Maximization of Methane Production in Anaerobic Digestion Systems: an Extremum-Seeking Approach

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Abstract: Anaerobic digestion is commonly used nowadays to treat winery or brewery effluents and produce biogas. Aside the treatment efficiency, the maximization of the biogas production is of high importance. This paper presents a control law that allows the maximization of the methane outflow rate for anaerobic digestion systems characterized by two-step models. The control law employs the principle of high order sliding mode control and it is developed based on the measurements of methane outflow rate and volatile fatty acids concentration. The sliding surface is the derivative of methane outflow rate with respect to volatile fatty acids concentration and it is estimated from the measurements using a discrete time algorithm. Simulation results show that the system reaches the optimal steady state where the methane outflow rate is maximum.

Keywords: process control, sliding mode control, biogas production

INTRODUCTION

Winery and brewery effluents must undergo treatment before being discharged. Various treatment methodologies exist, each of them having its own advantages and disadvantages. Sometimes, methodologies are integrated to improve performance while minimizing drawbacks. The integration of anaerobic and aerobic treatments is an example (Chan et al, 2009, Simate et al, 2011). While anaerobic treatment is suited for high strength wastewater, allowing for bioenergy production and nutrient recovery, the aerobic treatment improves the anaerobic effluent which results in very high overall treatment efficiency. Since the biogas (the source of energy) is produced only during the anaerobic treatment, it is natural to drive the operation of the anaerobic digestion system towards maximum productivity. However, maximum productivity of an anaerobic system is generally unknown and may vary during the operation due to changes in the influent characteristics. These make extremum seeking techniques particularly suited for achieving the goal.

This paper presents an extremum seeking algorithm based on high order sliding mode control (Jamilis et al, 2018) to maximize the methane outflow rate in anaerobic digestion systems characterized by a two-step model.

PROCESS DESCRIPTION

Although anaerobic digestion comprises many biological processes, it is widely acknowledged that two-step models, characterizing the acidogenesis and methanogenesis reactions, describe the system dynamics accurately enough, at least from a control point of view:

$$as_1 \rightarrow cs_2 + x_1; \qquad ds_2 \rightarrow CH_4 + x_2 \qquad (1)$$

The reaction network (1) (Sbarciog et al, 2012) states that acidogenic bacteria x_1 grow on the organic substrate s_1 (growth rate $\mu_1(s_1)$) and produce volatile fatty acids s_2. Subsequently, the methanogenic bacteria x_2 use the volatile fatty acids as substrate for growth (growth rate $\mu_2(s_2)$) and produce methane. In an ideal continuous stirred tank reactor, operated at constant temperature, the system dynamics described by the reaction network (1) are given by the following differential equations:

$$\begin{aligned}
\dot{s}_1 &= u\left(s_{in_1} - s_1\right) - a\mu_1\left(s_1\right)x_1 \\
\dot{s}_2 &= u\left(s_{in_2} - s_2\right) + c\mu_1\left(s_1\right)x_1 - d\mu_2\left(s_2\right)x_2 \\
\dot{x}_1 &= -ux_1 + \mu_1\left(s_1\right)x_1 \\
\dot{x}_2 &= -ux_2 + \mu_2\left(s_2\right)x_2
\end{aligned} \quad (2) \qquad
\begin{aligned}
\mu_1\left(s_1\right) &= \mu_{m_1}\frac{s_1}{K_{S_1} + s_1} \\
\mu_2\left(s_2\right) &= \mu_{m_2}\frac{s_2}{K_{S_2} + s_2 + {s_2^2}/{K_{I_2}}}
\end{aligned} \quad (3)$$

where the outflow rate of methane gas reads:

$$Q\left(x_2, s_2\right) = q \cdot \mu_2\left(s_2\right) \cdot x_2 \quad (4)$$

with u - the dilution rate; s_{in_1}, s_{in_2} - the concentrations of organic substrate and of volatile fatty acids in the influent; $a, c, d > 0$ - the stoichiometric coefficients; $q > 0$ - the yield for the methane production.

CONTROL DESIGN

The purpose of the control is to drive and keep the system at the optimal steady state (characterized by maximum methane production) by measuring the methane outflow rate Q and volatile fatty acids (VFA) concentration s_2 (for which on-line sensors are available) and by manipulating the dilution rate u. The knowledge of the growth rates (structure and parameters) is not required for the design of the control law, however the stoichiometric parameters (some ratios of the parameters) are assumed to be known. The control law relies on the principles of sliding mode control, where the control goal is achieved by driving and keeping the system dynamics on the sliding surface. Since the maximization of methane production is desired, the optimal operating point must belong to the sliding surface. The control law is designed i) based on the assumption that acidogenesis proceeds much faster than methanogenesis; ii) to compensate some of the system dynamics; iii) to bring the system dynamics on the sliding surface σ.

The assumption that acidogenesis is much faster than the subsequent step (Sbarciog et al, 2018) implies that the system operates in a quasi-steady state, where the supply rate of substrate approximately equals the utilization rate of substrate: $us_{in_1} \simeq a\mu_1\left(s_1\right)x_1$. Under this assumption and employing (4), the dynamics of the VFA concentration becomes:

$$\dot{s}_2 = u\left(s_{in_2} + {c}/{a}\, s_{in_1} - s_2\right) - {d}/{q}\, Q \quad (5)$$

which depends entirely on the measured variables. The sliding surface σ is chosen as the gradient of the methane outflow rate with respect to the VFA concentration, ie. $\sigma = \frac{\partial Q}{\partial s_2}$. Notice that according to (4) the maximum methane production is given by $\frac{\partial Q}{\partial s_2} = 0$. Since the purpose is to implement a robust control law, which does not rely on the kinetics model, the sliding surface will not be computed using (4), but estimated using a discrete time algorithm as in (Lara-Cisneros et al, 2014). To this end, one considers the sampling period T_s and uses the measured values of methane outflow rate and VFA concentration at the sampling instant $t = kT_s$, $Q_k = Q(kT_s)$, $s_{2k} = s_2(kT_s)$ to estimate the sliding surface as:

$$w_k = \hat{\sigma}_{k-1} - \frac{\Delta Q_k}{\Delta s_{2k}},\ \hat{\sigma}_k = \hat{\sigma}_{k-1} - k_0 \cdot T_s \cdot sign\left(w_k \cdot \Delta s_{2k}\right) \cdot sign\left(\Delta s_{2k}\right) \quad (6)$$

where $\Delta Q_k = Q_k - Q_{k-1}$, $\Delta s_{2k} = s_{2k} - s_{2k-1}$ and k_0 is a tuning parameter such that $\left|\hat{\sigma}_k - \partial Q_k / \partial s_{2k}\right| < d$, with $d > 0$.

The higher order sliding mode controller (Jamilis et al, 2018) which drives the anaerobic digestion system to the optimal operating point characterized by maximum methane production is:

$$u = \frac{\left(d/q\, Q + u_1 + u_2\right)}{\left(s_{in_2} + c/a\, s_{in_1} - s_2\right)}, \qquad \text{with} \quad \begin{aligned} u_1 &= k_1 \left|\hat{\sigma}\right|^{1/2} sign\left(\hat{\sigma}\right) \\ \dot{u}_2 &= k_2 sign\left(\hat{\sigma}\right) \end{aligned} \quad (7)$$

where $k_1, k_2 > 0$ are tuning gains.

SIMULATION RESULTS

To assess the performance of the extremum-seeking algorithm, the system (2)-(4), the estimation (6) and the control law (7) are implemented in Matlab with the parameter values given in (Sbarciog et al, 2012). The system (2)-(4) emulates the process which provides measurements with a sampling period $T_s = 0.1$d of methane outflow rate and VFA concentration. Control parameters are set to $k_0 = 20$, $k_1 = 10$ and $k_2 = 0.01$.

Figure 1.1 shows the system response using the extremum-seeking technique (continuous line) in comparison to the switching strategy (dashed-dotted line) proposed by Sbarciog et al (2012) for some specific inlet concentrations and initial condition. The switching strategy is designed such that the optimal operating point is reached by changing the dilution rate between minimum, maximum and optimal dilution rate. It assumes that the optimal point and the corresponding dilution rate are known and it was shown that it is a good approximation of the optimal solution. For the extremum-seeking algorithm no constraints were imposed for the dilution rate and its main advantage is that only the values of the inlet concentrations and the ratios c/a and d/q are needed to bring the system to the optimal point, which is unknown.

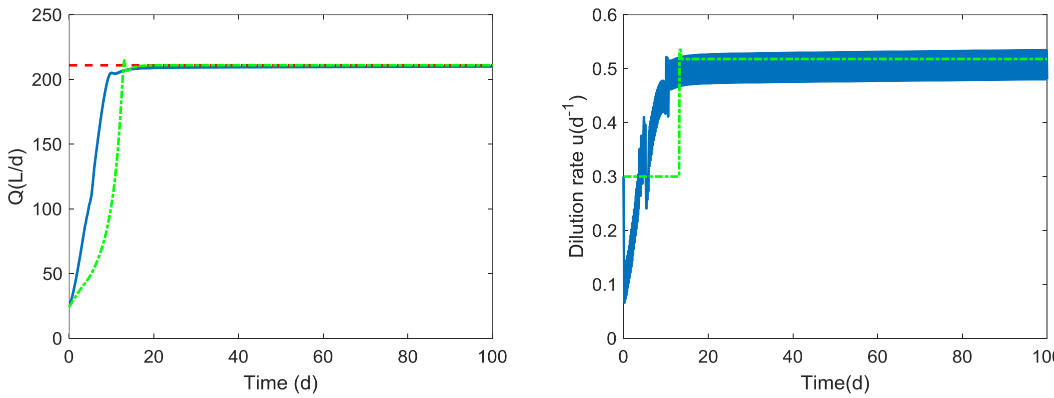

Figure 1.1 Methane outflow rate and dilution rate. Extremum seeking algorithm – continuous line, switching strategy as in (Sbarciog et al, 2012) – dashed-dotted line, optimal steady state computed analytically – dashed line

Figure 1.2 shows the robustness in the presence of measurement noise and the effectiveness of the extremum-seeking technique when the inlet concentrations vary. Both measurements, the methane outflow rate and VFA concentration are affected by noise, while the inlet concentrations change at $t = 100\,\mathrm{d}$ as: s_{in_1} from 50 to 40 g/L, s_{in_2} from 275 to 175 mmol/L. Consequently, the maximum achievable methane production changes and the extremum-seeking algorithm drives smoothly the system to the new optimal operating point.

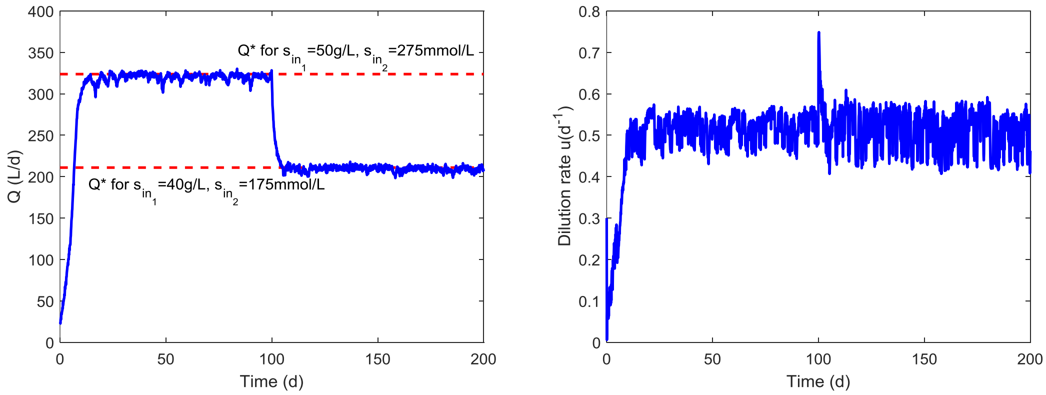

Figure 1.2 Methane outflow rate and dilution rate when measurements are affected by noise and the inlet concentrations change. Extremum seeking algorithm – continuous line, optimal steady state computed analytically – dashed line

CONCLUSIONS

The presented extremum-seeking technique is an efficient and robust approach for maximizing the methane production in an anaerobic digestion system. Its implementation is affordable as instrumentation for measuring VFA concentration and methane outflow rate is nowadays commonly available. The disadvantage of the method is that it requires the knowledge of the inlet concentrations to compute the control law, which may not be available in practice. However, this may be overcome by employing unknown input observers (Sbarciog et al, 2013).

REFERENCES

Chan Y.J., Chong, M.F., Law, C.L. & Hassell D.G. 2009 A review on anaerobic–aerobic treatment of industrial and municipal wastewater. *Chem. Eng. J.* **155**, 1-18.

Jamilis, M., Garelli, F. & De Battista, H. 2018 Growth rate maximization in fed-batch processes using high order sliding controllers and observers based on cell density measurement. *J. Proc. Control.* **68**, 23–33.

Lara-Cisneros, G., Femat, R. & Dochain, D. 2014 An extremum seeking approach via variable-structure control for fed-batch bioreactors with uncertain growth rate. *J. Proc. Control.* **24**, 663–671.

Sbarciog, M., Moreno, J.A. & Vande Wouwer A. 2012 A biogas-based switching control policy for anaerobic digestion systems. In: *Preprints of the 8th IFAC Symposium on Advanced Control of Chemical Processes*. Singapore, pp. 603-608.

Sbarciog, M., Moreno, J.A. & Vande Wouwer, A. 2013 Application of super-twisting observers to the estimation of state and unknown inputs in an anaerobic digestion system. *Water Sci. & Technol.* **69**, 414-421.

Sbarciog, M., Giovannini, G., Chamy, R. & Vande Wouwer, A. 2018 Control and estimation of anaerobic digestion processes using hydrogen and volatile fatty acids measurements. *Water Sci. & Technol.* **78**, 2027–2035.

Simate, G.S., Cluett J., Iyuke, S.E., Musapatika, E.T., Ndlovu, S., Walubita, L.F. & Alvarez A.E. 2011 The treatment of brewery wastewater for reuse: State of the art. *Desalination*. **273**, 235-247.