Understanding and Managing the Start-up Phase in Dry Anaerobic Digestion

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Abstract—**In anaerobic digestion systems which are operated with a high content of total solids (so-called dry digestion) and without mixing the reactor content during digestion, the start-up phase is decisive to the overall success of the process. Mixing of biomass fractions prior to filling the substrate into the digester and management of the liquid phase (leachate) are the two most relevant factors to encourage the start-up phase. Highest possible intensities both of mixing biomass fractions prior to digestion and of leachate recirculation are not advisable, as they bear the risk of spreading acidification instead of encouraging methanisation. This paper compiles the most relevant facts in a compact form to provide an overview to researchers and especially to practitioners to avoid common pitfalls in start-up procedures in dry digestion.**

Keywords- dry digestion; biogas; start-up procedure; solid biomass; batch anaerobic digestion; process water recirculation

I. INTRODUCTION

Anaerobic digestion (AD) is a biological process that occurs in the absence of oxygen if the involved microbial consortia meet favourable environmental conditions (temperature, pH, availability of nutrients, and limitation of inhibitory or toxic components). In AD with biogas production, the resulting gaseous product is a mixture of mainly two predominant components: methane (50–75% v/v) and carbon dioxide (25–50% v/v). Other components such as hydrogen, hydrogen sulphide, ammonia are generated in small or trace concentrations. The specific composition of the resulting biogas depends on substrate characteristics and process conditions. Biogas production is the result of a series of microbiological steps which are linked to each other. The AD process chain for biogas production begins with hydrolysis which is followed by activities of acidogenic and acetogenic bacteria. Methanogenesis is the final step.

Biogas is a versatile energy carrier, in which the contained energy is mainly provided by methane. 1 m^3 of biogas with a methane content of 55% has the energy content of 0.55 litres of oil. It can be converted into useful energy in different ways: heat production, electricity generation, and vehicle use or injection into the gas grid after upgrading.

The second main output of AD is digestate (digester effluent of non-metabolised substrate constituents). When spread on agricultural land, the fertiliser value of digestate is particularly attractive. Upgraded digestate can be a source of additional energy generation.

AD with biogas production has established itself among the common bioenergy generation technologies in practice [1]. However, the degree of adoption varies in different countries (including EU), and huge untapped potential exists for further exploration. A range of different reactor types is to be found in practice. While in other areas (e.g., wastewater treatment, special industrial applications) further process types exist, the following provides an overview on the utilisation of solid substrates.

1) Mode of operation with a view to process continuity

a) Batch systems: The reactor is filled at once with the substrate, which is then digested over a pre-defined period of time. For commercial operation several (at least three) reactors need to be run offset (alternative loading and unloading) to equalise gas production.

b) Fed-batch systems: Substrate is added by and by while digestion proceeds, until the reactor is filled.

c) Continuous systems: The amount of reactor filling is kept constant, i.e., effluent is unloaded when new substrate is fed. This type is most common now. It is in general the preferred choice in cases of large-scale operations [2].

2) Number of stages in the system

a) One-stage processes: The AD plant consists of one single reactor, which is in general followed by a storage tank. This is by far the most common AD plant type.

b) Two- or multi-stage processes: Process conditions are optimised for different groups of microorganisms (first stage: in general optimisation of hydrolysis). This results in more rapid and stable operation, but at higher cost.

3) Movement and homogenisation of digester content

a) Digesters based on the concept of the continuously stirred tank reactor (CSTR): The reactor is equipped with facilities for continuous or semi-continuous stirring for homogenisation of the content (results in differing retention times for particles).

b) Plug-flow digesters: In these long, narrow reactors (inlet and outlet at opposite ends, in general without internal stirring devices) material advances longitudinally whenever new substrate (typically thick, around 15% TS) is added (minimum retention times better assured than in CSTR).

4) Content of total solids (TS)

a) Wet digestion (also called liquid-phase digestion): This is the most commonly used type in agriculture. It is operated at TS < 12%. When higher amounts of solids are used, TS content is adjusted with the addition of liquid substrates or water or by recirculation of digester effluent.

b) Dry digestion (also called solid-phase digestion): Dry digestion processes are typically operated at elevated TS content (in general > 20% TS). TS content is often not adjusted to a specific value, but is the result of digesting substrates. Dry digestion is predominant in digestion of municipal biowaste (to be explained by technology history: development and implementation of technical processes designed for higher TS content was and is a logical step), but gains attractivity in agriculture, where the traditional liquid substrates are more and more underpinned or replaced by solid materials.

c) Semi-dry digestion: This third type is sometimes introduced to refer to processes operated between 12 and 20% TS. It needs to be considered that the mentioned definitions are not final, and literature has other TS ranges too.

5) Digestion temperature

a) Psychrophilic temperature: AD plants operated below 20°C are less common and restricted to low-tech applications. Degradation is slow (long retention times).

b) Mesophilic temperature: Most biogas plants are operated between 30 and 38°C.

c) Thermophilic temperature: Operation of AD at elevated temperature range (around 48–57°C) is quite common and has several advantages: better hygienisation, faster biomass degradation, shorter retention times. However, the number of thermophilic microorganism species is lower compared to mesophilic plants, which makes the process less stable. Higher energy input for reactor heating is another disadvantage.

In contrast to processes based on the CSTR concept (which prevails in wet digestion), dry digestion systems are characterised by limited or absent mixture of the reactor content during digestion. Pre-conditioning of the substrates prior to filling material into the reactor is therefore of special relevance in dry digestion. The addition of methanogenic inoculum that is appropriate in ratio and in quality prevents digester failure during start-up [3–7]. If acetic acids are not metabolised by methanogens in the AD process chain, conversion of hydrolysed organics to volatile fatty acids (VFA) will result in acidification due to VFA accumulation and in consequence to inhibition of methanogenesis [8, 9].

In batch digestion anaerobic degradation needs to be restarted with each reactor filling, which increases the necessity of optimising the biomass before starting the process, and in particular of managing the start-up phase by best possible procedures. The most common batch dry digestion type is the box-type reactor (Figure 1).

Figure 1. Box-type dry anaerobic digestion plant (left: with material in front of plant ready to be loaded into the digestion box; right: loading with wheel loader) (© S. Kusch)

Robust technology, high flexibility and the ability to cope with biomass that contains stones, woody components or other materials that would be problematic in wet (liquid) digestion are among the main advantages associated with this technology.

In this dry AD plant type, the biomass is stacked in the box-type reactor and after closing the box, liquid is sprinkled over the substrate to initiate biogas production and encourage bacteriological activity in the decomposing biomass throughout the process (no mixing of biomass takes place after the closure of the box). Beside substrate preconditioning, process water management can therefore be a second key factor to consider when optimising the process. In the majority of plants leachate of all digestion boxes is collected in one common process water tank to be recirculated. Process water recirculation influences degradation through different mechanisms [10–15]:

- Moisture content changes with avoidance of lack of moisture and dilution of inhibitory substances
- Movement of moisture through the biomass bed with transport of nutrients, microorganisms, and inhibitory components

The aim of this paper is to provide an overview of the most relevant factors that influence the start-up phase in dry anaerobic digestion. Starting points of this work are questions and problems occurring mainly in practice, but also still existing uncertainties in the field among scientists. To a significant extent, this presentation builds on content which has previously been published as part of an experimental study [16]. However, this alternatively focussed presentation elaborates the key factors that need to be understood to successfully manage the start-up phases in practice.

II. Initiation and Maintenance of Anaerobic Digestion by Seed Bodies and Methanogenic Zones

The anaerobic digestion is initiated in a bed of organic substrate by seed bodies around which reaction zones gradually develop, as described by Martin et al. [17]. Kalyuzhnyi et al. [18] refer to seed particles with high methanogenic activity on one hand and highly degradable particles of fresh waste with low (if any) methanogenic activity on the other hand. Successful methanisation with biogas production is ensured when stable methanogenic activity is established throughout the reactor. Chanakya et al. [19] use the terms acidogenic and methanogenic pockets to describe the set-up of the occurring processes in degrading solid biomass.

Veeken and Hamelers [20] postulated that increasing the transport of VFA from acidogenic to methanogenic pockets would be positive unless the methanogenic activity of the seed was too low to consume the acids. Martin [12] highlighted that transport of acids to methanogens, in particular acetic acid as principal precursor for methanogenesis, may be a more important mechanism than the reverse process, since methanogens transported to the fresh biomass would become inactive due to acid inhibition.

III. Addition of Inoculum

A too high ratio of inoculum would unnecessarily occupy reactor volume, which is undesirable for biogas generation and economic viability of the facility. Therefore, the aim is to use as little inoculum as possible but as much as necessary to ensure successful start-up of the degradation process resulting in reliable biogas production. Different substrates require very different amounts of inoculum. While some biomass will process well without or with little addition of inoculum, others require up to 70% of solid inoculum to ensure a stable process [21]. To mix fresh biomass and solid inoculum, utilisation of a compost windrow turner was demonstrated a suitable method in practice [21].

The underlying theory presented in Section II shows that methanogenic areas need to remain active in the presence of acidity in the surroundings. To sustain the population of methanogens sufficiently active despite rapid acidification after start-up of the process, the methanogenic areas need 'safe havens' [22] for the methanogens, i.e. zones where methanogenic activity of the seed remains high enough to consume incoming acids and then expand methanogenic reaction zones throughout the reactor.

No information is available in literature on the optimum size of the initial methanogenic areas. The theory presented above shows that a too rigorous mixing of fresh biomass and inoculum would result in very small methanogenic areas available during the start of the process, and hence is not suitable. Such an approach would increase the risk of methanogenic areas getting rapidly overwhelmed by acid inhibition. The necessary minimum size of methanogenic areas certainly depends on the degradation characteristics of fresh biomass, in particular hydrolysis rates. Aside of the abovementioned mixing of fractions with a compost windrow turner which produces pre-mixed biomass prior to filling the load into the reactor, in practice strategies are as well successful where the reactor is filled by inserting shovel loads of fresh biomass and solid inoculum alternately, e.g., by the operating wheel loader.

The more stable persistence of separate methanogenic and acidogenic areas probably also explains the observation that dry digestion with recirculation of the liquid phase is more stable (but proceeds less rapid) when fresh biomass and solid inoculum has not been mixed, but is placed into the reactor in layers (see [21, 23]). This indicates that too little mixing of substrate and inoculum might retard the process, while too rigorous mixing might result in digester failure due to reduced availability of methanogenic zones with sufficient capacity to retain methanogenic activity during acidifying conditions following the start of the process.

IV. Management of the Liquid Phase

Experimental studies show that dry digestion is sensitive to leachate recirculation strategy (see in full detail in a previous publication [16]). In any case, positive effect was not found on the degradation process for continuous recirculation of the liquid phase, neither in set-ups where methanogenesis is the rate-limiting step and development of a methanogenic population is essential for the further degradation, nor in set-ups where methanisation is in a stable phase and hydrolysis is the rate-limiting step.

It is evident that optimal conditions for methanogens are especially important in the initial stage during start of the process. Experimental findings show that continuous water recirculation would result in higher risk of acidification [16]. This is in agreement with literature data. While initiating an AD process, low leachate recirculation rates are also recommended by Veeken and Hamelers [20] and Vavilin et al. [24, 25]. A low liquid flow in the initial stage is assumed to be beneficial for the expansion of methanogenic areas [24, 25]. It can further be assumed that, when incoming acids cannot be sufficiently degraded in methanogenic areas, acidogenic areas expand throughout the reactor. In consequence, high rates of mass transfer may have inhibitory effects after overwhelming the assimilative capacity of methanogens, while low rates may simply retard the process [12].

A higher rate of mass transfer between methanogenic and acidogenic areas [24], and improved solubilisation [10] are associated with higher rates of liquid recirculation. In consequence, it has been recommended [20, 24] to increase the leachate recirculation rate when it is hydrolysis that is rate-limiting and not (or no longer) methanogenesis. However, experimental results show no beneficial effects at all for continuous leachate recirculation, neither during start of the process nor in a system with stable methanogenic population [16]. This indicates that a continuous water flow through the biomass bed might not be an efficient means to improve biomass solubilisation, although this might depend on the type of biomass and the pathways of flow of moisture through biomass bed, which among others is influenced by the structure of solid biomass. Similar to landfilled material [26], large pore volumes and heterogeneity of the material may lead to rapid vertical flow of leachate along preferential flow paths. Compaction of substrate is further relevant.

Besides the flow of moisture through the biomass bed, the biomass moisture content itself is a decisive factor in AD [27, 28]. Digestion of biomass with its initial water content adjusted to water-holding capacity may proceed quite similarly both with and without leachate recirculation; in experiments, methane yield was only 5% higher after six weeks when leachate recirculation was applied [16]. It is therefore to be recommended to adjust water content of the biomass before closing the reactor, i.e., before starting the digestion process, as this will be more efficient than gradual adjustment through sprinkled liquid after closure of the fermenter.

Aside of optimisation of the degradation process itself, in an overall assessment, it should be considered that operation of pumps for recirculation of liquids results in significant consumption of electricity. Under this aspect, it is desirable to operate pumps as little as possible. As highlighted above, this is rather in agreement and not in disagreement with optimisation of degradation process conditions. Especially in small full-scale applications with simple technical equipment the flow of pumps can often not be regulated (direct variation of leachate sprinkling rate is therefore not possible). The abovementioned experimental results provide evidence that intermittent and short operation of pumps is appropriate.

In any case, biogas production occurring in the liquid phase needs to be considered; depending on the type of digesting biomass, significant amounts of biogas can originate from organic material which leaves the digestion box and is further degraded in the process water tank [29]. The collection of biogas not only from digestion boxes but also from the process water tank should therefore be considered as a standard even while trying to reduce the degree of technical complexity of the AD plant and necessary investment costs.

Changing the overall quantum of circulating liquid is not of decisive influence on the amount of biogas generated in the process water tank, whereas it is the presence of easily hydrolysable biomass which increases the share of biogas generated in the process water tank. Figure 2 shows the results of an experiment in which 10–21% of total methane was generated in the process water tank. When digesting substrate with 20% maize, 10–11% of the methane was produced in the liquid, regardless of the ratio of solid material to liquid in the process water tank in the system (1:2.9, 1:3.4 or 1:10.0), which shows that the volume of free liquid is not of decisive influence. It is further evident that the amount of easily hydrolysable organic material in the system clearly influences the proportion of methane generated in the process water tank (in this case maize silage as easily hydrolysable material, detailed results in [29]).

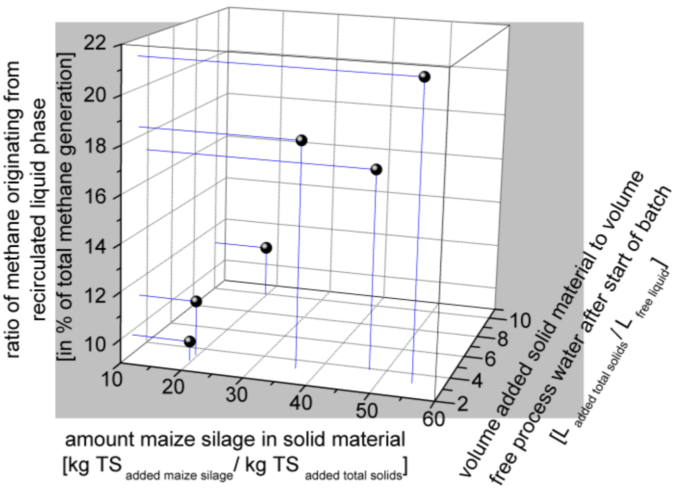

Figure 2. Experimental results showing the effect of the amount of process water in the system and of biomass characteristics (presence of easily hydrolysable fractions) on biogas generation in the external process water tank. The percentage of methane attributed to generation in the process water tank is dependent on the level of easily hydrolysable substrate (maize silage) and on the volumetric ratio of added solids to liquid in the process water tank [29]. (© S. Kusch)

The results confirm that even when deciding in favour of a very small process water tank or when reducing the volume of free liquid, the generated biogas needs to be collected, as it is not the amount of free liquid in the system which is of decisive influence on occurrence of biogas in the liquid phase. The results further suggest that applying discontinuous recirculation of liquid (in this experiment liquid was recirculated 4 × 15 min per day) is beneficial to assure necessary water quality. Organic material washed out from the solid biomass was successfully metabolised in the process water tank, thus allowing for a liquid that could enrich itself again with hydrolysed organic components during the next process water recirculation interval.

V. Conclusions

Managing the start-up phase in a routinely successful manner is highly important in batch-operated dry anaerobic digestion. Optimisation strategies are limited since no direct process control is possible during actual digestion. Pre-treatment of substrate by mixing fresh material with solid inoculum and leachate management are key factors. Both are related to creation and maintenance of methanogenic areas within the decomposing biomass bed. Such areas need to function as seeding from which methanogenic activities expand throughout the digester, but they need capacity to in any case operate as safe surviving zones for methanogens on acid formation after process start-up. This requires a minimum size of such methanogenic zones, which means that in cases of acidification, optimising the start-up conditions by more intense mixing of fresh biomass and solid inoculum is not an ideal and in most cases not a suitable solution.

With a view to leachate recirculation, continuous recirculation is not advisable. Experimental results show that continuous recirculation of leachate increases the risk of acidification during start-up and consequently can induce an inhibited methane production. Intermittent operation of recirculation pumps is therefore advisable. The moisture content of biomass should be adjusted prior to process initiation. If the water content of the biomass is favourable and the proportion of solid inoculum added is adequate, long process water recirculation intervals are acceptable. Very little leachate recirculation may retard the methanisation process, but if recirculation is too intensive the digestion process may fail.

Biogas production will take place not only in the digestion box while solid biomass is degrading, but also in the process water tank, where washed out organics are metabolised.

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