10th International IFAC Symposium on
Computer Applications in Biotechnology
Preprints Vol.1, June 4-6, 2007, Cancún, Mexico

CONTROL OF AN ANAEROBIC MESOPHILIC REACTOR USING PERIODIC TEMPERATURE VARIATIONS

B. Tartakovsky[1*], E. Morel[1,2], L.-P. Dansereau[2], M. Perrier[2], S. R. Guiot[1]

[1]Biotechnology Research Institute, NRC, 6100 Royalmount Ave, Montréal, QC, Canada H4P 2R2
[2]Département de Génie Chimique, École Polytechnique de Montréal, C.P. 6079 Succ. Centre-Ville, Montréal, QC, Canada H3C 3A7

Abstract: In this study, temperature variations in a mesophilic anaerobic reactor were used to control the reactor degradation capacity. When the reactor temperature was periodically changed from 32°C to 46°C with a period of 12 h, a near liner increase in methane production in response to temperature augmentation was observed. Furthermore, when the reactor temperature was increased during increased organic load, it resulted in a lower effluent concentration of volatile fatty acids and an increased chemical oxygen demand (COD) removal rate. A feedback control algorithm, which was based on a multi-model observer-based estimator of the anaerobic digestion process, was developed. The algorithm increased reactor temperature in response to increasing effluent COD concentration. It was successfully tested in a 10 L laboratory-scale reactor.

Keywords: anaerobic mesophilic digestion; temperature control; periodic operation; multi-model.

1. INTRODUCTION

Anaerobic treatment of wastewaters in a continuous reactor system has a limited number of inputs available for process control. Wastewater strength can be changed only by dilution, thus influencing reactor hydraulic retention time (HRT). Therefore, organic load can only be controlled by installing an additional storage tank. Most often control of anaerobic reactors is limited to reactor pH stabilization. Meanwhile, it is well known that biodegradation rates are sensitive to temperature variations (Ward et al., 2005). Anaerobic degradation of organic materials can be carried out in a wide range of temperatures including psychrophilic (below 20°C), mesophilic (25-45°C), and thermophilic (above 50°C) conditions (Pavlostathis and Giraldo-Gomez, 1991). The Arrhenius equation is often used to describe the influence of temperature on microbial growth and biodegradation in anaerobic digestion (Batstone et al., 2002; Hao et al., 2002; Siegrist et al., 2002). In practice, however, a temperature increase above the usual operating point was shown to cause a period of decreased methane production required for adaptation of methanogenic microorganisms to a new temperature. Furthermore, reactor overload during the period of temperature transition was often observed to cause a reactor failure (van Lier et al., 1990; Visser and Lettinga, 1993). Nevertheless, an improved methane production has been reported after a short-term temperature increase from 25 to 45°C (Speece and Kem, 1970) and a recovery of methanogenic activity was observed after a short-term temperature increase above 45°C followed by a return to mesophilic conditions (Ahn and Forster, 2002). Also, sludge exchange in a two-phase mesophilic-thermophilic digestion process was shown to improve the overall reduction of volatile solids (Song et al., 2004).

This study presents an experimental demonstration of mesophilic anaerobic reactor operation under periodic variations of reactor temperature. Furthermore, augmentation of reactor temperature to near-thermophilic levels was used as a mean to avoid overproduction of volatile fatty acids during short-term organic overloads.

2. MATERIALS AND METHODS

2.1 Reactor setup and media composition

A 10 L upflow anaerobic sludge bed (UASB) reactor with an external recirculation line was used for the experiments (Zeng et al., 2005). The reactor was equipped with a water jacket and a water heating system for temperature control. The synthetic wastewater and trace metals were added into the bicarbonate buffer stream at a feeding rate of 0.4 Ld^{-1} each. The total influent flow rate was 20 L d^{-1}. The reactor was inoculated with 3 L of an anaerobic granular sludge from a wastewater plant (A. Lassonde Inc., Rougemont, QC, Canada) with an average volatile suspended solids (VSS) content of 50 g L^{-1}.

Synthetic wastewater had a COD content of 315 g COD L^{-1} and contained (in g L^{-1}): sucrose 100, yeast extract 60, whey 100, KH_2PO_4 3, K_2HPO_4 3.5, and NH_4HCO_3 34. In feedback control experiments whey was replaced with 35 g of 95% ethanol and 48 g of butyric acid. A solution of trace metals contained (in g L^{-1}): $AlK(SO_4)\cdot 12H_2O$ 0.0006; H_3BO_3 0.001; $Ca(NO_3)_2\cdot 4H_2O$ 0.5351; $Co(NO_3)_2\cdot 6H_2O$ 0.0075; $Cu(SO_4)$ 0.0003; $Fe(SO_4)\cdot 7H_2O$ 0.0546; $MgSO_4$ 0.1973; $Mn(SO_4)\cdot H_2O$ 0.0151; $Na_2(MoO_4)\cdot 2H_2O$ 0.0023; $NiSO_4\cdot 6H_2O$ 0.0007; Na_2SeO_4 0.0013; and $ZnSO_4\cdot 7H_2O$ 0.0035. A bicarbonate buffer was composed of 1.36 g L^{-1} of $NaHCO_3$ and 1.74 g L^{-1} of $KHCO_3$.

2.2 Reactor instrumentation and analytical methods

Biogas production and composition was measured on-line using an electronic bubble counter and a methane analyzer (Nova Analytical Systems, Hamilton, ON, Canada), respectively. Reactor pH was measured by a pH-meter (Cole-Parmer Instrument, Vernon Hills, IL, USA) with the probe inserted in the external recirculation line. TH series temperature sensors (Roctest, Saint-Lambert, QC, Canada) were used for on-line measurements of temperature in the reactor, water jacket, and air. A PC equipped with a PC-1200 acquisition board (National Instruments, Austin, TX, USA) was used for data acquisition and pump control. The software for reactor monitoring and control was developed in-house using Visual Basic v6 (Microsoft Corporation, Redmond, WA, USA) and MATLAB (MathWorks Inc., Natick, MA, USA).
COD concentrations in the reactor effluent were measured on-line using a multi-wavelength fluorometer installed in the external recirculation loop of the reactor (Morel et al., 2004). For calibration purposes, analytical measurements of COD concentrations were carried out according to Standard Methods (APHA, 1995). Concentration of volatile fatty acids (VFA) in the effluent was determined using a gas chromatograph (Sigma 2000, Perkin-Elmer, Norwalk, Connecticut, USA) equipped with a 91 cm x 4 mm i.d. glass column packed with 60/80 Carbopack C/0.3% Carbopack 20 NH_3PO_4 (Supelco, Mississauga, Ontario, Canada).

2.3 Multi-model adaptive controller

The adaptive controller implemented in this study was based on the multi-model of the anaerobic digestion process developed previously (Tartakovsky et al., 2002; Tartakovsky et al., 2005). The multi-model was modified to include the effect of temperature on the biotransformation rates and then transformed into an observer-based estimator. The input-output linearization method was then used to design a multi-model adaptive controller as described below.

The multi-model consisted of three submodels describing normal (methanogenic), organic overload, and acidogenic process states. Multi-model outputs were defined by the weighted sums of the submodel outputs. The weights were calculated by a knowledge-based system, which used on-line measurements of biogas composition and reactor pH for process diagnosis (Morel et al., 2006a). The influence of temperature on the microbial activity was modeled using a modified Arrhenius equation, which linked the biotransformation rate with the temperature in the following form:

$$f(T) = e^{\theta(T-T_0)}, \qquad (1)$$

where θ is the temperature coefficient (θ=0.025) and T_0 is the relative temperature (T_0=35°C) (Hao et al., 2002; Siegrist et al., 2002). To account for temperature influence, all maximal biodegradation rates of the multi-model were multiplied by Eq (1).

The temperature model of the reactor used the assumptions of ideal mixing and isothermal biochemical reactions. The model was simplified by neglecting the contribution of the influent stream :

$$\frac{dT}{dt} = K_1(T_h - T) + K_2(T - T_{air}) \text{ with } K_1 = U_1A_1 \text{ and } K_2 = -U_2A_2 \qquad (2)$$

where T, T_{air}, T_h are the reactor, the air, and the water jacket temperatures (°C), K_1 and K_2 are the overall heat transfer coefficients (W °C^{-1}), U_1, U_2 are the heat transfer coefficients (W m^{-2} °C^{-1}) and A_1, A_2 are the heat transfer areas (m^2).

To obtain a multi-model observer-based estimator the multi-model submodels were converted into corresponding sub-estimators and tuned as described in Morel et al (2006b).

The multi-model adaptive controller was designed by linearizing the multi-model observer. The input/output linearization method (Bastin and Dochain, 1990) was applied with the tracking error $(\zeta^* - \zeta)$ defined using the following first order reference model :

$$\frac{d}{dt}(\zeta^* - \zeta) + \lambda(\zeta^* - \zeta) = 0 \quad \text{and} \quad \lambda > 0 \qquad (3)$$

The set point ζ^* was defined as a constant, $\frac{d\xi^*}{dt} = 0$, and the reference model was simplified as follows :

$$\frac{d\xi}{dt} = \lambda(\zeta^* - \zeta) \qquad (4)$$

For each sub-controller (i=1..3) the COD concentration ($\xi_{i,1}$) and the local reactor temperature (T_i) were defined as the controller set point and the manipulated variable, respectively, and the following adaptive controller was obtained:

$$T_i = T_0 + \frac{1}{\theta}\ln\left[\frac{\lambda_i(\zeta^*_{i,j} - \zeta_{i,j})}{r_{i,j}(\zeta_{i,j},t)} + \frac{F}{V}\frac{(\zeta_{i,j} - \zeta^*_{i,j})}{r_{i,j}(\zeta_{i,j},t)} - \frac{Q_i}{V}\right],$$
$$i = 1,\ldots,n, \quad j = 1,\ldots,m \qquad (5)$$

where $r_{i,j}$ is the estimated reaction rate, and λ_i is the tuning parameter of the *i-th* controller corresponding to *i-th* submodel.

The required reactor temperature (T^*) was calculated by summation of local submodel-based reactor temperatures weighted by the vector (β_i) given by the knowledge-based system :

$$T^* = \sum_{j=1}^{n} \beta_j T_j \qquad (6)$$

The adaptive temperature controller was obtained using the linearization method, where the previously calculated reactor temperature was used as the set point (T^*) for the temperature controller and the water jacket temperature (T_h) was the manipulated variable :

$$T_h = T + \frac{1}{K_1}\left[\lambda_T(T^* - T) + K_2(T_{air} - T)\right] \qquad (7)$$

where λ_T is the tuning parameter of the controller.

3. RESULTS AND DISCUSSION

3.1 Reactor operation with periodic temperature variations

The experiment was started up at an organic loading rate of 25 g COD d^{-1} and a reactor temperature of 23°C. Under these operating conditions stable reactor performance was observed shortly after startup with a methane production rate of 6.7 L d^{-1} and soluble COD and total VFA concentrations in the reactor effluent below 300 and 100 mg L^{-1}, respectively. Based on preliminary tests, a period of 12 h was then chosen for reactor temperature variations from 23 to 42°C with a heating period of 3 h. Notably, a temperature of 42°C corresponds to a boundary between mesophilic and thermophilic conditions and was not expected to significantly decrease mesophilic activity. Because of a small reactor size, the temperature decreased to below 30°C within 6 h from the start of each cycle. During each heating period, the rate of methane production increased to 12 L d^{-1} and then slightly declined while remaining above the methane production level at 23°C (results not shown). A calculation of methane released due to changes in methane solubility showed that it accounted for less than 3% of methane produced during each cycle. After observing stable reactor performance, the organic loading rate was increased to 55 g COD d^{-1} and temperature was varied from 32°C to 46°C with a period of 6 h and a heating interval of 2.4 h (Figure 1). As before, stabilization of reactor performance was observed shortly after new operating parameters were implemented. The rate of methane production was 9 L d^{-1} at a temperature of 32°C while reaching 16 L d^{-1} at the highest temperature within each cycle. An average rate of methane production during a cycle was 11.8 L d^{-1}.

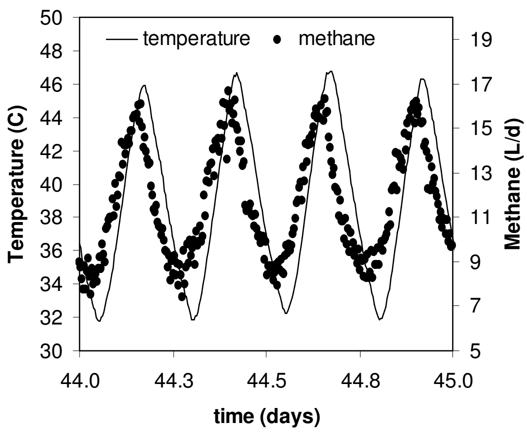

Fig. 1. Reactor operation at an OLR of 55 g COD d^{-1} and periodic temperature variations from 32C to 47C.

Analysis of soluble COD and VFA concentrations in the reactor effluent showed an average of 240 mg L^{-1} and 52 mg L^{-1}, respectively. With respect to an influent COD concentration of 5500 g L^{-1}, this corresponded to a COD removal efficiency of 96%. Also, reactor pH slightly increased during each heating period suggesting an improved VFA degradation (results not shown).

To compare methanization rates at different temperatures, the reactor was operated at constant temperatures of 32, 35, 40, and 45°C until steady methane production was observed (4 - 6 retention times). Methane production rates obtained at the end of these periods were then plotted against reactor temperature (Figure 2) suggesting a near linear response to temperature variations in this temperature range. This linear response to temperature variations was contrary to the often observed decrease in methane production upon changes in the reactor temperature (van Lier et al., 1990; Visser and Lettinga, 1993). A temperature of 35°C is considered optimal for mesophilic anaerobic digestion, and reactor operation at temperatures over 40°C is expected to cause a shift in the distribution of microbial populations with proliferation of thermophilic microorganisms. This population change limits the use of temperature for process control. A near-linear response of microbial populations to temperature changes observed in this study after periodic temperature variations suggested that either mesophilic meethanogens developed a tolerance for the above-optimal temperatures or a consortium of mesophilic and thermophilic methanogens has been developed. In either case, this response suggested that a temperature-based process control system, which would increase reactor temperature in order to control effluent COD concentration, can be developed.

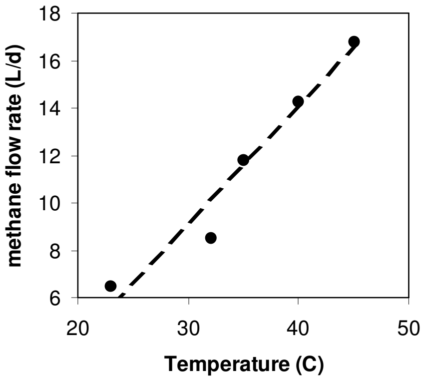

Fig. 2. The effect of temperature on the methane production rate at an OLR of 55 g COD d^{-1}

3.2 Temperature-based reactor control

The proposed control strategy was tested in a 10 L UASB reactor operated at a temperature of 25°C and an OLR of 60 g COD d^{-1}. In this test the influent composition was slightly different from that used in the previous experiment with whey replaced by sucrose and butyric acid, i.e. biodegradability of the influent organic materials was improved. The reactor was periodically overloaded by increasing the OLR from 60 to 120 g COD d^{-1} and the reactor temperature was controlled by an adaptive controller. Figure 3 shows the results of an experiment in which the controller setpoint was 0.6 g COD L^{-1}. Prior to the test, the reactor produced 17 ± 0.1 L CH_4 d^{-1} and a COD concentration of 0.34 ± 0.04 g COD L^{-1} was measured in the effluent. Also, the effluent was mostly composed of VFAs, which comprised 87 % of the COD content. The OLR was changed to 120 g COD d^{-1} at t=0.1 day. In response, the methane production rate increased to 34 ± 2 L d^{-1} and pH declined.

After a short transition period, the adaptive controller stabilized the effluent COD concentration at a preset level of 0.6 g COD L^{-1} and the temperature was stabilized at 38°C while pH increased to 6.7. The heating of the reactor resulted in a peak of methane production with the methane production rate reaching a maximum of 52 L CH_4 d^{-1} (Fig. 3c). The COD load was returned to 60 g COD d^{-1} at t=0.85 d. Shortly after the OLR change, the adaptive controller returned the reactor temperature to 25°C.

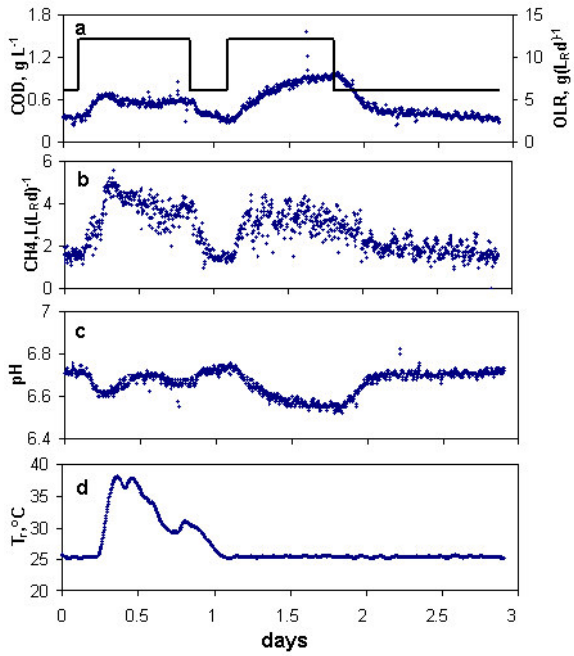

Fig. 3. Dynamics of key process parameters (a-d) and temperature (e) in a 10 L reactor during feedback control (0-1.1 day) and open-loop (1.1-3 day) experiments.

To compare reactor performance with and without temperature control, the reactor overload test was repeated without increasing the reactor temperature.

As in the previous test, at startup the reactor was operated at a temperature of 25°C and then the OLR was changed from 6 to 120 g COD d^{-1} at t= 1.1 d. As a result, the effluent COD concentration reached 1.0 g L^{-1} and pH declined to 6.5. The overload experiment had to be terminated in order to avoid reactor failure and at t=1.8 d the OLR was returned to 60 COD d^{-1}.

4. CONCLUSION

This work was aimed at studying the influence of short exposures of a mesophilic anaerobic reactor to near-thermophilic conditions. The experiments suggested that periodic exposure of mesophilic sludge to temperatures of 42-46°C is well tolerated by the mesophilic anaerobic consortium and has no long-term consequences on biodegradation rates under mesophilic conditions. Meanwhile, a significant increase of the rate of methane production was observed during the periods of increased temperature. This increase can be attributed both to increased enzymatic activity of the mesophilic methanogenic populations and increased substrate availability due to enhanced hydrolysis. However, the exposure of mesophilic sludge to high temperatures had to be limited in time so that irreversible changes of the microbial consortium are avoided.

These findings were used to develop a temperature-based reactor control strategy in which short temperature increases were used to improve the COD removal efficiency of the reactor during spikes of organic materials. The proposed strategy was successfully demonstrated in a 10L UASB reactor in which effluent COD concentration was monitored using a multi-wavelength fluorometer and reactor temperature was controlled using a model-based adaptive controller. This combination of advanced process instrumentation with a novel control strategy resulted in successful stabilization of reactor performance during organic overloads.

ACKNOWLEDGEMENT

This is NRC paper no 00000.

REFERENCES

Ahn J.-H., Forster C.F. (2002). The effect of temperature variations on the performance of mesophilic and thermophilic anaerobic filters treating a simulated papermill wastewater. *Process Biochemistry* **37**(6), 589-594.

APHA, AWWA, WEF. (1995). *Standard Methods for Examination of Water and Wastewater*, American Public Health Association/American Water Works Association/Water Environment Federation, Washington.

Bastin G., Dochain D. (1990). *On-line estimation and adaptive control of bioreactor*, Elsevier, Amsterdam.

Batstone D.J., Keller J., Angelidaki R.I., Kalyuzhnyi S.V., Pavlostathis S.G., Rozzi A.G., Sanders W.T.M., Siegrist H., Vavilin V.A. (2002). *Anaerobic Digestion Model No.1 Technical and Scientific Report No.13*, IWA Publishing, London, UK.

Hao X., Heijnen J.J., Van Loosdrecht M.C.M. (2002). Model-based evaluation of temperature and inflow variations on a partial nitrification-ANAMMOX biofilm process. *Water Research,* **36**(18), 4839-4849.

Morel E., Santamaria K., Perrier M., Guiot S.R., and Tartakovsky B. (2004). Application of multi-wavelength fluorometry for on-line monitoring of an anaerobic digestion process. *Water Research,* **38**(14-15), 3287-3296.

Morel E., Tartakovsky B., Guiot S.R., Perrier M. (2006a). Design of a multi-model observer-based estimator for anaerobic reactor monitoring. *Computers Chemical Engineering*, **31**(2), 78-85.

Morel E., Tartakovsky B., Guiot S.R., Perrier M. (2006b). On-line estimation of kinetic parameters in anaerobic digestion using observer-based estimators and multiwavelength fluorometry. *Water Science Technology,* **53**(4-5), 77-83.

Pavlostathis S.G., Giraldo-Gomez E. (1991). Kinetics of anaerobic treatment: a critical review. *Critical Review in Environmental Control,* **21**(5-6), 411-490.

Siegrist H., Vogt D., Garcia-Heras J., Gujer W., (2002). Mathematical model for meso- and thermophilic anaerobic sewage sludge digestion. *Environmental Science and Technology,* **36**(5), 1113-1123.

Song Y.-C., Kwon S.-J., Woo J.-H. (2004). Mesophilic and thermophilic temperature co-phase anaerobic digestion compared with single-stage mesophilic- and thermophilic digestion of sewage sludge. *Water Research,* **38**, 1653-1662.

Speece R.E., Kem J.A., (1970). The effect of short-term temperature variations on methane production. *Journal Water Pollution Control Federation,* **42**, 1990-1997.

Tartakovsky B., Morel E., Guiot S.R. (2005). Application of VSM-based process control to a bench-scale anaerobic digestor. *Industrial and Engineering Chemistry Research,* **44**(1), 106-113.

Tartakovsky B., Morel E., Steyer J.P., Guiot S.R. (2002). Application of a variable structure model in observation and control of an anaerobic digestor. *Biotechnology Progress*, **18**(4), 898-903.

van Lier J.B., Rintala J., Sanz Martin J.L., Lettinga G. (1990). Effect of short-term temperature increase on the performance of a mesophilic UASB reactor. *Water Science and Technology,* **22**(9), 183-190.

Visser A., Lettinga G. (1993). Effects of short-term temperature increases on the mesophilic anaerobic breakdown of sulphate containing synthetic wastewater. *Water Research,* **27**(4), 541-550.

Ward J.D., Mellichamp D.A., Doherty M.F. (2005). Novel reactor temperature and recycle flow rate policies for optimal process operation in the plantwide context. *Industrial and Engineering Chemistry Research,* **44**(17), 6729-6740.

Zeng Y., Mu S.J., Lou S.J., Tartakovsky B., Guiot S.R., Wu P. (2005). Hydraulic modeling and axial dispersion analysis of UASB reactor. *Biochemical Engineering Journal,* **25**(2), 113-123.