H_2 CONCENTRATION CONTROL OF AN EXPERIMENTAL ANAEROB BIOGAS REACTOR

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SUMMARY: A control system for an experimental anaerob biogas reactor for production of biogas (methane) fed with leachate from apple waste is presented. The control system is used to stabilize the gas production by controlling the H_2 concentration of the gas. Industry standard PI (proportional plus integral) control is used to adjust continuously the reactor feed flow to keep the measured H_2 concentration at the concentration setpoint. The controller is tuned from a mathematical model of the process in the form of a transfer function estimated from a step-response experiment on the process. The feed flow range demanded by the controller is in the very lower end of the range of the feed pump, causing problems with obtaining the demanded flow. Satisfactory pump control is obtained with Pulse-Width Modulation where the pump is controlled as a binary (On/Off) device with the average flow being equal to the demanded flow. The noisy H_2 measurement signal is smoothed with a lowpass filter before being connected to the controller. Remote Internet-based access to the lab PC is implemented.

1. INTRODUCTION

This paper presents the control system of an experimental rig for production of biogas (methane) by anaerob digestion. Figure 1 shows a P&ID (Process and Instrumentation Diagram) of the biogas system, and Figure 2 shows a picture of the system. The anaerobic digester is a mixed reactor with semi-continuous flow, combining suspended biomass and biofilm on a fixed support medium. Leachate from apple waste stored in a barrel is used as feed to the reactor. A PC-based system is used to monitor the rig and to stabilize the gas production by controlling the H_2 concentration of the gas. The system provides Internet-based remote monitoring and control.

The purpose of the H_2 concentration control system is to keep the H_2 concentration (ppm) of the biogas sufficiently close to a given setpoint to obtain stable methane production. The setpoint is about 25 ppm. The controller adjusts the feed flow from the feed tank into the reactor to control the anaerob digestion (AD) process based on continuous H_2 concentration measurements. The aim of AD control based on H_2 concentration is to avoid accumulation of intermediate acidic products. This also indirectly ensures that the pH of the reactor content does not drop too too low for methane production (Rodriguez et. al., 2006; Tchobanoglous et. al., 2003). Accumulation of these products and H_2 implies that the AD methane production capacity is limited by the methane generating organisms capacity to consume these intermediates.

This paper is organized as follows. Chapter 2 gives an overall presentation of the functionality and implementation of the process control system. Chapter 3 presents details about the H_2 concentration control system, including mathematical modeling and controller tuning, lowpass filtering of the (noisy) H_2 measurement signal, and binary control of the feed pump using Pulse-

Width Modulation. Conclusions are given in Chapter 4.

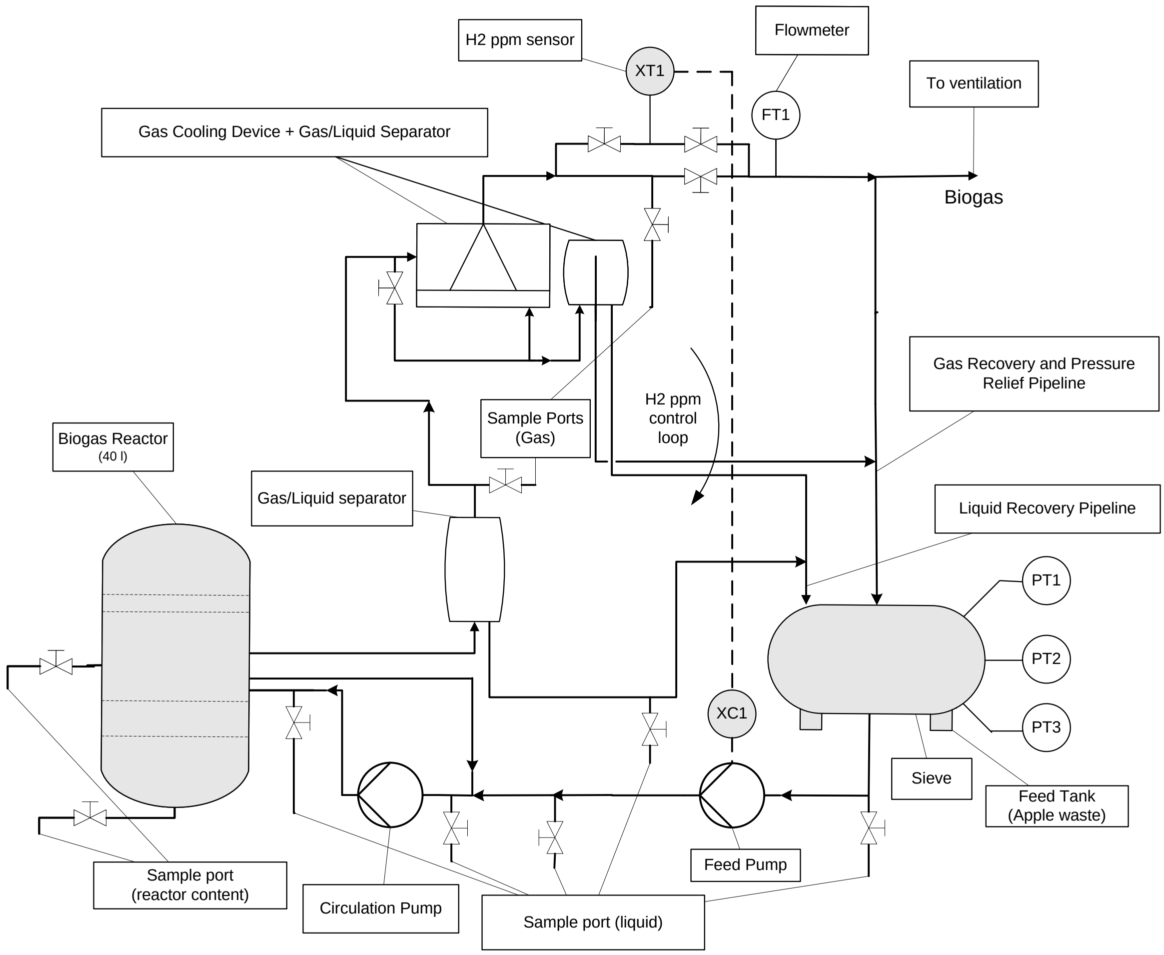

Figure 1. P&ID (Process and Instrumentation Diagram) of the biogas system.

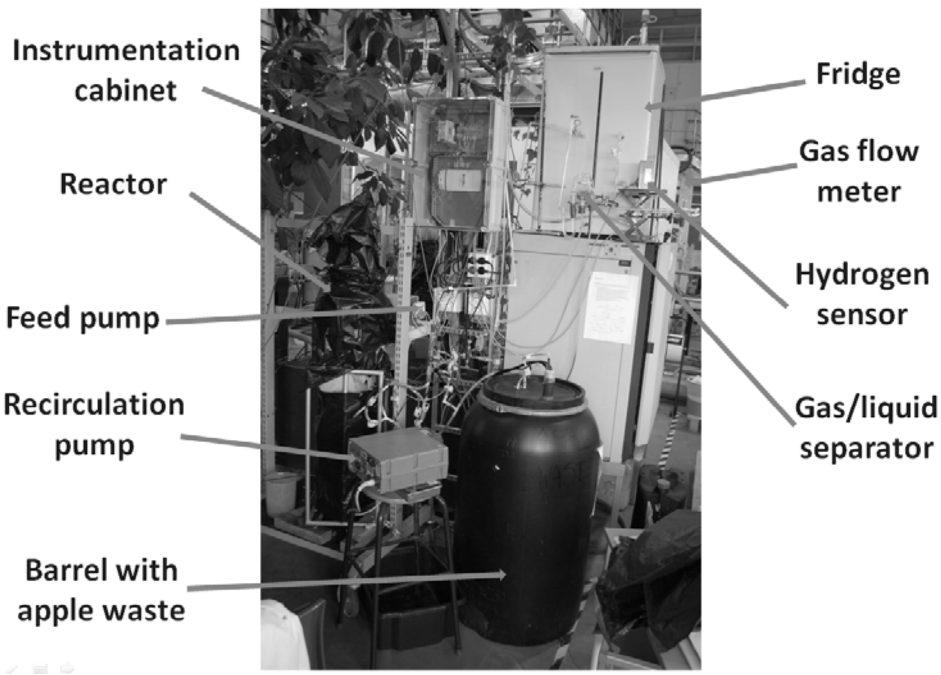

Figure 2. The biogas reactor.

2. THE PROCESS CONTROL SYSTEM

2.1 Block diagram of the control system

Figure 3 shows a block diagram of the feedback H_2 concentration control system based on continuous measurements of the H_2 concentration of the effluent gas from the reactor.

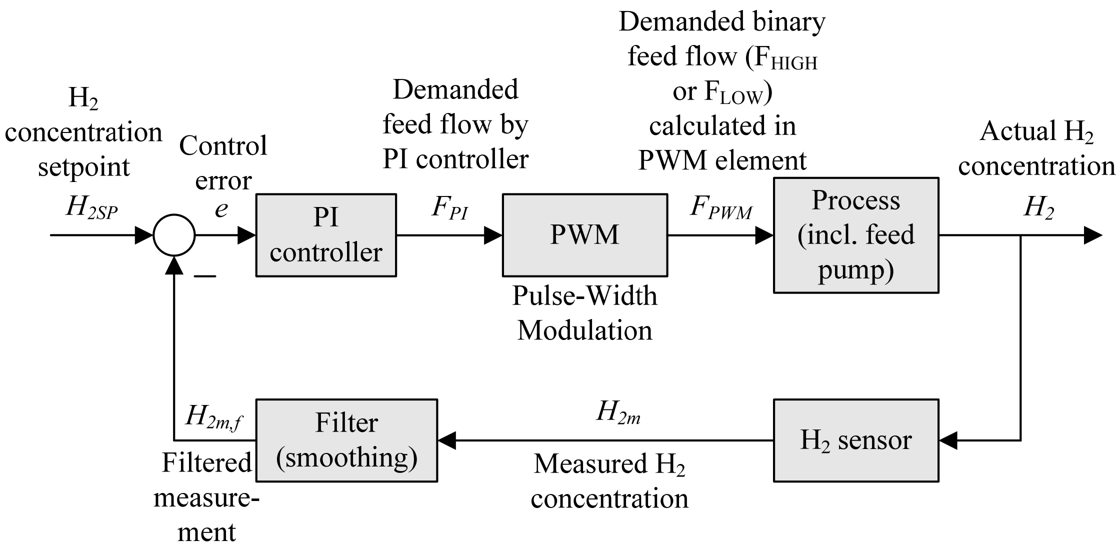

Figure 3. Block diagam of the H_2 concentration feedback control system.

2.2 Implementation of the control system

The control system is implemented with National Instruments LabVIEW software running on a PC. Analog voltage I/O (Input/Output) is implemented with the NI USB-9211 device which connects to the USB port of the PC. National Instruments technology was selected because it provides sufficient functionality and flexibility regarding controller implementation, signal processing, mathematical modeling, and data analysis and plotting. Alternative technologies exist, as PLC-based systems (Programmable Logical Control) which are common in industrial applications where the control task consists of routine operations. However, typically the functionality is less in such systems.

2.3 Remote Internet-based supervision and control

Remote Internet-based access for the project team members to the lab PC is set up using a secure service (LogMeIn, 2010). The PC can be accessed with LogMeIn via a standard Web browser, for example Firefox or Internet Explorer, to remotely manipulate parameters in the LabVIEW program, download data files from the lab PC for further analysis, and even to do further programming. The remote access via a browser has been very convenient in the present project, and in other similar projects. Figure 4 shows the Front panel of the LabVIEW program as it appears in a Web browser (here Firefox).

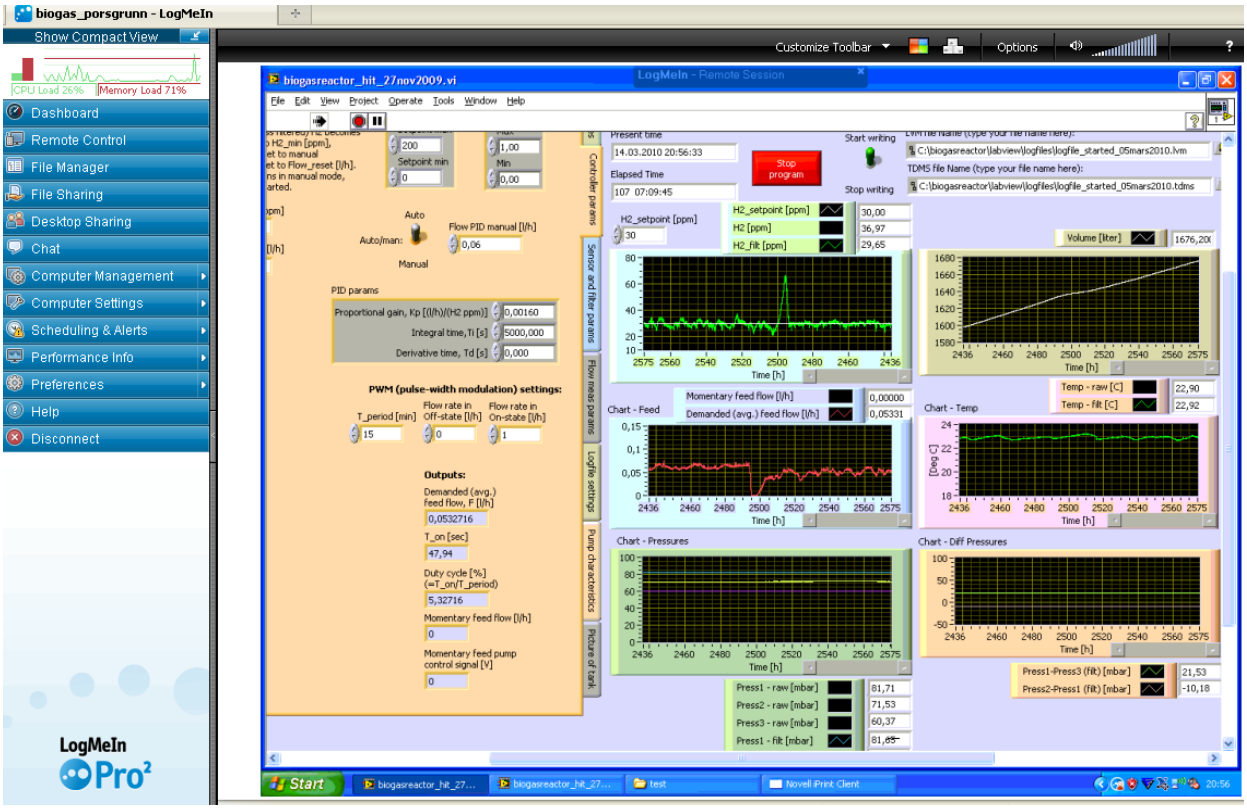

Figure 4. Remote access to the lab PC via a Web browser.

3. H_2 CONTROL

3.1 Feedback controller

The controller function is an industry-standard PI controller (Proportional + Integral) with fixed parameter values tuned at the operating point ccorresponding to H_2 concentration of about 25 ppm (the controller gives stable control also at other operating points). The controller function is

$$u(t) = K_c e(t) + \frac{K_p}{T_i} \int_0^t e(\tau) d\tau$$

where u is the control signal, which is the demanded feed flow, F, in the present application. e(t) is the control error, which is the difference between the setpoint and the measurement of the H_2 concentration. K_c is the controller gain. T_i is the integral time. The parameters K_c and T_i must be tuned to suitable values to ensure that the control system have acceptable performance. Controller tuning is covered in Section 3.4.

In the PC-based LabVIEW control program the Advanced PID function is used as PI controller.

3.2 Process measurement filter

The measurement signal from the H_2 sensor is noisy. The signal must therefore be smoothed through a (lowpass) signal filter before being used by the controller, to reduce the propagation of the noise through the controller. LabVIEW contains several pre-programmed filtering functions, but they are either not sufficiently flexible (adjustable) or they give zero output initially which is unfortunate when the control system is started.

To obtain a filter with easily adjustable filtering effect and with the initial filter output being equal to the unfiltered measurement signal (i.e. a bumpless filter), a native filter algorithm was programmed in C-code in a Formula Node in the LabVIEW program. The filter is a discrete-time implementation of the "time-constant" filter given by the following continuous-time transfer function (s is the Laplace variable):

$$\frac{H_{2mf}(s)}{H_{2m}(s)} = \frac{1}{T_f s + 1} = G_f(s)$$

T_f [sec] is the filter time-constant (adjustable). H_{2m} is the filter input signal (the raw, unfiltered measurement signal). H_{2mf} is the filter output signal (the smoothed measurement signal). The discrete-time filter is obtained by discretizing $G_f(s)$ using Backward differentiation approximation. It can be shown (Edgar et.al., 2004) (Haugen, 2010) that the resulting discrete-time filter algorithm can be written as

$$H_{2mf}(t_k) = (1-a)H_{2mf}(t_{k-1}) + aH_{2m}(t_k)$$

where k is the discrete time index. (The above discrete-time filter is sometimes referred to as the Exponentially Weighted Moving Average (EWMA) filter or simply Exponential filter.) The filter parameter a is given by

$$a = \frac{1}{T_f / T_s + 1}$$

where T_s is the time-step (cycle-time) of the filtering algorithm. In the H_2 control system presented in this article, T_s is 2 sec. By trial and error, T_f is set to 600 sec to get acceptable smoothing. In a typical experiment the filter reduced the standard deviation of the H_2 measurement signal by a factor of 13 (variance reduction was 169).

3.3 Controller output with Pulse-Width Modulation

The Hydrogen concentration PI controller is a controller which calculates a continuous (or analog) control signal, here: feed flow. However, it is impractical to obtain the very low required feed flow, a few dl/h, with continuous pumping with the installed pump, which has maximum flow of 5 l/h. As a solution to the problem about low flow, Pulse-Width Modulation (PWM) pump control is used. PWM is a principle commonly used to control electrical heaters and electrical motors. In the present application, with PWM, approximate continuous pump control is obtained with the pump operated as a binary (On/Off) device. (It is also assumed that intermittant flow is benefical for the bioprocess.)

Figure 3 illustrates PWM for the present application. The binary control signal has the following two possible values: F_{high} (high flow) and F_{low} (low flow). The period T_p is fixed. The part of the period where the PWM element is in the High-state (or On-state) is denoted the Duty Cycle, D, which is given in the unit of percent. We want the mean value, F_{mean}, of the binary signal to become equal to the specificed continuous-time control signal being demanded by the PI controller.

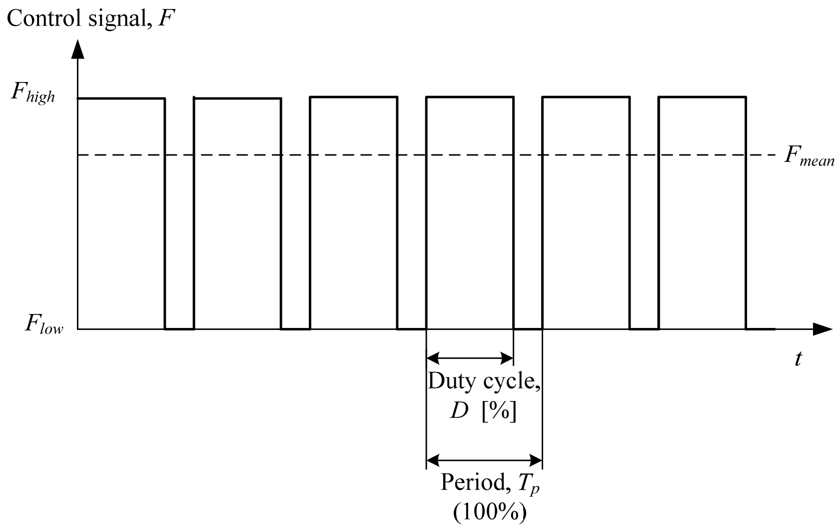

Figure 3. Pulse-Width Modulation (PWM), which is used to control the feed pump.

PWM can be implemented with a square pulse wave function where the durations (times) of the High and Low states are adjustable, and the period T_p is fixed. In the present application, the Square Wave PointByPoint function in LabVIEW is used. This function requires the Duty Cycle D to be specified at any instant of time. This implies that D must be calculated as a function of the control signal F_{PI} calculated by the PI controller. It can be shown that the relation between D [%] and F_{mean} is

$$D = \frac{F_{mean} - F_{low}}{F_{high} - F_{low}} \cdot 100$$

Thus, the relation between D and the control signal generated by the PI controller is

$$D = \frac{F_{PI} - F_{low}}{F_{high} - F_{low}} \cdot 100$$

In the present application, we typically set F_{high} = 1.0 l/h, F_{low} = 0 l/h, and T_p = 15 min.

3.4 Mathematical modeling and controller tuning

3.4.1 Introduction

A large number of methods for tuning the PI controller exists (O'Dwyer 2003). In the present application, Skogestad’s PID controller tuning method (Skogestad, 2003) is used. This is a simple method based on process transfer function parameters which can be found from a step response experiment on the process.

3.4.2 Mathematical modeling

Figure 4 shows the process step response, i.e. the response in the measured and filtered H_2 concentration (process output) due to a step change of amplitude 0.027 l/h of the reactor feed flow (process input). Note that deviations from the operating point are plotted, which is why negative flow and negative H_2 concentration appears in the plots (the absolute values of flow and concentrations are of course positive). The process was being controlled with a PI controller with non-optimized settings up to time t = 32000 s (approximately), when the controller was switched from automatic to manual mode and the control signal was changed in a step as mentioned. (The smooth curve in the upper diagram of Figure 4 shows the simulated response with the estimated model, see below.)

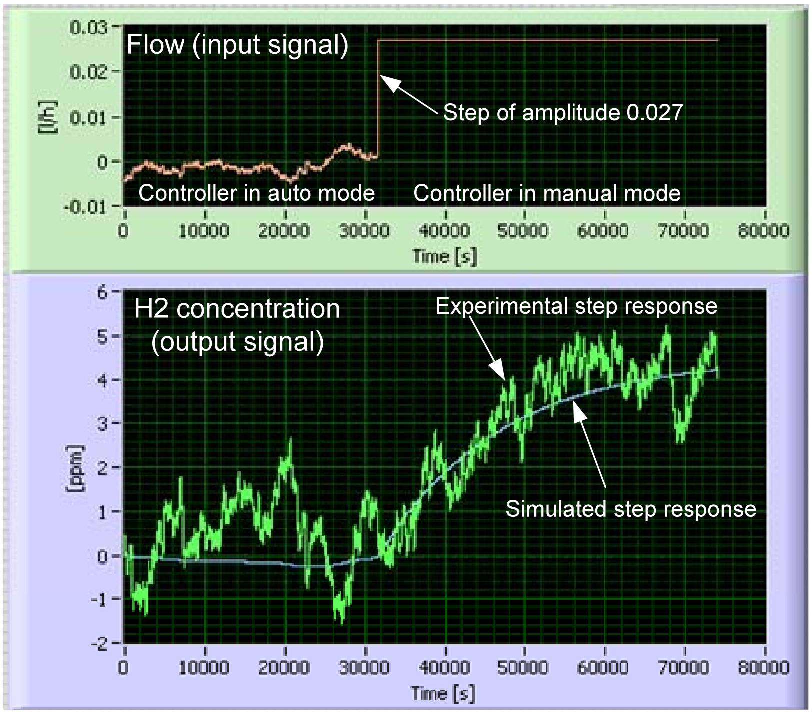

Figure 4. Response in measured (and filtered) H_2 concentration due to a step change of the feed flow. Also, the simulated response with the estimated model is shown. *Deviations* from the operating point are plotted.

The step response indicates that a proper transfer function of the process (including the measurement filter) is similar to the standard “time-constant with time-delay” model:

$$\frac{H_{2mf}(s)}{F(s)} = \frac{K}{Ts+1} e^{-\tau s} = H_{pf}(s)$$

(Here, the variables H_{2fm} and F represent deviations from the operating point.) From the responses shown in Figure 4 we find that the steady state response is roughly

$$\Delta H_{2mf} = 4.5\,\text{ppm}$$

The time-constant (i.e. the 63% rise time) is roughly read off as

$$\text{Time-constant: } T = 14000\,\text{s}$$

From Figure 4 we see that the time-delay of the response is negligible compared with T, so we set

$$\text{Time-delay: } \tau = 0\,\text{s}$$

The gain K can be calculated as the ratio between the change of the steady state response,

ΔH_{2mf}, and the input step amplitude, ΔF:

$$\text{Process gain: } K = \frac{\Delta H_{2mf}}{\Delta F} = \frac{4.5\text{ppm}}{0.027 \text{l}/\text{h}} = 167 \text{ ppm/(l/h)}$$

Figure 4 shows the simulated response with the time-constant model derived above.

Above, the model parameters were calculated manually from the experimental step response. In this project, two methods of automatic model estimation from the experimental sequence of data points of the input (flow) and ouput (H_2 concentration) were also tried:

1. A prediction error method (PEM) for estimating an ARMAX model (Auto-Regressive Moving Average with eXogenuous inputs), which is a discrete-time model basically in the form of a linear difference equation (Ljung, 1999). Basically, the user must select the model order prior to the estimation of the model parameters. (This method is available in LabVIEW with the SI Estimate ARMAX Model function.)

2. A subspace identification method which automatically estimates a canonical discrete-time state-space model of best (optimal) order, but the user can also select the model order prior to the estimation. (This method is available in LabVIEW with the SI Estimate State-Space Model function.)

It turned out that the subspace method did not produce a suitable (accurate) model. The reason may be too poor excitation (manipulation) of the system. However, the PEM method for estimating an ARMAX model did produce a suitable model. The best model (model order) was found by comparing the simulated response with the experimental response. The estimated model was

$$H_{2mf}(k) = 0.999819 H_{2mf}(k-1) + 0.023 F(k-200) + \varepsilon(k) + 0.0056 \varepsilon(k-1)$$

where k is the discrete-time index. ε is random model noise or error. The time-step is 2 sec. This difference equation can be converted to a continuous-time model with the following parameters:

Gain = 127 ppm/(l/h). Time-constant = 11067 sec. Time-delay = 400 sec.

These parameters are not very different from the parameters calculated manually (167, 14000 and 0, respectively). However, the simulated response based on this model fitted the experimental data worse than the simulated response based on the manually estimated model. Therefore, the latter model was used as the basis of the controller tuning.

3.4.3 Tuning of the PI controller

In Skogestad's controller tuning method the suggested controller for a time-constant process is a PI controller with the following parameter settings:

$$\text{Controller gain: } K_c = \frac{T}{K(T_C + \tau)}$$

$$\text{Integral time: } T_i = \min[T, c(T_C + \tau)]$$

where c = 4 according to Skogestad's original rules. You can set c to a smaller value, e.g. 1.5, to obtain better disturbance compensation while maintaining acceptable stability robustness of the control loop. T_C is the specified time-constant of the closed-loop system (the control system).

Skogestad gives the following rule of thumb for selecting T_C:

$$T_C = \tau$$

However, when τ is neglible (0), as in the present application, this rule can not be used as it would result in infinite K_C and zero T_i. In this case, one can try with

$$T_C = 0.5T = 0.5 \cdot 15000 = 7500\,\text{s}$$

This gives

$$K_c = \frac{T}{K(T_C + \tau)} = \frac{T}{K(0.5T + 0)} = \frac{2}{K} = \frac{2}{167} = 0.012\,\text{(l/h)/ppm}$$

and (with c = 1.5)

$$T_i = \min[T, c(T_C + \tau)] = \min[T, 1.5(0.5T + 0)] = 0.75T = 0.75 \cdot 14000 = 10500\,\text{s}$$

Figure 5 shows the responses due to a step in the H_2 concentration setpoint from 25 to 30 ppm with the above PI controller settings. The responses indicate that the stability of the control system is acceptable. It is interesting to compare the practical closed-loop time-constant T_C with the specified T_C of 7500 s. The response shown in Figure 5 indicates that the actual control system is nonlinear or is influenced by disturbances after the setpoint step since the H_2 concentration response *departs* somewhat from the setpoint after the relatively fast response just after the setpoint step change. (In an ideal, linear system with Skogestad's tuning of a PI controller for a time-constant process the response would not depart like this from the setpoint, but instead continue to approach the setpoint.) Because of this non-typical response in the practical system, it is reasonable to estimate the actual T_C from the response just after the setpoint step change. From the plot in Figure 5 we can read off $T_C \approx 8000$ s, which is almost the same as the specified T_C of 7500 s. Hence, the controller tuning roughly works as assumed.

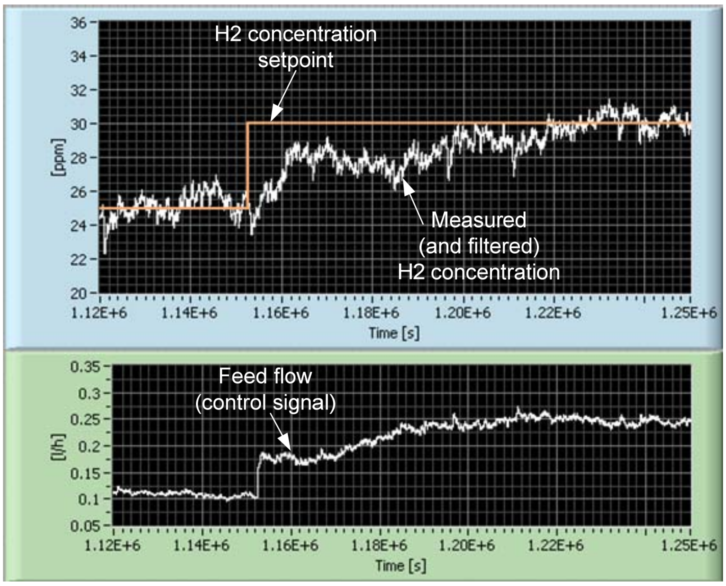

Figure 5. Responses in the H_2 concentration control system.

4. CONCLUSIONS

A PC-based control system for an experimental rig with a biogas reactor for production of biogas (methane) by anaerobic digestion of leachate from apple waste as feed has been implemented. The control system stabilizes the gas production by maintaing the H_2 concentration of the gas at a setpoint of about 25 ppm. Industry standard PI (proportional plus integral) control is used to adjust continuously the reactor feed flow.

Remote Internet-based access for the project team members to the lab PC has been set up using a secure service.

The H_2 measurement signal is noisy and is therefore smoothed with a lowpass filter before being connected to the controller to reduce the propagation of the noise through the controller. It is found by trial-and-error that a filter time-constant of 600 sec is a proper value in this project. This filter reduces the standard deviation of measurement variations by a factor of 13.

The controller is successfully tuned with Skogestad's method from a mathematical model of the process in the form of a transfer function representing time-constant dynamics estimated from a step-response experiment on the process. The model parameters are adjusted manually to fit the experimental responses. Also automatic model estimation of a first order ARMAX model with the Prediction Error method has been implemented, but the manually adjusted model is more accurate here and therefore used for controller tuning.

Satisfactory pump control is obtained with Pulse-Width Modulation where the pump is controlled as a binary (On/Off) device with the average flow being equal to the demanded flow.

5. FUTURE WORK

Future work about control of this experimental anaerob biogas reactor may include gas production rate control, H_2 control with a predictive controller as an alternative to the standard PI control used in the present project, reactor temperature control, soft-sensors to estimate non-measured process parameters as feed composition, and developing a mathematical model based on physical and chemical phenomena to be used as a basis for simulation and design of estimators (soft-sensors) and various controllers.

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