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Avoiding Digester Imbalance Through Real-Time Expert System Control of Dilution Rate

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ABSTRACT

Process control of anaerobic digesters is a particularly challenging problem because of the diversity of possible causes that can lead to digester imbalance. Conventional control schemes can fail in consequence of a reversal in the sign of the steady-state gain caused by some type of disturbance. In this work we present an expert system approach that takes into account the particularity of this process. The developed algorithm is demonstrated to compensate successfully for changes in the digester feed medium when simulated against a model for a continuous anaerobic digester.

Index Entries: Anaerobic digestion; imbalance; process control; expert systems.

INTRODUCTION

Anaerobic digestion, traditionally used as a method for waste treatment (*1*), has recently been considered as a possible process for energy production. This is because of its potential for methane production coupled with low nutrient requirements and low yields of microbial mass (*2,3*).

A serious problem occasionally arising in anaerobic digester operation is the development of an imbalance, that may cause a lengthy and costly shutdown. Digester imbalance is generally attributed either to a feed rate

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that overloads the system or to inhibiting factors, such as chloroform or ammonia, in the supplied feed. Process control strategies may be developed in order to solve or reduce the extent of this problem. Several investigators have developed approaches to the control of anaerobic digesters (*4–11*). These works, however, did not consider the possibility of digester imbalance arising from feed inhibitors. Such inhibition complicates the control problem considerably as will become apparent in the discussion to follow.

In this work we develop an expert system for preventing digester imbalance in a continuous anaerobic digester, whether it is caused by inhibitors in the feed or by feed overloading. The control scheme uses methane production rate as the measured output, and dilution rate (inverse hydraulic retention time) as the manipulated input. Methane production rate is not only a readily measured quantity, but also has the advantage of providing an earlier indication of digester imbalance than pH depression or fatty acid accumulation. Dilution rate is the process variable most easily manipulated.

THE PROBLEM WITH CONVENTIONAL CONTROL

A control law is the functional relationship that dictates how the manipulated input (here dilution rate) varies as a function of the measured output (here methane production rate). Commonly used control laws are the proportional-integral-derivative (PID) (e.g., *see* ref. *12*), the proportional-integral (PI), and internal model control (IMC), which is often equivalent to PI or PID (*13*). All the conventional controllers require knowledge of the sign of a process parameter called the steady-state gain. If increasing the manipulated input causes an ultimate increase in the measured output, then the steady-state gain is positive; if the output decreases, then the steady-state gain is negative. Control-law design on the basis of incorrect gain sign leads to instability (a disastrous result).

For an anaerobic digester under normal operating conditions, an increase in the dilution rate (decrease in the hydraulic retention time) leads to an increase in the methane production rate. Thus, the sign of the steady-state gain is positive. A conventional controller will increase the dilution rate whenever an increase in the methane production rate is desired. However, if it acts this way in response to a drop in the methane rate, and if this drop is a result of the entry of inhibitors with the feed, then the increase in the dilution rate will cause a build-up of the inhibitor in the reactor, which in turn will cause a further drop in the methane rate. In turn, the controller will increase the dilution rate even further, attempting to raise the methane rate, and this scenario will continue until complete failure of the digester is reached. What has happened is that the digester became unstable because the entry of inhibitors in the feed reversed the sign of the steady-state gain. A control scheme based on methane-rate measurements will be unable to discriminate between different causes for an observed drop, and therefore cannot determine a reversal of the sign of the process steady-state gain.

THE CONSTANT-YIELD OPERATING POLICY

The expert system that we are proposing makes use of the following key concept: The dilution rate is continually manipulated to keep the reactor yield constant, where

$$\text{(Reactor Yield)} = \frac{\text{(Methane Production Rate)}}{\text{(Volumetric Feed Rate)} \cdot \text{(Feed Concentration)}}$$

This is very easily implemented when interrupted feeding is employed: at each instant an amount is fed that corresponds to the previous methane-production-rate measurement, hence keeping the specified yield.

This control policy responds to a drop in the methane production rate (caused by inhibition) by decreasing the dilution rate in an effort to keep the reactor yield constant. This is, of course, a move in the right direction and can save the digester from failure. The same constant-yield control policy would also respond the right way to a sudden change in the feed substrate concentration, provided that the feed substrate concentration is measured on line. Thus, an increase in the feed concentration (overload) will be compensated for by a corresponding decrease in the dilution rate, avoiding the problem of fatty acid build-up. The latter would cause fatty acid inhibition of methanogenesis and possibly digester imbalance. The problem, however, is that an appropriate measurement of feed substrate concentration on line (e.g., chemical oxygen demand or biochemical methane potential) is not currently possible.

The lack of availability of feed substrate concentration measurement forces us to consider a nominal apparent reactor yield, defined as

$$\text{(Apparent Reactor Yield)} = \frac{\text{(Methane Production Rate)}}{\text{(Volumetric Feed Rate)} \cdot S_{nom}}$$

where S_{nom} is a standard expected value for the feed substrate concentration.

Implementing a constant-apparent-yield operating policy would certainly work very well for the case of inhibitors in the feed. This approach, however, can fail in the case of changes in the feed substrate concentration. An increase in the methane production rate caused by an overload will be compensated for by a corresponding increase in the dilution rate, causing possible fatty acid accumulation and digester imbalance. A decrease in the methane production rate caused by an underload will be answered by a corresponding decrease in the dilution rate. It may be impossible to maintain the desired constant apparent yield, in which case the dilution rate will continue dropping until, eventually, the reactor goes to batch mode. These facts have been verified by testing the performance of the constant-apparent-yield operating policy against the model of Smith et al. (*14*). Consequently, we see that a constant-apparent-yield operating strategy would work well in responding to a drop in the methane production rate whenever this is caused by inhibitors in the feed, but could fail if the cause is a feed underload (i.e., substrate concentration drop in the feed). In the later instance it would suffice to drop the dilution rate to a level low enough to avoid methanogen washout. The next section describes the expert system at which we arrived by taking these considerations into account.

THE EXPERT SYSTEM

The developed expert system is outlined in the block diagram of Fig. 1. This diagram can be summarized as consisting of five basic loops. Loop 0 is the normal operation sequence (no disturbances). Loop 1 contains corrective action for the case of inhibiting factors in the feed, and Loop 3 handles the case of feed underload. Loop 2 controls the flow of the algorithm between Loops 1 and 3. Finally, for the case of overloading, Loop 4 is used.

At fixed sampling instants, the methane production rate is measured. If it is within a specified range, e.g., $\pm 10\%$ of the expected "base" value, then the dilution rate is maintained at its normal value. This allows for normal variations and measurement noise expected in the digester environment (Loop 0).

If the methane rate has dropped by $>10\%$ of its normal value, Loop 1 is entered. The first step in this loop is to implement a constant-apparent-yield operating policy, which responds to a drop in the methane production rate by dropping the dilution rate. The methane rate is subsequently checked to determine whether it has returned to within 10% of its normal value. This would happen if the cause of the methane drop has disappeared, in which case the constant-apparent-yield policy would have increased the dilution rate in response to the increase in the methane rate. This, of course, is expected to happen as the digester recovers from an underload or an inhibition disturbance. The last step in the loop is to test whether or not the dilution rate has dropped by more than a maximum allowable limit (e.g., by 25% of the value it had when the algorithm entered the loop). If not, the algorithm returns to the beginning of Loop 1. Otherwise, the dilution rate is kept constant at its current value. This is done because the drop in the methane production rate may have been caused by an underload instead of by inhibition. In the case of an underload, at a constant dilution rate the methane production rate will eventually level off at some positive value. In the case of inhibition, depending

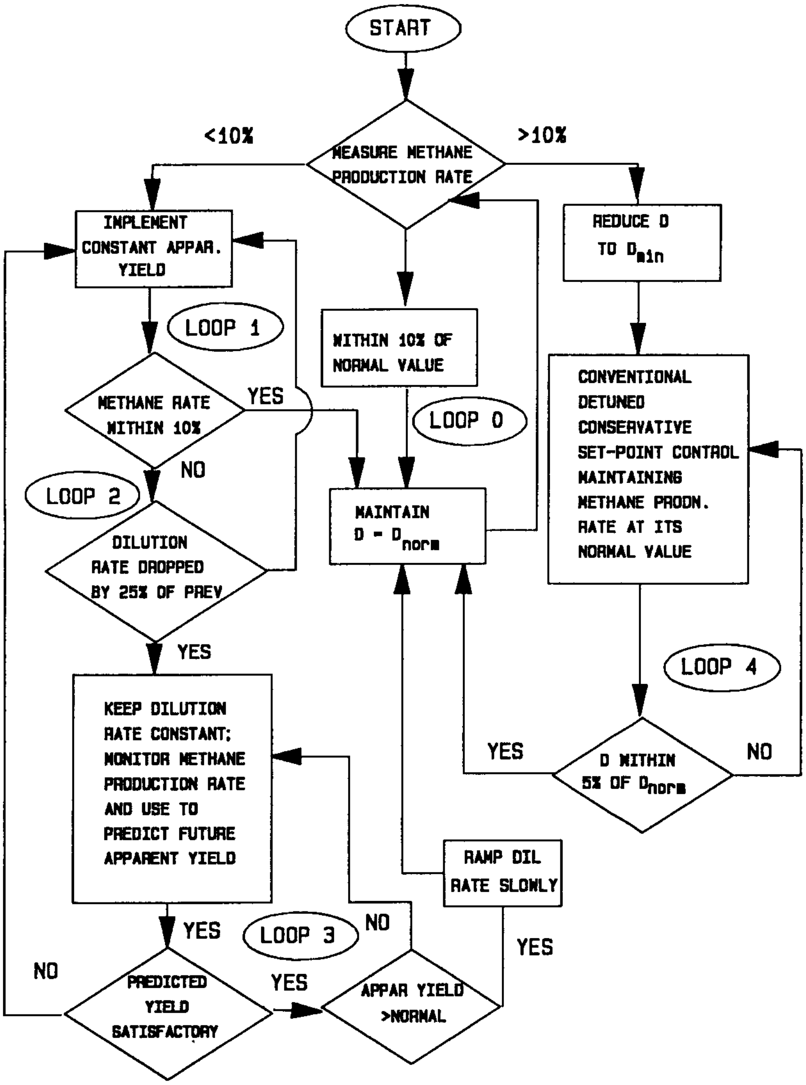

Fig. 1. Flow chart of the expert system for preventing digester imbalance.

on the concentration of the inhibitors and the value of the dilution rate, the methane rate may or may not level off. If the methane rate levels off (at a reasonable value), further decrease in the dilution rate is unnecessary. Thus the methane producton rate is monitored and the measurements used to extrapolate (by quadratic fitting) an expected future methane rate (equivalent to apparent yield, since the dilution rate is constant). If the extrapolated yield is not satisfactory, the constant-dilution-rate mode is immediately abandoned and the process is returned to Loop 1 via Loop 2, thus continuing the drop in the dilution rate. Otherwise, the process continues along Loop 3. The next step in this loop is to check whether the apparent yield is higher than the "base" value. This would happen if the cause for the apparent yield drop has disappeared, in which case it would be safe to return the dilution rate to its normal value. This is done with a slowly increasing ramp. As long as the apparent yield stays below its "base" value and its projected future value is satisfactory, the algorithm circles Loop 3, keeping the dilution rate constant.

If the methane production rate has increased by $>10\%$ of its normal value, this indicates increased feed strength and a danger of imbalancing the digester. A conventional controller trying to maintain the "base" methane rate as the set point is well suited for saving the digester, since there is no inversion of the sign of the steady-state gain. In response to the increase in the methane rate, it decreases the dilution rate (the indicated action). The controller chosen should be very robust, and for this reason we chose a conservatively tuned (detuned) IMC controller (*15*). A detuned controller changes the dilution rate slowly. To avoid approaching the new lower value of dilution rate from above, and thus running the risk of being too late in decreasing the flow rate, the algorithm first sets the dilution rate to a low "safe" value and then starts the control law in Loop 4. Once the overload has disappeared, the controller will start increasing the dilution rate towards its normal value. When the dilution rate approaches its normal value, e.g., it is within 5%, the algorithm exits Loop 4 and normal operation resumes.

In summary, the expert system responds to inhibitors in the feed by decreasing the dilution rate in proportion to the methane production rate, to severe underloads by dropping the dilution rate to a safe constant value, and to overloads by conventional set-point control of the methane rate.

TESTING OF THE EXPERT SYSTEM

In order to test the efficacy of the developed algorithm, we simulated anaerobic digestion using the model developed by Smith et al. (*14*) as it applies to a continuously fed stirred anaerobic digester. This model was modified to account for the effect of inhibitors entering with the feed by assuming that the maximum specific growth rate of the methanogens decreases exponentially with the concentration of the inhibitor in the reactor (e.g., $\exp(-[I])$, where $[I]$ is the inhibitor concentration). Methanogenesis can be affected by inhibitors in many different ways, depending on the type and concentration of the toxic element in the feed. Such inhibitors as ammonium chloride and L-dopa cause sudden decreases in the methane rate (*16,17*), which can be easily simulated with an exponential functionality in the methanogenic maximum specific growth rate. For the simulations the "base" case was taken to be a dilution rate of 0.1/d, with a corresponding methane production rate of about 4 L of methane/d for a 5-L digester.

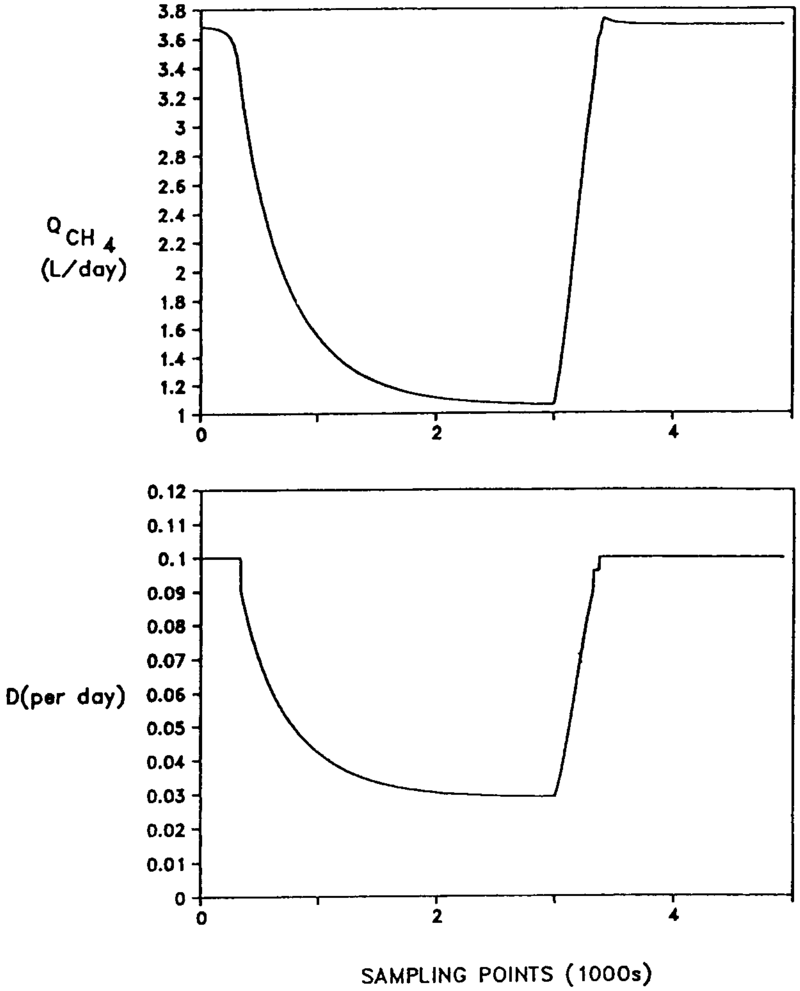

Fig. 2. Simulation of response to inhibitors in the feed.

Figure 2 shows the response of the expert system to a severe feed inhibition that caused a drop of the maximum methanogen specific growth rate from 0.36/d to 0.08/d over the time it persisted. As can be seen from the figure, the expert system caused a drop of the dilution rate from its base value of 0.1/d to about 0.03/d, avoiding methanogen washout. During this time, Loops 1 and 2 were active, implementing essentially a constant-yield operating policy. As soon as the inhibitor was removed from the feed, the dilution rate was brought back to its normal value. During the upset, the methane production rate of course dropped at first by a significant amount, but methanogen washout was prevented and the algorithm succeeded in recovering the digester.

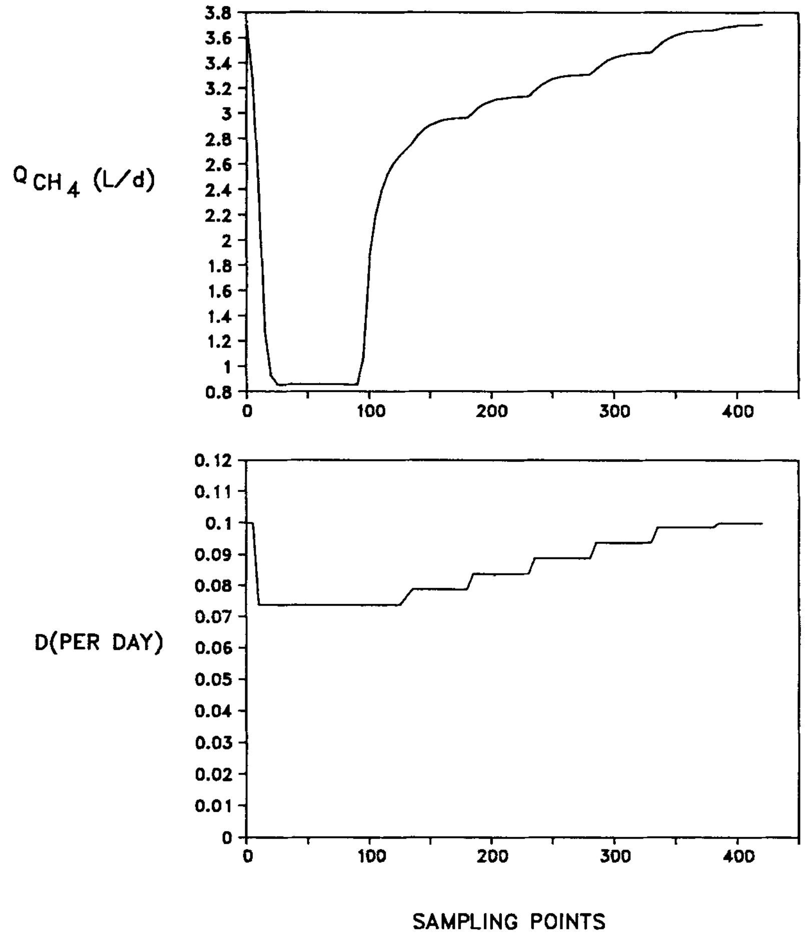

Fig. 3. Simulation of response to underloading.

Figure 3 shows the response of the algorithm to a drop in the feed concentration from its normal value of 30 g/L to 20 g/L. The dilution rate was decreased quickly to 0.075/d (Loop 1 being in effect). Since a leveling-off of the methane yield was predicted, Loop 3 was entered and remained in effect until the feed substrate concentration resumed its normal value. This caused an increase in the methane yield, and the expert system gradually brought the dilution rate back to its normal value.

Figure 4 shows the response of the expert system to a severe feed overload (90 g/L from 30 g/L). In the absence of a control action, this would cause fatty acid accumulation, and the digester would become imbalanced. As soon as an increase of the methane production rate in excess of 10% is observed, the dilution rate is cut down to a minimum and the conventional IMC controller is implemented. The controller succeeds in returning the methane production rate to its "base" value by properly adjusting the

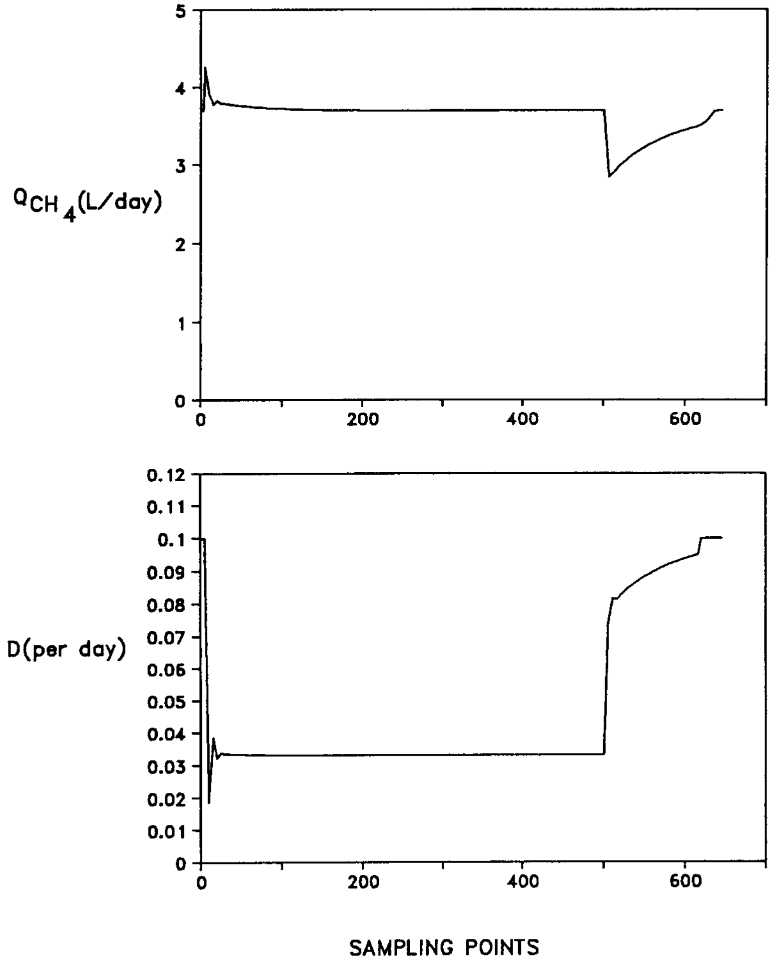

Fig. 4. Simulation of response to overloading.

dilution rate. As soon as the overload ceases, the controller returns the dilution rate to its normal value of 0.1/d.

CONCLUSIONS

We have developed an expert system that can prevent failure of an anaerobic digester when its regular operation is upset by changes in the feed substrate concentration or the presence of inhibitors in the feed. The algorithm was shown to be able to handle severe disturbances when simulated against a model for the continuous anaerobic digestion process, when conventional control schemes were bound to fail. In future work we will test the performance of the expert system on a lab-scale experimental digester.

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