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Feed control of anaerobic digestion processes for renewable energy production: A review

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A B S T R A C T

Over the last 40 years many different control methodologies for substrate feed control of anaerobic digestion processes have been proposed in order to increase plant efficiency and sustainable long-term energy production. This review shows that although sophisticated controllers exist, full-scale biogas plants are mostly still operated without a closed-loop feed control. No matter which application, such control always has to find a compromise between maximizing economic yield, minimizing the ecological footprint and minimizing the risk of process failure. For anaerobic wastewater treatment, control systems which come close to this ideal, exist, but for agricultural as well as industrial biogas plants such control has not yet been developed and neither been successfully implemented and validated at full-scale. Main challenges are a lack of robust and reliable process monitoring using online instrumentation as well as a conservative industry which is reluctant towards the implementation of fully automated process control strategies.

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1. Introduction

Anaerobic digestion (AD) is a well-known process for renewable energy production, which converts organic degradable material into biogas [1,2]. This biogas mainly consists out of methane and carbon dioxide and is mostly used for thermal and electrical renewable energy production by combustion in combined heat and power plants. Commonly used substrates are wastewater, manure, energy crops and the organic fraction of municipal solid

Abbreviations: ABP, Agricultural Biogas Plant; AD, Anaerobic Digestion; ADM1, Anaerobic Digestion Model No. 1; BSM2, Benchmark Simulation Model No. 2; COD, Chemical Oxygen Demand; D, Dilution Rate; IA/TA, Ratio of Intermediate Alkalinity over Total Alkalinity; MIMO, Multiple-Input and Multiple-Output; ORP, Oxidation / Reduction Potential; SISO, Single-Input and Single-Output; TOC, Total Organic Carbon; TA, Total Alkalinity; TS, Total Solids Content; VFA, Volatile Fatty Acids; VFA/TA, Ratio of Volatile Fatty Acids over Total Alkalinity

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waste. But many other substrates can be processed as well [3]. As the process is very complex due to four process stages, each requiring different optimal process variables (e.g. see [4] or [5] for a detailed process description), controlling the substrate feed is a challenging task.

Hence, substrate feed control of anaerobic digestion processes has by now a history of more than 40 years. In these years many contributions were published, proposing various different control methodologies ranging from simple PID controls up to sometimes very sophisticated adaptive, robust or linearizing control schemes. However, far most of these concepts have not been applied to full-scale plants yet, which is one of the reasons why until now feeding schemes for full-scale biogas plants are mostly controlled manually. Next to process complexity the two main reasons are on the one hand a lack of robust online measurement devices that would make the main process steps observable and on the other hand, the fact that many control strategies were developed and evaluated on laboratory-scale and sometimes relying on extensive equipment for process monitoring that is not available in practice. In the last decades a lot of research aimed to understand the AD process and to develop reliable process measurement systems. Thus, on the one hand detailed models of the anaerobic digestion process were developed (e.g. Anaerobic Digestion Model No. 1 (ADM1) [6], and Siegrist model [7]) and on the other hand sophisticated online measurement devices nowadays do exist [8].

The objectives for substrate feed control always depend on the application of the anaerobic digestion process. Objectives could be to stabilize the process or/and to maximize methane production. Ideally, a control should be able to cover both objectives. In reviewing the published control approaches, this review seeks for control approaches that are ideal for the two most encountered applications which are anaerobic waste(-water) treatment and biogas production from agricultural substrates.

This review revisits research done and the advancements made in the field of substrate feed control of anaerobic digestion plants.

The remainder of the paper is structured as follows. In Section 2 the basics of substrate feed control are explained and in Section 3 so far published control methodologies are thoroughly reviewed. Section 4 concludes this contribution.

2. Substrate feed control

The anaerobic digestion process is used for a wide range of applications [9]. Depending on the application the main objectives for process control vary. Whereas the goal of ABP is renewable energy production, anaerobic wastewater treatment aims for minimization of the pollution (measured as chemical biological oxygen demand (COD/BOD)) in the effluent while maximizing the throughput. Therefore, control objectives and properties of potential feed control algorithms must be adapted to match the needs of the application. Although the primary goal of ABP is energy production a control also needs to assure safe and stable process conditions. At the same time profit has to be maximized and ecological criteria have to be met. Nevertheless, most control methods proposed so far are only capable of satisfying one or two of these criteria at the same time. The most often encountered ones are:

- maximization or set-point tracking of methane production rate (economical criteria)
- minimization or set-point tracking of COD in the digester effluent (ecological criteria)
- control of stability criteria, such as volatile fatty acids (VFA), VFA/TA (total alkalinity TA), propionate or dissolved hydrogen

An important difference between ABP and anaerobic waste treatment plants is that in the latter application the operator often cannot choose between different feeds, because there often is only one mixed feedstream available, e.g. wastewater. Given a limited storage capacity for the input, the scope of feed control is restricted. This is different from ABP, where it is common to use a range of different feeds. These are all separately stored and solely used for energy production.

To investigate whether control methods exist, which optimally control either an ABP or a waste treatment process, respectively, a definition of optimal control for both applications is necessary. This definition is given in Definitions 1 and 2.

Definition 1. A substrate feed control for an ABP is said to be optimal if it is a robustly stable setpoint control for the produced volumetric flow rate of methane, while maximizing the economical benefit, minimizing the ecological footprint and maximizing process stability.

Definition 2. A substrate feed control for an anaerobic waste treatment process is said to be optimal if it is a robustly stable setpoint control for effluent COD, while maximizing the throughput as well as economical benefit, minimizing the ecological footprint and maximizing process stability. Instead of a COD setpoint control, minimizing the effluent COD is possible as well.

Most of the published control methods are applied to anaerobic wastewater treatment systems, while only very few are focused on controlling dry (total solids content TS $>20\%$) or semi-dry ($8\% <$ TS $<15\%$) digestion processes.

Due to that most controls are only capable to control the feed of one substrate, mostly wastewater, the dilution rate of the feed is very often used as the manipulated variable. The dilution rate D is defined as

$$D := \frac{Q}{V_{liq}} \tag{1}$$

with the volumetric flow rate of the substrate Q and the liquid volume of the digester V_{liq}. Depending on the application, control variables such as methane flow rate or COD in the effluent as well as stability parameters such as VFA/TA, bicarbonate [10], propionate or dissolved hydrogen are used. In low-buffered systems pH can also be an indicator for process stability [11]. For a more elaborate discussion on the selection of variables for process monitoring, see [12] in which variables are selected based on a Factorial Discriminant Analysis or [13] that discusses several variables based on research carried out using a lab-scale digester.

The following extensive review of control methods proposed for biogas plant control is presented to give an overview of the state of the art of AD control mainly focusing on substrate feed control with a few exceptions. The control methods range from simple on/off and PID controllers over fuzzy and neural network control up to linearizing and other advanced approaches such as adaptive, robust and model-based control methods.

Excellent reviews on monitoring and control of anaerobic digesters can be found in [9,14] and quite recently in [15,16]. In [17,18] comparisons of different control approaches are performed in simulation studies using the ADM1. They are two of the very few objective control comparisons of three, respectively four control methods. However, a broad comparison of the high number of existing control methods has not yet been performed. Thus, the need for further objective performance evaluation and comparison of control strategies at full-scale AD plants is high.

3. Review

The review includes 167 publications focusing on the development of algorithms for substrate feed control for anaerobic