Automatic control of volatile fatty acids in anaerobic digestion using a fuzzy logic based approach

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Abstract A control law based on fuzzy logic was developed and validated for an anaerobic wastewater treatment process. The controlled variable was the concentration of volatile fatty acids (VFA) in the reactor and the manipulated variable was the input flow rate. In order to use it as the input of the fuzzy sets, the controlled variable was treated using an algorithm of interpolation, extrapolation and filtering. The treatment of VFA values attempted to anticipate the behaviour of the variable and to avoid the inherent delay of the response, associated to the time constant of the system. Furthermore, the controlled variable derivative was used as a second input of the fuzzy sets to increase or decrease the speed of the control action. The control law was applied to a 0.948 m³ fixed-bed anaerobic reactor treating raw and diluted (1:2) industrial distillery vinasses. The validation was performed establishing different transient states between different set points in the range of 0.8 and 1.8 g VFA/l and different concentrations of the influent. The control law proved to be reliable supplying an adequate control action in terms of amplitude and velocity to achieve the desired set point for different types of perturbation and control purposes.

Keywords Anaerobic treatment; automatic control; fuzzy logic; influent flow rate; vinasses and volatile fatty acids

Introduction
The anaerobic digestion is a complex process in which organic matter is converted into a mixture of methane and carbon dioxide. The overall conversion is carried out by a mixture of micro-organisms through several biochemical reactions in series and in parallel (Henze and Harremoes, 1983). It is generally proved that, in case of non particulate substrate or non-excessively complex organic matter, the limiting step is the conversion of volatile fatty acids (VFA) into methane (Batstone et al., 2002). Hence, VFA are intermediates, which may accumulate provoking a decrease of reactor pH and the overall failure of the operation. The control of anaerobic digestion may attempt different goals, e.g. to maintain a constant concentration of organic matter at the output of the reactor, according to legislation; to optimise methane production for further energy exploitation; or to ensure a stable operation in case of systems treating high organic loading rates exposed to input concentration and/or flow rate variations. The control of VFA concentration within the reactor either directly or indirectly, is required in order to maintain the stability of the operation in variable-loaded reactors. This is the case of the majority of industrial plants. The most important drawback to fulfil VFA automatic control is the lack or the high cost of devices allowing its on-line measurement. To address this drawback some authors have developed and tested relatively inexpensive systems for the monitoring of, first, bicarbonate alkalinity (Hawkes et al., 1993, 1994) and, later, VFA (Feitkenhauer et al., 2002), using titration principles. Our laboratory developed one of these sensors (Bouvier et al., 2002), capable of measuring VFA, as well as partial and total alkalinity based on a titrimetric method, supplying one measurement every half hour (3 minutes if required) and having proven its reliability over a five year period of daily use.

For the purpose of controlling VFA, several approaches can be used, fuzzy logic being
one among them. Zadeh introduced the theory of fuzzy sets in 1965 constituting an easy way to represent heuristic knowledge using linguistic labels implemented in linguistic rules. It presents the advantage of dealing with uncertainties and the non-requirement of complex mathematical relationships. The fuzzy inference process involves membership functions, fuzzy logic operators and knowledge rules. The membership functions allow the representation of a degree of membership to a fuzzy set, associated to a linguistic label, for a given input numerical value. The rules if-then introduce the expert knowledge in a computable way by means of the operators, which may be and or. The fuzzy set theory has been discussed in detail by several authors (Zimmermann, 1985; Li and Yen, 1995) and applied to anaerobic processes in some cases (Müller et al., 1997; Giraldo-Gómez and Duque, 1998; Estaben et al., 1997; Genovesi et al., 1999; Puñal et al., 2000; Murnleitner et al., 2002). In this work, a control law taking advantage of the theory of fuzzy sets has been built and implemented in an anaerobic digestion process treating raw industrial distillery vinasses. The concentration of VFA was set as the controlled variable and the input flow rate was the manipulated variable. The law was validated on-line under different influent concentrations and under different control requirements, e.g. VFA set points.

Material and methods

Anaerobic wastewater treatment plant

Raw and diluted (1:2) industrial wine distillery effluents were anaerobically treated in a 0.948 m³ fixed bed upflow reactor. The results presented in this work correspond to operation with diluted wastewater (1:2) except those corresponding to the validation of the control law against a sudden increase in influent COD concentration. In those cases, diluted wastewater alternated with raw wastewater was fed to the system. The wastewater characterization is presented in Table 1. The detailed description of the anaerobic plant can be found elsewhere (Steyer et al., 2002).

For this study, the interval between the titrimetric measurements was established at 30 minutes, as it was considered fast enough compared to the hydraulic residence time of the process (between 19 and 190 h) in order to obtain information about the operational state. The sensors are connected to an input/output device that allows the acquisition, treatment and storage of data on a PC using a modular software developed in our laboratory and freely available. The interval of reception and sending of information between the software and the process was fixed at 2 minutes, as it was considered a good solution to be fast enough for control and supervision purposes, however generating reasonable size data files. The COD was measured off-line (NF T 90-101) following the principle of oxidation of the organic matter in excess of potassium dichromate and acid media (H₂SO₄) at boiling temperatures. The excess of dichromate is titrated by a solution of ammonium-iron sulfate.

Control law

The chosen fuzzy methodology was the Mamdani’s fuzzy inference method (Mamdani and Assilian, 1975). In this method, the first and the second part of the fuzzy inference process

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Typical characteristics of wine distillery wastewater</th>
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<tbody>
<tr>
<td>Component</td>
<td>Raw vinasses</td>
</tr>
<tr>
<td>Total COD (g/l)</td>
<td>26.40</td>
</tr>
<tr>
<td>Soluble COD (g/l)</td>
<td>23.60</td>
</tr>
<tr>
<td>Volatile Fatty Acids (g/l)</td>
<td>5.50</td>
</tr>
<tr>
<td>Total Suspended Solids (g/l)</td>
<td>3.70</td>
</tr>
<tr>
<td>Volatile Suspended Solids (g/l)</td>
<td>1.95</td>
</tr>
<tr>
<td>pH</td>
<td>5.20</td>
</tr>
</tbody>
</table>
consist in the fuzzification of the inputs and application of fuzzy operators. Based on acquired knowledge of the process, a set of rules handling the regulation of the input flow rate in dependence on the concentration of VFA in the effluent of the reactor was set up. The controlled variable was the VFA concentration, the input flow rate being the manipulated variable. In order to detect and identify in a clearer way the variation of VFA concentration, another variable, the derivative of VFA concentration, was generated. This second variable represents the velocity of change of VFA concentration and was used as input of the set of rules, together with the VFA concentration itself. The output of the control law was the degree of modification required for the influent flow rate in order to lead the system to achieve the desired set point. The first step to build the control law was the translation of possible values of the different inputs and output variables into linguistic labels given by membership functions. The summary of rules implemented in the control law is presented in Table 2.

In Figure 1, the membership functions for the inputs and output of the first approach to the control law are presented. An important aspect to carry out the distribution of membership functions is the consideration of the time interval to apply the control action. At this point, two intervals were considered: 2 and 30 minutes; given by the fixed interval of exchange of information between the software and the process and by the interval of analysis of the titrimetric sensor, respectively. The membership functions present some differences in terms of amplitude considering the possibilities: (i) reaction every 30 minutes having the actual concentration of VFA at this moment and (ii) reaction every two minutes having the actual concentration of VFA every 30 minutes. This last possibility (case ii) requires a more careful treatment of signal since the action of the controller is performed based on a value of VFA, which is not the actual value each two minutes. This was the reason to choose this approach. This approach was considered the most interesting one as it comprises the understanding of signal evolution to be implemented into the control law structure and could be used as well as a basis for the other one. The extension to the case i) can be easily done by maintaining the distribution of membership functions for the action (\( \Delta F_{\text{in}} \)) and increasing the interval from \([-0.5, 0.5]\) to \([-10, 10]\) (data not shown). The

<table>
<thead>
<tr>
<th>Input ( \varepsilon )</th>
<th>gp</th>
<th>p</th>
<th>0</th>
<th>n</th>
<th>gp</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input ( \Delta \varepsilon )</td>
<td>n</td>
<td>gn</td>
<td>n</td>
<td>p</td>
<td>gp</td>
<td>gp</td>
</tr>
<tr>
<td>Input ( \Delta \varepsilon )</td>
<td>0</td>
<td>gn</td>
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<td>0</td>
<td>p</td>
<td>gp</td>
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<tr>
<td>Input ( \Delta \varepsilon )</td>
<td>p</td>
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<td>gn</td>
<td>n</td>
<td>p</td>
<td>gp</td>
</tr>
</tbody>
</table>

Output \( \Delta F_{\text{in}} \)

Table 2 Summary of rules implemented in the control law. Input \( \varepsilon \) represents the VFA concentration minus the set point in g/l. Input \( \Delta \varepsilon \) is the derivative of \( \varepsilon \) and represents its variation with time in g/l min. Output \( \Delta F_{\text{in}} \) is the increment or decrease of the actual input flow rate in l/h

![Figure 1](https://iwaponline.com/wst/article-pdf/48/6/103/423573/103.pdf)

**Figure 1** Membership functions of the input and output variables to the control law. 

a) \( \varepsilon \) represents the VFA concentration minus the set point in g/l; b) \( \Delta \varepsilon \) is the derivative of \( \varepsilon \) and represents its variation in time in g/l min. c) \( \Delta F_{\text{in}} \) is the increment or decrease of the actual input flow rate in l/h.
relationship between the two inputs and the output of the control law is established by means of the set of rules. The surface of response according to the set of rules is presented in Figure 2. It is important to note that the intensity of response proposed for the region close to the set point is very small (showed in detail in Figure 2b) according to the established membership functions for $\Delta F_{in}$ (Figure 1c), due to the fast frequency of actuation (2 minutes). The non-linear variation of the response intensity for the different values of $\varepsilon$ and $\Delta \varepsilon$ represents the main advantage of this control law when compared to classical PID controllers based in the same process variables, while maintaining simple structure and implementation requirements.

**Results and discussion**

The first requirement for the proper performance of the control law was data treatment. For this purpose, a mean moving window applied to the last hour of data was used, as well as the removal of huge variations, due to signal displacement. Furthermore, in order to take into account the delay registered in the VFA concentration response to input flow rate variations, the prediction of VFA concentration evolution was also included in the law. The delay in the VFA concentration response is due to the time constant of the system and to the non registered response (one VFA value each 30 minutes) of the action (adjusted each 2 minutes) on the input flow rate. For this purpose, a simple algorithm predicting the next immediate values expected, according to the evolution (VFA derivative) during the last hour of process, was included.

The application was tested using both, data generated using a general model, which was developed and validated for the process (Bernard *et al*., 2001), and real data from the process. The final on-line validation was performed in the fixed bed upflow reactor described above. The VFA concentration required at the output of the reactor, e.g. the set points of the control law, were set between 800 and 1800 mg/l. This range of concentrations, according to the performance previously observed in the process, was considered representative of the operation under different regimes, without attaining the destabilization of the reactor. An example of the performance of the control law is presented in Figure 3. The results presented correspond to 75 hours of operation, when switching the set point from 1,000 to 1,800 mg VFA/l at $t = 16.77$ h. It can be observed that the control law led the process to a stable state in a short period of time (less than 10 hours), which represents 19% of the hydraulic residence time. However, some punctual disturbances must be pointed out. They are shown as insets in Figure 3 and they appear associated to noise from the VFA sensor. This induces some fluctuations of the response of the control law, which increases or decreases the input flow rate according to these fluctuations in VFA concentrations. The

![Figure 2](https://iwaponline.com/wst/article-pdf/48/6/103/423573/103.pdf)

**Figure 2** a) Surface of response of the law based on the divergence of VFA concentration from the desired set point ($\varepsilon$) and the variation of VFA concentration with time ($\Delta \varepsilon$). The output of the rules is the degree of modification of the influent flow rate ($\Delta F_{in}$). b) Detail of the surface response
sensitivity of this first approach of the control law to process disturbances, reflected in VFA concentration disturbances, represents an aspect to be improved, since the law responds to signal noise, which does not correspond to an event related to the process. In this sense, it was necessary to improve the processing procedure of the signal in order to distinguish between the different types of signal perturbation.

The modification of signal processing was performed by including an algorithm for linear/quadratic interpolation of VFA values in the moving window with respect to the previous one-hour measurements and the corresponding extrapolation for the next half-hour. An example of results obtained with the control law following this procedure is shown in Figure 4. During the 50 hours period of operation, the VFA set point was changed several times between 800 to 1,200 mg/l in order to evaluate the robustness of the control law. The starting point is a non-stable state, as the VFA are decreasing from a previous disturbance in the reactor. However, this event does not hinder obtaining a satisfying response from the control law, which adapts gradually the input flow rate from the minimum value of 5 l/h up to 12 l/h in 5 hours (less than 5% of the HRT). The input flow rate established at this point by the control law remains stable until the next shift in the VFA set point (800 to 1,200 mg/l on hour 27 of operation). The set point was maintained at 1,200 mg VFA/l only from hour 27 to hour 32, because of an erroneous sensor measurement, marked with an arrow in Figure 4. This kind of default, corresponding to a lack of signal during a short period of time, pointed to further modifications in signal processing. In fact, as the time constant of the system is much longer than the measurement interval, an extrapolation-estimation algorithm of VFA concentration can be done for at least one or two hours within an acceptable confidence interval. This procedure would avoid the shift in the response of the control action at hour 30, due to the failure of the VFA sensor and the lack of measurement during one half-hour. At that moment of operation, the input flow rate was fixed at 15 l/h during 2 hours, when the set point for VFA was fixed again at 800 mg/l and the control law was re-triggered. After \( t = 32 \) h, the good performance of the control law can be observed, attaining the desired VFA set point in 10 hours, which represents 10% of the HRT in the reactor. Concerning the improvement in data treatment with extrapolation extended for 1–2 hours

Figure 4 Results obtained from the on-line validation of the control law processing wine distillery wastewater of 10 g COD/l. The VFA concentration fixed as set point of the control law varied between 800 and 1,200 mg/l. The insets correspond to signal disturbances, discussed in the text.
period, together with interpolation and elimination of high divergent measured values, an example of obtained results is showed in Figure 5. In this case, the extrapolation was done during two hours (arrow c), obtaining the agreement between the data supplied by the measurement device and previous extrapolated values after sensor restarting. Arrows a and b in Figure 5 point to two examples of correct elimination of divergent values provided by the measurement device. The effect of the interpolation procedure can be observed as well during the 40 hours monitoring interval presented in Figure 5, obtaining a quality signal, which contributes to the improvement of control law performance.

A typical disturbance in anaerobic digestors, together with variations in the input flow rate, is the sudden change of influent COD, which usually is not detected in real time. In our process configuration, the equalisation tank previous to the reactor makes a buffer effect on the influent COD to the reactor, which will change gradually as the complete volume of the tank is displaced. An aspect to point out is that, although the control law does not include the influent COD within the managed variables, it is adequate to test and validate it under influent COD changing conditions. This issue improved the performance of the control law and in general made it more suitable for real disturbances in real plants. The results of the on-line validation of the control law processing wine distillery wastewater with a gradual but large change of COD concentration are presented in Figure 6a. For this purpose, raw wastewater was suddenly fed to the system, obtaining a gradual increase in the COD directly fed to the reactor due to the effect of the equalisation tank volume (0.2 m$^3$). The VFA concentration fixed as set point of the control law was 1,000 mg/l, which was maintained...
during the whole 50 hours in order to observe the performance of the controller until the stabilisation of the system. The VFA within the reactor increased gradually (Figure 6b) together with the increase of the influent COD concentration, resulting in a decrease in the feeding flow rate estimated as output of the control law (Figure 6c). The feed flow rate stabilisation was achieved approximately 20 hours after the perturbation, while less than 8 hours were needed to attain VFA values less than 20% divergent from the desired set point. These results show the major difficulty to manage a changing COD concentration in the influent flow rate, when compared to changes in control (e.g. set points) purposes. However, the control law proposed can properly manage this sudden and usually not detected perturbation, leading the system to the appropriate operational conditions and maintaining a performing and stable behaviour.

Conclusion
A control law based on fuzzy logic features was developed and validated for an anaerobic wastewater treatment process treating wine distillery wastewater. The controlled variable was the concentration of Volatile Fatty Acids (VFA) in the anaerobic reactor and the manipulated variable was the input flow rate. The validation was performed establishing different transient states between different set points in the range of 0.8 and 1.8 g VFA/l. This approach was tested as well for managing disturbances in COD influent concentrations (usually unknown by operators or by the control law), which represent the usual situation, associated to the variations in process production in real plants. The sensitivity of the control law was optimised by interpolation, extrapolation and filtration procedures in order to avoid the undesired effects due to signal noise, without loosing sensitivity to detect disturbances in the process. The control law proved then to be reliable, supplying an adequate control action in terms of amplitude and velocity to achieve the desired set point as well as to manage a sudden change in influent COD concentration. It is important to note that one of the main advantages of this approach is the simplicity in terms of variables used as well as of development and implementation, which may be comparable to a simple controller, but supplying a more satisfying performance.

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