II. BIOAUTOMATICS AND BIOINFORMATICS

EXTREMUM SEEKING CONTROL OF TWO-STAGE ANAEROBIC DIGESTION SYSTEM: A MINI REVIEW

Nicolai Christov, Haoping Wang and Ivan Simeonov

Abstract. Anaerobic digestion (AD) is a biotechnological process, in which microorganisms degrade organic matter under anaerobic conditions to produce biogas. It has long been known that the two main species (acidogenic and methanogenic) in the community of microorganisms in AD differ in many aspects and the optimal conditions for their growth and development are different. Therefore, in AD in a single bioreactor (BR) (single-phase process), the optimal conditions are selected taking into account the slow-growing methanogens at the expense of fast-growing acidogens, which affects the efficiency of the whole process. This has led in recent years to the development of two-stage AD (TSAD), in which processes are divided into a cascade of two separate BRs. It is known that this division of the processes into two consecutive BRs leads to significantly higher energy yields for the two-phase system ($H_2 + CH_4$), compared to the traditional single-stage CH_4 production process.

In our previous studies different mathematical models of the TSAD have been developed. It was shown that in both BRs the input-output characteristics have a clear maximum, which allows the yields to increase significantly if operations are provided around the maximum points. However, in order to maintain the sustainability of the biogas plants work, it is necessary to introduce automatic control with sophisticated extremum seeking control (ESC) algorithms.

This paper presents the pioneering research on ESC of AD process with production of hydrogen and methane. This research has been realized by the Department of Biotechnology at The Stephan Angeloff Institute of Microbiology (SAIM) and the French-Chinese Laboratory on Automatic Control and Signal Processing (LaFCAS), in collaboration with the Laboratory of Signals and Systems (L2S) at the French National Center of Scientific Research CNRS.

Keywords: two-stage anaerobic digestion, organic waste, hydrogen, methane, mathematical models, extremum seeking control, maximal energy production

1. INTRODUCTION

In the anaerobic digestion (AD) process the microorganisms degrade the complex organic matter to simpler components under anaerobic conditions to produce biogas and fertilizer. This process has many environmental benefits, such as: green energy production; organic waste treatment; environmental protection and greenhouse gas emissions reduction.

It is well known that input-output static characteristics of the AD process present a clear maximum concerning the biogas production [Simeonov, 1999]. That is why the idea to develop the so called "Extremum Seeking Control (ESC)" for AD process is not new [Simeonov et al., 2007; Caraman et al., 2015; Condriachi et al., 2017; Pessoa, et al., 2019]. Such kind of control algorithms are developed for other biotechnological processes [Nguang and Chen, 2000; Guay et al., 2004; Cougnon, et al., 2011; Lara-Cisneros et al., 2014; Barbu et al., 2017].

The two-stage AD (TSAD) consists of hydrogenic process followed by methanogenic process. The resulted overall energy recovery is significantly higher (up to 43 %) for the TSAD system, as compared to the traditional one-stage CH_4 production process.

In our previous studies different mathematical models of the TSAD have been developed [Simeonov and Chorukova, 2016; Borisov et al., 2016; Borisov et al., 2020a; Borisov et al., 2020b;

Chorukova and Simeonov, 2020]. It was shown that in both bioreactors the input-output characteristics have a clear maximum, which allows increasing significantly the yields if operations are provided around the maximum points. However, to maintain the sustainability of the TSAD biogas plants work, it is necessary to introduce automatic control with sophisticated ESC algorithms.

This survey presents the pioneering research on the theory of ESC for TSAD systems. This research has been realized by the Department of Biotechnology at The Stephan Angeloff Institute of Microbiology, Bulgarian Academy of Sciences, and the French-Chinese Laboratory on Automatic Control and Signal Processing (LaFCAS) at Nanjing University of Science and Technology and Lille University.

2. PROCESS DESCRIPTION

In the TSAD system, relatively fast growing acidogens and H_2 producing microorganisms are grown in the first-stage, the hydrogenic bioreactor (BR_1 with working volume V_1). They are involved in the production of volatile fatty acids (VFAs) and H_2 . On the other hand, the slow growing acetogens and methanogens are grown in the second stage, the methanogenic bioreactor (BR_2 with working volume V_2) in which the produced VFAs are further converted to CH_4 and CO_2 .

Fig. 1. Two-stage AD process for hydrogen and methane production [Chorukova and Simeonov, 2020]

Assume that the volumes V_1 and V_2 of the bioreactors are constant. Let F_1 and F_2 be the inflows in the first and in the second bioreactor,

respectively and let $F_1=F_2=F$ be valid. It is well known that the dilution rates D_1 and D_2 are defined as [Aruna et al., 2018]:

$$D_1 = F/V_1, D_2 = F/V_2, \text{ then } D_2 = (V_1/V_2) D_1 = \gamma D_1 \text{ within } \gamma = V_1/V_2$$

It is known that the volume V_2 of the second bioreactor for methane production is larger than the volume V_1 of the first bioreactor. Therefore, the constant $\gamma < 1$ should be valid.

It is known that more than 95 % of the working industrial biogas plants operate with the so called continuously stirred tank reactors (CSTRs). In this case the effluent organics is 3-4 times lower than the influent one. That means the degree of biodegradation (DBD) is 66-75 %. In the case of TSAD with CSTRs the effluent organics is 9-16 times lower than the influent one (e.g. DBD = 89-93 %) [Aruna Devi et al., 2018; Krishnan et al., 2016] and even DBD = 96.6 % in the case of some specific bioreactors [Ramadhani et al., 2021].

Main advantages of two-stage process of AD with production of hydrogen and methane are:

- a) Maximization of the energy production;
- b) Maximization of the DBD

3. APPLICATION OF EXISTING EXTREMUM SEEKING CONTROL ALGORITHMS TO TWO-STAGE ANAEROBIC DIGESTION PROCESS

The first research results in the field of ESC of two-stage AD processes have been obtained in 2007

[Simeonov and Stoyanov 2007; Simeonov and Stoyanov, 2011] by the research team of the Department of Biotechnology at The Stephan Angeloff Institute of Microbiology, Bulgarian Academy of Sciences. Classical ESC algorithm has been applied to a cascade of two anaerobic bioreactors and its performances have been investigated. The theoretical analysis and simulation studies have shown that it is possible to optimize the steady-state operation of a cascade of two anaerobic bioreactors with classical ESC techniques. However, in these papers the two-stage AD process was of the “old” type – only methane was produced.

In 2018, based on the Krstic and Wang's extension of classical extremum seeking algorithm, an extremum seeking stable feedback control has been designed for the two-stage anaerobic digestion experimental platform of The Stephan Angeloff Institute of Microbiology [Simeonov et al., 2018]. The numerical simulations have shown the high performances of the proposed extremum seeking controller. The mathematical models used in [Simeonov et al., 2018] are presented in subsection 3.1 and the obtained results – in subsection 3.3.

3.1 Mathematical Models of Two-Stage Anaerobic Digestion Process

[Chorukova and Simeonov, 2020; Chorukova et al., 2021]

3.1.1. Modeling of the hydrogen production in BR₁

Model 1a

$$\begin{aligned}
 \frac{dS_1}{dt} &= -\frac{1}{Y_1} \mu_1 X_1 + D_1 (S_1^{in} - S_1) && \text{(cellobiose)} \\
 \frac{dX_1}{dt} &= \mu_1 X_1 - D_1 X_1 && \text{(Clostridium thermocellum)} \\
 \frac{dAc_1}{dt} &= \frac{1}{Y_2} \mu_1 X_1 - D_1 Ac_1 && \text{(acetate)} \\
 Q_{H_2} &= Y_{H_2} \mu_1 X_1 && \text{(hydrogen)} \\
 \mu_1 &= \frac{\mu_{1max} S_1}{K_{s1} + S_1}
 \end{aligned} \tag{1}$$

The algebraic equation describes the flow rate of the hydrogen (Q_{H_2}) in the gas phase of BR₁. In this model S_1^{in} [g/l] is the concentration of the inlet substrate (cellobiose).

Model 1b

$$\begin{aligned}
 \frac{dS_0}{dt} &= -D_1 S_0 - \beta X_1 S_0 + D_1 Y_p S_0^{in} && \text{(cellulose)} \\
 \frac{dS_1}{dt} &= -D_1 S_1 + \beta X_1 S_0 - \frac{1}{Y_1} \mu_1 X_1 && \text{(cellobiose)} \\
 \frac{dX_1}{dt} &= \mu_1 X_1 - D_1 X_1 && \text{(Clostridium thermocellum)} \\
 \frac{dAc_1}{dt} &= \frac{1}{Y_2} \mu_1 X_1 - D_1 Ac_1 && \text{(acetate)} \\
 Q_{H_2} &= Y_{H_2} \mu_1 X_1 && \text{(hydrogen)} \\
 \mu_1 &= \frac{\mu_{1max} S_1}{K_{s1} + S_1}
 \end{aligned} \tag{2}$$

S_0^{in} is the cellulose concentration in the inlet flow of BR₁ and Q_{H_2} is the hydrogen flow rate [dm³/l.h].

Model 1a describes a one-step transformation of

organic substrate into hydrogen and acetate by one type of microorganisms. Model 1b adds hydrolysis as first step conducted by the same microorganisms.

3.1.2. Modeling of the methane production in BR₂

$$\begin{aligned}
 \frac{dX_2}{dt} &= \mu_2 X_2 - D_2 X_2 && \text{(methanogenic bacteria)} \\
 \frac{dAc_2}{dt} &= -\frac{1}{Y_3} \mu_2 X_2 + D_2 (Ac_1 - Ac_2) && \text{(acetate)} \\
 Q_{CH_4} &= Y_{CH_4} \mu_2 X_2 && \text{(methane)} \\
 \mu_2 &= \frac{\mu_{2max} Ac_2}{K_{s2} + Ac_2}
 \end{aligned} \tag{3}$$

X_2 is microbial biomass concentration in BR₂ [g/l], Ac_2 is acetate concentration in BR₂ [g/l], Ac_1 is the concentration of acetate coming from BR₁ [g/l], Q_{CH_4} is the methane flow rate [dm³/l.h], μ_2 is the specific growth rate of methanogens [h⁻¹], Y_{CH_4} , Y_3 are yield coefficients, μ_2^{MAX} [h⁻¹] and K_2^S [g/l] are

kinetic coefficients. All parameters values are presented in [Chorukova and Simeonov, 2020; Chorukova et al., 2021].

The model presented with (3) describes a one-step transformation of the inlet acetate Ac_1 (coming from BR₁) into methane by methanogenic microorganisms.

3.1.3. Static characteristics of BR_1 and BR_2 [Chorukova and Simeonov, 2020]

Fig. 2. Input-output static characteristic of BR_1

Fig. 3. Input-output static characteristic of BR_2

3.2 Extremum Seeking Control Problem for Two-Stage AD Processes

Consider first the continuous AD process in BR_1 which goal is the production of biohydrogen. As an optimization objective it is natural to consider the maximization of the biogas flow rate Q_{H_2} :

$$Q_{H_2} \Rightarrow \text{Max} \quad (4)$$

The steady states of the AD process in BR_1 are characterized by a non-monotonic relation between

the biogas flow rate Q_{H_2} (controlled output) and the dilution rate D_1 , which is the control input.

The purpose of the extremum seeking control (ESC) is then to iteratively adjust the dilution rate D_1 in order to steer the process to the maximum of this characteristic.

For the two-stage AD process, the objective function to be maximized is

$$Q = Q_{H_2} + Q_{CH_4} \Rightarrow \text{Max} . \quad (5)$$

The control action D_2 for BR_2 is fixed as a part of the control action D_1 for BR_1 through the coefficient K . The optimal value for K is

$$K^{OPT} = \frac{D_1^{OPT}}{D_2^{OPT}}. \quad (6)$$

In [Chorukova, et al., 2021] it was demonstrated that in the case of an optimal ratio (by criterion “maximal energy production”) of the working volumes of both CSTR bioreactors it is possible to use only one ESC algorithm (for the first bioreactor of the cascade). If the ratio of the working volumes of both bioreactors is not optimal, two different ESC algorithms are needed.

A number of algorithms for extremum seeking process control have been proposed, but the stability of most of them is not proven [Dochain et al., 2008].

In [Krstic et al., 2000] a stable ESC is developed using periodic external perturbation signal with sinusoidal form.

In [Simeonov et al., 2018], based on the Krstic and Wang’s extension of classical extremum seeking algorithm [Krstic et al., 2000], an extremum seeking stable feedback control has been designed for the two-stage anaerobic digestion experimental platform of The Stephan Angeloff Institute of Microbiology. The obtained results are briefly presented in the next subsection.

3.3 Extremum Seeking Stable Feedback Control of AD Processes

The basic AD process control scheme using Krstic and Wang’s extremum seeking algorithm [Krstic et al., 2000] is shown on Fig. 4.

Fig. 4. Basic AD process control scheme using Krstic and Wang’s algorithm

The main idea is to use periodic excitation signal $a \sin \omega t$, which is added to the signal $\hat{D}$. If this excitation signal is slow, the process can be represented by the static characteristic $Q = Q(D)$, and its dynamics do not interfere with the extremum seeking scheme. If D is on either side of D^{OPT} , the excitation signal $a \sin \omega t$ creates a periodic response of Q , which is either in phase or out of phase with $a \sin \omega t$. The gradient update law

$$\frac{d}{dt} \hat{D} = k(a^2/2) \frac{d}{dt} [Q(D)](\hat{D}) \quad (7)$$

is driven by the sensitivity function $(a^2/2)[Q(D)]$, which tunes $\hat{D}$ to D^{OPT} .

Simulations with two variants of the two-stage process have been made [Simeonov et al., 2018]. The first variant uses Model 1a of BR_1 and the second variant uses the Model 1b of BR_1 , the model of BR_2 being the same for the two variants. The effect of the extremum seeking controller has been tested for both variants, starting from left and right of the maximum. The starting values of D_1 have been chosen 0 and D^{RIGHT} (the highest possible value for which the process stays vital). Fig. 5 and Fig. 6 present the trajectories of the working points of the two variants of the system in the phase plane Q - D . That is a demonstration that the ESC algorithm is applicable for different process models.

Fig. 5. BR₁ process with ESC for variant 1, $D^{RIGHT} = 0.522$

Fig. 6. BR₁ process with ESC for variant 2, $D^{RIGHT} = 0.482$

4. KALMAN FILTER BASED EXTREMUM SEEKING CONTROL OF TWO-STAGE ANAEROBIC DIGESTION PROCESS

In order to improve the performances of the closed-loop control system, advanced extremum seeking algorithms using Kalman filters have been thereafter developed by the teams of the Department of Biotechnology at Stephan Angeloff Institute of Microbiology and the French-Chinese Laboratory on Automatic Control and Signal Processing at Nanjing University of Science and Technology.

In 2019, an Extend Kalman Filter (EKF) based extremum seeking algorithm has been proposed, where EKF is used to obtain more accurate gradient estimation and eliminate the shortcoming of steady-state oscillations. This ESC was applied to a one-stage AD process and the obtained results

are described in [Hu et al., 2019]. Two Newton-based ESC algorithms have been further developed using Kalman Filters, and have been applied to two-stage AD processes [Tian et al., 2020] and [Wang et al., 2021]. These algorithms and the obtained application results are briefly presented in this section.

4.1 Kalman Filter based Newton Extremum Seeking Control

In 2020, a new Newton-based ESC (NESC) has been proposed using Kalman Filter (KF), instead of linear filter based estimator, to obtain more accurate gradient and Hessian estimates of the system input-output static map [Tian et al., 2020]. The proposed KF based NESC (KFNESC) algorithm do not require any process model information and uses only input and output measurements – dilution rate and the biogas outflow rate. The gradient and Hessian of

the static input-output map are estimated using Kalman filter, which makes possible to speed up the convergence to the extremum. Moreover, there are no steady-state oscillations because the amplitude of the perturbation signal converges to zero during steady state regime. This ensures the smoothness of the dilution rate and the gas production rate.

4.1.1 KFNEESC algorithm

Considered the nonlinear dynamic system

$$\begin{cases} \dot{x} = \varphi(x, u) \\ y = \psi(x) \end{cases} \quad (8)$$

where $x \in R^n$, $u \in R$ and $y \in R$ are the system state, input and output, and $\varphi: R^n \times R \rightarrow R^n$ and $\psi: R^n \rightarrow R$ are smooth functions.

Suppose that there exists a smooth control law

$$u = \alpha(x, \theta) \quad (9)$$

parameterized by a scalar parameter θ , for which the closed-loop system has a unique equilibrium. The input-output static function $y = f(\theta)$ of the system has an extremum point (θ^*, y^*) , where y^* is the maximum value of the system output.

The estimate $\hat{\theta}$ of the parameter θ is computed by the Newton-based optimization algorithm

$$\frac{d\hat{\theta}}{dt} = -k\Gamma\hat{b} \quad (10)$$

$$\frac{d\Gamma}{dt} = h\Gamma - h\Gamma^2H \quad (11)$$

until reaching the extremum point. Here $\hat{b}$ and $\hat{H}$ are the estimates of the gradient and the second derivative (the Hessian) of the static function $y = f(\theta)$, and Γ is the estimate of the inverse of the Hessian H .

In the proposed ESC algorithm, $\hat{b}$ and $\hat{H}$ are computed by Kalman filter [Simon, 2006], instead of the linear filter in the classical ESC algorithm. The use of KF makes possible to obtain faster and more accurate gradient and Hessian estimation, which can speed up the convergence of the algorithm. To ensure the feasibility of the gradient and Hessian estimation in real time, a perturbation signal $aS(t)$ is superimposed on the Newton optimizer output $\hat{\theta}$, where

$$a = r \frac{w_l}{s + w_l} (y - \zeta), \quad \zeta = \frac{s}{s + w_h} y \quad (12)$$

$$S(t) = \sin(\eta(t)), \quad \eta(t) = w\pi(1 + \sin W(t)) \quad (13)$$

Here w_l and w_h are the cutoff frequencies of the corresponding low-pass high-pass filters, $r > 0$ is a constant gain for adjusting the convergence speed, $W(t)$ is the standard Brownian motion process, and w is a positive constant. When the system output y converges to its maximum value y^* , the amplitude of the perturbation signal approaches to zero, which makes possible to eliminate the steady-state oscillations.

The structure of the proposed ESC is shown in Fig. 7.

Fig.7. Structure of Kalman Filter based Newton Extremum Seeking Control

4.1.2 Application of KFNEESC to two-stage AD process

Consider the BR1 and BR2 models established by the principle of mass balance [Chorukova and Simeonov, 2020]:

BR1	BR2
$\frac{dS_0}{dt} = -D_1 S_0 - \beta X_1 S_0 + D_1 Y_p S_0^{\text{in}}$	$\frac{dX_{\text{Pr}}}{dt} = \mu_{\text{Pr}} X_{\text{Pr}} - D_2 X_{\text{Pr}}$
$\frac{dS_1}{dt} = -D_1 S_1 + \beta X_1 S_0 + \frac{\mu_1 X_1}{Y_1}$	$\frac{d\text{Pr}_2}{dt} = -\frac{\mu_{\text{Pr}} X_{\text{Pr}}}{Y_{\text{Pr}2}} + D_2 (\text{Pr}_1 - \text{Pr}_2)$
$\frac{dX_1}{dt} = \mu_1 X_1 - D_1 X_1$	$\frac{dX_{\text{But}}}{dt} = \mu_{\text{But}} X_{\text{But}} - D_2 X_{\text{But}}$
$\frac{d\text{Pr}_1}{dt} = \frac{\mu_1 X_1}{Y_{\text{Pr}1}} - D_1 \text{Pr}_1$	$\frac{d\text{But}_2}{dt} = -\frac{\mu_{\text{But}} X_{\text{But}}}{Y_{\text{But}2}} + D_2 (\text{But}_1 - \text{But}_2)$
$\frac{d\text{But}_1}{dt} = \frac{\mu_1 X_1}{Y_{\text{But}1}} - D_1 \text{But}_1$	$\frac{dX_{\text{Ac}}}{dt} = \mu_{\text{Ac}} X_{\text{Ac}} - D_2 X_{\text{Ac}}$
$\frac{d\text{Ac}_1}{dt} = \frac{\mu_1 X_1}{Y_{\text{Ac}1}} - D_1 \text{Ac}_1$	$\frac{d\text{Ac}_2}{dt} = -\frac{\mu_{\text{Ac}} X_{\text{Ac}}}{Y_{\text{Ac}2}} + \frac{\mu_{\text{Pr}} X_{\text{Pr}}}{Y_{\text{Pr}2}} + \frac{\mu_{\text{But}} X_{\text{But}}}{Y_{\text{But}2}} + D_2 (\text{Ac}_1 - \text{Ac}_2)$
$Q_{H_2} = Y_{H_2} \mu_1 X_1$	$Q_{CH_4} = Y_{CH_4} \mu_{\text{Ac}} X_{\text{Ac}}$

where μ_1 , μ_{Pr} , μ_{But} , μ_{Ac} denote respectively the Mono-type growth rate of acidogenic bacteria, propionic acid-degrading bacteria, butyric acid-degrading bacteria and methanogenic bacteria; Y_p , $Y_{\text{But}1}$, Y_{H_2} , Y_1 are yield coefficients; Q_{H_2} , Q_{CH_4} represent the hydrogen

and methane production rate, and β is a constant parameter.

The considered AD process has a distinct optimum in the input-output static characteristic maps, see Fig. 8 and Fig. 9.

Fig. 8. Static characteristic $D_1 - Q_{H_2}$ for different S_0^{in}

Fig. 9. Static characteristic $D_1 - Q$ for different S_0^{in}

The performances of the proposed KF based NESC have been compared with the performances of the sliding mode ESC (SMESC) [Pan et al., 2003]

and Newton ESC (NESC) [Moase et al., 2010]. The obtained comparison results for $D_1(0)=0.01\ h^{-1}$ and $S_0^{in}=30\text{g/L}$ are shown in Fig. 10.

(a) Input dilution rate D_1

(b) Optimization target: hydrogen production rate Q_{H_2}

(c) Methane production rate Q_{CH_4}

Fig. 10. AD processes for hydrogen production rate as optimization target

4.2 Kalman Filter based Newton ESC for Dynamic Systems

Since 2020, the teams of the Department of Biotechnology at Stephan Angeloff Institute of Microbiology and the French-Chinese Laboratory

on Automatic Control and Signal Processing at Nanjing University of Science and Technology work on development and application of a new KFNEESC for dynamic systems. The new KFNEESC is based on the existing Newton-based extremum

seeking control for dynamic systems [Liu and Krstic, 2014].

4.2.1, Algorithm of KFNEESC for dynamic systems

Consider the single-input nonlinear dynamic system

$$\begin{cases} \dot{x} = f(x, u) \\ y = h(x) \end{cases} \quad (15)$$

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}$ and $y \in \mathbb{R}$ are the system state, input and output, and $f: \mathbb{R}^n \times \mathbb{R} \rightarrow \mathbb{R}^n$ and $h: \mathbb{R}^n \rightarrow \mathbb{R}$ are smooth functions. If $u = \alpha(x, \theta)$ is a smooth control law parameterized by a scalar parameter $\theta \in \mathbb{R}$, the closed-loop system

$$\dot{x} = f(x, \alpha(x, \theta)) \quad (16)$$

has equilibria parameterized by θ . Suppose that there exist a smooth function $l: \mathbb{R} \rightarrow \mathbb{R}^n$ and $\theta^* \in \mathbb{R}$, such that $f(x, \alpha(x, \theta)) = 0$ if and only if $x = l(\theta)$, and

$$\left. \frac{\partial(h \circ l)}{\partial \theta} \right|_{\theta=\theta^*} = 0, \quad \left. \frac{\partial^2(h \circ l)}{\partial \theta^2} \right|_{\theta=\theta^*} = H < 0.$$

The extremum-seeking control makes possible to maximize the steady-state value of y without requiring the knowledge of either θ^* or the functions h and l .

The structure of the proposed Kalman filter based Newton extremum-seeking control for dynamic systems is shown in Fig. 11.

The estimate $\hat{\theta}$ is computed by the Newton optimization algorithm (10), (11). The Kalman filter [Simon, 2006] is used to estimate the gradient b and the Hessian H of the system output equilibrium map $y = h(l(\theta))$. This makes possible to obtain more accurate gradient and Hessian estimates, and enables to speed up the convergence to the extremum. To attenuate the steady-state oscillations, the stochastic perturbation signal (12), (13) is used.

Fig. 11. Structure of the Kalman filter based Newton extremum seeking control for dynamic systems

4.2.2 Application of KFNEESC for dynamic systems to two-stage AD process

The performances of the proposed control are compared with the performances of the classical ESC, sliding mode ESC (MSESC) [Pan et al., 2003] and Newton ESC (NESC) [Moase et al., 2010] for the two-

stage AD process model (14). The results obtained for initial dilution rate $D_1(0) = 0.01 h^{-1}$ and inlet organics concentration $S_0^{in} = 30 g/L$ are shown in Fig. 12. At 1000 h of the reaction, the inlet organics concentration changed to 25 g/L.

(a) Input: dilution rate D_1 (b) Optimization target: hydrogen production rate Q_{H_2} (c) Methane production rate Q_{CH_4}

Fig. 12. AD processes for hydrogen production rate as optimization target

5. CONCLUSION

This survey presents the pioneering research on ESC of the two-stage AD process with simultaneous production of hydrogen and methane. This research has been realized by the Department of Biotechnology at The Stephan Angeloff Institute of Microbiology (SAIM), Bulgarian Academy of Sciences (BAS), and the French-Chinese Laboratory

on Automatic Control and Signal Processing (LaFCAS) at Nanjing University of Science and Technology and Lille University.

The classical ESC of cascade of two anaerobic bioreactors was first investigated in 2011. After then, the Department of Biotechnology team has continued, in collaboration with the LaFCAS team, the research upon the improving biogas production of two-

stage AD processes developing more performant ESC algorithms.

An Extend Kalman Filter based extremum seeking algorithm was proposed in 2018, and in 2019, a new Newton-based ESC was developed using Kalman Filter to obtain more accurate gradient and Hessian estimates of the system input-output static map. In 2020, a Kalman Filter based Newton ESC for dynamic systems was proposed.

Development and testing of advanced ESC algorithms for the pilot biogas plant of the SAIM-BAS is the main research areas of the international multidisciplinary team.

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Nicolai Christov

Centre de Recherche en Informatique,
Signal et Automatique de Lille - UMR 9189,
Université de Lille
59655 Villeneuve d'Ascq, France

Haoping Wang

LaFCAS Laboratory, Automation School,
Nanjing University of Science and Technology
200 Xiao Ling Wei St,
210094 Nanjing, China

Ivan Simeonov

The Stephan.Angeloff Institute of Microbiology
– BAS,
Bl. 26, Acad. G. Bonchev Str.
1113 Sofia, Bulgaria
e-mail: issim@abv.bg