Research Inventy: International Journal of Engineering And Science
Vol.10, Issue 11 (November 2020), PP 51-67
Issn (e): 2278-4721, Issn (p):2319-6483, www.researchinventy.com

Output Feedback Control of an Acetate-Fed Anaerobic Digester

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Abstract:*Anaerobic digestion is a complex biochemical process and one of the most widespread methods for the treatment of high organic content waste, aiming at the production of biogas (energy) (Tsonis et al. 1988, Wujsik and Jewell 1980, Haberl et. al. 1991) while treating the waste, as well as at the production of energy from plant biomass (Chynoweth et al. 1987). A common process objective is the maximisation of the biogas production. A two-state model was developed for the simulation of an experimental reactor (CSTR), fed with acetic acid. This type of feeding is very important, as quite often anaerobic digestion is carried out in two sequential reactors, a hydrogen and fatty acids (mainly acetate) producing hydrolysis reactor, followed by a methanogenic reactor, which produces biogas (methane and carbon dioxide). The hydraulic retention time, which maximizes the production rate of biogas was determined and a process control algorithm was utilised to secure fast transition to a new optimal steady state when there are changes in the feed loading rate.*

Keywords:*Automatic control, anaerobic digestion, biogas production rate, methane.*

Date of Submission: 05-11-2020 Date of Acceptance: 18-11-2020

I. INTRODUCTION

Anaerobic digestion is the biological process through which biogas is produced (CH4 and CO2) from organic matter through the concerted action of a mixed population of microbial species, in the absence of oxygen. The productivity of biogas per unit volume and time is the most important index of the performance (effectiveness) of an anaerobic reactor. Due to the fact that there exists a hydraulic retention time which maximizes this performance index, the most decisive factor in optimizing an anaerobic reactor is the optimal choice of the hydraulic retention time. The optimal value of the hydraulic retention time depends on the composition of the feed. When the composition of the feed is altered (something which often happens in waste-fed digesters), the use of process control schemes is required, in order to secure operation at the optimal hydraulic retention time for the altered properties of the feed. In a previous work with an experimental anaerobic reactor (CSTR), which was fed with a glucose-based medium, a model-based feedback control law was implemented (Savoglidis et al. 2010, Syrou et al. 2004, Karafyllis et al. 2006, Karafyllis et al. 2008) to secure fast transition to the optimum steady-state when there was a change in the feed concentration. In the present work, the same experimental apparatus and the same control law were used, with the difference that the feed of the digester was a synthetic solution of acetic acid.

The study of acetic acid as the key organic source in a feed medium is particularly significant, since quite often, a two-stage process is used (Largus et al. 2004, Ahring et al. 2003). The first stage, consists of a hydrolyzing reactor, typically has a low retention time (of the order of a few hours) and it generates hydrogen which is a useful by-product as it may itself be used as a fuel e.g. in a fuel cell (Nandi and Sengupta 1998, Li and Fang 2007, Zoetemeyer et al. 1982) and a mixture of volatile fatty acids, mostly acetic acid. The second reactor then, which is a methanogenic reactor, receives the liquid effluent of the first reactor (mostly acetate) and coverts acetate to methane. This second reactor is actually characterized by much higher retention times (of the order of days), since methanogenesis is a slow step. Such a two-reactor configuration has been shown to have significant advantages, the most important ones being a much more stable operation and the production of hydrogen gas, as a by-product. As methanogenesis is the slow step, it becomes particularly important to operate the methanogenic reactor at the optimum retention time. This is attained in the present work through the use of a feedback process control algorithm, which is based on a simple (two-state) model of the methanogenic reactor.

II. EXPERIMENTAL PROCEDURE

2.1Materials and methods.

For the needs of the experiment, a mesophilic (35-37 ^{o}C) CSTR-type anaerobic reactor was used. The capacity was 3 litres (or 3 l). The reactor was started up with anaerobic biomass taken from a municipal sludge processing anaerobic digester. The feed to the reactor was a sterilized synthetic solution, containing acetic acid

and other necessary nutrients, given in Table 1. A peristaltic computer-controlled pump was used for feeding. As a result, following some acclimation time, a culture of acetoclastic methanogens prevailed in the reactor.

Table1.Composition of synthetic solution of acetic acid.

Components	Concentration (g/l)
$(NH_4)2HPO_4$	0.0721
$FeSO_4 *7H_2O$	0.07
$CaCL_2*2H_2O$	0.225
NH_4Cl	0.359
$MgCl_2*6H_2O$	0.162
KCl	1.17
$MnCl_2*4H_2O$	0.018
$CoCl_2*6H_2O$	0.027
H_3BO_3	0.00513
$CuCl_2*2H_2O$	0.00243
$Na_2MoO_4*2H_2O$	0.0023
$ZnCl_2$	0.00189
$NiCl_2*6H_2O$	0.002
H_2WO_4	0.0001
$NaHCO_3$	5
Yeast Extract	1.33
Peptone of Casein	1.33
CH_3COONa	14.24

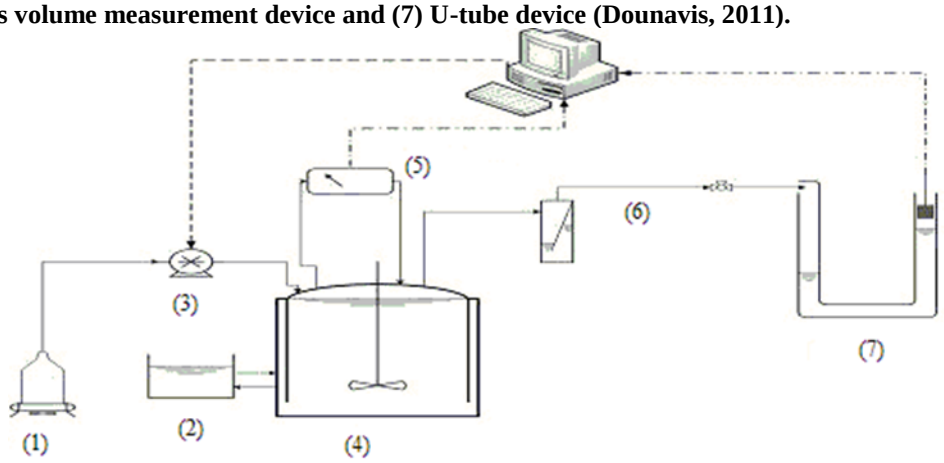
The experimental apparatus was equipped with the essential measurement devices for monitoring and control purposes. In particular, a system (U-tube) of continuous measurement for the produced biogas, based on the method of displacement of a predetermined volume of liquid, was used. Furthermore, details for this U-tube device may be found very easily (Dounavis 2011).

Monitoring of the process was carried out in a LabView environment. After a steady state for a hydraulic retention time of 6 days was achieved, additional measurements for pH, volatile suspended solids, volatile total solids and volatile fatty acids, through regular sampling were taken.

In order to determine the percentage of methane in the biogas, which is also the final desirable product of anaerobic digestion, an LMSxi Type G4.18 analyzer was used, which is based on a non-destructive photometric measurement of methane and carbon dioxide composition.

The biogas production rate is the most important measurement, typically used for monitoring and control of anaerobic digesters (Ehlinger et al. 1994, Moletta et al. 1994, Estaben et al. 1997, Renard et al. 1988, Renard et al. 1991, Boscolo et al. 1993, Steyer et al. 1997). The biogas methane content depends on the oxidation state of the waste/substrate used. Finally, the pH and the alkalinity in the reactor affect the release of CO_2 gas and consequently the composition of biogas.

Figure1. Schematic representation of experimental apparatus of automatic control process: (1) solution of feed, (2) buffer, (3) peristaltic computer-controlled pump, (4) bioreactor, (5) biogas analyser, (6) biogas towards volume measurement device and (7) U-tube device (Dounavis, 2011).



As shown in Figure 1, the computer takes measurements from the gas measurement device and the biogas composition analyser and the retention time to be applied is calculated through the control law. The retention time is controlled by manipulating the percentage of time that the peristaltic pump is on, in a sufficiently frequent on/off switching scheme. For following-up the anaerobic reactor, measurements of the pH, COD, alkalinity, the daily biogas and methane production and finally the total and the volatile suspended solids were carried out according to the Standard Methods for the Examination of Water and Wastewater.

2.2 Modelling of anaerobic digestion

In the vicinity of operating conditions corresponding to maximal biogas production, the process becomes marginally stable. Even small disturbances could potentially destabilize the system and finally lead it to washout.

For the purpose of developing a process control algorithm, a simple model was developed, which describes anaerobic digestion as a single-step biochemical process, without taking into consideration the complicated biochemical reactions. Such a two-state model describes the process of methanogenesis only, without accounting for hydrolysis and acidogenesis. This is a reasonable assumption in the case of an acetate-fed digester, because the feed is composed of a synthetic solution of mainly acetic acid and the transformation of organic material to biogas is directly carried out directly via the stage of methanogenesis. It should be mentioned that such a two-state model may be sufficient also for other readily degradable substrates (such as glucose) as demonstrated very simply (Savoglidis 2010). The reason is that hydrolysis and acidogenesis may be assumed instantaneous for all practical purposes, as methanogenesis is the rate-controlling step.

The microbial growth of microorganisms is assumed to follow Monod kinetics:

$$\mu(s) = \frac{\mu_{\max} s}{K_S + s} \qquad \text{(Equation 1)}$$

The biogas production rate is considered to be the measured output:

$$Q = Y_{meth}\mu(s)x \qquad \text{(Equation 2)}$$

With the above assumptions, the simplified two-state Monod model for the anaerobic digestion of acetate is (Bailey and Ollis 1986, Smith and Waltman 1995):

$$\frac{dx}{dt} = (-D + \mu(s))x \qquad \text{(Equation 3)}$$

$$\frac{ds}{dt} = D(S_0 - s) - \frac{\mu(s)x}{Y_{x/s}} \qquad \text{(Equation 4)}$$

where **x** is the biomass concentration, s is the substrate concentration (in COD), **D** is the dilution rate, μ_{max} is the maximum specific growth rate, K_s is the saturation constant, S_0 is the feed substrate concentration, Y_{meth} is the yield coefficient for methane production and $Y_{x/s}$ is the biomass yield.

At this point, it should be mentioned that a hydraulic retention time of 6 days was studied, which corresponds to the dilution rate, D = 0.167 d^{-1}, and a sudden pulse disturbance was imposed in the composition of the feed (see the Figures 2 and 3). In particular, the concentration of acetic acid in the feed, which was 5 g/l,

was increased to 7.5 g/l for 3 days and then it was decreased back to 5 g/l, as it was initially. Figures 2 and 3 present the data, which were used for model development. It can be seen from the following experimental results (see the Figures 2 and 3)the higher concentration of digester feed, the more biogas production with the simultaneoustotal soluble COD consumption.

Figure2. Concentration of total (TSS) and volatile (VSS) suspended solids and dissolved COD (between 6th and 9th day, a pulse disturbance was imposed).

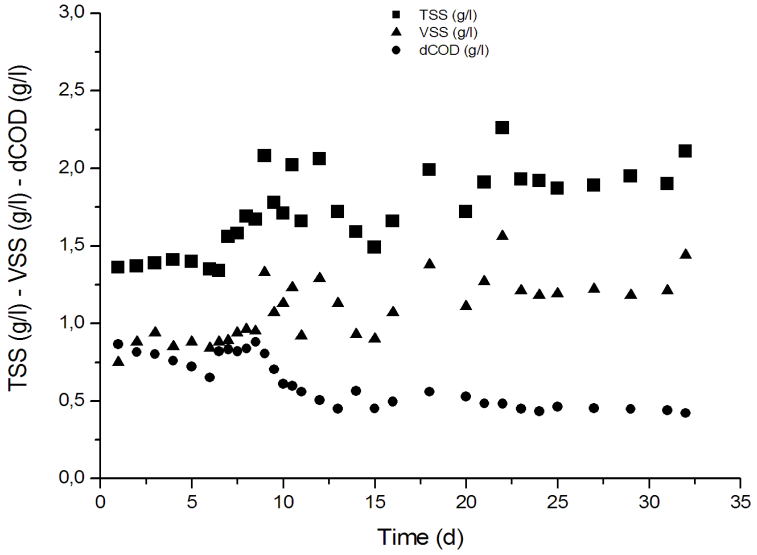
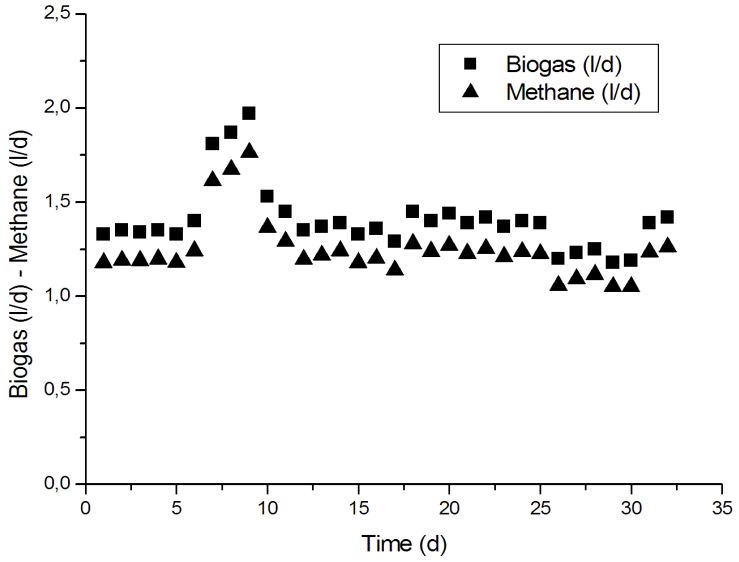


Figure3. Biogas and methane production rate (between 6th and 9th day, a pulse disturbance was imposed).



2.3 Parameter Estimation for the model

Parameter estimation was carried out in the Aquasim 2.0 environment (Reichert 1998), which constitutes a significant tool for the simulation of chemical and biochemical reactors, as well as for the analysis of sensitivity and parameter estimation. The estimated parameter values of the two-state model are given in Table 2. In Figures 4, 5 and 6, it is shown that the experimental results are very satisfactory according to the prediction of the simplified model.

Table2.Estimated Parameters for the 2-state model.

Parameters	Value
μ_{max}	$0.3701 d^{-1}$
K_s	0.6785 g COD / l
$Y_{x/s}$	0.1157 g COD_x / g COD_s
Y_{meth}	6.6901 $l_{methane}$ $l_{reactor}$ / gCOD_x

Figure4. Experimental and calculated biomass (g/l).

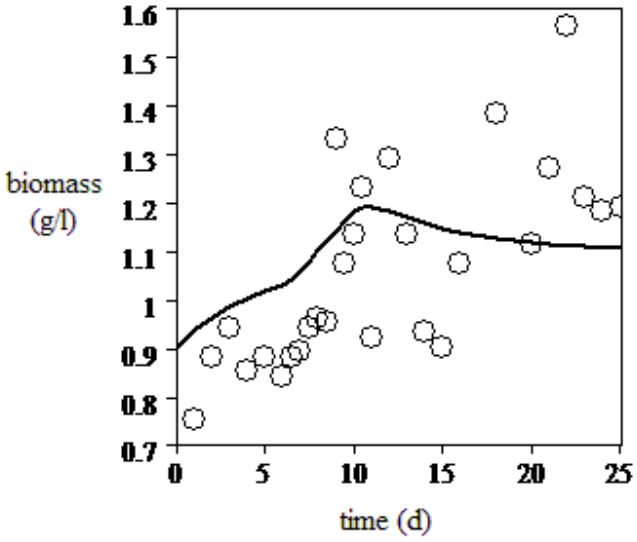


Figure5. Experimental and calculated substrate (dissolved COD) values (g/l).

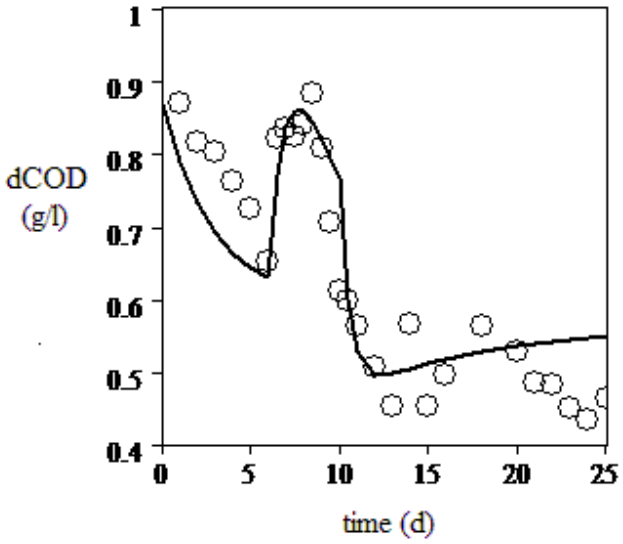
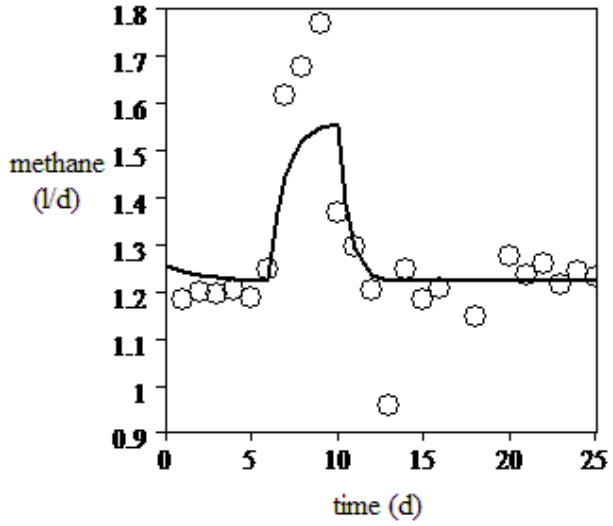


Figure6. Experimental and calculated methane production rate (l/d).



2.4 Output feedback control of the anaerobic digester

The basic aim of process control of a continuous anaerobic digester is its stabilization at a given steady state, such as the optimal steady state, which maximizes the production rate of methane. For control purposes, a successful practical approach is a constant-gain output feedback control law, which is based on the idea of maintaining a constant ratio of the production rate of methane to organic loading rate in the feed (Pullammanappallil et al. 1998, Dounavis 2011). The theoretical properties of this control law are well established (Syrou et al. 2004, Karafyllis et al. 2006). This control law guarantees global stabilization of the process at the optimal steady state, and it is given by the relation (Dounavis et al. 2012):

$$D = \frac{Q}{Y_{meth} Y_{x/s} (S_0 - s_s^{des})} \quad \text{(Equation 5)}$$

where

$$s_s^{des} = s_s^{opt} = -K_S + \sqrt{K_S \cdot (K_S + S_0)} \quad \text{(Equation 6)}$$

and $\mathbf{s_s^{des}}$ is the design steady state value, corresponding to the optimal steady state. The control law (Eq. 5) has the following important properties: a) it is proportional (with respect to the measurement) with a constant gain, which depends on the design steady state b) it is robust to changes of the feed substrate concentration S_0 and c) the closed loop system is globally asymptotically stable over the entire first quadrant (Karafyllis et al. 2008).

Under the above control law, the closed loop system becomes:

$$\frac{dx}{dt} = (1 - \frac{x}{Y_{x/s}(S_0 - s_s^{des})})\mu(s)x \quad \text{(Equation 7)}$$

$$\frac{ds}{dt} = \frac{s_s^{des} - s}{Y_{x/s}(S_0 - s_s^{des})}\mu(s)x \quad \text{(Equation 8)}$$

2.5Optimal steady state for the anaerobic digester

For the values of model parameters, which were determined by the open loop experiments, the optimal steady state, which corresponds to the maximum methane production rate, can be calculated.

At the optimal steady state:

$$D_s = \mu(s_s) \quad \text{(Equation 9)}$$

$$x_s = Y_{x/s}(S_0 - s_s) \quad \text{(Equation10)}$$

The biogas production rateis:

$$Q_s = Y_{meth} Y_{x/s} \mu(s_s)(S_0 - s_s) \quad \text{(Equation 11)}$$

Therefore, tofindtheoptimalsteadystate:

$$\frac{dQ_S}{ds} = 0 \quad \text{(Equation 12)}$$

And from the Equations 10, 11 and 12, it is calculated that:

$$Y_m Y_{x/s} \cdot \left[\frac{d\mu}{ds}(s_s) \cdot (S_0 - s_s) - \mu(s_s) \right] = 0 \quad \text{(Equation 13)}$$

The optimal value for the substrate concentration is:

$$s_s^{opt} = -K_S + \sqrt{K_S(K_S + S_0)} \text{ (Equation 14)}$$

$$s_s = s_s^{des} = s_s^{opt} \quad \text{(Equation 15)}$$

For the reference value of the organic load in the feed S_{0s} = 10 g/l and the values of the parameters given in Table 2, the optimal steady state corresponding to maximal production rate of methane is:

The biomass concentration is:

$$x_s^{opt} = 0.9241 g/l \quad \text{(Equation 16)}$$

The substrate concentration is:

$$s_s^{opt} = 2.0132 g/l \quad \text{(Equation 17)}$$

The Dilution rate is:

$$D^{opt} = 0.2768 d^{-1} \quad \text{(Equation 18)}$$

The Methane production rate is:

$$Q^{opt} = 1.7113 l/d \quad \text{(Equation 19)}$$

From the bibliography (Savoglidis 2010), it is concluded that the optimal steady state of the process will be for the hydraulic retention time between three (3) and five (5) days. Therefore, the proposed optimal hydraulic retention time (3.61 days) is within the theoretical limits. The above is the reference steady state, to be used in subsequent calculations and experiments. Furthermore, phase portraits for the open and closed loop system respectively are shown in Figures 7 and 8.

Figure7. Phase portrait of the open loop system.

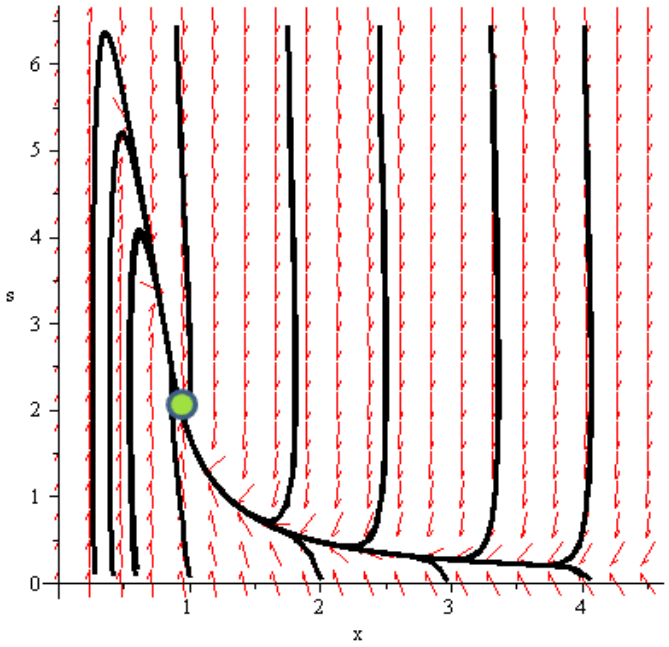
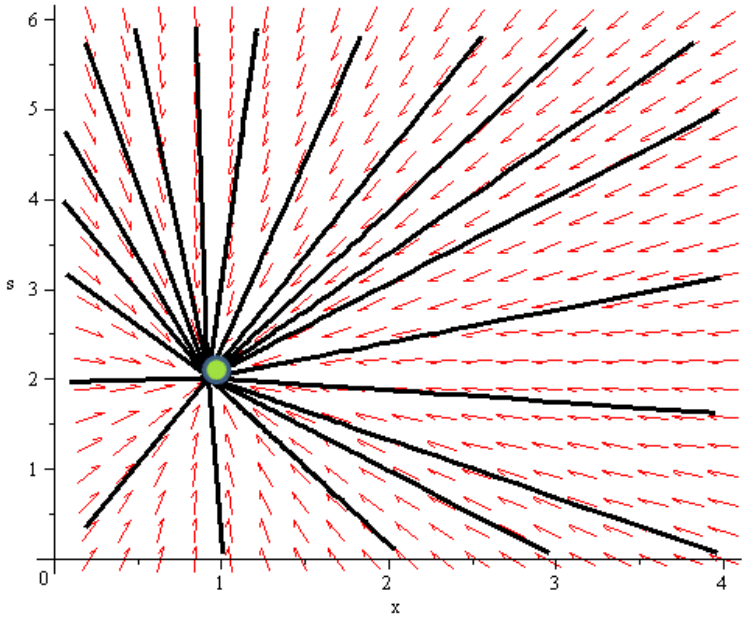


Figure8. Phase portrait of the closed loop system.



The phase portraits of Figures 7 and 8 depict the regulatory behaviour of the system without and with the controller. Specifically, as it can be seen, the optimal permanent state is locally asymptomatic stable, but its stability range is quite limited due to the existence of unstable permanent state near it. There are trajectories which lead to the stable permanent state near the point of the stable and unstable equilibrium point and very close to them some other orbits which lead the system to biomass leaching. This dynamic behaviour makes the process of anaerobic digestion quite sensitive to disturbances. In the closed loop diagram, the dynamics of the process changes and the trajectories of the system approach the optimal state with straight lines, faster and with smaller deviations. Therefore, the controller enables a more direct approach to the system steady state and it turns out that the response is also faster (Savoglidis and Kravaris 2013).

2.6Simulations for the open and closed loop system after the upward and downward step change

a) The upward step change

In addition to regulatory behaviour, the controller can result in improved response in the transition from one steady state to another. In particular, consider that (for time t=0) an upward step change is imposed on the organic load in the feed S_0 (of size 2.5 g/l). For the new value of S_0 (S_0^{new} =12.5 g/l), the new optimal steady state is:

$$x_s^{new} = 1.179 g/l \quad \text{(Equation20)}$$

$$s_s^{new} = 2.312 g/l \quad \text{(Equation 21)}$$

$$D_s^{new} = 0.2861 d^{-1} \quad \text{(Equation22)}$$

$$Q_s^{new} = 2.2564 l/d \quad \text{(Equation 23)}$$

In Figures 9 and 10, the responses of the open loop and of the closed loop system for the biomass x and the substrate s, for the applied step change are compared.

Figure9. Open loop (red curve) and closed loop (green curve) response for biomass concentration (x).

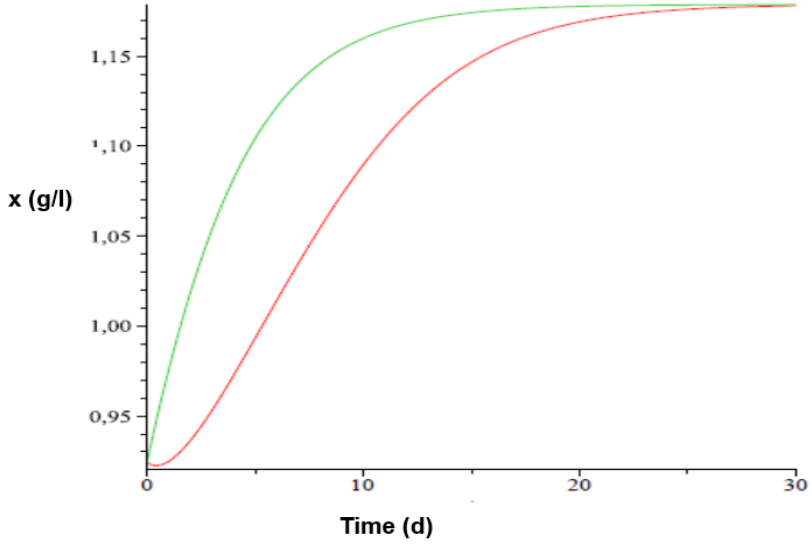
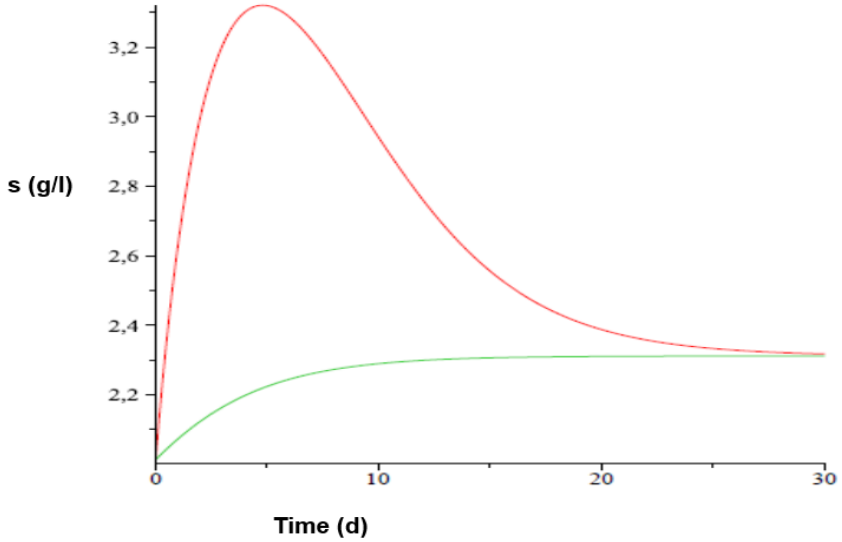


Figure10. Open loop (red curve) and closed loop (green curve) response for the substrate concentration (s).



b) The downward step change

In addition to regulatory behaviour, the controller can result in improved response in the transition from one steady state to another. In particular, consider that (for time t=0) a downward step change is imposed on the organic load in the feed S_0 (of size 2.5 g/l). For the new value of S_0 (S_0^{new} =7.5 g/l), the new optimal steady state is:

$$x_s^{new} = 0.6737 g/l \quad \text{(Equation 24)}$$

$$s_s^{new} = 1.6772 g/l \quad \text{(Equation 25)}$$

$$D_s^{new} = 0.2822 d^{-1} \quad \text{(Equation 26)}$$

$$Q_s^{new} = 1.1876 l/d \quad \text{(Equation 27)}$$

In Figures 11 and 12, the responses of the open loop and of the closed loop system for the biomass x and the substrate s, for the applied step change are compared.

Figure11. Open loop (red curve) and closed loop (green curve) response for biomass concentration (x).

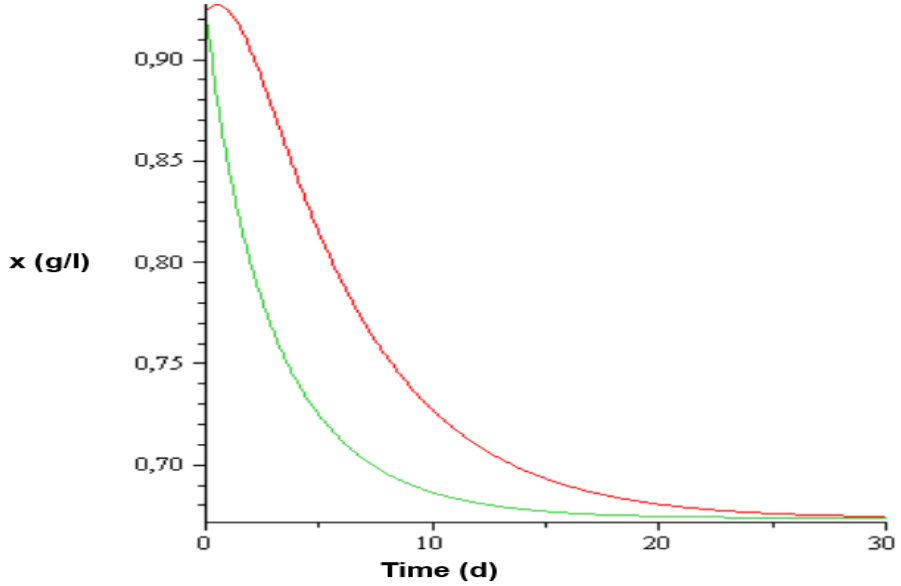
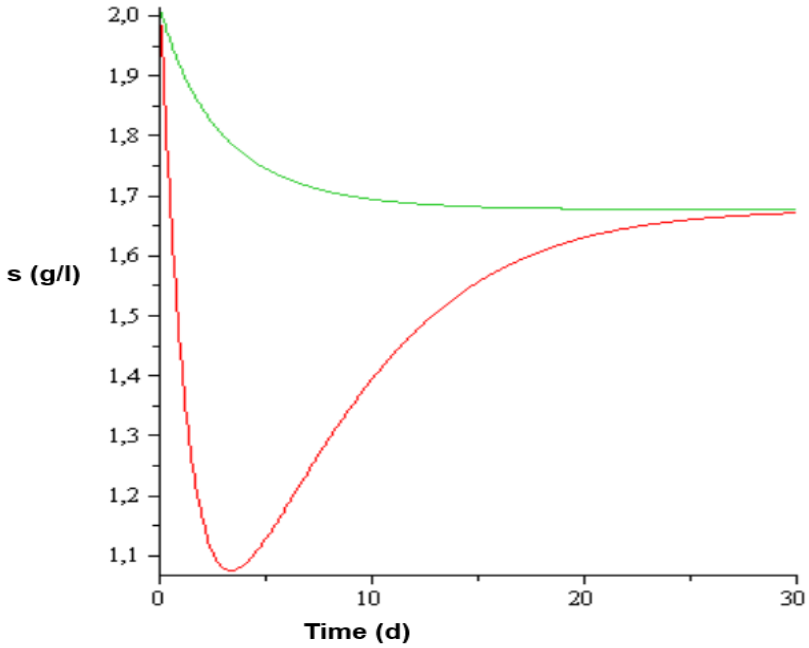


Figure12. Open loop (red curve) and closed loop (green curve) response for the substrate concentration (s).



As it is observed, the response of the closed loop system to the new optimal steady state is much faster than the response of the open loop system. It also avoids an overshoot in s, which is observed in the open-loop case.

A significant consequence of the increase of the speed of response (closed loop system) is a much smaller loss of methane production rate (Equation 28) with the application of the control law (Equation 5) than in the open loop system at the transition period from the old optimal steady state to the new optimal steady state (see the Figures 13 and 14).

$$R = Q^{opt}t - \int_0^t Q(\tau)d\tau \quad \text{(Equation 28)}$$

The loss of methane production rate, as it is shown in Figures 13 and 14, is significantly smaller in the closed loop system than in the open loop system because the approach to the new optimal steady state becomes directly, faster and with smaller deviations. Finally, it may be proved that the particular control law globally

stabilises the system even in the case of discrete-time measurement, without the total stability being lost (Savoglidis 2010).

Figure13. Loss of methane production rate under open loop (red curve) and closed loop (green curve) operation (the upward step change).

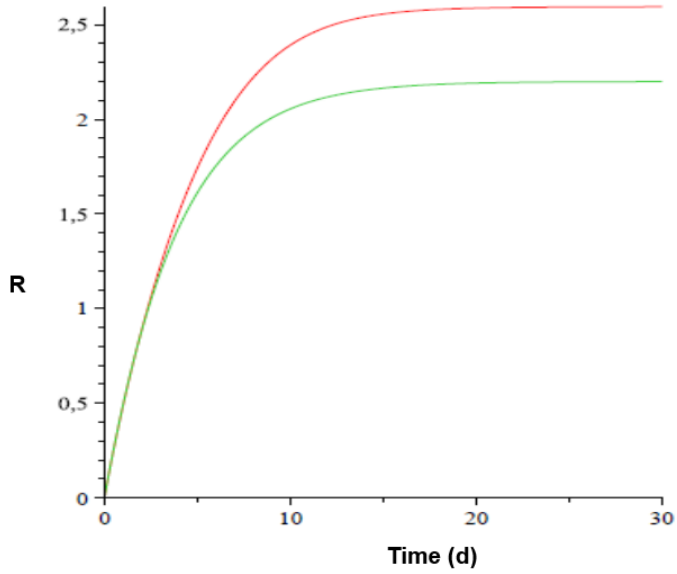
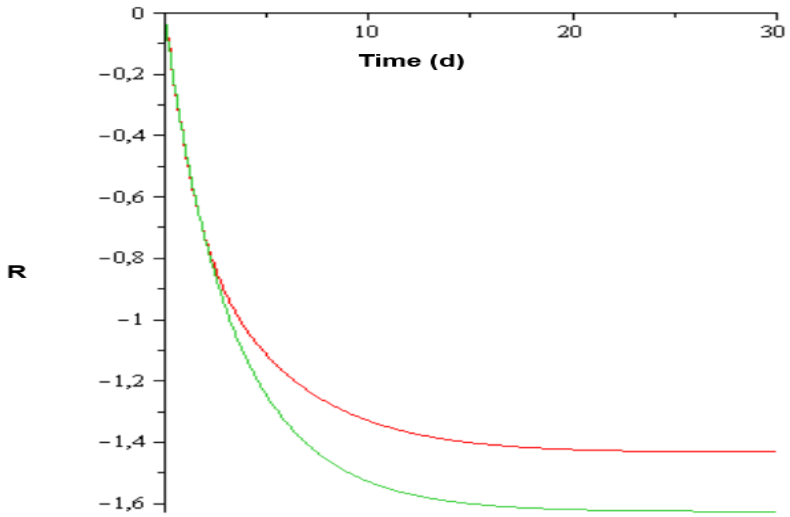


Figure14. Loss of methane production rate under open loop (red curve) and closed loop (green curve) operation (the downward step change).



III. RESULTS AND DISCUSSIONS

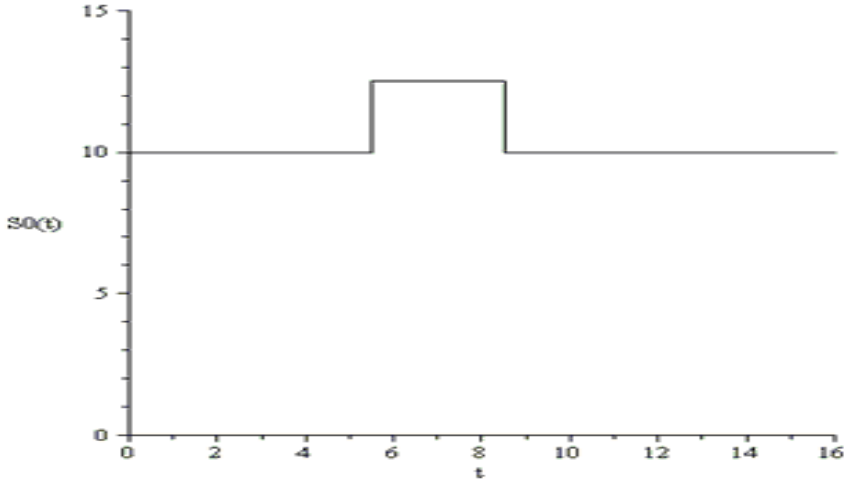
3.1. Experimental testing of open and closed loop system response in the case of pulse-up disturbances

For the evaluation of the control law, two pulse disturbances were imposed on the organic loading in the feed of the anaerobic reactor: a) an upward pulse change of the organic load in the feed of the reactor and b) a downward pulse change of the organic load in the feed of the reactor.

It is worth noting that the reactor (in both the pulse-up and the pulse-down disturbance) was also at the same steady state before the entry of pulse disturbances, which corresponds to an organic loading in the feed equal to S_0^{ref} = 10 gCOD/l .

The pulse-up disturbance in feed concentration was of size 2.5 g/l (so that S_0^{new} = 12.5 g/l) for three days, and after this time period it changed back to its original value (S_0^{ref} = 10 g/l), as it was initially, a) for the closed loop system without the disturbance being accounted for in the control law and b) for the open loop system (see Figure 15).

Figure15. Upward pulse disturbance on the organic load in the feed.



Also, the experimental results and simulations for the pulse-up disturbance in the feed both for the open and the closed loop system are presented in Figures 16 to 19.

Figure16.Simulation and experimental data for biomass concentration (pulse-up disturbance, S_0^{new} = 12.5 g/l, for 3 days, open and closed loop).

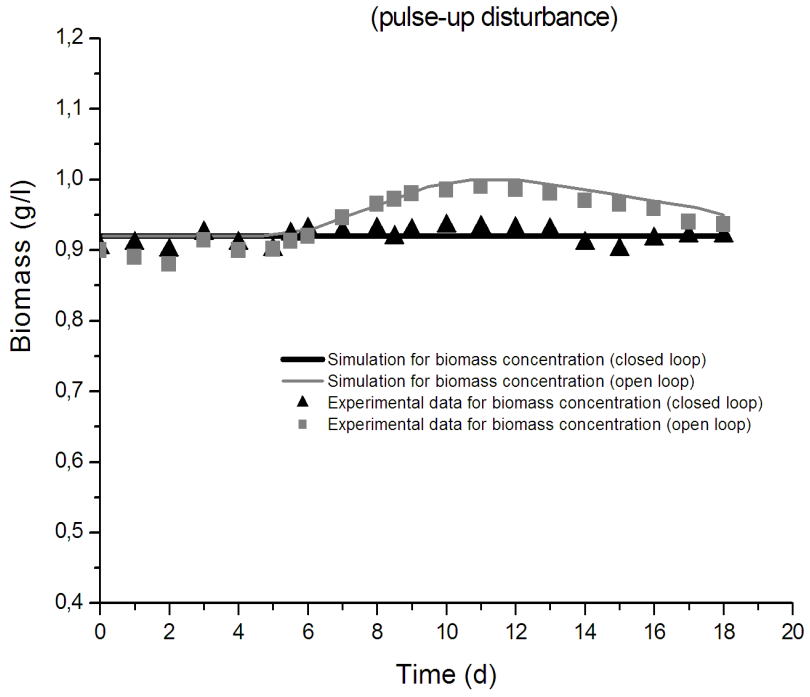


Figure17. Simulation and experimental data for substrate concentration (pulse-up disturbance, S_0^{new} = 12.5 g/l, for 3 days, open and closed loop).

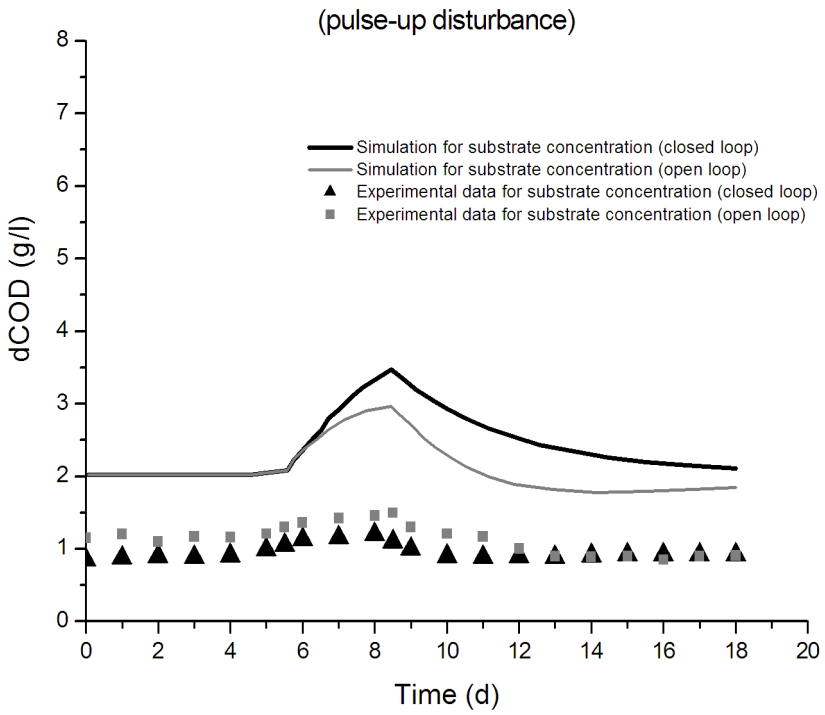


Figure18. Simulation and experimental data for methane production rate (pulse-up disturbance, S_0^{new} = 12.5 g/l, for 3 days, open and closed loop).

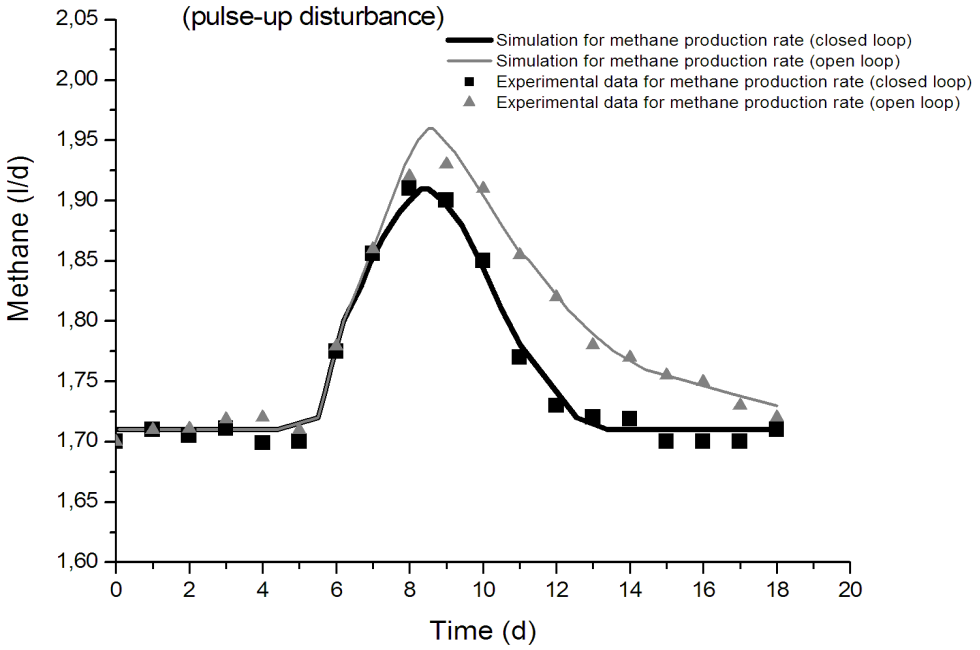
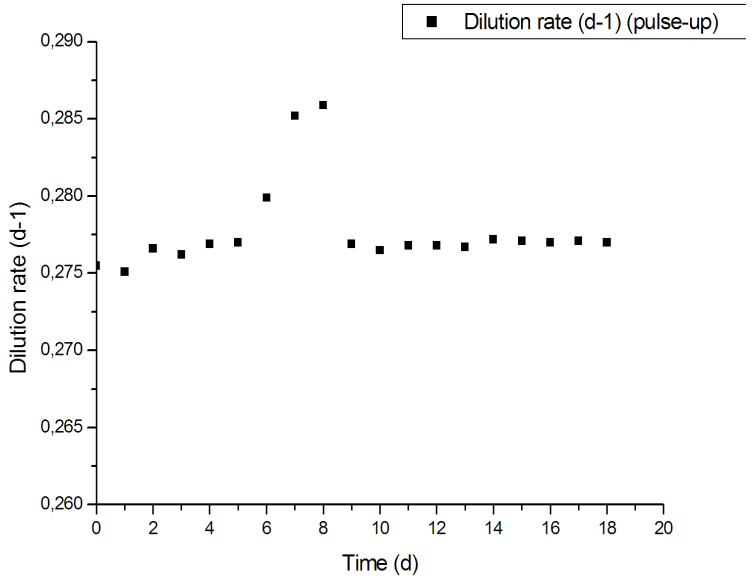


Figure19. Dilution rate D (pulse-up disturbance, S_0^{new} = 12.5 g/l, for 3 days, closed loop).

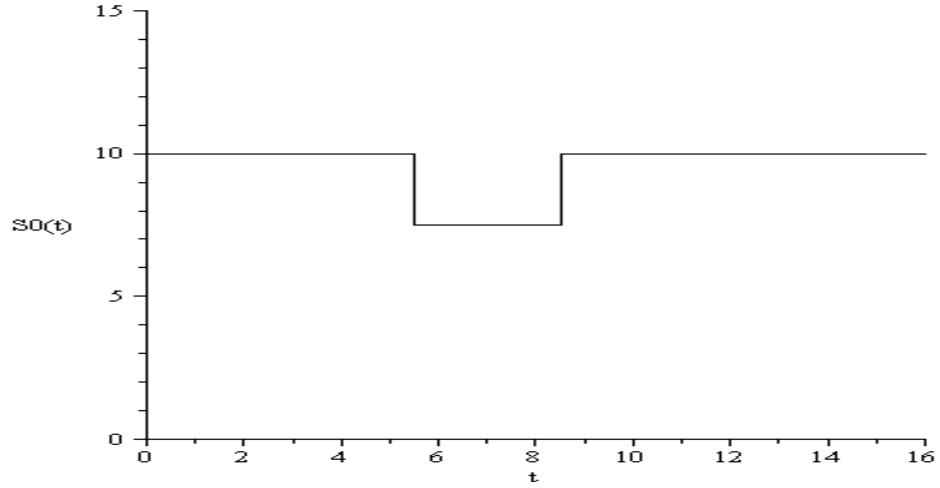


As it is observed in Figures 13 to 16, the increased organic loading in the feed has as a significant effect, which is the increase in the methane production rate, and because the control law is proportional, the system is led to an increase of the dilution rate (a decrease of the retention time). It is seen that the biomass and methane production data are in good agreement with the simulated results in both the open-loop and the closed loop cases. As far as the COD is concerned, the trend in experiments is the same as that in simulations, but there is a difference in the values of the COD (approx. 1 g/l, which is about 10% of the base value). This may be attributed to the presence of non-readily degradable substrates contained in the yeast extract or alternately, to the high sensitivity of the Ks value on the dilution rate (the optimal retention time is close to 4 days, but the model was developed for a retention time of 6 days).

3.2 Experimental testing of open and closed loop system response in the case of pulse-down disturbances

A pulse-down disturbance has also been applied in the feed concentration of size 2.5 g/l (so that S_0^{new} = 7.5 g/l) for three days, and after this time period it changed back to its original value (S_0^{ref} = 10 g/l), as it was initially, a) for the closed loop system without the disturbance being accounted for in the control law and b) for the open loop system (see Figure 20).

Figure20. Downward pulse disturbance on the organic load in the feed.



What is more, the experimental results and simulations for the pulse-down disturbance in the feed both for open and closed loop are presented in Figures 21 to 24.

Figure21. Simulation and experimental data for biomass concentration (pulse-down disturbance, S_0^{new} = 7.5 g/l, for 3 days, open and closed loop).

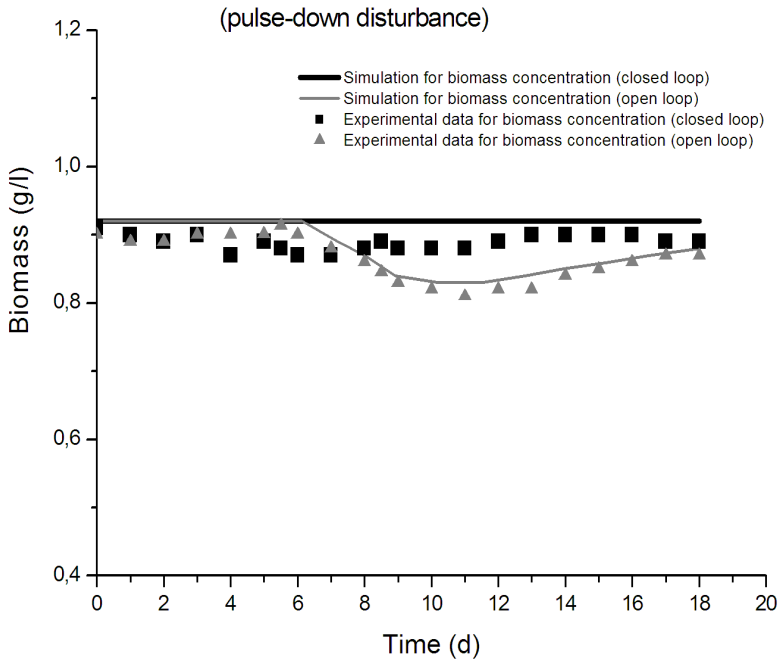


Figure22. Simulation and experimental data for substrate concentration (pulse-down disturbance, S_0^{new} = 7.5 g/l, for 3 days, open and closed loop).

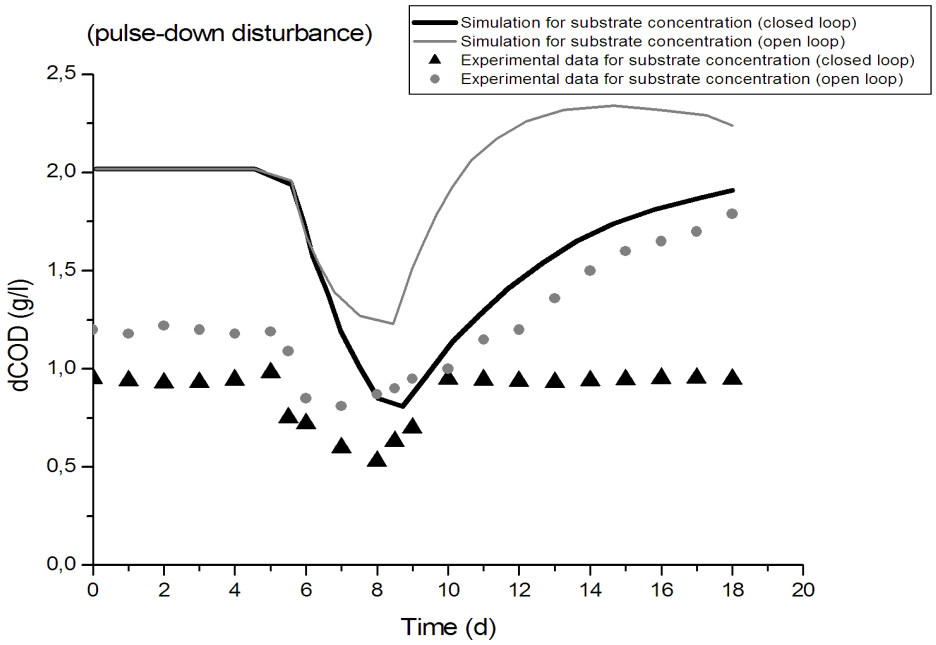


Figure23. Simulation and experimental data for methane production rate (pulse-down disturbance, S_0^{new} = 7.5 g/l, for 3 days, open and closed loop).

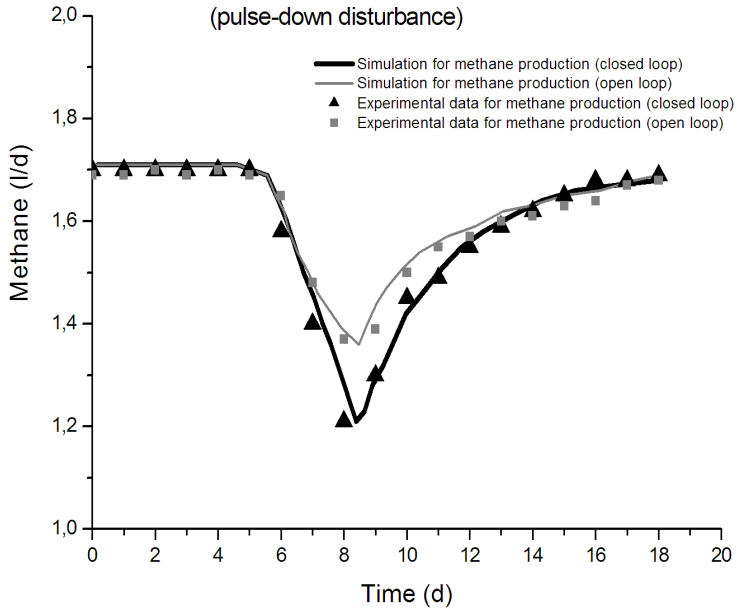
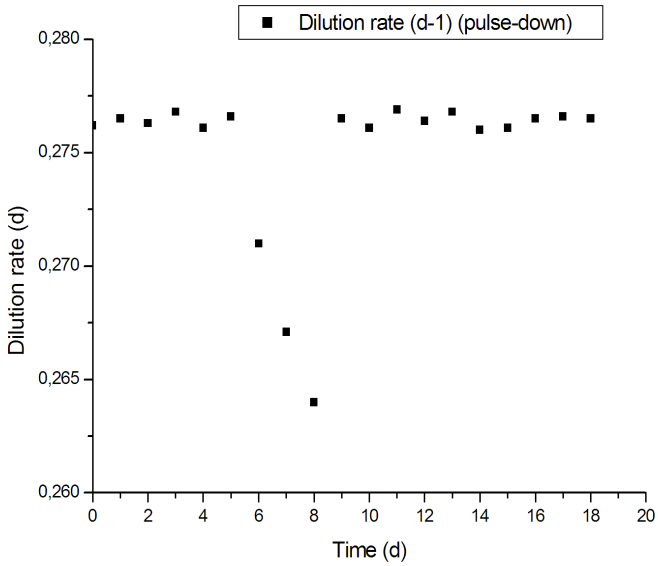


Figure24. Dilution rate D (pulse-down disturbance, S0new = 7.5 g/l, for 3 days, closed loop).



As it is observed in Figures 21 to 24, the decreased organic load in the feed is accompanied by a reduction of the dilution rate and a reduction of the methane production rate. The controller, just like in the pulse-up case, succeeds in bringing the system back to the initial optimal steady state, after the end of the pulse disturbance and this occurs with a smaller "excursion" of the state variables.

IV. CONCLUSION

In the present work, the problem of controlling an acetate-fed anaerobic CSTR was studied. A simple two-dimensional model for the description and the simulation of the anaerobic digester was developed. For the stabilisation of the process, a control law was applied, which a) is quite robust in changes in the organic load, b) completely stabilizes the system even in the case of discrete measurement, without losing total stability, c) leads to higher biogas production rate during the transition phase to the new permanent state in the stepwise increase of organic load and d) stabilises the system globally, resulting in faster transition to the steady state in the closed

loop system. Thus, at the period transition from a steady state to another, the loss in the methane production rate (R) are remarkably smaller than in the case without control both an upward and downward step change of the organic load (S0). The ability of the controller to restore the system to the initial steady state very fast was experimentally confirmed, in both an upward and a downward pulse disturbance in the feed concentration where the biomass concentration is stable and the methane production is higher. The experimental results for both closed and open loop cases matched the simulations satisfactorily. Finally, the proposed optimal hydraulic retention time is shown that it is within the theoretical limits which is confirmed from the experiments for the closed loop system with the pulse disturbance in the organic load.

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Athanasios Sotirios Dounavis. "Output Feedback Control of an Acetate-Fed Anaerobic Digester." *International Journal of Engineering and Science*, vol. 10, no. 11, 2020, pp. 51-67.