Estimation and control of winery wastewater treatment by anaerobic digestion

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Abstract
The anaerobic digestion technology is widely used in the treatment of winery wastewater. To ensure the treatment efficiency and to increase the production of biogas, which can be reused as a renewable energy source, a good understanding of the process and tight control are needed. This paper presents an estimation and control scheme, which can be successfully used in the operation of the anaerobic digestion process. The process is simulated by ADM1 model, the most complex and detailed model developed so far to characterize anaerobic digestion. The controller and the observer, which provides estimates of the unmeasurable variables needed in the computation of the control law, are designed based on a simplified model developed in a previous work. Since it has been shown that hydrogen concentration is an accurate and fast indicator of process stability, it was chosen as controlled variable. Aside the hydrogen concentration, the only measurement employed by the proposed structure is the volatile acids concentration. Simulation results prove the effectiveness of the proposed control structure.

Keywords
Anaerobic digestion; ADM1; estimation; control

INTRODUCTION

Anaerobic digestion (AD) is an efficient technology to treat various types of wastewater. Additionally, biogas is produced, which can be used as a renewable energy source. However the process is very complex and needs expertise to be properly operated. Aside the numerous variables and the interaction between them, the difficulty in operating these systems is also caused by the lack of measurement of key variables. Among the measurements which can be taken from an AD process, the gaseous compounds are quite common. Experimental evidence and various studies reviewed by Giovannini et al (2016) have shown that hydrogen is an accurate and fast indicator of process stability. This paper presents a control loop which controls the hydrogen produced by an AD process treating winery wastewater at imposed setpoint values. Low levels of hydrogen imply increased process stability and high biogas production. Except of the hydrogen measurement, the proposed loop employs also the measurement of volatile fatty acids for estimating the unmeasurable variables needed by the controller. Simulation results are provided, which demonstrate the effectiveness of the control structure. Note that although the control and estimation algorithms are designed based on a simplified process model, the process is emulated here by the complex ADM1 (Batstone et al, 2002).

CONTROL STRUCTURE DESIGN

The proposed control structure is illustrated in Figure 1. The controlled variable is the hydrogen concentration, while the manipulated variable is the dilution rate. Further, we briefly describe each component of the control loop.

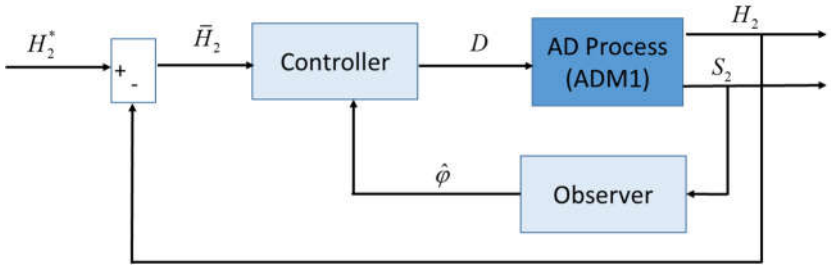

Figure 1. Layout of the control structure.

The simplified model

The model employed in the design of the control law has been developed by Giovannini et al. (2017), who built a simplified two step model of the complex ADM1 using model reduction techniques. The model implements the commonly used reaction scheme (acidogenesis and methanogenesis)

$$k_1 S_1 \xrightarrow{r_1} X_1 + k_3 S_2 + k_7 H_2 + k_5 CH_4$$
$$k_4 S_2 + k_8 H_2 \xrightarrow{r_2} X_2 + k_6 CH_4 + k_2 S_1$$

where the concentrations of organic substrate S_1, volatile fatty acids S_2, acidogenic biomass X_1, methanogenic biomass X_2, total hydrogen H_2 and total methane CH_4 are given by

$$\frac{dX_1}{dt} = \mu_1 X_1 - \alpha D X_1 \quad (1)$$

$$\frac{dX_2}{dt} = \mu_2 X_2 - \alpha D X_2 \quad (2)$$

$$\frac{dS_1}{dt} = D(S_{1in} - S_1) - k_1 \mu_1 X_1 + k_2 \mu_2 X_2 \quad (3)$$

$$\frac{dS_2}{dt} = D(S_{2in} - S_2) + k_3 \mu_1 X_1 - k_4 \mu_2 X_2 \quad (4)$$

$$\frac{dCH_4}{dt} = D(CH_{4in} - CH_4) + k_5 \mu_1 X_1 + k_6 \mu_2 X_2 \quad (5)$$

$$\frac{dH_2}{dt} = D(H_{2in} - H_2) + k_7 \mu_1 X_1 - k_8 \mu_2 X_2 \quad (6)$$

$r_1 = \mu_1 X_1$, $r_2 = \mu_2 X_2$, μ_1, μ_2 are respectively the growth functions $\left(\frac{\mu_{m1,2} S_{1,2}}{K_{S1,2} + S_{1,2}}\right)$ for the acidogenic and methanogenic biomass, D is the dilution rate (the ration between the inlet flow rate and the liquid volume), α is the biomass retention factor and $k_i, i = 1..8$ are the stoichiometric parameters. The numerical values of the model parameters are given in Table 1.

Table 1. Numerical values of model parameters.

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
α	0.5	K_{S1}	0.614 Kg/m^3	k_2	9.89e-05	k_5	6.9927
μ_{m1}	3.616 d^{-1}	K_{S2}	0.352 Kg/m^3	k_3	7.7107	k_6	3.2317
μ_{m2}	0.437 d^{-1}	k_1	10.0026	k_4	11.2983	k_7	5.11e-04
						k_8	6.06e-04

Controller design

The controller proposed initially by Dochain et al (1991) is a linearizing feedback controller, which specifically employs the process model to develop the control law. Since the structure of the model

used here is different, we briefly describe further the steps of the controller design. The main assumption is that the acidogenesis proceeds faster than the rest of the process dynamics, ie. $S_1 \ll k_1\mu_1 X_1 - k_2\mu_2 X_2$. Under this assumption, the differential equation (3) can be replaced by the algebraic equation:

$$DS_{1in} = k_1\mu_1 X_1 - k_2\mu_2 X_2 \qquad (7)$$

Using (7) in the dynamics of the controlled variable (6), leads to

$$\frac{dH_2}{dt} = D(H_{2in} - H_2) + KDS_{1in} + \theta\mu_2 X_2 \qquad (8)$$

where $K = \frac{k_7}{k_1}$ and $\theta = \frac{k_7 k_2}{k_1} - k_8$. Denoting by H_2^* the imposed reference for the hydrogen concentration and by $\bar{H}_2 = H_2^* - H_2$ the control error, a first-order linear closed loop dynamics is imposed

$$\frac{d\bar{H}_2}{dt} + C_1\bar{H}_2 = 0, \qquad C_1 > 0 \quad (9)$$

The control law and the adaptation of the parameter θ, which will bring integral action in the control loop, are respectively given by

$$D = \frac{\frac{dH_2^*}{dt} - \theta\mu_2 X_2 + C_1\left(H_2^* - H_2\right)}{KS_{1in} + H_{2in} - H_2} \qquad (10), \qquad \frac{d\theta}{dt} = -C_2\mu_2 X_2\left(H_2^* - H_2\right), \quad C_2 > 0 \quad (11)$$

Note that aside the measurement of the controlled variable H_2 the implementation of the control law (10) and of the adaptation rule (11) requires the knowledge of the reaction rate $r_2 = \mu_2 X_2$, which cannot be measured in practice. Therefore an observer is designed for estimating this unmeasurable variable.

Observer design

The observer design relies on the principles introduced by De Batista et al (2012) and uses the approach described by Sbarciog et al (2014) to estimate $r_2 = \mu_2 X_2$ from the measurement of the volatile fatty acids S_2. To this end, the assumption of fast acidogenesis is used to rewrite the dynamics of S_2 as

$$\frac{dS_2}{dt} = f\left(S_2, t\right) + \varphi\left(t\right)\cdot S_2 \qquad (12)$$

where $f\left(S_2,t\right) = D\left(S_{2in} + K_1 S_{1in} - S_2\right)$, $\varphi\left(t\right) = K_2\frac{\mu_2 X_2}{S_2}$, $K_1 = \frac{k_3}{k_1}$, $K_2 = \left(\frac{k_3 k_2}{k_1} - k_4\right)$. The proposed observer for (12) is

$$\dot{z}_1 = \left(\frac{f\left(S_2,t\right)}{S_2} + \rho z_2 + 2\rho b\left|\sigma\right|^{1/2} sign(\sigma)\right) z_1 \qquad (13)$$

$$\dot{z}_2 = a\cdot sign(\sigma) \qquad (14)$$

$$\sigma = \frac{1}{\rho}\ln\left(\frac{S_2}{z_1}\right) \qquad (15)$$

$$\hat{\varphi} = \rho\cdot z_2 \qquad (16)$$

where z_1 is the estimate of the measurement S_2 and $\hat{\varphi}(t)$ is the estimate of $\varphi(t)$. The control law and the adaptation rule become now

$$D = \frac{\frac{dH_2^*}{dt} - \theta \cdot \hat{\varphi} \cdot {S_2}/{K_2} + C_1\left(H_2^* - H_2\right)}{KS_{1in} + H_{2in} - H_2} \qquad (17), \qquad \frac{d\theta}{dt} = -C_2 \cdot \hat{\varphi} \cdot {S_2}/{K_2}\left(H_2^* - H_2\right) \qquad (18)$$

SIMULATION RESULTS & CONCUSIONS

The process (ADM1) and the estimation, control and adaptation algorithms are implemented in Matlab. A sampling time $T_S = 0.1$d is used for the simulation results. The controller parameters are $C_1 = 0.5$, $C_2 = 80$, while the observer parameters are $\rho = 1.5$, $a = 2.3$, $b = 2.5$. The performance of the proposed control structure is illustrated in Figure 2. An effective control of hydrogen concentration is obtained, in spite of modelling errors and simplifying assumptions. Their effect can be clearly seen in the estimation of the reaction rate. The steady state error in the estimation of the reaction rate does not affect the performance of the control due to the presence of integral action.

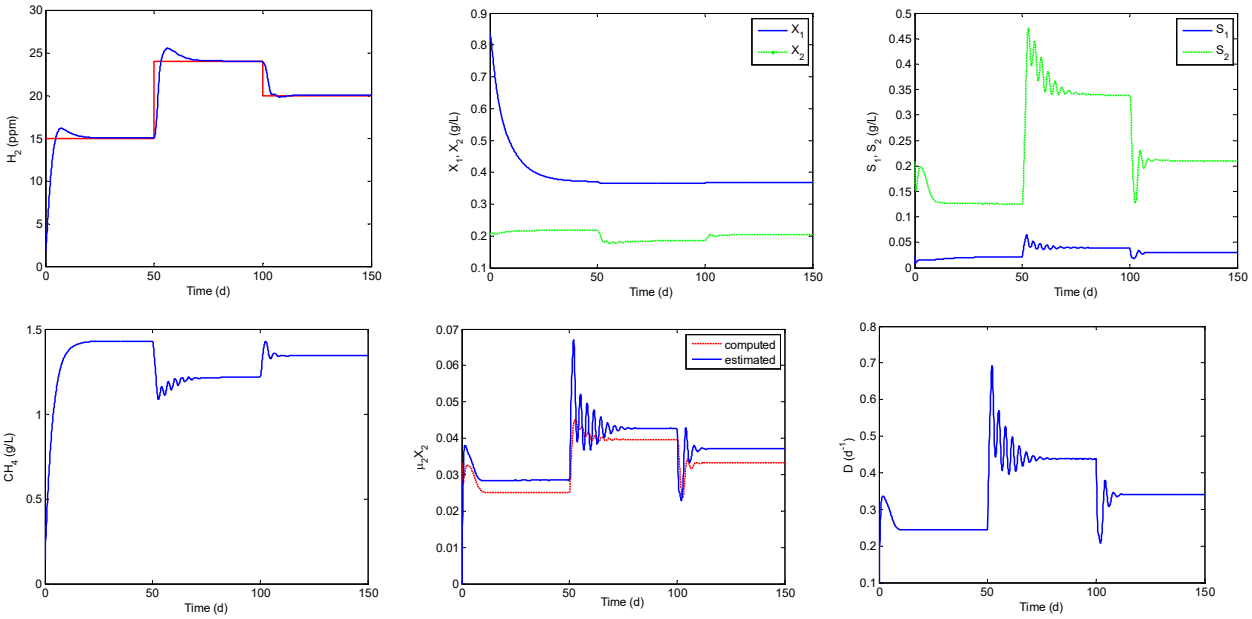

Figure 2. Controlled process: controlled variable, biomass concentrations, substrate concentration, methane concentration, reaction rate and manipulated variable.

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