63g glucose/L.

The feed concentration was increased to 63g glucose/L to determine whether or not a further increase in the feed concentration would give the same maximum sustainable loading rate found in the previous experiments (24 g glucose/L and 48g glucose/L). The methane production rate continually increased when the loading rate was increased stepwise from 9.5 mmoles glucose/L day to 19 mmoles glucose/L day (HRT =18 days, Fig. 5a). A further increase in the loading rate to 23 mmoles glucose/L day (HRT =15 days) resulted in an only 8% increase in the methane production rate and a drop in the conversion efficiency from 70% to 65%. A clear increasing trend in the hydrogen concentration (greater than 100 ppm) was evident as the loading rate was increased (Fig. 5c). The continued increase in the H_2 partial pressure and its correlation with the increasing VFA concentration indicated that H_2 could be a good process indicator in anaerobic digesters. In this experiment, an obvious accumulation of the acetic acid when the loading rate was increased from 15 to 19 mmoles glucose/l day again indicated that the maximum sustainable loading rate of the digester had been reached at 19 mmoles glucose/l day. Moreover, the sharp increase in the acetic acid concentration from 5 mM to 15 mM when the loading rate was further increased to 23.1 mmoles glucose/L d signified an organic overloading which resulted in acetic acid accumulation only (Fig. 5d).

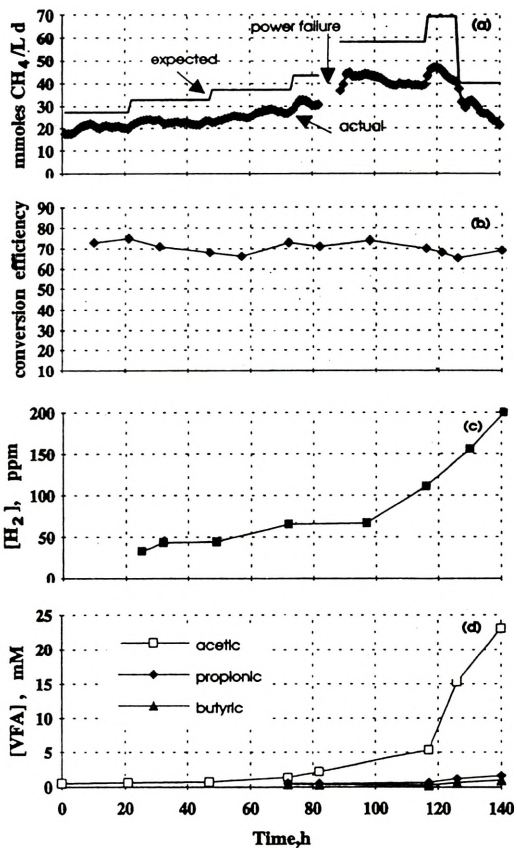

Figure 5. Response of the laboratory digester to continued increases in the loading rate using high feed concentration of 63 g/L.

Comparison of digester performance at different feed concentrations

The results of the three experiments conducted at similar organic loading rate but different feed concentrations indicate that the maximum sustainable loading rate of the digester is dependent on the amount of organic load added. On the other hand, it appeared that within the loading rates tested, the maximum sustainable loading rate of the digester is independent of the hydraulic retention time. In the three experiments, the maximum loading rate was found close to 19 mmoles glucose/L d (VFA concentrations < 6 mM) despite the differences in the HRT.

The differences in the type of overloading that occurred after the maximum sustainable loading rate was exceeded demonstrate the effect of feed concentration and HRT on the performance of the digester. The propionic, acetic and butyric accumulation found in the first experiment could have been due to hydraulic overloading. The observed increases in acetic, propionic and butyric acids during an organic overloading in the second experiment using a more concentrated feed (48 g glucose/L) is a typical response of an anaerobic reactor to organic shockload (Kennedy and van den Berg, 1982; Cohen et al., 1980). However, the predominant acetic acid accumulation during the organic overloading at the feed concentration of 63 g glucose/L is in contrast with the observations of Barnes et al.(1984), who reported that the main acid constituent during organic overloading is propionic acid. This contradiction reflects differences in the adaptation of the reactor's microbial populations, the type of waste used and the reactor configuration.

Digester recovery after a loading rate reduction

Towards the end of the experiments, the digester was allowed to recover by decreasing the loading rate. In the first experiment, feed reduction was not successful in recovering the digester since the biomass had been severely damaged due to the accumulation of propionic, acetic, and butyric acid (Fig 3d). In the second experiment, digester recovery was attempted by reducing the loading rate by about 2/3. This successfully prevented the digester from acidifying and failure (Fig 4d). Acetic acid was readily removed, although propionic and butyric acids showed difficulty in degrading. The methane gas was continually produced at a rate higher than what was expected, obviously because of the undegraded organics from the previous load. In the third experiment, the loading rate was decreased by 30% to prevent a further increase in the acetic acid concentration. In this case, digester overloading was not prevented. In spite of the feed reduction, the methane production rate continued to decline (Fig 5a) This is very interesting, as there was no real reason for the gas production to decrease. A pH of 6.0 was not too low to cause souring. Furthermore, propionic acid did not accumulate and the acetic acid concentration (15 mM) was just a little higher than its concentration at the time overloading occurred in the previous experiment. One plausible reason could be that the reduced loading rate (14 mmoles glucose/L d) was still high for the biomass. It should be noted that the acetic acid concentration continued to increase to about 23 mM even after the lowering of the feed. In this case, feed termination was definitely necessary for digester recovery.

CONCLUSIONS AND RECOMMENDATIONS

Based on the observations presented, the following conclusions can be drawn:

*The relationship between the gas production rate to the loading rate could be a useful indicator of digester performance especially to biogas operators who consider productivity as an important aspect in digester operation and optimization. As long as gas production rate increases proportionally with the loading rate, the amount of feed to the reactor could be further increased, thus maximizing waste addition. Conversely, the unproportional relationship between the gas production rate and the loading rate could signal that the sustainable loading rate of the digester had been exceeded and that an imbalance in the microbial activity is likely to occur.

*Organic overloading could be confirmed by the following indicators: 1) an increase in the hydrogen level above 100 ppm, 2) a rapid rise in the concentrations of acetic acid (about 12 mM), and pronounced increases in propionic and butyric acid concentrations, 3) a drop in pH below 6.0; 4) a sharp decrease in the methane production rate and consequently a drop in the digester conversion efficiency below 70 %.

*H_2 concentration could play an important role in the development of a process control technique for the safe operation of anaerobic digesters An early sign of digester imbalance could be detected through constant monitoring of the changes in the hydrogen concentration. Its usefulness could be further

enhanced when monitored together with conversion efficiency.

*The acetate concentration is another useful indicator of process upsets in anaerobic digestion, especially during organic overloading.

*The concentration of the feed influences the type of acid that predominates in the reactor and within the loading rates tested was independent of the hydraulic retention time.

*Further acidification in the reactor which is slightly overloaded could be prevented by an immediate reduction in the loading rate. In severe cases, feed termination is definitely necessary. This provides a relevant information for the development of a control technique that could safely operate anaerobic digesters under high loading rates.

*The feed used in the experiments was glucose, an easily digestible substrate of known composition. As most industrial and agricultural wastes contain high concentration of proteins, fats, cellulose, etc, the results presented in this study could be verified in large digesters (pilot scale, full scale) degrading different types of wastes. The results of the experiments have shown that VFA measurements could reliably assess the performance of anaerobic digesters. However, the monitoring of this parameter is often not available on-line and needs highly trained staff and expensive equipment. Further studies on the usefulness of control parameters which can be monitored on-line (i.e. gas production rate, H_2 concentration) could be conducted for digester control and optimization.

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