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Disintegration of liquid manure in a parallel operating pilot plant

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The treatment (disintegration) of biogas substrates and fermentation media is carried out aiming in process optimization and thus increasing efficiency. Newly developed disintegration procedures are often tested on a laboratory scale or in single-line pilot plants to prove their effectiveness in a first test phase. Due to the constantly changing properties of biogas substrates, especially in the case of solid substrates, a parallel fermentation of treated and untreated substrate is recommended. In this way it is possible to assess the effectiveness of the newly developed disintegration method, even if the substrate quality changes over time. We present a concept in which two identically structured digester lines, each with a 200 L digester (D) and a second step digester (SD, 100 L), are operated in parallel in a pilot plant. The treatment takes place in one digester line (DD, SDD; D = disintegration) while in the second digester line (DB, SDB; B = blind, flow through) the substrate flows through a chamber of the same geometry but without treatment facilities.

Keywords
parallel fermentation, synergy effect, pulsed electric field, shock wave, biogas yield

The fermentation of biogas substrates (liquid manure, solids) is subject to economic constraints (Wieland 2010). Therefore, there is increasing effort to run this process more efficient. The importance of the pretreatment of biogas substrates with various methods (Zeynali et al. 2017, Almomani et al. 2019, Westerholm et al. 2019), but also the treatment during fermentation, has been described frequently (Yadvika et al. 2004). In the past, biogas plants were mostly operated in a simple way with manual process management. Neither the control of important operating parameters nor an analysis of the energy balance was used to optimize the yield (Vollmer 2011, Wolf et al. 2013). Due to increasing cost, not only for the raw materials, process optimization gains increasing interest (Ahring and Angelidaki 2003). In particular, the rate-limiting step in the fermentation of biomass. Today, a pretreatment like hydrolysis (Climent et al. 2007, Alvira et al. 2009) plays an increasing role in optimizing the overall process. Moreover, mechanical comminution can increase the surface that can be reached by microorganisms. Fermentation is often delayed due to very inhomogeneous raw materials with high content on long fibers. Without pre-treatment, dwell times are longer with a correspondingly low yield of biogas. Besides this, long fibers cause system malfunctions due to clogging of conveyor systems. In this context, lignin-containing components are problematic. However, lignin can be disintegrated thermally or chemically (Carlsson et al. 2012) yielding cellulose and hemicellulose available for fermentation. By increasing the assessable surface, the speed of the process is increased, but this does not significantly affect the biogas or methane yield. Nevertheless, the availability of previously unreachable substrate components die to pretreatment can speed up the fermentation process. In general, substrate digestion

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yields a reduction in the mean particle size, the release of dissolved substances and a reduction in dynamic viscosity (Climent et al. 2007).

Mechanical pre-treatment using cutters and mills is currently the most widespread method. An emerging technique for disintegration is ultrasonic treatment (Castrillón et al. 2011). Low frequency ultrasound (20 - 50 kHz) of high intensity yields cavitation especially in regions of rapidly changing ultrasonic impedance (e.g. particle boundaries). The fast jets due to the collapse of gas bubbles lead to the destruction of long-fiber structures such as grass (Rodriguez et al. 2017). Thermal and chemical processes have been investigated under practical conditions for various raw materials, but are currently only rarely used despite the sometimes considerable increase in gas yield. In the case of long-fiber materials with a high content of lignin, in addition to mechanical shredding, heat treatment at temperatures above 100 °C (Xie et al. 2011) is also possible. The combination of mechanical and thermal procedures is particularly effective. When using a twin screw extruder, sufficient heating occurs due to the friction during the milling process (Thoss 2007, Hjorth et al., 2011). Biological digestions by adding enzymes or microorganisms are intended to improve the productivity of biogas plants. However, the effect is discussed contrary in science and practice. On the one hand, a considerable effect of over 30% is found for some substrates (Karray et al. 2015), on the other hand, the effect can be considerably lower, as with corn stalks (Schroyen et al. 2014). The additional costs for enzymatic digestion, however, exceed often the benefit (Brulé et al. 2008, Brulé et al. 2011, Müller et al. 2016).

The combined effect of a very short, high amplitude pressure wave (shock wave) synchronized with the application of a high electrical field of short duration ($E > 3$ kV/cm, $t < 10$ µs) can improve the biogas yield with a positive energy balance. The mechanical shock wave destroys cellular structures (tissue) and breaks up clumps while short but strong electrical pulses permeabilize cell membranes. This effect, known as electroporation, allows parts of the cytoplasm to leak out. This material is therefore immediately available for fermentation (Vorobiev and Lebovka 2008). It should be noted that the effect of electroporation on cells increases with their size, so that large plant cells are disrupted while bacteria and archaea mostly survive, which is an essential prerequisite for process stability. Long-lasting electrical fields can electrophoretically extract ions and charged molecules from cells and clumps (Casciola 2016), which supports their rapid bioavailability. A pilot plant with parallel fermentation was constructed for the direct comparison between substrate treated with shock waves and high-voltage pulses and such without any treatment. Therefore, the two fermentation lines differ only in the treatment chamber in one line and a geometrically identical flow chamber in the other one.

Material and methods

Structure of the pilot plant

The plant was designed for the test fermentation of pumpable substrates. A combination of corn silage and cattle manure, which is widely used in practice, was inoculated for test digestions. Due to the parallel design of the main digester and the secondary digester, the fermentation process with treated and untreated fermentation substrates could take place under comparable conditions. For the current study, the treatment chamber was equipped with an electrode system for applying electrical fields and a shock wave device while the flow chamber is a duplicate but without treatment facilities.

Digester

The pilot plant consisted of two digesters (2 x 200 L fermentation volume) and two secondary digesters (2 x 100 L fermentation volume). Each of them had a stirrer connected to a common motor via belt drive (M-1). A storage vessel (approx. 60 L) serving both lines was stirred using a separate motor. Both main digesters were fed sequentially using piston pumps (P-1 and P-2). To prevent clogging, the substrate was conveyed directly into the pump cylinder via pipes with a diameter of 48 mm. The piping and instrument flow diagram of the pilot plant is shown in Figure 1.

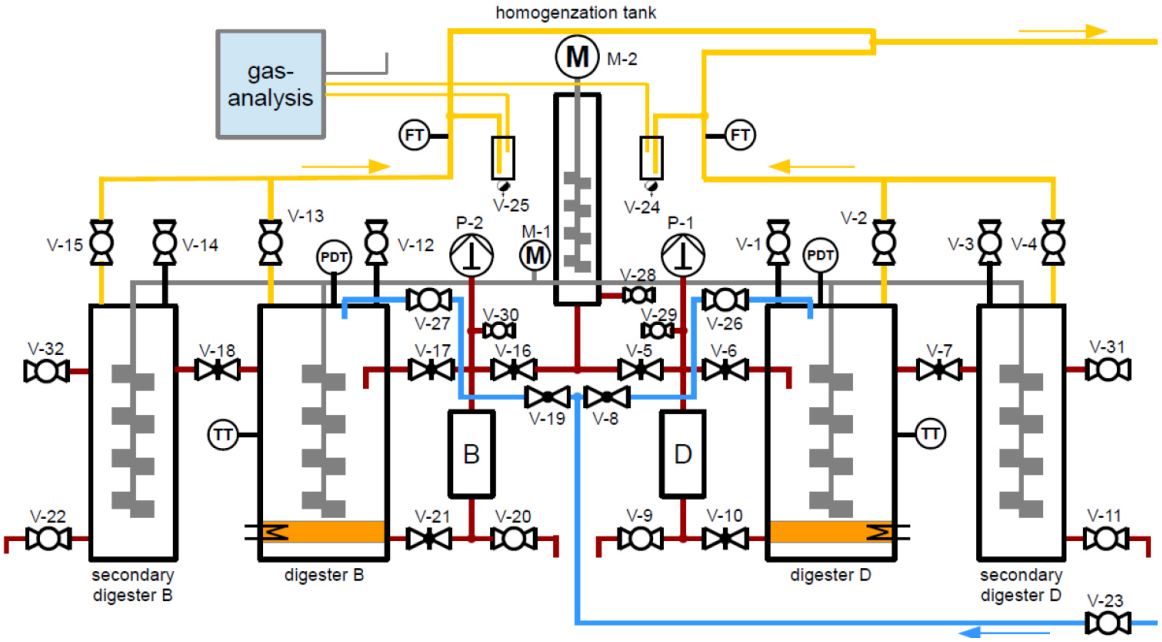

Figure 1: Piping and instrument flow diagram of the pilot plant consisting of line 1 without disintegration and line 2 with disintegration. In the treatment chambers, D (disintegration) stands for the actual treatment chamber, while B (blind) represents a flow chamber of the same geometry but without electrodes and piezo elements. The abbreviations for the digesters in text are. DD, SDD – digester and secondary digester with disintegration; DB, SDB – without disintegration (© D. Echtermeyer)

By controlling the pumps and valves P1/V (5, 6, 10) (digester with treatment, DD) and P2/V (16, 17, 21) (digester without treatment (blind conveying), DB), two essential regimes could be set:

(1) Feeding from the storage vessel with or without treatment and
(2) disintegration (or blind conveying) of the substrate (recirculate) conveyed from the digester via valve V10 at DD (V21 at DB).

Emptying of the digesters was possible by means of the valves V30 and V9. V15/V13 (B) and V4/V2 (D), were used to harvest gas. A partial flow was fed to the gas analyzer (Awite, Langenbach, Germany) via the liquid traps V24/V25. A baffle plate trickled with tap water (V8/V19) was used for defoaming.

With the structure implemented here, parallel digestion with the opportunity of direct comparison of the process parameters in both lines was given. The only difference between the two lines was that one had a treatment chamber (DD, electrical treatment and shock wave) while the other line had a flow-through chamber (DB, without treatment) with the same geometry as the treatment chamber. Both digesters are equipped with a heating mat (1 kW) for temperature control (Figure 2).

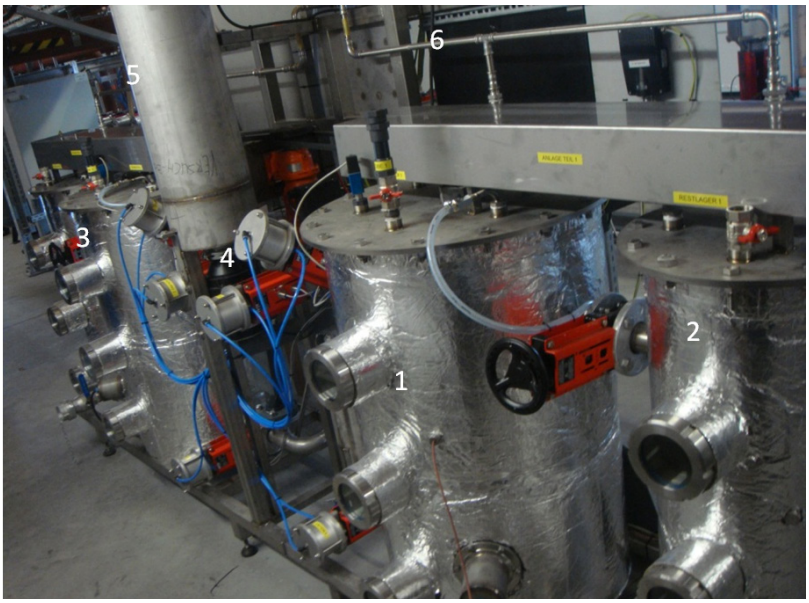

Figure 2: Partial view of the pilot plant installed at the DBFZ (Deutsches Biomasseforschungszentrum gGmbH)
1: digester 2, DD; 2: secondary digester 2; 3: digester 1, DB; 4: pneumatically operated slides V5 / V6;
5: homogenization tank; 6: biogas pipeline (© U. Pliquett)

Data collection

The following data was continuously recorded:

- Temperature in digester 1 and digester 2
- Relative pressure in digester 1 and digester 2
- Gas yield (separately for line 1 and line 2) by means of volume flow sensors (EL-FLOW, Bronkost, Ruurlo, NL)

The gas composition of line 1 and line 2 as well as the ambient air was measured and recorded every hour. The following gases were monitored:

- Methane - CH_4
- Carbon dioxide - CO_2
- Oxygen - O_2
- Hydrogen - H_2
- Hydrogen sulfide - H_2S

In addition to the automatically recorded data, events such as malfunctions and errors as well as process-specific values and events were noted in a system diary.

Process control

The entire process was divided into three essential sub-processes as well as a schedule for feeding and treatment which were implemented in a programmable logic controller (PLC, Figure 3).

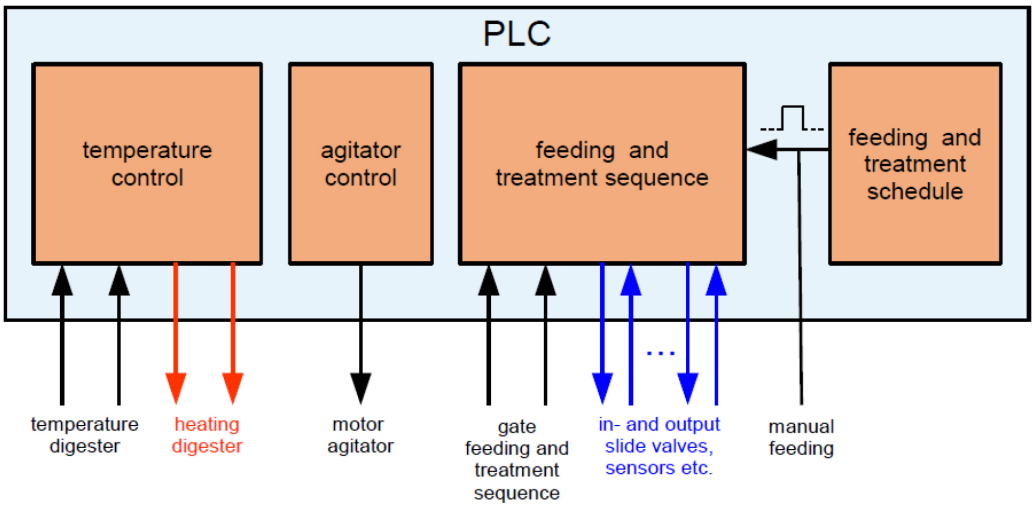

Figure 3: Block diagram for the programmable logic controller (PLC) (© D. Echtermeyer)

Temperature control

The temperature was controlled using a two-point control with a hysteresis of around 1 °C. The fermentation run in the mesothermic range between 37 °C and 38 °C. 1 kW heating mats (80 cm x 160 cm) were used as heating elements.

Control of the stirrers

Continuous stirring was realized by means of a gear motor rotating at 71 rpm. This motor served all four digesters (2 main digesters and 2 secondary digesters) using a belt transmission. For stirring the substrate in the storage vessel, a separate motor was used. The speed could be varied to account for different rheological properties of the substrate.

Feeding and treatment process

A distinction must be made between two scenarios for the feeding and treatment process:

- Treatment of the substrate during the feeding process
- Treatment of the recirculate

The processes (Figure 4) of the two types of test fermentation are implemented in the form of a state machine in separate programs for the PLC and must be transferred to this before starting the experiment.

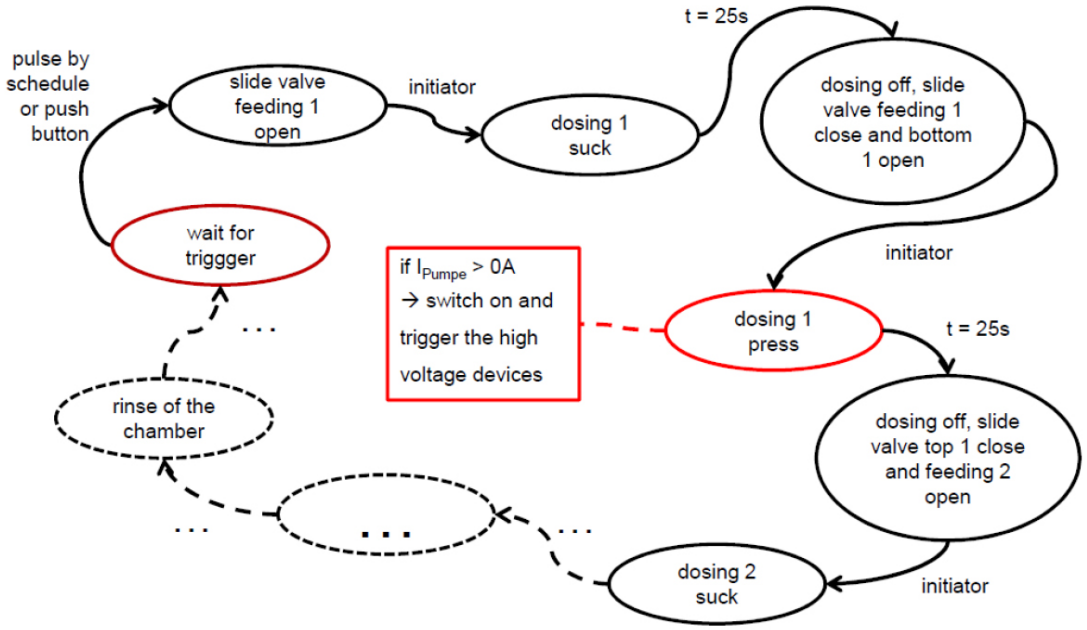

Figure 4: State diagram for the feeding and treatment process. In the idle state, the controller waits for a trigger signal, which is normally given by a timer. The conveying process (dosage) can be carried out several times, depending on the experimental needs (© D. Echtermeyer)

Since feeding from the storage vessel continued during the treatment of the recirculate, the feeding regime remained unaffected, but without treatment. The treatment of the recirculate took place between feeding cycles.

Dosing pump

The dosing pump was designed as a piston pump in combination with three valves. The three operating modes were controlled by the program:

- Fill the pump from the storage vessel
- Empty the pump into the digester
- Fill pump from digester (recirculate)

In order to avoid blockages during dosing due to narrowed profile of the treatment- and flow chamber with respect to the pipes, both chambers are flushed twice in the opposite direction after the actual feeding. For this purpose, both dosing pumps were controlled synchronously. However, we could not always prevent jamming. For this reason, special ball valves were installed that allowed the treatment chambers to be easily emptied in the event of blockage.

Treatment facility for disintegration

Treatment chamber

The treatment chamber is the essential part of the digestion plant for testing new methods for substrate processing. The fluidic part was specially designed with regard to the electrical field distribution with the lowest risk of clogging. This was necessary because the electrode spacing limited due to the envisioned field strength (> 10 kV/cm) and the maximal voltage of the high voltage generator (30 kV). A distance of 1 cm has been specified here. In addition, the aim was to achieve the largest possible area with a homogeneous field distribution, which is why plane-parallel electrodes were chosen rather than the often employed coaxial arrangements. The body of the treatment chamber was machined from PVC and glued with a special adhesive. For coupling the 2 “pipe system to the chamber, a piece of pipe was deformed under heat tach the cross section of the chamber. This avoided sharp edges in the transition region. The electrodes for high-voltage pulse application and electrophoresis were attached above and below the chamber. The piezo transducer for generating the shock wave was arranged in the middle of the chamber. It was clamped between two steel plates in order to close the acoustic circuit. At the opposite side of the piezo element was a blind stopper for easy cleaning in case of a blockage. Another chamber with identical geometry but without piezo transducer and electrodes was installed in the other line of the system (DB/SDB, system line 2*).*

High-voltage pulse system

The high voltage system consisted of three separate devices that form self-contained, independent units.

Microsecond pulse generator SCRPuls30-1500

This generator was used for electrical high-voltage treatment, especially of membrane structures. These membrane structures were temporarily permeabilized by electroporation so that components of the cytosol could escape from the cells. The pulse energy reached up to 100 J, depending on the load, respectively the substrate conductivity. The generator was designed for continuous operation with 1 µs pulses of 30 kV and a pulse repetition rate of 15 pulses/s given that the resistance of the load (treatment chamber) did not fall below 50 Ω. The generator (Figure 5) consisted of a 220 nF storage capacitor which is charged from a 30 kV/1.5 kW power supply. Triggered internally or by external source, the capacitor is discharged into the output by means of a SCR switch module.

Both the voltage and the pulse repetition frequency were variable. The SCRPuls30-1500 is designed for load impedances from 10 Ω to a maximum of 1 kΩ. The pulse duration is in the order of magnitude of 5 µs - 20 µs depending on the load. At low load impedances (< 10 Ω) or in the event of a short circuit, the pulse duration becomes longer again due to the effect of the output choke. Continuous operation in the event of a short circuit leads to shut down after certain time due to the excess temperature at the freewheeling diode. The pulse generator has a shielded output cable where the shield carries the return current from the load. Due to low load impedances, high currents occurred with long pulse durations. At peak currents > 1500 A the internal overload monitoring suppressed the pulse trigger.

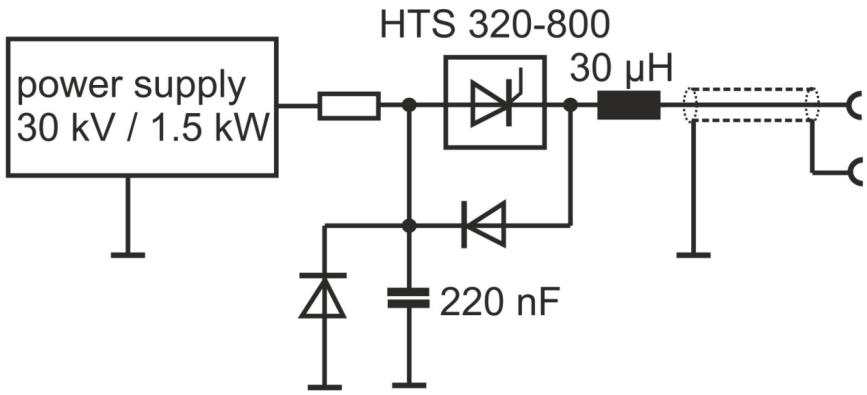

Figure 5: Principle of the high voltage pulse generator. A high-voltage power supply (30 kV) charges the capacitor (220 nF) via a series resistor. The capacitor is connected to the output by means of a high-voltage switching module. The coil (30 µH), the coaxial cable at the output and the two diodes are used for pulse shaping and protection against short circuits at the output (© J. Brutscher)

Electrophoresis power supply

Charged molecules and ions are transported by means of electrophoresis from the previously disintegrated cells but also from clumps and other conglomerates into the surrounding medium which significantly increases their bioavailability. The power supply unit was used to generate the necessary electrical field. Unlike the previously applied high-voltage pulses, the voltage generated with this device is not sufficient to disintegrate the cells. To avoid rapid corrosion of the electrodes, but also to minimize electrochemical effects in the biogas slurry, the device was designed as a bipolar source. The electrophoresis power supply (Figure 6) consisted of a 1000 V, 250 W voltage source and a transistorized full bridge (H-bridge) connected downstream. By controlling the H-bridge, frequency and phase relation, what determined the duty cycle at the output, was adjustable.

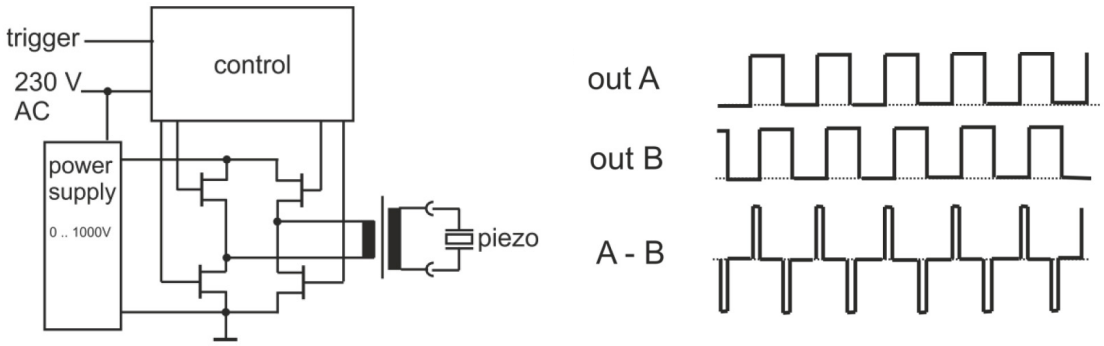

Figure 6: Schematic circuit on the left, output signal form of the electrophoresis power supply as a superposition of two square waves on the right. This allowed the generation of bipolar pulses with variable pulse length (© J. Brutscher)

The electrophoresis power supply is designed for load impedances from 50 Ω up to several kΩ. The load can be adapted to the available power by adjusting the duty cycle via the phase position of the both outputs. In the case of a short circuit or the current exceeds 20 A, the output is switched off.

Shock wave generator

The shock wave was generated by a high-performance piezo ceramic from CeramTec (SONOX® P 8, SONOX® P 4) using a high-voltage pulse. The piezo disks have a diameter of 5 cm and a thickness of 8 mm. The breakdown field strength is given as 1 kV/mm. The use of up to 8 kV eliminates the need to use a stack as is common with low-voltage systems. The resonance frequency of the built-up system is around 36 kHz, which is why pulse lengths of around 10 µs (1/3 of the period) were used for excitation. A pulse generator (Figure 7) was developed for this purpose, which has been specially optimized for bipolar control of capacitive loads up to 2 nF. The piezo pulse generator consists of a 1000 V full bridge and a downstream 1 : 5 transformer. In response to a trigger signal, the full bridge first delivers a positive, then a negative pulse. This voltage is stepped up using the transformer. Depending on the adjustment of the pulse widths, there is also a resonant voltage increase.

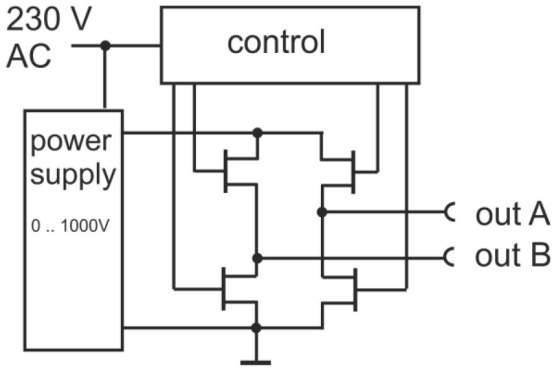

Figure 7: Schematic of the shock wave generator (© J. Brutscher)

Process description

The digesters were operated with a substrate mixture of 55% corn silage and 45% cattle manure (based on the proportion of organic matter (OM)). To start the process, the space loading was increased from 2.5 $kg_{oTS}m^{-3}d^{-1}$ to 3.5 $kg_{oTS}m^{-3}d^{-1}$ in daily steps of 0.2 $kg_{oTS}m^{-3}d^{-1}$. The residence time was adjusted to 30 days by adding tap water in the start-up phase. This was no longer necessary in the further course of the fermentation. Maize silage and cattle manure were obtained from a farm in the region. A batch of maize silage was stored under a tarpaulin for up to a week. The cattle manure was stored in a 185 m^3 container at ambient temperature. The dry matter (DM) of the maize silage varied between 27–35% of the fresh matter, the organic matter (OM) between 89–98% DM. In the case of cattle manure, the DM was 5–11% fresh mass and 74–82% DM. The chemical composition of the substrates was analyzed according to Weender (VDLUFA 2007). The inoculum was drawn from a 188 m3 stirred tank reactor of the research biogas plant at the DBFZ, which was operated with corn silage mono-fermentation. A chronological overview of the test phases can be found in Table 1. In all phases the digester 2 (DB, with blind chamber) was operated without treatment of substrate or recirculate. The periods of time with automatic (6 times a day) and manual feed (1 time a day) varied depending on the test phase as shown in Table 1.

Table 1: Time sequence of the test phases

phase	Duration	fresh substrate		recirculate	
	d	feed	treatment	feed	treatment
I	0 – 64	auto	no	-	no
II	65 – 112	auto	yes	-	no
III	113 – 146	auto	no	-	no
	147 – 182	manually	no	-	no
IV	183 – 268	manually	no	auto	yes
V	269 – 282	-	no	auto	yes

In the start-up phase (test phase I), both digestion lines were operated in parallel, without treatment of raw substrate or recirculate. In test phase II, raw substrate in line 1 was treated (HFB, treatment chamber), while no treatment took place during an intermediate phase (test phase III). Due to various process disturbances, mostly as a result of constipation, test phase III could later be differentiated into irregular feeding (113 d–146 d) and manual feeding (147 d–182 d). In test phase IV, fermentation medium from the digester was pumped through the treatment chamber (blind chamber in line 1) and then returned to the digester (recirculate treatment). The final test phase IV was characterized by the cessation of feeding while the disintegration of the recirculate was continued.

Process monitoring (laboratory analyzes)

To evaluate the biogas process, critical parameters were recorded online while the substrate composition and the fermentation medium were analyzed offline in the biogas laboratory of the DBFZ. The biogas quantity and quality were recorded at the pilot plant using an AWIFLEX gas analyzer (AWITE Bioenergie GmbH, Langenbach). Besides this, the temperature in the main digesters was recorded and the fill level was either assessed optically or set via an overflow. In the biogas laboratory, samples from the main digesters (Strach 2015) were frequently monitored for DM and OM, the sum of volatile organic acids (VFA) and the ratio of VFA content to total inorganic carbon (VFA/TIC) (Strach 2015b). Moreover, the pH value and ammonium nitrogen content (Strach 2013) were assessed. Single acid spectra were determined using a gas chromatograph (Agilent 7980A with FID detector, Agilent Technologies; ZB-FFAP column (30 m x 0.32 mm x 0.25 µm), Phenomenex) (Apelt 2015). In order to assess the possible changes in the flow properties, especially when comparing the two system lines, viscosity was determined using a rotation viscometer (Viscometer, Brookfield, Spindel 65).

Results of experimental fermentation

Parallel fermentation without treatment

These tests should show the comparable results of the fermentation in both lines of the pilot plant. In test phase I (start-up phase), both digesters were operated in parallel without any treatment. Substrate from an active research reactor based on corn silage mono-fermentation was used as the inoculum. After a start-up phase of about 10 days, the specific gas production (Figure 8) had stabilized and was 403 ± 88 Lkg^{-1} for DD and 415 ± 91 L kg_{OM}-1 for DB, above the expected range of 204 L kg_{OM}^{-1} to 275 L kg_{OM}^{-1} (Amon et al. 2006).

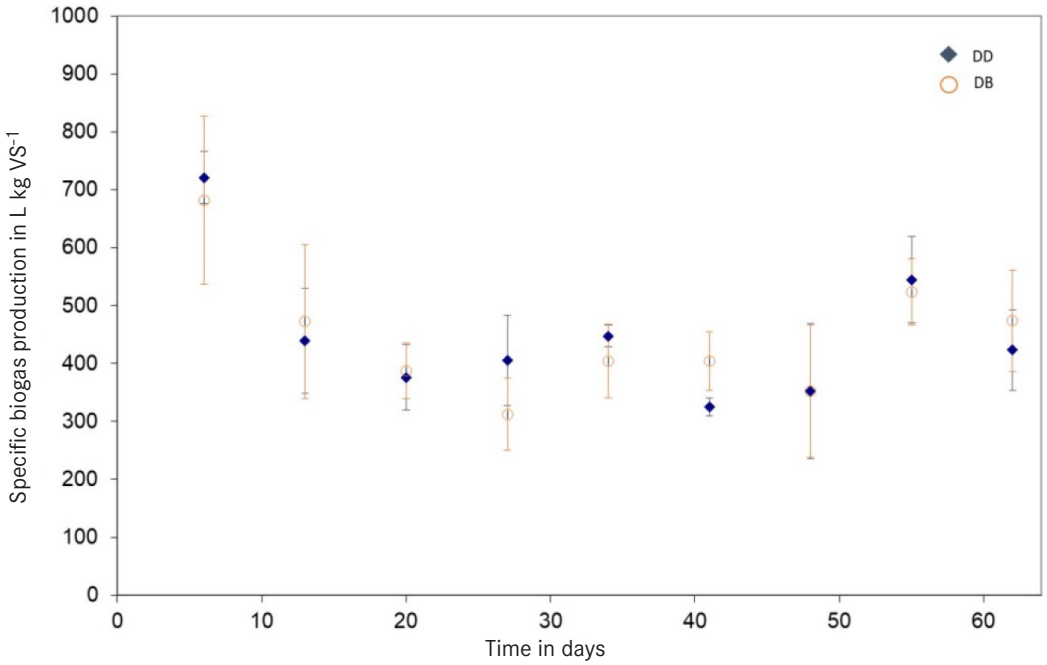

Figure 8: Specific biogas production of the digesters DD (with treatment) and DB (flow only) in test phase I (given as weekly mean values)

The gas composition (Table 2) was also in line with expectations and was stable over the considered period.

Table 2: Gas composition in the digesters DD and DB in the test phases I - V (mean values ± standard deviation). The sometimes high uncertainty in the gas composition results from the brief aeration during the removal of blockages.

Test phase	CH_4 in %	CO_2 in%	O_2 in %	H_2 in ppm	H_2S in ppm
DD					
I	58 ± 2	42 ± 2	0,2 ± 0,4	29 ± 22	372 ± 144
II	60 ± 2	40 ± 2	0,1 ± 0,1	22 ± 20	282 ± 183
III	56 ± 2	44 ± 2	0,1 ± 0,3	15 ± 12	783 ± 505
IV	57 ± 2	43 ± 2	0,2 ± 0,6	11 ± 8	676 ± 485
DB					
I	58 ± 2	41 ± 2	0,3 ± 0,5	25 ± 23	344 ± 154
II	59 ± 2	40 ± 2	0,1 ± 0,2	18 ± 18	281 ± 181
III	55 ± 4	43 ± 2	2,5 ± 5,1	14 ± 11	641 ± 501
IV	56 ± 3	42 ± 2	1,1 ± 4,1	10 ± 8	655 ± 485

The pH value (Figure 9) was initially higher (around pH 7.9) and fell to pH 7.8 during the start-up phase. On average, the pH value in the start-up phase of both digesters was in the range of 7.6–7.9 and showed no noticeable fluctuations. In test phase I, the VFA content in the fermentation medium is 1.4 ± 0.4 g L^{-1} or 1.2 ± 0.4 g L^{-1} and the VFA/TIC ratio 0.18 ± 0.04 or 0, 17 ± 0.01 in DD and DB. This means that the process conditions in both reactors are comparable and stable. There were considerable fluctuations in the acetic acid concentration during test phase I, while regular feeding resulted in

stable values of 28 ± 11 mg L^{-1} for acetic acid in the untreated line of the system and 31 ± 13 mg L^{-1} in the line with electrical treatment. The values for all other acids (propionic acid, iso-butyric acid, n-butyric acid, iso-valeric acid, n-valeric acid) were stable below 10 mg L^{-1} in both digestion lines.

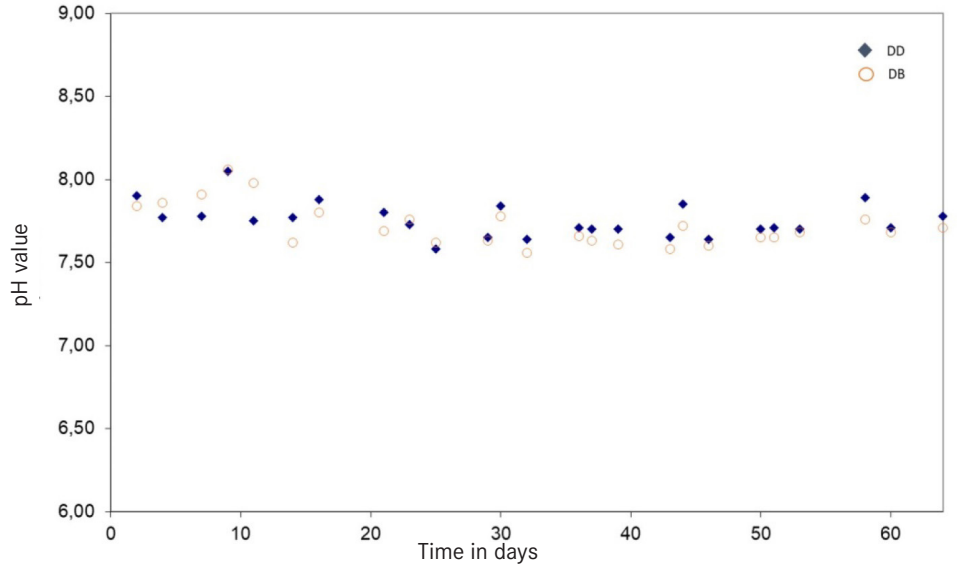

Figure 9: pH value in the digestate of the digesters DD and DB in test phase I.

Influence of the combined treatment with high voltage pulses and shock waves

In test phase II the substrate and in test phases IV and V the recirculate was treated by means of high-voltage pulses and shock waves. The treatment had no significant influence on the specific biogas production (Figure 10). Even with a decrease in specific biogas production in test phase IV, which can be attributed to irregular feeding during this test period, there was no significant difference between the two lines of the plant. The gas composition with regard to CH_4 in test phase II was 60 ± 2% in DD and 59 ± 2% in DB or 57 ± 2% in DD and 56 ± 3% in DB in test phase III. No difference in methane levels attributable to the treatment could be found. Owing to the frequent blockages in the line without treatment (DB), where the loosening was accompanied by the introduction of oxygen, a higher oxygen concentration was recorded during test phases III and IV in the line with treatment (DD) (Table 1).

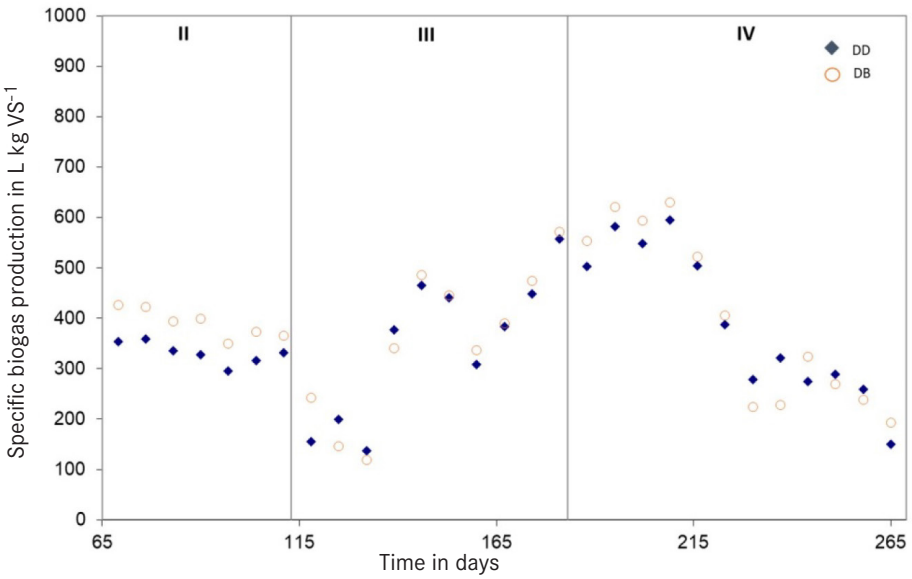

Figure 10: Specific biogas production of the digesters DD and DB in test phase II - IV (given as weekly mean values)

The electrical treatment had no significant influence on the pH value, which was stable between pH 7.6 and pH 7.8. The VFA content in test phase III was 0.9 ± 0.05 g L^{-1} in DD and 0.7 ± 0.03 g L^{-1} in DB. The VFA content in the line with treatment treated was also stable in test phases IV and V, but increased by a factor of 1.2 (Figure 11).

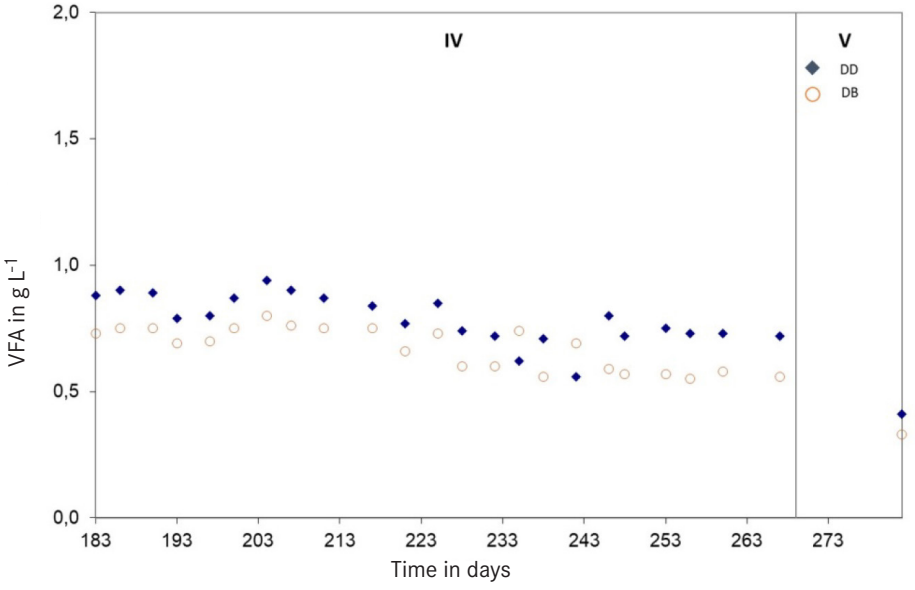

Figure 11: VFA content in the fermentation medium of the digesters DD and DB in test phases IV and V.

In terms of the acetic acid concentration in the fermentation medium, there were clear differences between the lines with and without treatment in test phase IV (treatment of the recirculate, Figure 12), despite the low total concentration. While the acetic acid concentration with electrical treatment

was 30 ± 10 mg L^{-1}, the value without treatment was mostly stable at 16 ± 4 mg L^{-1}. It is possible that the electrical treatment was periodically disrupting the microbial community and took time to regenerate. It is also conceivable that as a result of the treatment, for example, conglomerates were reduced that released additional nutrients, which in turn could be partially converted into acetic acid. In test phase V (decay phase), the ratio of the difference in acetic acid content of the fermentation media remained the same (DD: 29 mg L^{-1}; DB: 15 mg L^{-1}). The acetic acid content as well as the VFA content are in the „normal“ range in both reactors and do not indicate an inhibition.

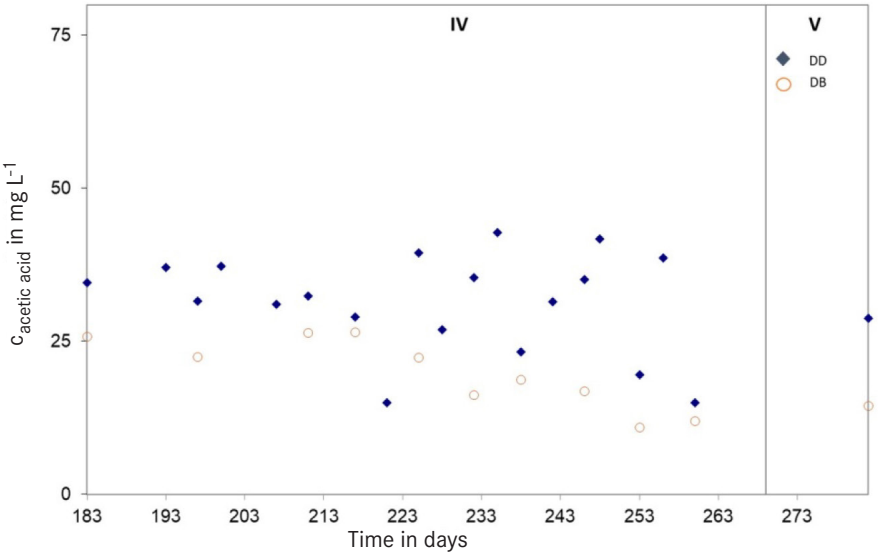

Figure 12: Acetic acid concentration in the fermentation medium of the digesters DD and DB in test phases IV and V.

In test phase II the ammonium nitrogen content of the fermentation medium in the treated line was 1.6 ± 0.3 g L^{-1}, somewhat higher than in the untreated digester, where only 1.4 ± 0.3 g L^{-1} was measured. In the following test phases, both lines showed comparable ammonium nitrogen contents (test phase III: DD with 1.1 ± 0.06 g L^{-1}; DB with 1.0 ± 0.04 g L^{-1} and test phase IV: DD with 1.1 ± 0.1 g L^{-1}; DB with 0.9 ± 0.1 g L^{-1}) During the decay phase this value decreased in DD to 0.8 g L^{-1} and in DB to 0.7 g L^{-1}.

Discussion

In this project, the advantages of parallel fermentation for investigation of the disintegration of fermentation media and biogas substrates could be demonstrated on a pilot scale. Despite the changing quality of the starting substrates (especially in the case of corn silage), a comparison of the two reactor lines was possible. This makes it possible to carry out an objective assessment of the process conditions and thus to judge the influence of the treatment. Unfortunately, a far more precise differentiation of the effects of the disintegration method shown on the biogas formation was prevented by the high number of operational disruptions. Although program changes and changes to the pipeline periphery succeeded in reducing the risk of interference during the course of the project, typical scaling effects continued to occur. The use of 2-inch pipelines for a pilot plant represented a common pipe cross-section for such plant sizes. However, there were limitations with the fiber lengths or lump sizes of the starting substrates that could not be scaled. An additional mechanical pretreatment of

the substrates was deliberately avoided with regard to the evaluation of the disintegration method. Initially, both reactor lines were started up together, without treatment, with the aim of achieving stable joint operation (test phase I). This could be shown by, for example, parameters such as the pH value or the VFA content represented a stable course in both reactor lines. The treatment of the raw substrate by means of high-voltage pulses and shock waves took place in test phase II and showed no significant change neither in the specific biogas production nor in the biogas quality in relation to test phase I. Trial phase III was characterized by various malfunctions in the automatic loading, which was circumvent by changing from 6 automatic loading to one manual loading per day. The process then stabilized, which was reflected in the high specific biogas production in both lines of the plant. Manual feeding was continued in test phase IV together with the treatment of the recirculate. Despite the stable VFA content, where the values in the DD were higher, a reduction in the specific biogas production was found. The higher biogas production in the DD is attributed to the digestion the nutrients accumulated during blockages but released afterwards and disintegrated during treatment of the recirculate, thereby making additional nutrition available for the process. The measured VFA levels of 0.5 to 1 g L^{-1} indicate a stable biogas process. VFA levels greater than 10 g L^{-1} would indicate a perturbation of process biology (Voss et al. 2009). This was not achieved over the entire test period, which shows that the disturbances that occurred (oxygen entry by loosening blockages) did not have a long lasting negative influence on the process stability. In test phase V, the feeding was stopped while the treatment continued. The expected decrease in the process parameters (Angelidaki et al. 1999, Mauky et al. 2016) occurred within this time range.

Conclusions

In the course of the economic use of biogas, the optimization of process management is an important part of research and development. New concepts are developed on a laboratory scale and then transferred to production. It must be ensured that a new treatment method meets the requirements with regard to gas yield, gas composition and stability of the overall process and meets the economic requirements. Comparative experiments with multiple individual digesters are not problematic on a laboratory scale because of the small quantities of raw material required, but do not allow upscaling because of the immense effort involved. Testing the limits of a new process could, however, under certain circumstances lead to considerable losses in a large biogas plant in regular operation. Pilot biogas plants are an essential tool in the transition from laboratory to industrial scale. Particularly when producing biogas from substrates such as liquid manure or corn silage, the result always depends on the supply of the raw materials. A comparison of the processes with the same substrate but at different times poses immense risks due to the changing substrate quality during storage.

Only the parallel fermentation of treated and untreated substrate mixtures can make a clear statement about the effect of the treatment. The pilot plant described here meets these requirements. While in successive fermentations with the same treatment, considerable differences were found in some cases (Rittmann et al. 2008), there were no significant deviations in parallel fermentation. These occurred only due to different treatments.

A final evaluation of the process-describing parameters for a general recommendation for procedures can hardly be achieved due to the various operational disruptions. The determination of the possible influences as a result of the treatment with high-voltage pulses in combination with shock

waves can only be partially understood. Both reactor lines showed similar measured values with different process-describing parameters, regardless of treatment and involvement of the disturbance.

The project results shown here refer exclusively to the heterogeneous substrate combination of maize silage and cattle manure. In the future it would be interesting to validate the treatment method with more homogeneous substrate combinations.

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