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Pilot-scale Biogas Plant: Description, Modelling and Composed Recursive Control

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Abstract: This paper deals with the experimental description, mathematical modeling and recursive feedback control of a pilot-scale biogas anaerobic plant. Based on experimental results obtained during the start-up and operating of a pilot bioreactor, a five-order continuous-time anaerobic digestion model is obtained. Output trajectory tracking and disturbance compensation for the bioprocess model are realized using a new composed recursive controller comprising a recursive model free stabilization term and a recursive time delay compensation term. The performances of the new bioprocess controller are compared by numerical simulation with the performances of an existing nonlinear proportional-integral controller.

Keywords: Anaerobic digestion process, Composed recursive controller, Piecewise continuous systems, nonlinear proportional-integral controller

1. INTRODUCTION

Anaerobic digestion (AD) is an anaerobic biotechnology used for wastewater, slurry and solid waste treatment, in which the organic matter is depolluted by a community of several populations of microorganisms into biogas (mainly methane CH_4 and carbon dioxide CO_2) and fertilizer in the absence of oxygen (Simeonov and Queinnec, 2006; Diop and Simeonov, 2006; Deublein and Steinhauser, 2008). AD is a promising method for solving energy and ecological protection problems in agriculture and agroindustry (Steyer et al., 1997). AD technologies utilize different bioreactor types (fully mixed, plug-flow, biofilm, UASB, etc.) to maximize the energy output (methane). However, in practice they are usually carried out in fully mixed or the so-called Continuously Stirred Tank bioReactors (CSTR).

Unfortunately this process is very complex and can be unstable, particularly at changes in the environment, for example following an increase in influent concentration or in dilution rate, or a change in the nature of the feedstock and needs more studies (Deublein and Steinhauser, 2008). An active research problem is to better understand the dynamics of growth and death of the different populations of the complex community of bacteria acting during AD processes. However, it is practically impossible to measure on-line different bacterial concentrations or specific growth rates (Deublein and Steinhauser, 2008). Other biochemical variables important for the AD processes are too expensive to be measured. In practice, only biogas flow rate (and its compostion) can be easily measured on-line (Simeonov,2010).

Until now, various control algorithms such as feed rate feedback stabilization method (Harmon et al., 1990), methane-maximized-production optimal method (Pullammanappallil et al., 1991), linear parameterizations based adaptive control (Bastin and Dochain, 1988; Dochain, 1990; Petre et al., 2008), robust control (Méndez et al., 2010) or nonlinear PI set-point regulation control (Antonelli et al., 2003) have been developed (with and without process model) to control this complex and strongly nonlinear process. For the plant limiting available information, different estimators or observers such as neural network model based method (Simeonov and Chorukova, 2004; Galvan-Guerra and Baruch, 2008), Takagi-Sugeno fuzzy observer (Carlos-Hernandez et al., 2006), proportional-integral reduced order observer (Aguilar et al., 2001) or high-gain observer (Cunha et al., 2009) have been integrated with the control algorithms for plant coefficient estimation or state observation. Despite a long history of practical experience and decades of academic study (Loeser and Redfern, 2008; Curry and Pillay, 2009), the control of AD processes seems still open. Many mathematical models of these processes in CSTR of nonlinear ordinary differential equations with a great number of coefficients that are hard to be estimated (Dochain and Vanrolleghem, 2001; Simeonov and Queinnec, 2006; Dochain, 2003) are known. In these models, a limited number of variables characterizing the process are measurable online. Quite often one obtains only local solutions and it is impossible to validate the model in a large domain of experimental conditions (Diop and Simeonov, 2006). The five-order AD model is based on the three-stage biochemical scheme and may be accepted as a reasonable compromise between the real process complexity and the realistic basis for theoretical control algorithm design.

In this paper, a nonlinear five-order AD process model is first obtained using experimental data and then a Composed Recursive Model Free Controller (CRMFC) is used for output trajectory tracking and disturbance compensation of the AD process model. CRMFC uses only the output measurement - the methane outflow rate, and is composed of a recursive model free stabilization (RMFS) term and a recursive time delay compensation (TDC) term. The RMFS term is a recursive model free controller (Wang et al., 2010a; Wang et al., 2011a) based on the theory of Piecewise-Continuous Systems (PCS) which are a special class of hybrid systems with autonomous switchings and controlled impulses (Koncar and Vasseur, 2003; Wang et al., 2012). Using PCS theory, piecewise-continuous controllers were first developed, enabling sampled trajectory tracking of linear systems (Wang et al., 2008; Wang, 2011). Then for improving tracking performance, derived piecewise-continuous controller and recursive model free controller were proposed in (Wang et al., 2010; Wang et al., 2010a). Following (Youcef-Toumi and Fuhlbrigge, 1989; Youcef-Toumi and Shortlidge, 1991; Cho et al., 2005), the TDC term is used to directly compensate the plant unknown dynamics and disturbances employing past observations of the system output response and control inputs. CRMFC was first proposed and used for trajectory tracking control of a three tank system in (Wang et al., 2011). In this paper a monovariable CRMFC is designed and applied to the nonlinear AD process model.

The paper is organized as follows. In Section 2 the pilot AD platform is described, and then in section 3, from the realized experimental studies, a mathematical model which represents the AD process dynamics is given. This is followed, in Section 4, by the development of CRMFC for output trajectory tracking and disturbance compensation of the AD process model. CRMFC performances are studied by simulations and the obtained numerical results are presented and discussed in Section 5. Finally, some concluding remarks are given in section 6.

2. EXPERIMENTAL PLATFORM

2.1 Experimental Platform structure

Experimental studies of AD of cattle dung have been performed during the start-up of a pilot anaerobic plant (with full volume of the bioreactor of 100 l) at mesophilic temperature (34^0C) (Simeonov et al., 2012). According to Wang et al. (2013), the scheme of this pilot plant with a system for monitoring and control is shown on Fig. 1. On this figure: 1 - bioreactor (BR); 2 - gasholder; 3 - reservoir for digestate, 4 - vessel for substrate; 5 - controller Beckhoff; 6 - personal computer; 7,9 - drives; 8,10 - pumps; 11, 12 - stop valves; 13,14,15 - sensors for t_0, flow rate of biogas (Q), contents of CH$_4$ and CO$_2$ in the biogas.

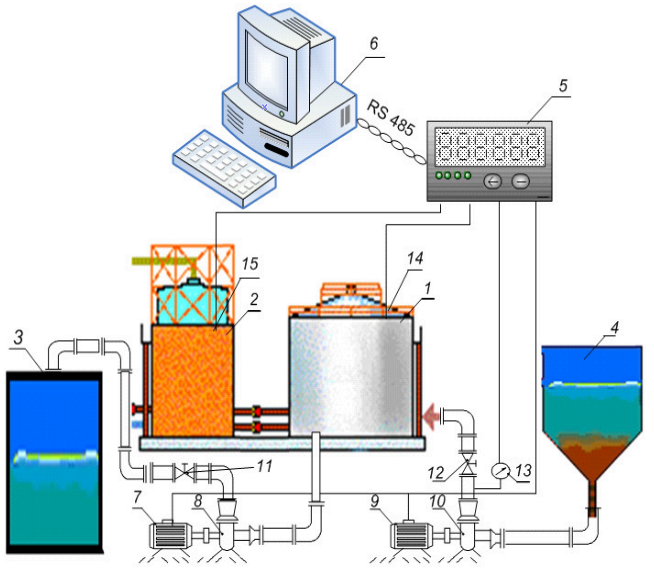

Fig. 1. Scheme of the pilot plant with a system for monitoring and control

2.2 Experimental Platform description

The substrate for the BR and the digestate taken out of it during semi-continuous operation (feeding one to six times daily) is stored in plastic cans of 50 L in the next-door auxiliary service premises of the biogas plant.

The 100 L bioreactor is designed for developing AD technologies based on standard and readily accessible types of feedstock such as diluted and suspended swine or cattle manure or chicken litter from agricultural farms, separately or in co-digestion with wasted fruits and vegetables from stock markets, finely grinded straw r restaurant wastes, activated sludge from the Waste Water Treatment Plants, etc.

The bioreactor is made of stainless steel and its upper flange is provided with magnetic coupling for the stirrer drive shaft. The drive itself is of AC type, the stirrer is of propeller type and deflectors to control the culture medium mixing are also available. The anaerobic bioreactor has been constructed with water mantle with a compensatory reservoir and a circulation pump. An additional feature is the thermal insulation (10 cm in width) in view of economic energy studies. The insulation has been designed on creating a theoretical stationary model of the anaerobic bioreactor heat losses for two temperature modes of biogas production - mesophilic and thermophilic. Thus, selected has been an effective thermal insulation of mineral wadding with coefficient of thermal conductivity =0,035 W/(m.K) and covered with aluminium foil. The bioreactor heat losses have been theoretically determined through the mathematical model at thermal insulation thickness $\delta = 1, 2...10$ cm. The heat losses have been established to

Fig. 2. General View of the real-time experimental platform

decrease according to parabolic dependence. Greater heat losses are found in the thermophilic mode compared to the mesophilic one. Conclusively, the uninsulated bioreactor has a high energy consumption to cover great heat losses at definite outer conditions - cold and moist weather. In this case, the bioreactor microorganisms situated near the metal wall could be at a different (lower) temperature for the given technological mode, which might affect their activity. The bioreactor thermal insulating has been performed in stages with experimental purpose. On each stage after stationing the object (every 4 hours) photos have been taken by a thermovision camera to establish weak points of the insulation. The insulation stages are at insulation thickness $\delta == 0, 5, 10$ cm, respectively. On placing the first insulation layer, bioreactor surface temperatures equalize along vertical axis, whereas the intensity of heat regulation decreases.

On placing the second layer, the small heat losses can expectedly be covered by bioreactor's own biogas production at its burning.

The general view of this pilot plant is shown on the following Fig. 2.

A biogas outlet from the upper bioreactor flange leads off the biogas to a 200 L metal gasholder operating on the water displacement principle. The main actuators are two feeding pumps that can be used interchangeably - of peristaltic and of progressive cavity type. The first one is self-drawing the input substrate, whereas the second one operates under substrate-submerged inlet, which requires auxiliary equipment to be built in the nearest future. On the other hand, the second pump gives the possibility to approach closely the operation mode to that of a real continuous process by apportioning the daily feed into greater number of dosages, as well as to avail of the theoretical process control algorithms requiring multiple changes of the dilution rate over a day. Other important inlet (on the substrate line) and outlet (on the digestate line and on the line from the bioreactor to the gasholder) flow control elements are the spherical valves (0 to 100%) being now manual, but some of them are provisioned to be replaced by automatic ones.

The actuator of the temperature control system is an electrical heater. In this pilot-scale biogas plant, sensors for the following physicochemical variables are available:

- **temperature in the culture medium** - standard thermal resistance type Pt100 in two different points (submerged through openings on the upper flange and on the corpus;
- pressure of the gas phase of the bioreactor - this sensor is a produce of Comeco Systems Ltd (Bulgaria). It has a measurement range 0-250 mbar, an indicator for the operator and a standard current output (4-20mA) for connection with computer;
- **biogas flow rate** (through transformation of the linear shift of the gasholder into normalized electrical signal). This sensor has been developed by the team of Stephan Angeloff Institute of Microbiology, Bulgarian Academy of Sciences. It operates on the capacitive principle and consists of a primary transducer, an electronic measurement block and a digital indication device to visualize the measured value. The primary transducer transforms the change in the gasholder level (in the float position) in a variable capacity and its construction is based on a metalized polypropylene tube with externally insulated metal layer. The tube is hermetically fixed on the upper surface of the gasholder float and is immersed in the water contained in the outer vessel. Changing the immersion depth changes tube's capacity with respect to the water. One of the electrodes of the variable capacitor is the metal layer in the tube, the tube's outer insulation is the dielectric, and the second electrode is the water around the tube. This water should not be distilled, i.e. it must contain a certain amount of salts in order to be conductible. The capacity of the variable capacitor changes linearly as a function of the measured level. The electronic measurement circuit transforms the capacity of the primary transducer in an electrical signal - voltage (0-5 V) or current $(4-20$ mA), depending on its further processing;
- **content of methane, carbon dioxide and hydrogen in the biogas** (see Fig. 1). These sensors are produces of MSR (Germany) with the following characteristics:
  (1) *sensor for CH4 measurement* - infrared sensor with a measurement range of $0 - 100$ %/vol., a measurement precision of 1%, a monthly drift of 1%, a linear output signal of $4 - 20$ mA, a transient process time of less than 30 s and a lifetime greater than 5 years;
  (2) *sensor for CO2 measurement* - infrared sensor with a measurement range of $0 - 70$ %/vol., a measurement precision of 1%, a monthly drift of 1%, a linear output signal of $4 - 20$ mA, a transient process time of less than 30 s and a lifetime greater than 5 years;
  (3) *sensor for H2 measurement* - catalytic bead sensor for combustible gases with a measurement range of $0 - 100$ LEL %, (corresponds to $0 - 4$ %/vol.), a measurement precision of 1 LEL %, an

Table 1. Experiment change conditions for inputs of D and S_{in}

Time [day]	D [day^{-1}]	S_{in} [g/l]
0	0.01	69
1	Pulse$_1$=0.025	69
9	Pulse$_2$=0.02	69
16	Pulse$_3$=0.0225	86
30	Pulse$_4$=0.025	40

annual drift of 5 LEL %, a linear output signal of $4-20$ mA, a transient process time of less than 10 s and a lifetime greater than 3 years.

These sensors are situated consecutively to each other and to a pump creating the biogas flow through them which gets out of and back into the gaseous phase of the bioreactor. The measurements are visualized on the display of an electronic module GC-4 and are recorded on a PC.

The monitoring system consists of two web cameras and software sensors for video observation, control, recording a video image on a server at a system failure or gas leak, automatic sending of snapshots on controller's signalling (at reporting parameters beyond admissible ranges) and for presenting experiments and remote (through internet) training in methods for biofuel production. The web camera SONY IPELA SNC-RZ25P has been installed in the biogas laboratory. The camera features an intelligent monitoring software with possible monitoring of images, different modes of recording, motion detection, filtering of the data from camera, sound from a microphone to the camera or other audio input device, etc.

The control system is composed on the lower level of a Beckhoff controller receiving the sensor information (see Fig. 2) with the sensors in the middle), and on the higher level - a PC with specialized software shows a board containing measurement and control devices - frequency converters for AC drive control, electrical protection device, different electrical supplies and an electrometer taking account of the energy consumption. A fire-and-explosion protection system has been installed in the pilot-scale biogas laboratory.

3. MATHEMATICAL MODELING OF THE AD PROCESS

3.1 Analysis of Experimental Measurements

The pilot anaerobic BR has been started and operated in continuous mode with different values of the dilution rate (D) and of the concentration of dry matter in the influent (S_{in}). Some experimental data from a very particular experiment with pulse-wise changes of D for different values of S_{in} (described in Table 1) are presented on Fig. 3 (With Q the daily biogas flow rate per 1 l of the working volume of the BR) and Fig. 4(see Wang et al. (2013)).

From Fig. 3, one may conclude that the community of microorganisms in the BR reacts immediately on pulse-wise changes of the control input (D) and different values of the concentration of dry matter in the influent (S_{in}). From the evaluations of CH_4 and CO_2 concentrations in the biogas, presented on Fig. 4, one may conclude that the ratio CH_4/CO_2 in the biogas for the above described experiment is practically not sensible to pulse changes of the control input (D) and different values of the concentration of dry matter in the influent (S_{in}).

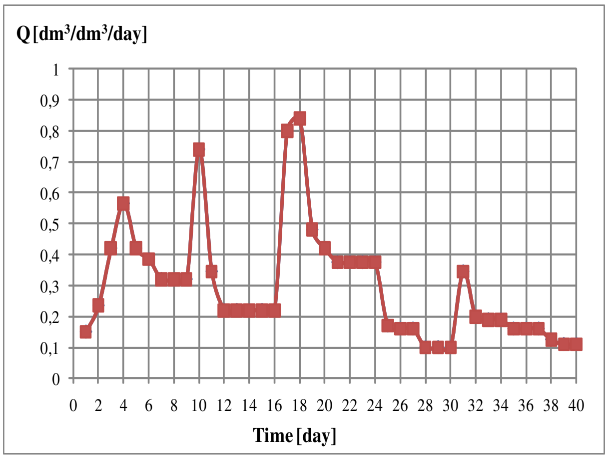

Fig. 3. Specific daily biogas flow rate evaluation during the experiment described in Table 1

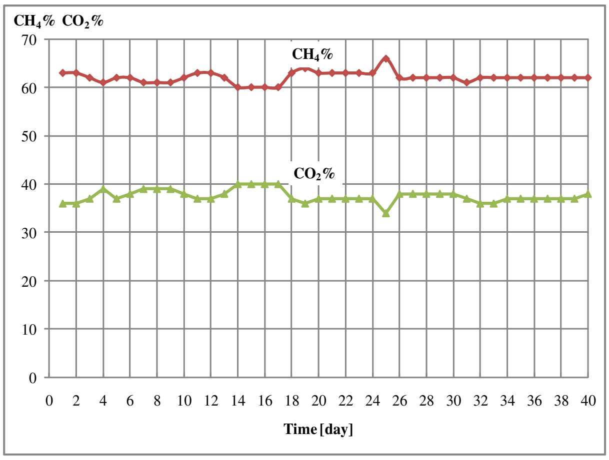

Fig. 4. Evaluations of CH4 and CO2 in the biogas during the experiment described in Table 1

3.2 Mathematical Modeling of the AD Process

On the basis of the above-presented experimental investigations and following the so-called three-stage biochemical scheme of the AD, the following 5th order Barth-Hill nonlinear model with one control input is proposed (Simeonov and Chorukova, 2004):

$$\frac{dS_0}{dt} = -bX_1S_0 + DY_pS_{in} - DS_0 \tag{1}$$

$$\frac{dX_1}{dt} = (\mu_1 - D)X_1 \tag{2}$$

$$\frac{dS_1}{dt} = -k_1\mu_1X_1 + bX_1S_0 - DS_1 \tag{3}$$

$$\frac{dX_2}{dt} = (\mu_2 - D)X_2 \tag{4}$$

$$\frac{dS_2}{dt} = -k_2\mu_2X_2 + Y_b\mu_1X_1 - DS_2 \tag{5}$$

$$Q = Y_g\mu_2X_2 \tag{6}$$

in which

$$\mu_i = \frac{\mu_{mi} S_i}{k_{si} + S_i} \quad i = 1, 2. \tag{7}$$

In this mass balance model, equation (1) describes the hydrolysis in a very simple way, where the first term reflects the hydrolysis of the diluted organics by acidogenic bacteria, the second term - the influent flow rate of liquid with concentration of the diluted organics S_{in} [g/l] (presenting a sum of a constant component S_{io} and a disturbance $w(t)$) and the third one - the effluent flow rate of liquid. Equation (2) describes the growth and changes of the acidogenic bacteria (with concentration X_1 [g/l]), consuming the appropriate substrate (with concentrationS_1, [g/l]). The mass balance for this substrate is described by (3), where the first term reflects the consumption by the acidogenic bacteria, the second term - the substrate S_0, [g/l] formed as a result of the hydrolysis, the third and the last one - the substrate S_1 [g/l] in the effluent flow rate of liquid. Equation (4) describes the growth and changes of the methane producing (methanogenic) bacteria (with concentration X_2, [g/l]), consuming acetate (with concentration S_2 [g/l]). The mass balance equation for acetate in (5) has three terms in his right side. The first one reflects the consumption of acetate by the methanogenic bacteria, the second one - the acetate formed as a result of the activity of acidogenic bacteria, and the third one - the acetate in the effluent liquid.

The algebraic equation (6) describes the formation of biogas with flow rate Q [l gas/l medium × day] measurable with error (measurement noise) $v(t)$. The relations (7) present the specific growth rate of the acidogenic bacteria μ_1 [day^{-1}] and the specific growth rate of the methanogenic bacteria μ_2 [day^{-1}], both of Monod Type. b, Y_p, k_1, k_2, Y_b, Y_g, μ_{m1}, μ_{m2}, k_{s1}, k_{s2} are coefficients. D [day^{-1}] is the dilution rate - the control input.

It is assumed that $S_2(t) < \bar{S}_2$, where $\bar{S}_2$ is the $S_2(t)$ bound whose exceeding leads to acetate inhibition.

Using the parameter estimation approach proposed in (Simeonov et al., 2011) the following model parameters values were obtained: $b = 3$, $Y_p = 0.144$, $S_{i0} = 40$ g/l, $\mu_{m1} = 0.4$ day^{-1}, $k_{s1} = 1.9$ g/l, $k_1 = 6.67$; $\mu_{m2} = 0.25$ day^{-1}, $k_{s2} = 0.37$ g/l, $Y_b = 5$; $k_2 = 4.17$, $Y_g = 3.1$.

4. COMPOSED RECURSIVE CONTROLLER DESIGN

In this section a composed recursive model free controller (CRMFC) is designed to ensure output trajectory tracking and disturbance compensation for the nonlinear AD process model. CRMFC consists of recursive model free stabilization (RMFS) and time delay compensation (TDC) terms and generates the bioreactor control input

$$D(t) = \big(D_s(t) + D_c(t)\big)/G \tag{8}$$

where $D_s(t)$ is the RMFS term output enabling system stabilization, $D_c(t)$ is the TDC term output aiming to compensate unknown system nonlinearities, and G is a positive constant.

Both $D_s(t)$ and $D_c(t)$ are determined by recursive calculation loops (Wang et al., 2011). The stabilization control term $D_s(t)$ is computed as

$$\lambda(t^+) = |e(t)|e(t) + \xi(t)\lambda(t) \tag{9}$$

$$D_s(t) = C_c \lambda(t) \tag{10}$$

where $\lambda(t) \in \Re$ is the RMFS term state, $e(t) = Q_r(t) - Q(t)$ is the output trajectory tracking error, Q_r denoting desired bounded process output trajectory; $C_c \in \Re_+$ is the RMFS output gain, and $\xi(t)$ is a tracking coefficient. To obtain $e(t) \to 0$, the value of $\xi(t)$ is tuned as (Wang et al., 2010a)

$$\xi(t) = \exp\big(\frac{-e(t)^2}{2\sigma^2}\big) \tag{11}$$

with $0 < \sigma \leq 1$.

The compensation control term $D_c(t)$ is determined by using time delay estimation techniques (Youcef-Toumi and Fuhlbrigge, 1989; Youcef-Toumi and Shortlidge, 1991; Cho et al., 2005) as

$$D_c(t) = \dot{Q}_r(t) - P(t - \epsilon) \tag{12}$$

where $P(t - \epsilon)$ is an estimate of

$$P(t) = \dot{Q}(t) - GD(t). \tag{13}$$

For $\epsilon \to 0$ one has

$$P(t) \cong P(t - \epsilon) = \dot{Q}(t - \epsilon) - GD(t - \epsilon). \tag{14}$$

Thus CRMFC does not require knowledge of process parameters which facilitates its implementation.

It can be easily shown that CRMFC ensures asymptotically exact tracking of desired output trajectory Q_r for the nonlinear AD process model. By using the relationship (13) one obtains

$$\begin{aligned} \dot{e}(t) &= \dot{Q}_r(t) - \dot{Q}(t) \\ &= \dot{Q}_r(t) - P(t) - GD(t) \\ &= \dot{Q}_r(t) - P(t) - GG^{-1}\big(D_s(t) + D_c(t)\big) \\ &= \dot{Q}_r(t) - P(t) - D_s(t) - \underbrace{D_c(t)}_{\dot{Q}_r(t) - P(t-\epsilon)} \\ &= -D_s(t) + P(t) - P(t - \epsilon). \end{aligned} \tag{15}$$

Since

$$\lim_{\epsilon \to 0} \big(P(t) - P(t - \epsilon)\big) = 0$$

one has

$$\dot{e}(t) \cong -D_s(t). \tag{16}$$

In turn, $D_s(t)$ can be approximated as (Wang et al., 2010a)

$$D_s(t) \cong \frac{2C_c\sigma^2}{|e(t)|} e(t) \tag{17}$$

and thus

$$\dot{e}(t) \cong -\frac{2C_c\sigma^2}{|e(t)|} e(t). \tag{18}$$

Choosing $C_c = \alpha|e(t)|/2\sigma^2$, $\alpha > 0$, one obtains

$$\lim_{t \to \infty} e(t) \cong \lim_{t \to \infty} e^{-\alpha t} e(0) = 0.$$

5. NUMERICAL RESULTS

CRMFC performances are studied by numerical simulations with Matlab/Simulink for the nonlinear AD process model described in Section 2.

The initial conditions are chosen to be $S_0(0) = 10$ g/l, $X_1(0) = 0.36$ g/l, $S_1(0) = S_2(0) = 0.18$ g/l and $X_2(0) =$

15.66 g/l according to (Yordanova et al., 2005). The desired piecewise-continuous output trajectory reference Q_r has the following time profile [l gas/l medium × day]: 0.3 - up to day 60; 0.50 - day 60 to 160; 0.3 - day 160 to 250. Additive measurement noise $v(t)$ and disturbance $w(t)$ of S_{i0} are taken into account. $v(t)$ is considered as a zero-mean Gaussian white noise with a sample time of 1 day and with covariance parameter value corresponding to average relative error of 5%. The additive disturbance $w(t)$ of S_{i0} is considered consisting of two components: first, a zero-mean Gaussian white noise with the same sample time and with covariance parameter value corresponding to average relative error of 20%; second, a step-wise parameter disturbance of $20\% S_{i0}$ at simulation day 140 and of $-20\% S_{i0}$ at day 170. The bound $\bar{S}_2$ is 1.6 g/l. For $S_2(t) \geq \bar{S}_2$, $D(t) = 0$.

The parameters of the proposed controller are tuned as $C_c = 3$, $\sigma = 0.12$, $G = 1$ and ϵ is chosen equal to the simulation sampling period used $T = 0.01$ day.

CRMFC performances are compared with those of the Nonlinear Proportional Integral (NPI) control proposed in (Antonelli et al., 2003). This control is defined and tuned according to (Antonelli et al., 2003) as

$$\dot{D} = k(Q-Q_r)(D-\overline{D})(D-\underline{D}), D(0) = D_0 \in (\underline{D}, \overline{D}) \quad (19)$$

with $k = 10$, $\overline{D} = 0.29$ and $\underline{D} = 0.01$.

The output trajectory tracking results for CRMFC and NPI control are shown in Fig. 5.

It can be seen that CRMFC ensures a faster time response with small tracking error. For significant increase of biogas outflow rate reference, CRMFC continues to ensure reference tracking while the NPI control produces a wash out phenomena. The AD process states evolution using CRMFC and NPI control is depicted in Fig. 6 – Fig. 9 and the corresponding control signals are shown in Fig. 10 and Fig. 11.

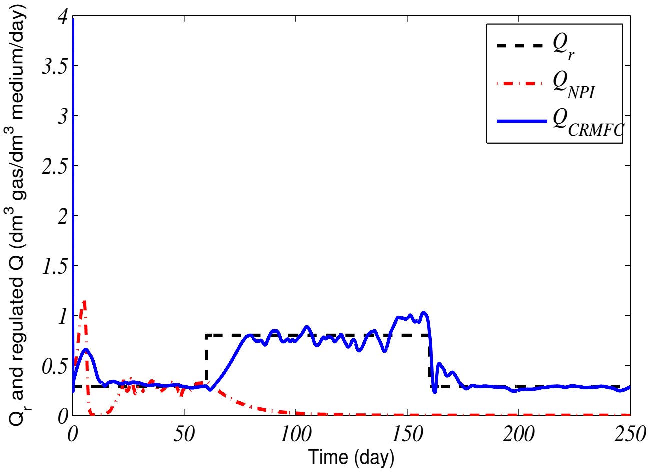

Fig. 5. Output trajectory tracking using CRMFC and NPI control

6. CONCLUSIONS

In this paper, the pilot biogas plant is firstly described. And then from the analysis of the experimental measurements, a five-order continuous-time model of an AD

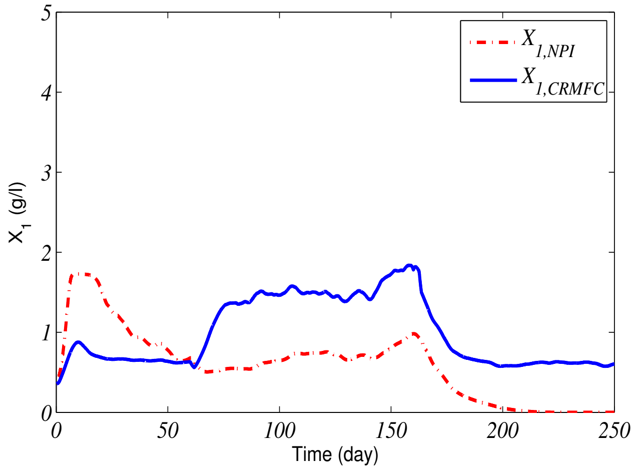

Fig. 6. Acidogenic bacteria concentration X_1 evolution

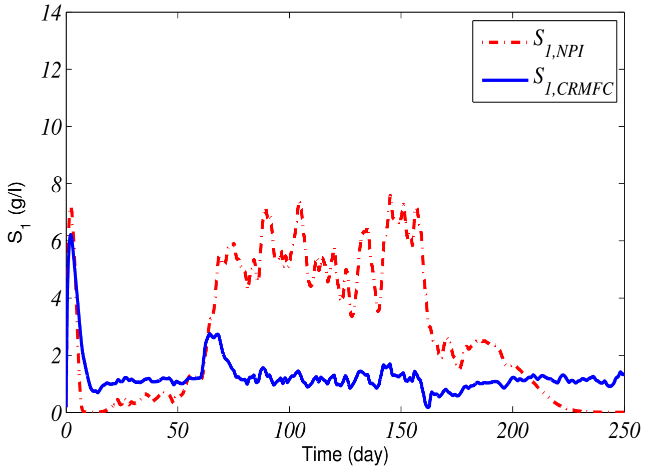

Fig. 7. Substrate S_1 evolution

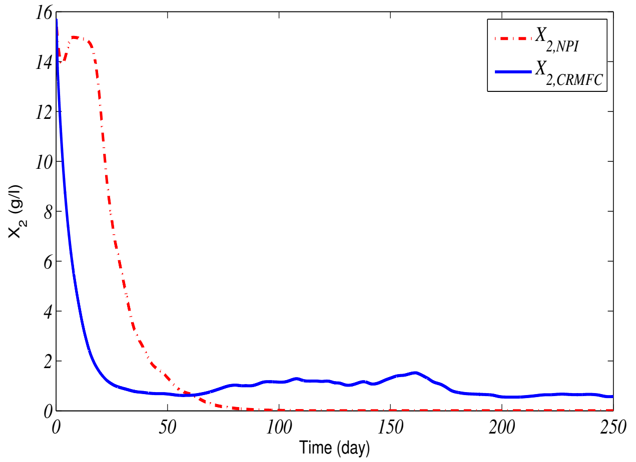

Fig. 8. Methanogenic bacteria concentration X_2 evolution

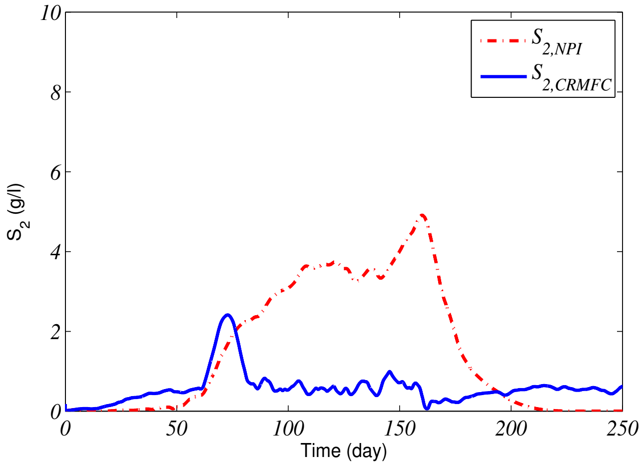

Fig. 9. Substrate S_2 evolution

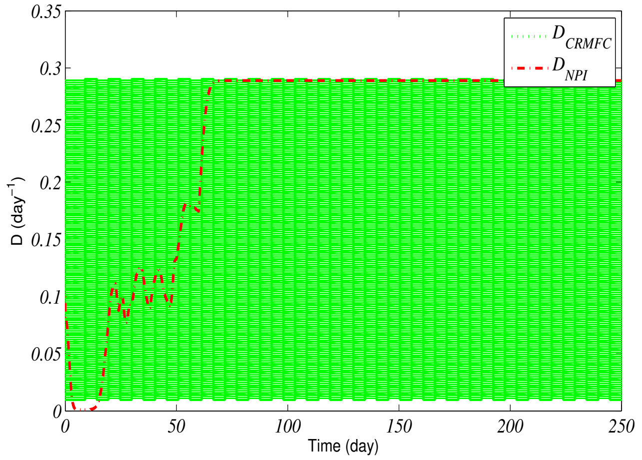

Fig. 10. CRMFC and NPI control signals

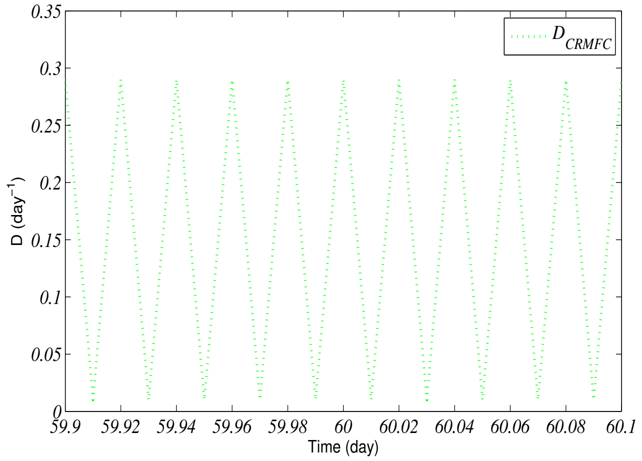

Fig. 11. Zoom of the CRMFC control signal

process is obtained for pilot-scale bioreactor and a composed recursive model-free controller is proposed for output tracking and disturbance compensation for the process model. This controller comprises recursive stabilization and time delay compensation terms and does not require knowledge of model parameters. Compared to the existing nonlinear proportional-integral controller, the proposed controller ensures better performances in tracking multi-step-wise reference trajectories under stochastic and step-wise disturbances of the inlet substrate concentration and measurement noise in the methane outflow rate.

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