**Memorias del XVI Congreso Latinoamericano
de Control Automático, CLCA 2014
Octubre 14-17, 2014. Cancún, Quintana Roo, México**

Passive control of a Two-stages Anaerobic Digestion Process

Victor Alcaraz-Gonzalez*. Denis Dochain **
Victor Gonzalez-Alvarez *

** Department of Chemical Engineering, University of Guadalajara-CUCEI.
Blvd. M. García Barragán 1451, C.P.44430. Guadalajara, Jalisco, México (Tel: +52-331378-5900 ext 27589;
e-mail: victor.alcaraz@cucei.udg.mx, victor.ga@redudg.udg.mx).
**ICTEAM, Université Catholique de Louvain, Bâtiment Euler, Avenue Georges Lemaître 4-6, B-1348,
Louvain-la-Neuve, Belgium (e-mail: Denis.Dochain@uclouvain.be)*

Abstract: A nonlinear passive control approach is proposed for the steady state regulation of a two-stages anaerobic digestion process for the treatment of tequila vinasses. The model consists of two interconnected continuous bioreactors for the acidogenic phase and methanogenic phase respectively. Dilution rates, one for each bioreactor, are the manipulated variables. A classical choice of the Hamiltonian as the sum of square errors around the steady state shows that the conservation matrix and the dissipation matrix are a function only of the reaction terms and yield coefficients. Simulation results show robustness against set-point changes and input perturbations.

Keywords: Anaerobic Digestion, Two-stages, Wastewater Treatment, Passive Control, Port-Hamiltonian Systems

1. INTRODUCTION

Anaerobic digestion (AD) is currently one the mostly used process for the treatment of wastewater with high organic load while it produces, at the same time, biogas that may be used as valuable fuel. However, this process exhibits a highly nonlinear behaviour as well as instability caused by inhibition by substrate (Bernard *et al*., 2001). As a consequence, last three decades have seen an active research work on different process configurations, modelling and several control approaches in order to improve its efficiency and stability conditions. Several models for one-stage processes have been presented with the aim of monitoring and control AD processes (e.g., Moletta *et al*., 1985; Guiot, 1990; Bernard *et al*., 2001; Batstone *et al*., 2002). However, some other authors (e.g., Ghosh and Klass, 1982) have proposed the physical separation of AD in two stages based on pH selectivity. This configuration has been evaluated for the treatment of different kinds of wastewaters (Ke *et al*., 2005) showing, in general, that two-stage AD process increases growth rates, consumes higher organic loads, uses low start-up times, generates high-purity biogas and improves process stability (Azbar and Speece, 2001; Demirel and Yenigun, 2002; Ke *et al*., 2005)

On the other hand, in our knowledge, only a few works have dealt with the control of two-stages AD processes (Aguilar-Garnica *et al*., 2009). Recently, Campos-Rodríguez *et al*., (2013) presented a cascade control for the regulation of Chemical Oxygen Demand (COD) and Volatile Fatty Acids (VFA), on the same process studied in this paper. Even when this approach performed very well, it is a multi-loop approach rather than a true multivariable approach. Unlike other successful control approaches like adaptive, linearizing etc., in which the control is only focused on one state variable or even on a subset of them, passive control allows the stabilization of the whole state (Hill and Moylan, 1976; Ortega *et al*., 2000). Most of literature on passive control focuses on electro-mechanical systems. However, in recent years some works with direct application in the chemical engineering domain have been also developed. For instance, Favache and Dochain (2009) and Favache *et al*., (2011) presented the design of a power-shaping control for reaction systems, namely in a Non isothermal Continuous Stirred Tank Reactor (CSTR) whose dynamics was formulated in the Brayton-Moser form, while Hoang *et al*., (2011) presented a similar study case, the CSTR, with a thermodynamical pseudo-Hamiltonian formulation. In these works, where thermodynamics properties are considered, variables like total energy or entropy may be used as Lyapunov function for control purposes. However, in the cases of isothermal CSTR or cases of dynamical systems where only mass balances are considered, fever works have been developed. The reason of this may be the fact that in these last cases, stability features directly related with an easily identifiable physic property or variable are not enough obvious, and need a more detailed dynamic formulation work. Nevertheless, this study flied in passive control, and particularly in continuous bioreactors, has gained interest recently. For instance, Sira-Ramirez, (1998) presented a general canonical form for feedback passivity of nonlinear systems and showed bioreactor controller design as example. Similarly, using a single-substrate, single-biomass fermenter as working model, Fossas *et al*., (2004) and Johnsen *et al*., (2008) have developed some nonlinear control approaches in terms of Port-Hamiltonian systems. Dörfler *et al*., (2009) summarized these passivity-based control approaches for continuous fermenters and other interconnected systems.

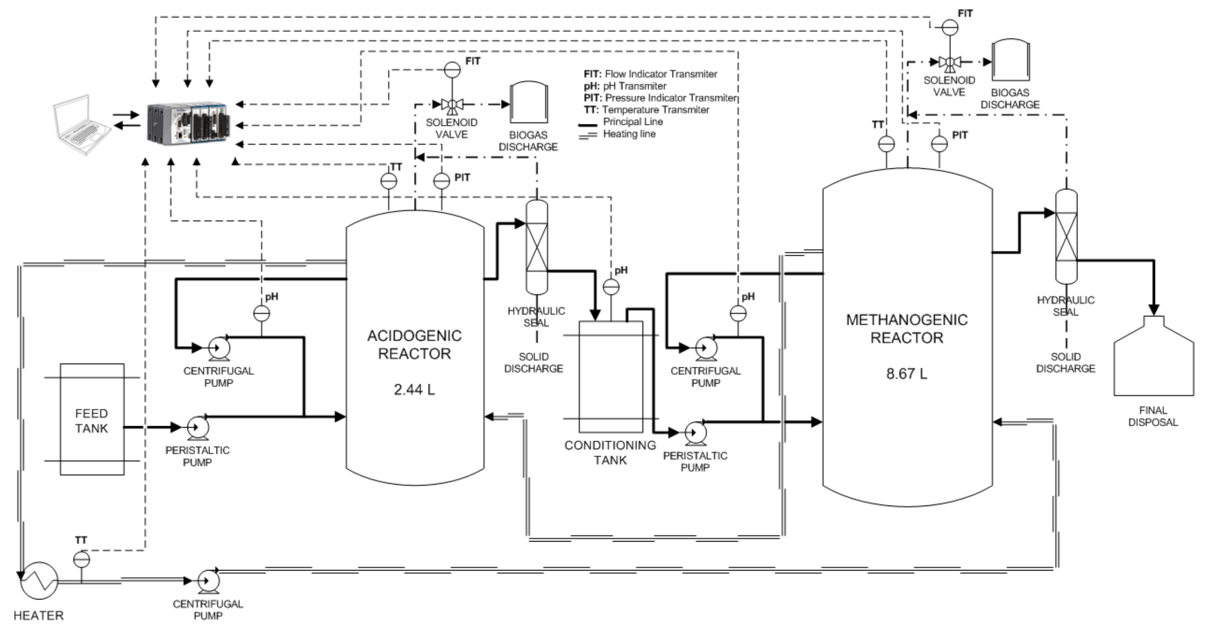

Fig. 1. Flow diagram and instrumentation of the two-stage AD system applied for the treatment of tequila vinasses.

Thus, based on the work of Dörfler *et al*., (2009), and some of the references cited in that work, we propose in this paper a passive control approach for the regulation of the two-stages anaerobic digestion processes. Simulation results using a validated model for the treatment of agricultural wastewater show a complete and promising stabilization of this kind of process with the most desired features like robustness against both, process inputs perturbations and step changes on the set point.

The paper is organized as follows. In Section 2, the actual two-stages AD process in which this work is based is presented. The model used for describing the dynamical behaviour of this process is depicted also in this section. Based on this model, the passive control approach proposed in this paper is developed in Section 3. Then, numerical simulations results are shown and discussed in Section 4 before some conclusions are given in Section 5.

2. TWO STAGES ANAEROBIC DIGESTION SYSTEM

In this paper we consider the two-stages AD system showed in Fig.1. In this system, the classical (single-stage) AD process is split in two stages: Acidogenic phase and Methanogenic phase.

In the first phase, acidogenic bacteria degrade the organic matter composed mainly by large chain compounds into CO_2, H_2 and VFA. Then, in the second phase, acetogenic bacteria degrade VFA into acetic acid while methanogenic bacteria convert acid acetic into methane. A simple model which describes in an easy manner the two-stage AD processes in order to promote their simple application for control purposes was developed and validated for the treatment of tequila vinasses by Robles-Rodríguez *et al*., (2013). This model is described by the following differential equations:

Acidogenic Reactor

$$\begin{aligned}\dot{x}_1 &= \mu_1(x_2)x_1 - \alpha_1 D_1 x_1\\ \dot{x}_2 &= \left(S_1^{in} - x_2\right)D_1 - k_1\mu_1(x_2)x_1\\ \dot{x}_3 &= \left(S_2^{in} - x_3\right)D_1 + k_2\mu_1(x_2)x_1\end{aligned} \tag{1}$$

Methanogenic Reactor

$$\begin{aligned}\dot{x}_4 &= \mu_2(x_6)x_4 - \alpha_2 D_2 x_4\\ \dot{x}_5 &= \mu_3(x_7)x_5 - \alpha_2 D_2 x_5\\ \dot{x}_6 &= (x_2 - x_6)D_2 - k_3\mu_2(x_6)x_4\\ \dot{x}_7 &= (x_3 - x_7)D_2 + k_5\mu_2(x_6)x_4 - k_4\mu_3(x_7)x_5\end{aligned} \tag{2}$$

with

$$\mu_1(x_2) = \frac{\mu_{1\max}x_2}{K_{S1} + x_2}, \tag{3}$$

$$\mu_2(x_6) = \frac{\mu_{2\max}x_6}{K_{S2} + x_6} \tag{4}$$

$$\mu_3(x_7) = \frac{\mu_{3\max}x_7}{K_{S3} + x_7 + (x_7/K_I)^2} \tag{5}$$

where x_1, x_4 (g/l) represent acidogenic biomass, and x_5 (g/l) represents the methanogenic biomass. x_2, x_6 (g/l) are the Chemical Oxygen Demand (COD) while x_3, x_7 (mmol/l) are the VFA concentrations in the acidogenic and methanogenic bioreactor respectively. The process inputs are represented by S_1^{in} (input COD) and S_2^{in} (input VFA). The dilution rates at each bioreactor are represented respectively by D_1, and D_2 (d^{-1}). k_{1-5} are the yield coefficients. α_1, and α_2 represent the fraction of biomass that is not attached to the support, and thus, leaves the bioreactor because of the dilution effect (Bernard *et al.*, 2001). The maximum specific growth rate for each microbial population is represented by $\mu_{1\max}$, $\mu_{2\max}$ and $\mu_{3\max}$. K_{S1}, K_{S2} and K_{S3} are the respective substrate affinity constants, while K_I is the substrate inhibition constant associated with the methanogenic bacteria growth. Model parameter values can be found in (Robles-Rodríguez *et al.* 2013) and are shown in Table 1.

Notice however that in (Robles-Rodríguez *et al.* 2013) only ratios of some yield coefficients are reported as k_2/k_1=3.5 $(mol\ VFA/Kg\ COD)$ and k_5/k_3=0.9 $(mol\ VFA/Kg\ COD)$ while k_4 is no reported. Then, in order to cover this lack of information, k_1, k_5 and k_4 were taken from a similar model (Bernard *et al.*, 2001) that was validated for the treatment of red wine vinasses which have chemical and phiysico-chemical properties very similar to tequila vinasses.

3. PASSIVE CONTROL APPROACH

The model (1)-(2) may be rewritten in the form of a Port-Hamiltonian system usually described as:

$$\dot{x} = Q(x)\nabla H(x) + G(x)u \tag{6}$$

where $x(t) \in \Re^n$ is the state vector, and $u(t) \in \Re^p$ represents the vector of systems inputs which affect the dynamic of the system through the matrix $G(x) \in \Re^{n\times p}$ and depicts the interconnection of the system with the environment. $H(x)$ is a continuously differentiable, scalar function called the *Hamiltonian*. $Q(x) \in \Re^{n\times n}$ is called the *structure matrix* given by $Q(x) = J(x) - R(x)$ where, $J(x) \in \Re^{n\times n}$ is explicitly called as the *interconnection* matrix, in the sense of the internal mass-conservation principle given by interactions between sate variables, while $R(x) \in \Re^{n\times n}$ is called the *dissipation* or *damping* matrix which complements the mass balance. In order to ensure stability, $Q(x) + Q(x)^T$ should be negative definite or at least semi-definite negative. In addition $H(x)$, should be lower bounded, which is usually achieved by taking the classical closed-loop desired Hamiltonian $H_d = \frac{1}{2}(x - x^*)^T(x - x^*)$, where the superindex "*" represents the setpoint. Thus, according with (6), the preliminary closed loop of (1)-(2) takes the Port–Hamiltonian form (7). Notice that the interconnection matrix $G(x)$ is partially a function of the perturbations given by the process inputs, but at the same time it is a function of the flow inputs and outputs between the acidogenic bioreactor and the methanogenic bioreactor. In this sense, $G(x)$ represents the interconnection of these two subsystems between them and with the environment as well. On the other hand, the structure matrix $Q(x)$ is a function only of the reaction terms and yield coefficients. Thus, unlike electromechanical systems in which the (internal) interconnection and the dissipation are relatively easily identifiable, this is not the case in (bio)chemical systems in which these features are implicit in the same reaction terms.

$$\dot{x} = \underbrace{\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -k_1\mu_1 & -\left(\frac{\mu_1}{\alpha_1}\right) & 0 & 0 & 0 & 0 & 0 \\ k_2\mu_1 & 0 & -\left(\frac{\mu_1}{\alpha_1}\right) & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -k_3\mu_2 & 0 & -\left(\frac{\mu_2}{\alpha_2}\right) & 0 \\ 0 & 0 & 0 & p(x) & -k_4\mu_3 & 0 & -\left(\frac{\mu_3}{\alpha_2}\right) \end{bmatrix}}_{Q(x)} \underbrace{\begin{bmatrix} x_1 - x_1^* \\ x_2 - x_2^* \\ x_3 - x_3^* \\ x_4 - x_4^* \\ x_5 - x_5^* \\ x_6 - x_6^* \\ x_7 - x_7^* \end{bmatrix}}_{\nabla H(x)} + \underbrace{\begin{bmatrix} -\alpha_1 x_1 & 0 \\ (S_1^{in} - x_2) & 0 \\ (S_2^{in} - x_3) & 0 \\ 0 & -\alpha_2 x_4 \\ 0 & -a_2 x_5 \\ 0 & (x_2 - x_6) \\ 0 & (x_3 - x_7) \end{bmatrix}}_{G(x)} \underbrace{\begin{bmatrix} \nu_1(x) \\ \nu_2(x) \end{bmatrix}}_{\nu(x)} \tag{7}$$

with

$$p(x) \triangleq \frac{k_5\mu_2\left(x_4 - (\mu_3/\mu_2)x_4^*\right)}{x_4 - x_4^*} \tag{8}$$

Thus, according with Dörfler *et al.,* (2009), we propose the function $\nu(x) = -\kappa y_p$ with $\kappa = K_{p1}/x_1^2\ 0;\ 0\ K_{p2}/x_7^2$ that provides the closed system with additional damping injection control, where $K_{p1}, K_{p2} > 0$ are the controller gains. In this paper, these gains were taken as $K_{p1} = K_{p2} = 5$. Now, if the aforementioned conditions for $Q(x) + Q(x)^T$ and $H(x)$ about stability are satisfied, then, according with Hill and Moylan, (1976), the output given by $y_p = G(x)^T \nabla H(x)$ can be used to achieve asymptotic stability of the system by feedback. In our case, the passive output belonging to the Hamiltonian H_d (x) is given by equations (9). Thus the control input takes the form $\beta(x) = \mu + \nu(x)$ whit $\mu = [\mu_1\ \ \mu_3]^T$ and the closed loop takes the form $\dot{x} = \bar{Q}(x)(x - x^*)$ where the same stability conditions must be satisfied for $\bar{Q}(x) + \bar{Q}^T(x)$.

$$y_p = G(x)^T \nabla H(x)$$

$$y_p = G(x)^T \nabla H(x) = \begin{bmatrix} -\alpha_1 x_1 (x_1 - x_1^*) \\ -\alpha_2 x_4 (x_4 - x_4^*) - \alpha_2 x_5 (x_5 - x_5^*) \end{bmatrix} + \begin{bmatrix} (S_1^{in} - x_2)(x_2 - x_2^*) \\ (x_2 - x_6)(x_6 - x_6^*) \end{bmatrix} + \begin{bmatrix} (S_2^{in} - x_3)(x_3 - x_3^*) \\ (x_3 - x_7)(x_7 - x_7^*) \end{bmatrix} \tag{9}$$

Table 1. Model Parameters

Parameter	Value	Units
$\mu_{1\max}$	0.27	(d^{-1})
$\mu_{2\max}$	0.5	(d^{-1})
$\mu_{3\max}$	0.29	(d^{-1})
K_{S1}	24	$(Kg\ COD/m^3)$
K_{S2}	3.5	$(Kg\ COD/m^3)$
K_{S3}	16	$(mol\ VFA/m^3)$
K_I	27	$(mol\ VFA/m^3)^{1/2}$
α_1	0.13	*dimensionless*
α_2	0.38	*dimensionless*
k_2/k_1	3.5	$(mol\ VFA/Kg\ COD)$
k_5/k_3	0.9	$(mol\ VFA/Kg\ COD)$
k_1	42.14	$(Kg\ COD/Kg\ x_1)$
k_4	268	$(mol VFA/Kg x_5)$
k_5	116.5	$(mol VFA/Kg x_4)$

4. RESULTS AND DISCUSSION

Process inputs induced as perturbations in the system are shown in Fig. 2. In order to add realistic conditions as much as possible, process inputs were feed to the model with small fluctuations around their nominal values. In fact this is a normal situation in wastewater treatment were concentrations in the input streams varies according with human activity or seasonal conditions.

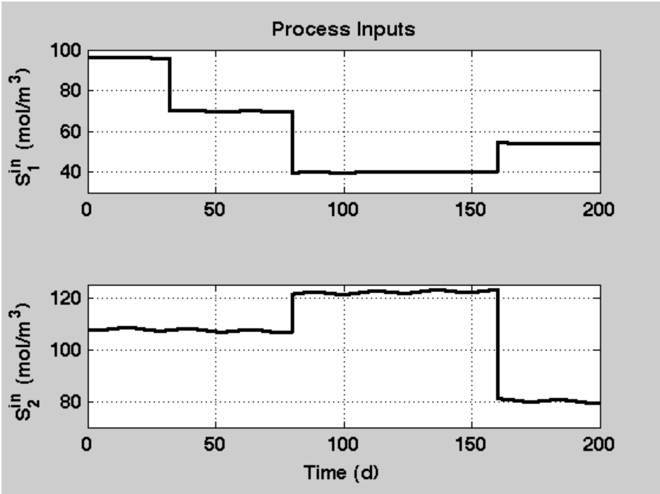

Fig. 2. Process inputs: COD (S_1^{in}) and VFA (S_2^{in}).

The dynamical behavior of dilution rates at each bioreactor that were used as control inputs are shown in Fig. 3. Note that D_1 exhibits temporal saturation at times 30 d, 80 d and 160 d, when perturbations in process inputs (see Fig. 2) take place. This can be dangerous because if this situation lasts a long time, the washout phenomena (total loss of biomass) may occur and the process may collapse. In practice, an anti-windup passive approach could be implemented in such a case, but it was not still investigated in this work. However, in the current study case it was not necessary because this situation was quickly reverted and D_1 returned to normal operational values in a relatively short time. This was not the case with D_2, which did not reach saturation values, but showed small overshoots at the same times than D_1. However, in the same manner than D_1, the normal operational conditions were recovered in a relatively short time.

Figs. 4-6 shows the stabilization of the main system state variables around different set points. These set points where calculated by fixing a unique set point on both the COD in the acidogenic bioreactor and the VFA concentration in the methanogenic bioreactor. The set-points for the rest of state variables were calculated accordingly and as a function of sudden changes induced on the process inputs S_1^{in} and S_2^{in}. Regulation on COD is acceptable in both bioreactors despite some overshoots given, once again, by the input perturbations. A similar response was observed in biomass concentrations. Notice that in this case, the control law is not only faced to process inputs perturbations but to step changes in the set-point. Despite this situation, the regulation of these variables was acceptable with a reasonable convergence rate.

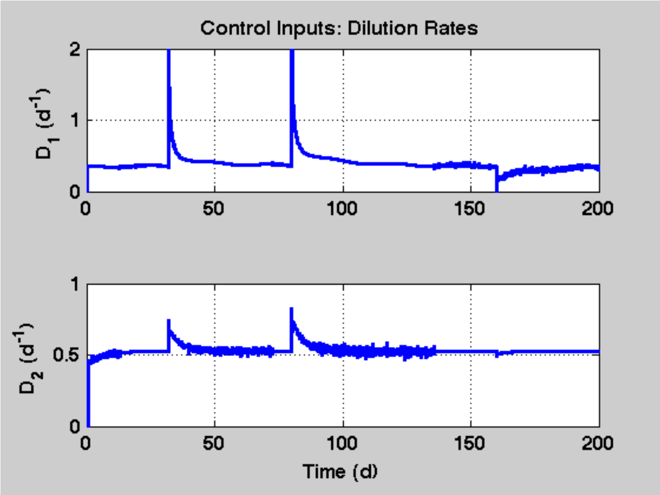

Fig. 3. Control inputs D_1 (dilution rate for the first stage) and D_2 (dilution rate for the second stage).

The regulation on VFA, the most critical state variable on AD, showed a dynamic behavior almost exact around their respective steady states. Once again, the control law was faced to perturbations in process inputs as well as sudden step changes in the set-point in the case of the acidogenic bioreactor.

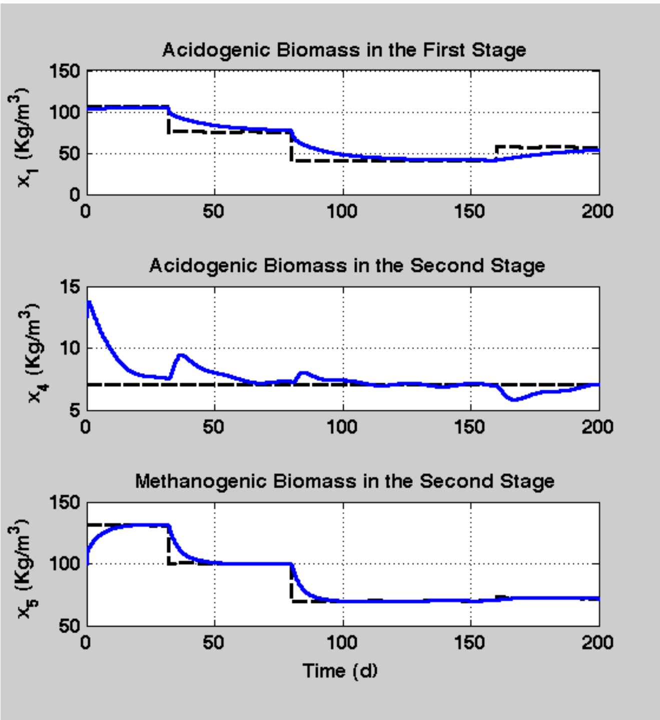

Fig. 4. Dynamical behavior of the biomass concentration in the system (continuous line) with respect to the steady state, which was set as set-point (dashed line).

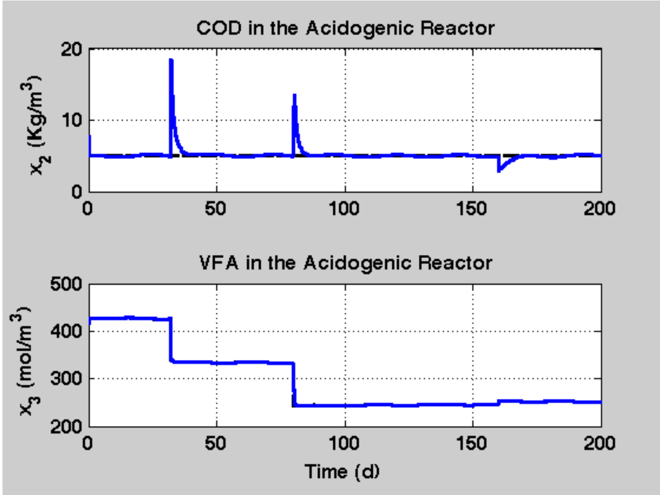

Fig. 5. Dynamical behavior of COD and VFA in the acidogenic bioreactor (continuous line) with respect to the steady state, which was set as set-point (dashed line).

However, even when these excellent results are very encouraging in the control of wastewater treatment plants, it is still necessary to improve some theoretical and practical aspects. For instance, in this paper it was supposed that biomass could be measured, which is very difficult and not realistic in the field of AD wastewater treatment. Instead of that, it is more common to use state observers for estimating such state variables. We are working on the implementation of these estimation approaches as future work. On the other hand, it is still pending to prove the negative definiteness or semi-definiteness of the closed-loop structure matrix.

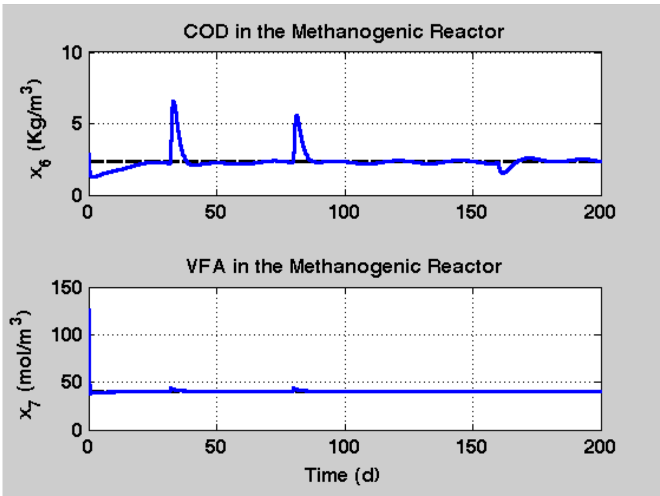

Fig. 6. Dynamical behavior of COD and VFA in the mathanogenic bioreactor (continuous line) with respect to the steady state, which was set as set-point (dashed line).

5. CONCLUSIONS

A passive control approach was applied to a two-stages AD process in the presence of both fluctuating process inputs and sudden process inputs steps showing acceptable performance and robustness features in face of this kind of perturbations. These results show the potential of passive control as a useful tool for controlling the whole state in mass balance models in general and for applying it successfully in biological bioreactors as AD process.

ACKNOWLEDGEMENT

This work was partially supported by the projects: BITA (PIRSES-GA-2011-295170) and CB-2008-01/101971.

REFERENCES

Aguilar-Garnica, E., Dochain, D., Alcaraz-González, V., and González-Álvarez, V. (2009). A multivariable control scheme in a two-stage anaerobic digestion system described by partial differential equations. *Journal of Process Control*, 19, 1324-1332.

Alcaraz-González, V., Fregoso-Sánchez, F.A., Méndez-Acosta, H.O., and González-Álvarez, V. (2013). Robust Regulation of Alkalinity in Highly Uncertain Continuous Anaerobic Digestion Processes. *CLEAN – Soil, Air, Water*., 41 (12), 1157- 1164.

Azbar, N., and Speece, R. (2001). Two-Phase, Two-stage, and single-stage anaerobic process comparison. *Environ. Eng*, 127, 240-248.

Batstone, D., Keller, J., Angelidaki, I., Kalyuzhnyl, S., Pavlostathis, S., Rozzi, A., Sanders, W., Slegrist, H., and Vavilin, V. (2002). The IWA Anaerobic Digestion Model No. 1 (ADM1). *Wat. Sci. Tech*., 45 (10), 65-73.

Bernard, O., Hadj-Sadok, Z., Dochain, D., Genovesi, T., and Steyer, J.P. (2001). Dynamical Model development and parameter identification of an anaerobic wastewater treatment process. *Biotech. Bioeng.,* 75, 424-438.

Demirel, B., and Yenigün, O. (2002). Two-phase anaerobic digestion processes: a review. *Chem Technol. Biotechnol*., 77, 743-755.

Campos-Rodríguez, A., García-Sandoval, J.P., Méndez-Acosta, H.O., and González-Álvarez, V. (2013). VFA and COD regulation in a two-stage anaerobic digester used in the treatment of tequila vinasses. *Proceedings of the 6th International Scientific Conference on Physics and Control*, San Luis Potosí, México, 6 pages in CD-ROM.

Dörfler, F., Johensen, J.K., and Allgöwer, F. (2009). An introduction to interconnection and damping assignment passivity-based control in process engineering. *Journal of Process Control*, 19, 1413-1426.

Favache, A., & Dochain, D. (2010). Power-shaping control of reaction systems: The CSTR case. *Automatica*, 46(11), 1877-1883.

Favache, A., Dochain, D., Winkinc. J.J. (2011). Power-shaping control: Writing the system dynamics into the Brayton–Moser form. *Systems & Control Letters,* 60, 618–624.

Fossas, E., Ros, R., and Sira-Ramírez, H. (2004). Passivity-based control of a bioreactor system, *Journal of Mathematical Chemistry*. 36 (4), 347–360.

Ghosh, S., Klass, D. (1982). Two phase anaerobic digestion. US Patent , 4318993.

Guiot, S. (1990). Modelling of the upflow anaerobic sludge bed-filter system: A case with hysteresis. *Water Res*., 25, 251-262.

Hill, D., Moylan, P. (1976). The stability of nonlinear dissipative systems, *IEEE Transactions on Automatic Control*, 21, 708–711.

Hoang, H., Couenne, F., Jallut, C., & Le Gorrec, Y. (2011). The port Hamiltonian approach to modeling and control of Continuous Stirred Tank Reactors. *Journal of Process Control*, 21(10), 1449-1458.

Ke, S., Shi, Z., and Fang, H. (2005). Applications of two-phase anaerobic degradation in industrial wastewater treatment. *Int. J. Environment and Pollution*, 23, 65-80.

Méndez-Acosta, H.O., Palacios-Ruiz, B., Alcaraz-González, V., González-Álvarez, V., and Garcia-Sandoval, J.P. (2010). A Robust Control Scheme to improve the Stability of Anaerobic Digestion Processes. *Journal of Process Control*, 20, 375–383.

Méndez-Acosta, H.O García-Sandoval, J.P. González-Álvarez, V., Alcaraz-González, V., and Jáuregui-Jáuregui, J.A. (2011). Regulation of the organic pollution level in anaerobic digesters by using off-line COD measurements. *Bioresource Technology*, 102, 7666-7672.

Moletta, R., Verrier, D., and Albagnac, G. (1985). Dynamic modelling of anaerobic digestion. *Water Res*., 20, 427-434.

Ortega, R., Astolfi, A., Bastin, G., and Rodríguez, H. (2000). Stabilization of Food-Chain Systems Using a Port-Controlled Hamiltonian Description. *Proceedings of the American Control Conference*, Chicago, USA, pp. 2245- 2249.

Johnsen, J. Dörfler, F. and Allgöwer, F. (2008). L2-gain of Port-Hamiltonian systems and application to a biochemical fermenter. *Proceedings of the American Control Conference*, Seattle, Washington, USA, pp. 153–158.

Robles-Rodríguez, C.E., Alcaraz-González, V., García-Sandoval, J.P., González-Álvarez, V., and Méndez-Acosta, H.O. (2013). Modelling and parameter estimation of a two stage anaerobic digestion system for the treatment of tequila vinasses. *Proceedings of the 13th World Congress on Anaerobic Digestion*, Santiago de Compostela, Spain, 4 pages in CD-ROM.

Sira-Ramirez, H. (1998). A general canonical form for feedback passivity of nonlinear systems. *International Journal of Control*, 71(5), 891-905.