Integration of equalisation tanks within control strategies for anaerobic reactors. Validation based on ADM1 simulations.

J. Alferes, J. L. García-Heras, E. Roca, C. García, and I. Irizar

ABSTRACT

The combination of equalisation tanks and anaerobic digesters represents a typical design scenario within the treatment of industrial wastewaters. In this context, if the hydraulic capacity of the equalisation tanks is effectively handled, significant improvements in the performance of anaerobic digesters can be achieved in terms of process stability and biogas production. This paper presents a rule-based control strategy for anaerobic reactors with the objective of maximising in the long-term the net production of biogas. The control algorithm combines real-time information about the state of the anaerobic digester with on-line measurements about the wastewater volume of the equalisation tank in order to set permanently the appropriate production of biogas. Such a strategy guarantees a continuous influent flow so that emptying and overflowing episodes in the equalisation tank can be prevented. Aiming at a further full-scale implementation, only reliable and cost-effective on-line instrumentation has been considered within the control architecture. The performance of the proposed control approach has been validated for an anaerobic hybrid configuration (AHR) by simulation using the IWA ADM1 model.

Key words | ADM1, anaerobic digestion, automatic control, biogas production, equalisation tank

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INTRODUCTION

An important drawback of anaerobic digesters (AD) is the high sensitivity of this process to different types of disturbances such as: (1) organic underloads and overloads; (2) the presence of inhibitory substances in the wastewater; and (3) environmental changes (pH, temperature, etc.). Therefore, the incorporation of on-line instrumentation as well as the deployment of real-time monitoring and control tools becomes essential to detect quickly all these situations and to respond accordingly. Despite recent developments in advanced on-line instrumentation for AD processes (COD, VFA, alkalinity …), this instrumentation is still too expensive and unreliable to be applied to full-scale practical control (Spanjers & Van Lier 2006). Alternatively, some software sensors have been proposed to get on-line estimations of alkalinity, VFA and COD, thus enabling the implementation of control approaches on the basis of such observations (Bernard *et al.* 2001). Likewise, some experimental studies demonstrate that very simple and effective control solutions can be developed using only low-cost and reliable sensors (pH, methane and biogas). In an AD pilot-plant, Steyer *et al.* (1999) implement an algorithm that introduces periodic disturbances on purpose with the objective of maximising the instantaneous production of methane. With the same objective, Liu *et al.* (2004, 2006) design and verify experimentally in a lab-scale plant a rule-based extremum-seeking algorithm that only requires pH and biogas flow rate sensors.

The treatment of industrial wastewaters often demands configurations where the biological process has to be operated with equalisation tanks. Equalisation tanks are especially advantageous in the case of AD since effective handling of the hydraulics in these tanks can ensure a more

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stable influent load to the reactor thereby improving the process performance in terms of stability and biogas production. This paper describes the design of a new control strategy based on exploiting the hydraulic capacity of the equalisation tanks to regulate the tendency of the process towards higher or lower biogas productions. An Anaerobic Hybrid Configuration (AHR) has been selected to assess the performance of the control strategy by simulation.

MATERIALS AND METHODS

Mathematical modelling of the anaerobic hybrid process

The mathematical description of biochemical transformations was based on the ADM1 model (Batstone *et al.* 2002). Likewise, some ADM1 extensions such as those proposed by De Gracia *et al.* (2004) and Soroa *et al.* (2006) were introduced. The hydrodynamics of the anaerobic hybrid reactor (AHR - combination of UASB and anaerobic filter placed in series) was modelled as follows: (1) hypotheses of constant volume and complete-mixing were assumed to model the UASB zone; and (2) neither volume nor biochemical reactions were considered in the anaerobic filter and only the effect of solids retention was modelled by means of the F parameter ($0 \leq F \leq 1$). Thus, the total solids concentration X_e at the effluent depends on the F parameter as follows: $X_e = (1 - F) \cdot X_r$ (Figure 1). An equalisation tank was also included within the whole model so as to reproduce more accurately a practical scenario for full-scale plants. Variable volume and no biochemical transformations were specified for the mathematical model of this tank. The plant-model was implemented in Matlab/ Simulink.

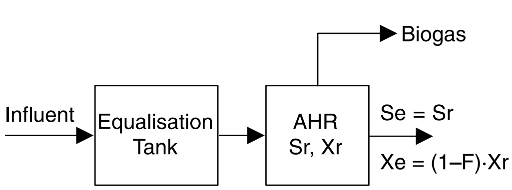

Figure 1 | Block diagram of the plant model.

Description of the proposed control approach

Only reliable and cost-effective on-line instrumentation has been considered for the design of the control strategy. In this respect, the control approach proposed in this paper has been designed taking as reference the control strategy described in Liu *et al.* (2004). Using pH and gas flow on-line measurements, the Liu controller (LC) employs a cascaded structure embedded into a simple rule-based supervisory system to achieve a high-loading rate operation and a good rejection of disturbances. At regular intervals, the supervisory module processes the values of the D variable (defined as the difference between the biogas flow rate, GF_m, and its setpoint value, GF_{sp}) in order to diagnose if the process is close to or has reached its maximum treatment capacity. Based on such observations, the supervisory system applies incremental steps to GF_{sp} so as to lead the process towards its maximum instantaneous biogas production. In order for GF_{real} to follow the increments of GF_{sp}, the outer and inner loops of the embedded cascaded controller act by adjusting the pH set-point (pH_{sp}) and the influent flow rate (Q_{feed}). The rule-based strategy introduces two parameters, D_{max} and D_{min}, whose values set the limits of three operating regions in relation to the D variable. Within each region the increments to be applied to GF_{sp} are specified (Figure 2). D_{max} and D_{min} represent the force that pushes the process towards its final operating point. Thus, depending on the selected values for D_{max} and D_{min}, different operating conditions with either lower or higher organic loading rates (OLR) can be promoted in the process. Liu *et al.* (2006) successfully verified the control strategy in a 1.5-litre lab-scale anaerobic digester. During the validation period, the application of constant values for D_{max} and D_{min} resulted in maximum instantaneous OLRs and, in addition, the process was maintained within its margins of stability. The controller response showed a

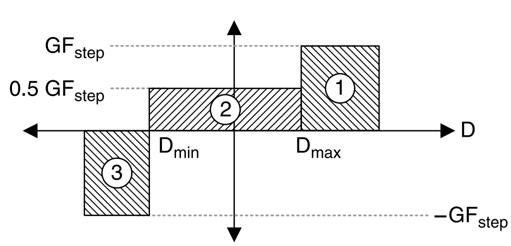

Figure 2 | Rule-based supervisory strategy.

satisfactory performance in handling different operating scenarios and disturbances such as start-up operation, underloads/overloads or sudden changes in reactor temperature.

Despite the excellent results of the LC in a small lab-scale plant, some practical considerations should be underlined before dealing with its implementation in a full-scale scenario that involves an equalisation tank. When constant values of D_{max} and D_{min} are tuned in order to maximise the production of biogas, the LC acts by keeping the influent flow rate to the anaerobic digester as high as possible; thus, the instantaneous OLR approaches the maximum treatment capacity of the plant. Nevertheless, a control strategy based on the application of high influent flow rates tends to progressively decrease the wastewater stored in the equalisation basin and, consequently, promotes the emptying of the tank. Every time an emptying event takes place, the LC must be switched off and, consequently, no biogas is produced in the anaerobic reactor. Moreover, this situation remains until the volume of wastewater in the equalisation tank reaches an appropriate level and the controller can be activated again. Such behaviour is illustrated in the Figure 3, where V_t, Q_{in} and V_{GF} represent the wastewater volume of the equalisation tank, the influent flow rate in the anaerobic digester and the accumulated biogas volume, respectively. The selection of more conservative values for D_{max} and D_{min} in order to limit the maximum production of biogas brings about lower OLRs and lower influent flow rates. While such a strategy reduces the frequency of the emptying events, it also promotes the opposite effect, i.e., the occurrence of overflowing events in the tank due to the fact that lower influent flow rates induce the progressive accumulation of wastewater.

The above considerations highlight the importance of combining the original LC with complementary strategies able to handle the hydraulic capacity of the equalisation basin so that both, emptying and overflow events can be prevented. In fact, by taking advantage of the dynamics in the equalisation tank, significant improvements can also be achieved in relation to the performance of the anaerobic digester. The incorporation of algorithms for controlling the instantaneous volume of wastewater in the equalisation tank ensures a more continuous influent flow rate that, as a result, increases both the digester efficiency and the net production of biogas. Figure 4 illustrates qualitatively the behaviour of the LC when a hydraulic control of the equalisation basin is incorporated (named “extended Liu Controller” - eLC). The underlying idea of the eLC is to permanently regulate the production of biogas, depending on the wastewater available in the equalisation tank. Thus, when the volume of wastewater in the tank decreases and gets close to its lower limit level the controller acts by progressively decreasing the influent flow rate and, therefore, the production of biogas. On the other hand, when the wastewater stored in the tank increases, the controller responds with a gradual increase in the influent flow so that the production of biogas is also increased. In comparison with the original approach, although the eLC leads to lower instantaneous productions of biogas flow rates, in the long-term the accumulated volume of biogas is higher (Figure 4). Figure 5 shows the whole architecture of the control approach proposed in this paper. The hydraulics of the equalisation tank are controlled by means of a rule-based strategy that monitors the volume of this tank and, depending on its on-line measurements, sets the appropriate values for D_{max} and D_{min}. Since these values determine if the process is to be operated at either lower or higher OLRs, the continuous tuning of these parameters acts as an automatic regulation of the force that pushes the process to reach lower or higher biogas productions.

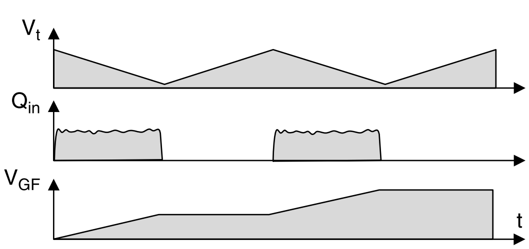

Figure 3 | Qualitative behaviour of the original Liu controller (LC) in a practical scenario.

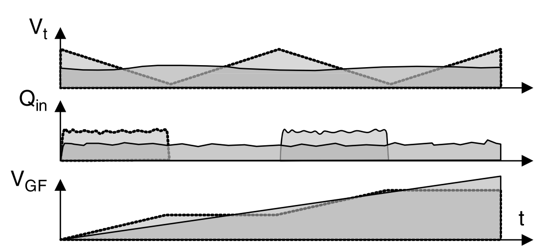

Figure 4 | Qualitative behaviour of the extended Liu Controller (eLC) in a practical scenario.

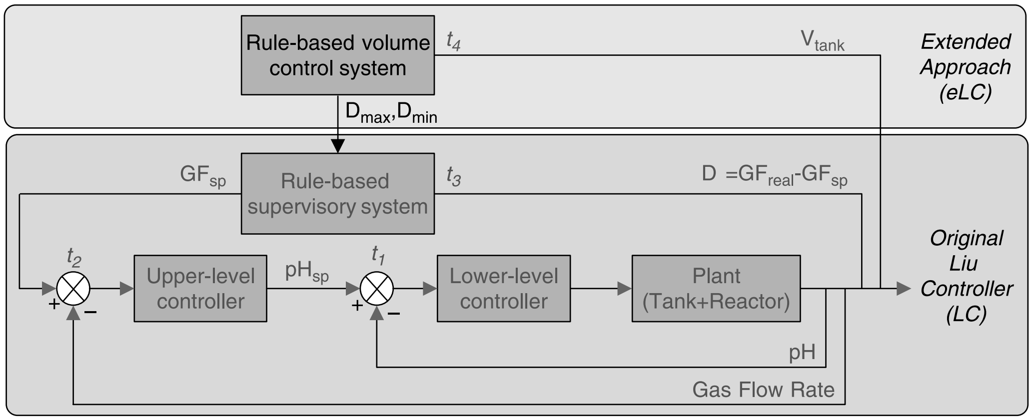

Figure 5 | Architecture of the proposed control approach (eLC).

Validation of the eLC: simulation set-up

Before validating the proposed control strategy (eLC), the performance of the LC was analysed by simulation in order to verify the reliability of the ADM1 for the design and validation of automatic controllers. Thus, the LC was tested in two different simulation scenarios: (Sim N1) a 1.2-l. lab-scale AHR operated without equalisation tank and under the same conditions as those described in Liu *et al.* (2004); and (Sim N2) a 1-m^3 pilot-scale AHR without equalisation tank and permanently fed with a dextrin substrate. In both scenarios, experimental data were available to assess the reliability of simulation results. Then, a third simulation scenario (Sim N3) was defined to compare the performance of both control approaches (LC and eLC). In Sim N3, a full-scale industrial AHR with equalisation tank was considered. In addition, available information about the weekly profiles of the wastewater characteristics from a slaughterhouse factory (Soroa *et al.* 2002) was employed to obtain the volume of the tank and that of the anaerobic digester (171 m^3 and 68 m^3, respectively).

RESULTS AND DISCUSSION

In Sim N1, the LC response under start-up, steady-state and overload/underload operating conditions was investigated. The ADM1 coefficients were fixed to their default values. The three control loops in the LC were sampled at regular intervals t_1, t_2 and t_3 of 2.5, 30 and 60 minutes, respectively (Figure 5). After tuning D_{max} and D_{min} (0.1 and −0.3 $m^3_{gas}\cdot m^{-3}_{react}\cdot d^{-1}$), the behaviour of the LC that resulted by simulation agreed with lab-scale experimental results. Figure 6 shows the response of the LC to a 6-h underload event starting at t = 30 h. The automatic regulation of pH_{sp} and GF_{sp} ensured that the disturbance was dealt with successfully, and the process returned to its normal operation after 36 h approx. As regards Sim N2, the response of the LC was analysed under the same operating conditions as in Sim N1. Default values for the ADM1 coefficients were selected initially. While D_{max} was kept at 0.1 $m^3_{gas}\cdot m^{-3}_{react}\cdot d^{-1}$ (i.e., the same value obtained in Sim N1), D_{min} had to be increased up to a value of −0.1 $m^3_{gas}\cdot m^{-3}_{react}\cdot d^{-1}$, which was attributed to the dependence of D_{min} on the characteristics of the substrate. The LC acted by regulating GF_{sp}, pH_{sp} and the influent flow appropriately; however simulation results provided maximum OLRs (≈25 kg COD/m^3 d) that were much higher than those observed from a previous experimental study in a 1 − m^3 AHR pilot-plant operated manually and fed with the same substrate (≈12 kg COD/m^3 d).

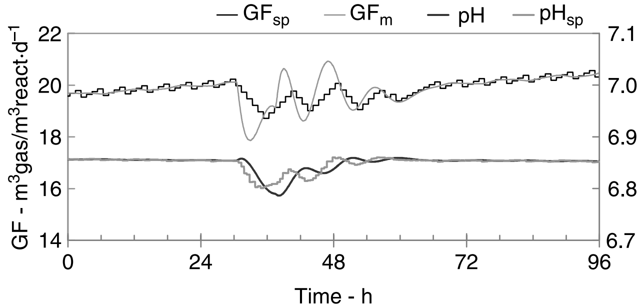

Figure 6 | Behaviour of the LC in SIM N1.

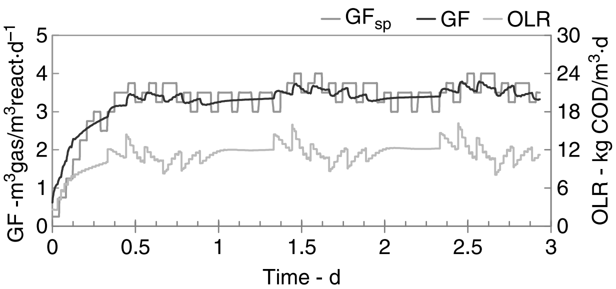

Figure 7 | Response of the original LC in SIM N2 ($k_{m\_ac} = 3\ d^{-1}$).

Since the simulation and experimental results presented similar total mass values in the anaerobic digester, the above discrepancy was attributed to the default values of the kinetic coefficients, in particular, that of the k_{m_ac} coefficient ($8\,d^{-1}$). Thus, by setting k_{m_ac} to a value of $3\,d^{-1}$, the original LC responded as expected and, moreover, satisfactory predictions of maximum OLRs were achieved (Figure 7).

In Sim N3, the minimum level (V_{min}) in the tank required by the original LC was set to 10% of the total volume. Such a low value was mandatory since otherwise the strong hydraulic peaks of the wastewater would provoke overflowing episodes in the tank. In many industries, the occurrence of weekend shutdowns is a very typical situation. Thus, a representative wastewater profile wherein the above situation was considered in Sim N3. Figure 8 shows the most significant results of each controller over a two-week period. Initially the original LC ($D_{max} = 0.1$; $D_{min} = -0.3$) pushed the influent flow rate (Q_{in}) towards high values in order to maximise the instantaneous OLR (days 1–5 in Figure 8a). This caused the wastewater mass in the equalization tank to decrease progressively (days 3–6 in Figure 8b). As a result, emptying events in the tank and inactivity periods in the AHR took place (days 6–8 in Figures 8b,c, respectively). In addition, a new parameter (V_{rst}) was introduced within the control strategy. When an inactivity period occurs, V_{rst} specifies the minimum volume of wastewater required in the tank before the LC is restarted again.

In relation to the performance of the eLC, Figures 8a,b show how the new strategy was able to maintain a more stable feed flow that prevented the occurrence of emptying episodes. At regular intervals of 60 minutes and based on the on-line measurements of the wastewater volume in the equalisation tank, the eLC acted by regulating the values of D_{max} and D_{min} within the range $\pm 0.5\,m^3_{gas}\cdot m^{-3}_{react}\cdot d^{-1}$. A previous sensitivity study proved that values out of this range did not have effect on the controller response.

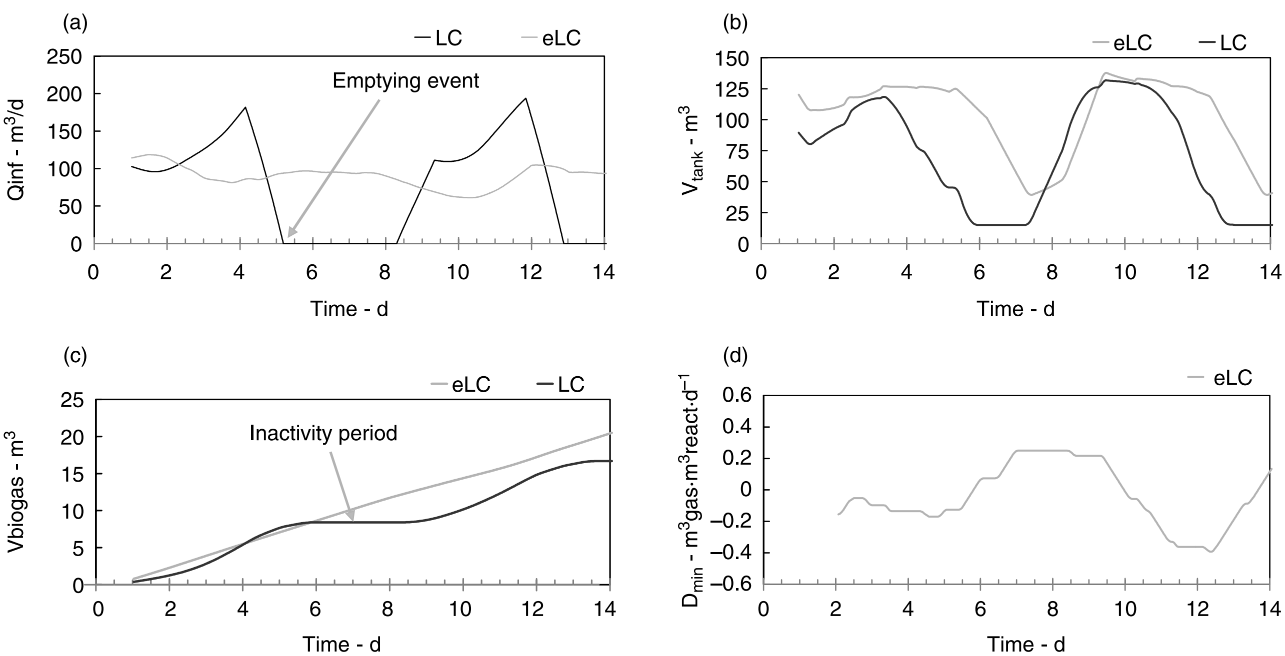

Figure 8 | Performance of the LC and the eLC in Sim N3: (a) Qinf; (b) Volume of the equalisation tank; (c) Accumulated Biogas; (d) Evolution of Dmin.

Figure 8d illustrates the evolution of D_{min} provided by the eLC in Sim N3. The analysis of Figures 8b,d clearly reveal opposite tendencies for V_{tank} and D_{min}. When the volume of the equalisation increases, the control action D_{min} decreases progressively so as to promote the application of higher Q_{in} values (days 9–12 in Figures 8a,b,d). On the other hand, when the volume of the tank decreases (e.g. in the weekend shutdowns), D_{min} is automatically increased promoting lower productions of biogas that give rise to lower values of Q_{in} (days 6–8 in Figures 8a,b,d). In this respect, unlike the LC approach, the eLC tries to preserve the equalisation tank buffer capacity needed to absorb the load peaks of the wastewater. Consequently, a more stable operation is achieved. Finally, Figure 8c shows a comparison of the accumulated biogas that each control approach produced for a 14-day period. It is observed that in those intervals in which both controllers are working, the slope of the accumulated biogas is higher in the case of the LC (days 9–12 in Figure 8c). Nevertheless, the inactivity episodes typical of the LC cause a reduction in the average slope of the accumulated biogas that leads to a lesser biogas production at the end of the 14-day period. Thus, the simulation results reveal that while the LC produce about $17\,m^3$ of biogas, the eLC increases that production up to $22\,m^3$ of biogas in the same period. Therefore, from the simulation results, it is concluded that, when the original LC is extended using the proposed control approach, increments of about 30% in the net biogas production can be expected.

CONCLUSIONS

The performance of full-scale anaerobic digesters can be improved by implementing control strategies where the hydraulics of equalisation tanks is considered. A simulation control study has demonstrated how the net production of biogas increases with an appropriate regulation of the wastewater volume in equalisation tanks. The proposed control strategy has been able to prevent the occurrence of emptying and overflowing situations in the tank. Compared to other controllers in the Literature, the proposed approach increased the biogas production by about 30%. Moreover, since the controller uses only reliable and cost-effective instrumentation, its practical implementation in full-scale plants is straightforward. The performance of the control strategy was analysed by simulation under different operational scenarios and disturbances with satisfactory results. In this respect, the simulation results represent a first step towards the progressive confirmation of the ADM1 as a valuable tool for the design and validation of control strategies in anaerobic processes. Finally, despite the promising results obtained with this controller by simulation, these results must be further validated at pilot and full scale plant before reaching definitive conclusions.

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