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An adaptive observer for operation monitoring of anaerobic digestion wastewater treatment

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HIGHLIGHTS

- We propose an adaptive observer for wastewater treatment via anaerobic digestion.
- Adaptive observer is a support for decision and control on anaerobic digestion.
- Kinetic parameter are estimated at same time than state vector.
- The proposed scheme is tested by experimental proof-of-principle.

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ABSTRACT

The operation of anaerobic digestion (AD) has a strong dependence on reliable information about the state variables and kinetic parameters. Such a dependence can lead the AD to restrictions for the implementation of advanced monitoring and automatic control schemes; with consequent implications at operation decisions. An adaptive observer is proposed to advise on organic matter degradation via AD. The underlying idea is to provide a scheme for monitoring simultaneously both the biomass concentration and parameter related to the maximum growth rates. The proposed scheme is based on a dynamical model of two steps wastewater digester which can be written as a general cascade system. The adaptive observer is experimentally evaluated in a pilot-scale anaerobic digester, which is used for the winery wastewater treatment. As a proof-of-principle implementation, the pilot-scale digester is operated under dilution rate with (arbitrary) bounded time-variation. The results show that the proposed estimation approach can provide a reliable information towards the monitoring and full-automation of AD processes.

1. Introduction

Wastewater treatment is a very important topic for the environmental science and technology. Recently, anaerobic digestion (AD) has attracted the interest to handle wastewater treatment as a secondary step for reducing the organic matter at industrial or municipal scale. AD provides well known advantages such as a high organic removal efficiency, a low sludge production and a potential net energy benefit through the methane production. However, a widespread implementation can be limited mainly due to intrinsic difficulties in achieving an efficient operation, such as: (i) highly nonlinear dynamical behavior; (ii) very complicated bioprocess kinetics; (iii) uncertain load disturbances due to fluctuations in the feeding composition; and (iv) the lack of reliable estimations from on-line measurements of the key process variables for monitoring and controlling. Technical alternatives have been reported in regard to handle with the first three issues. Among others, the control theory has been used to design feedback controllers capable of handling the nonlinear behavior and uncertainty on the kinetic terms [1–3]. But, although spectroscopy-based instrumentation schemes have been also explored as alternative for online measurements for COD, TOC and VFA [4], few theoretical frameworks can be found in regards to reliable schemes for advising AD monitoring and control. Such an issue is particularly relevant as we are interested in including biomass and kinetic data towards the AD operation decision.

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This manuscript is focused on problem (iv) and concerns the advanced monitoring of organic matter degradation via AD. In fact, the state and parameter estimation is a very important research issue in AD processes because of the biotechnological importance of having reliable information about unmeasured state variables such as biomass concentrations and the unknown kinetic terms. Although the idea of estimating parameters at same time of reconstructing states is a mature issue [5], this contribution is focused on exploiting the cascade structure of affine nonlinear systems to propose an adaptive observer. Actually, neither the classical assumption of linear structure on the parameters nor projection algorithms are unnecessary as the cascade structure is exploited. The proposed approach allows one to provide reconstructed values for biomass concentration along time together the estimation of kinetic parameter. Previous estimation schemes have been mainly proposed to attend state estimation/reconstruction via measurements under specific situations (e.g., robustness in face to uncertainties at the initial conditions, the process kinetics, or the input concentration and parameter). Examples of these contributions are in order: (i) classical approaches based on adaptive schemes for the state estimation [5], (ii) asymptotic [6] and interval observers [7] and recently (iii) fuzzy observers [8] and adaptive high gain observers [9]. A very comprehensive survey about this topic was presented by Dochain in 2003 [10], where a wide motivation for designing new estimation schemes is discussed to solve current challenges such as the timely state and parameter estimation for AD processes. In our contribution, a state and parameter estimation approach is proposed to estimate simultaneously the states related to the concentrations of acidogenic and methanogenic biomass, organic substrate and volatile fatty acids as well as the parameters related to the maximum microorganisms growth rates. The proposed approach provides improvement in the sense that its structure is flexible and can be adjusted to distinct AD process (as winery, tequila, or others fermentative). Thus, the estimation scheme can be applied to AD whose model is a cascade system [11,12]. The proposed scheme lies on the theory of adaptive observer and provides estimated values for biomass concentration and kinetic parameters. Flexibility of the proposed observer is shown by defining auxiliary variables for the kinetic activity. As a proof-of-principle, an experimental set-up is used to show the performance of the proposed scheme.

The manuscript is organized as follows. The AD model is briefly described in the Section 2. The Adaptive observer is designed at the Section 3, where assumptions are shown are main results are demonstrated. Then, the experimental setup is discussed and implementation is performed. Finally, Section 4 includes concluding remarks.

2. Model description

Bernard et al. [12] proposed a mathematical model that describes the dynamics of the organic matter degradation via a two-stages continuous AD process. Since such a model has allowed one the control synthesis [1–3], the model is a suitable one to design monitoring strategies based on the adaptive observers towards the operation decision (as, for example, tolerance margin in load disturbances or modifications of set-points).

The model includes two stages: the acidogenesis and the methanogenesis. In the first stage, the acidogenic bacteria ferment the organic compounds into volatile fatty acids (VFA) and carbon dioxide (CO_2), while in the second stage, methane (CH_4) and CO_2 are obtained from VFA through the action of methanogenic microorganisms. Here, a reduced version of the model by Bernard et al. becomes:

$$\begin{aligned}\dot{X}_1 &= (\mu_1(S_1) - \alpha D)X_1\\ \dot{X}_2 &= (\mu_2(S_2) - \alpha D)X_2\\ \dot{S}_1 &= (S_{1,in} - S_1)D - k_1\mu_1(S_1)X_1\\ \dot{S}_2 &= (S_{2,in} - S_2)D + k_2\mu_1(S_1)X_1 - k_3\mu_2(S_2)X_2\end{aligned} \tag{1}$$

where X_1, X_2, S_1 and S_2 denote, the concentrations of acidogenic bacteria (g/L), methanogenic microorganisms (g/L), organic substrate (expressed as chemical oxygen demand (COD, g/L)), and VFA (mmol/L), respectively. The subscript *in* stands for the concentration of each component in the feeding stream. The dilution rate, D (h^{-1}), is defined as the ratio between the inlet flow rate, Q (L/h), over the reaction (digestion) volume, V (L). k_1, k_2 and k_3 are constant yield coefficients. The hydrodynamic regime parameter α is introduced to include different dynamical behavior for distinct continuous bioreactor configurations. For instance, if $\alpha = 1$ then the model (1) describes the dynamics of the continuous stirred tank bioreactor (CSTB) whereas the batch configuration can de derived for $\alpha = 0$. Thus, the model (1) can approach different bioreactor configurations by setting a fixed value at the interval $0 < \alpha < 1$. Finally, the biomass growth rates for acidogenic and methanogenic microorganisms (namely X_1 and X_2, respectively) are assumed to be described by the Monod and Haldane kinetics, which mean that the acidogenesis is governed by saturation whereas methanogenesis is inhibited by substrate; i.e.,

$$\mu_1(S_1) = \frac{\mu_{1,max}S_1}{S_1 + K_{S1}}, \quad \mu_2(S_2) = \frac{\mu_{2,max}S_2}{S_2 + K_{S2} + (S_2/K_{I2})^2} \tag{2}$$

where real scalars $\mu_{1,max}$ (h^{-1}), K_{S1} (g/L), $\mu_{2,max}$ (h^{-1}), K_{S2} and K_{I2} (mmol/L), respectively denote the maximum value for the acidogenic growth rate, the half-saturation constant for acidogenesis, the maximum value for methanogenic growth rate, the half-saturation constant, and the inhibition constant.

3. Adaptive observer for anaerobic digester

In this section, the assumptions and main result on the adaptive observer are discussed. The assumptions are general for AD wastewater treatment but needed for mathematical formalism in the sense of ensuring the global convergence of the adaptive observer, the persistent excitation of the AD process by inputs, and both boundedness and uniqueness of the solutions for model (1). Complementary, the theoretical framework of the adaptive observer requires the system is written in cascade form and the observability be ensured to derive main result. In this manner, the adaptive observer is capable of providing an estimate value of state and parameters while ensuring exponential convergence.

3.1. Adaptive observer formulation

Let us suppose the vector field of the plant model has structure such that it can be written as $i = 1, 2, 3, \ldots p$ cascade subsystems; each one with the following state affine form:

$$\Sigma_i : \begin{cases} \dot{\mathbf{z}}_i = \mathbf{A}_i(y, u, \bar{\mathbf{z}}_{l-1}, \bar{\theta}_{l-1})\mathbf{z}_i + \beta_i(y, u, \bar{\mathbf{z}}_{l-1}, \bar{\theta}_{l-1}) \\ \qquad + \varphi_i(y, u, \bar{\mathbf{z}}_{l-1}, \bar{\theta}_{l-1})\theta_i + \mathbf{B}_p g_i(y, u, \mathbf{z}_i, \theta_i), \\ y_i = \mathbf{C}_i\mathbf{z}_i \end{cases} \tag{3}$$

where $\mathbf{z}_i \in R^{n_i}, \bar{\theta}_l = [\theta_1, \ldots, \theta_i], \theta_i \in R^{q_i}$, $u \in R^l, y_i \in R$. $\mathbf{A}_i, \beta_i, \varphi_i$, $\mathbf{B}_i$ and $\mathbf{C}_i$ are matrices of appropriate dimensions, for $1 \leqslant i \leqslant p$. It is important to remark that $z_0 = \theta_0 = 0$. Furthermore, n_i, q_i and l are, respectively, the dimension of the state space, parameter space, and control space for the i-th subsystem, with $n = \sum_{i=1}^{p} n_i$ and $q = \sum_{i=1}^{p} q_i$, where n and q represent the whole state and parameter