

Two years experience on a large German STP with acoustic disintegration of waste activated sludge for improved anaerobic digestion

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Abstract Biological cell lysis is known to be the rate-limiting step of anaerobic biosolids degradation. Due to the slow pace by which this reaction occurs, it is necessary to equip treatment plants with large digesters or alternatively incorporate technological aids to overcome the inherent enzymatic limitations. High-power ultrasound is a new and innovative approach to disintegrate bacterial cells. Sludge disintegration has recently gained more attention in the context of using renewable energy sources as it might be a way to improve anaerobic digestion for a better conversion of biomass to biogas. In addition, intensified anaerobic digestion leads to reduced amounts of residual sludge mass to be disposed of. In the past, a number of studies on laboratory and pilot scale have been published about the benefits of different sludge disintegration methods, sometimes with controversial results. For some years now, the authors of this paper have dedicated their efforts to investigating and promoting high-power ultrasound as an innovative technology for biomass disintegration. This paper reports on long term experiences with ultrasound sludge disintegration at a large municipal sewage treatment plant in Germany.

Keywords Anaerobic digestion; biogas; ultrasonic disintegration

INTRODUCTION

Worldwide, anaerobic digestion is the preferred method used for sludge stabilisation, primarily because the process has three very appealing advantages: 1) energy in the form of biogas from the end product of the anaerobic food chain can be harnessed, 2) further handling is made possible, especially dewatering, and 3) the sludge volume for disposal is reduced. With the ever-increasing number of people connecting to sewers, the optimisation of, and continuous attempts to improve, the anaerobic digestion process are essential.

There are several techniques (chemical, thermal, mechanical) available on the market today which claim to improve anaerobic digestion at wastewater treatment plants. A great amount of effort has been devoted by the authors to study acoustic disintegration (ultrasound) processes and their effects on sludge. Investigations in the field originated over a decade ago and since then, advances have been made in this area of research. It has been proven that low-frequency ultrasound (below 100 kHz) generates the cavitation necessary to produce the mechanical shear forces associated with sludge disintegration (Neis et al., 2000). Combined with high-intensity ultrasound of 25-50 W/cm² (Tiehm et al., 2001), the cells are actually destroyed and the intracellular material is released into the medium. Approximately three years ago, the first full-scale ultrasound installations appeared in Germany. Today plants equipped with this new technology can be found in various European countries including the Netherlands, Denmark, Italy and Austria. This paper reports on the first long-term experiences with ultrasound sludge disintegration at a large municipal sewage treatment plant (STP) in Germany.

ENHANCING ANAEROBIC DIGESTION

Controlled conditions and kinetics. In order to enhance the performance of anaerobic digesters, ultrasound can be used to disintegrate waste activated sludge (WAS) before it is fed to the digester. High-power ultrasound in a liquid medium creates cavitation. The bacterial cells in the sludge are subsequently destroyed, as the effects of cavitation are so powerful that microbial cell walls are broken when the cavitation bubbles implode. The contents of the cells are then released into the medium, resulting in a higher degree of substrate bio-availability for the remaining living micro-organisms. In effect, enzymatic-biological hydrolysis, which is the initial and rate-limiting step of the anaerobic food chain, is substituted and catalysed by this mechanical disintegration of the sludge.

At an earlier stage, pilot studies were conducted with five 200 liter digesters operating at 37°C under semi-continuous parallel conditions with variable test parameters (Nickel and Neis, 2007). Three different types of sludge were used 1) WAS, 2) raw sludge, and 3) digested sludge. The hydraulic retention time (HRT) was varied between 4 and 16 days. The test reactors were fed sonicated sludge (ultrasound treatment for 90 seconds at an intensity of 8 W/cm² and a frequency of 31 kHz) and the control reactors received untreated sludge as the organic load. In order to quantify the degree of cell disintegration (DD_{COD}), the chemical oxygen demand (COD) was determined in the supernatant of the centrifuged sludge samples according to Neis et al. (2000). In addition to these variables, biogas production, methane content and the volatile solids (VS) of the input and output sludge was measured and recorded.

Table 1 Effects of ultrasound pre-treatment (at 31 kHz) and subsequent digestion time on anaerobic VS degradation (VS_{deg}) of WAS and biogas production in long-term pilot scale studies using 200 liter digesters operating at 37°C with variable HRTs.

WAS	HRT [d]	Degradation rate [g VS _{deg} /(m ³ digester volume*d)]	VS degradation [%]	Biogas production rate [m ³ / m ³ digester volume*d)]
Untreated	16	257	32.3	0.19
Disintegrated	16	335	42.4	0.21
Untreated	8	430	27.0	0.31
Disintegrated	8	603	38.1	0.36
Disintegrated	4	1011	32.0	0.52

The DD_{COD}, gas production and VS degradation rate and degree in the digesters fed with ultrasonically treated sludge all exhibited higher values as compared to the digesters fed with untreated sludge (Table 1). A closer look at the results reveals that sonication is advantageous when undertaken as a pre-treatment step before anaerobic digestion. The VS degradation rate of the sonicated biosolids at HRT=16 days increased by more than 30% compared to conventional digestion at the same retention time. The effects were even more pronounced in the digesters operating at an 8 day HRT. Comparing the degree of degradation for this pair of reactors, an improvement in degradation of more than 40% was noted. The highest rate of VS destruction was observed in the digester operating at the shortest HRT (4 days). The volumetric degradation rate in this digester almost increased by a factor of four as compared to the conventional digester operating at 16 days HRT (1011:257).

The advantages of accelerating anaerobic digestion by applying a pre-treatment step can not only be expressed in the amount of biosolids degraded, but also in form of the increased biogas production rate. The most significant biogas production rate in relation to the digester's volume was seen in the digester operated at the lowest HRT of 4 days (Table 1).

Overall, all the digesters fed with ultrasonically treated sludge displayed an increased biogas production rate when compared to their conventional digester counterparts.

These results showed that the anaerobic digestion process could be significantly accelerated by the use of ultrasonic pre-treatment. The pilot studies conducted with the 200 liter digesters provided invaluable insight and knowledge to effectively handle the challenges that could arise at a full-scale installation.

BAMBERG STP

The Bamberg STP was designed for 220,000 PE. However, as a result of an improvement and extension of the sewerage system, the load on the plant increased to about 330,000 PE. The plant is equipped with three mesophilic anaerobic digesters to treat a mixture of primary and secondary sludge (WAS). As a consequence of the increased load, more sludge was produced and the HRT in the digesters dropped to just 18 days. The initial plan was to construct a new, fourth digester with a volume of 3,000 m³.

However, the management of the plant in 2002 decided to test the newly developed Ultrawaves ultrasound technology during a full-scale trial period of four months. After feeding the digesters with ultrasonically treated WAS, the gas production showed a marked increase of almost 30% (Figure 1). The methane content also increased slightly making the biogas a more attractive and energy rich product. The residual VS content in the digested sludge was reduced from 60% to 54%. The desired goal to reach a minimum of 45% VS degradation was not only met, but surpassed.

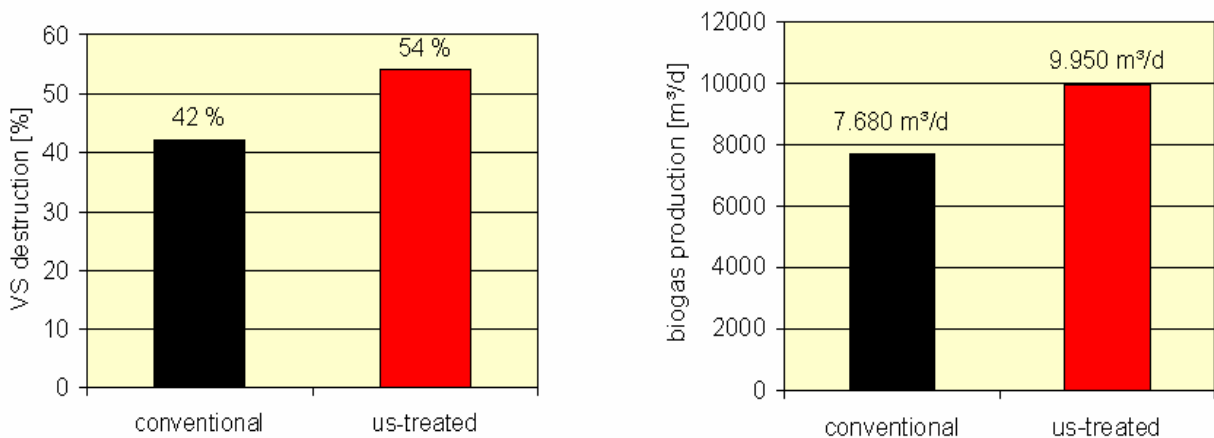


Figure 1 VS destruction and biogas production at the Bamberg STP before and after ultrasound treatment in 2002 (trial period).

After the successful trial period in 2002, the Bamberg STP management decided to purchase two US reactors (2 x 5 kW) instead of building a new digester, avoiding the costly undertaking of such a construction. The ultrasound units were installed in August 2004 with the same objective of enhancing VS degradation to a minimum of 45%. In order to achieve this, the system was designed to sonicate at least 30% of the thickened WAS (TWAS) flow before being fed to the digesters. Parallel to that, separate WAS thickening by a centrifuge was implemented. Primary sludge is still thickened by gravity.

Figure 2(A) is a picture of the two high-power ultrasound reactors that were installed at Bamberg. Figure 2(B) shows the uncovered ultrasound unit. As is clear in both pictures, the

small footprint of the equipment and the simple way that it can be connected to existing piping and installations make it a very attractive piece of technology.

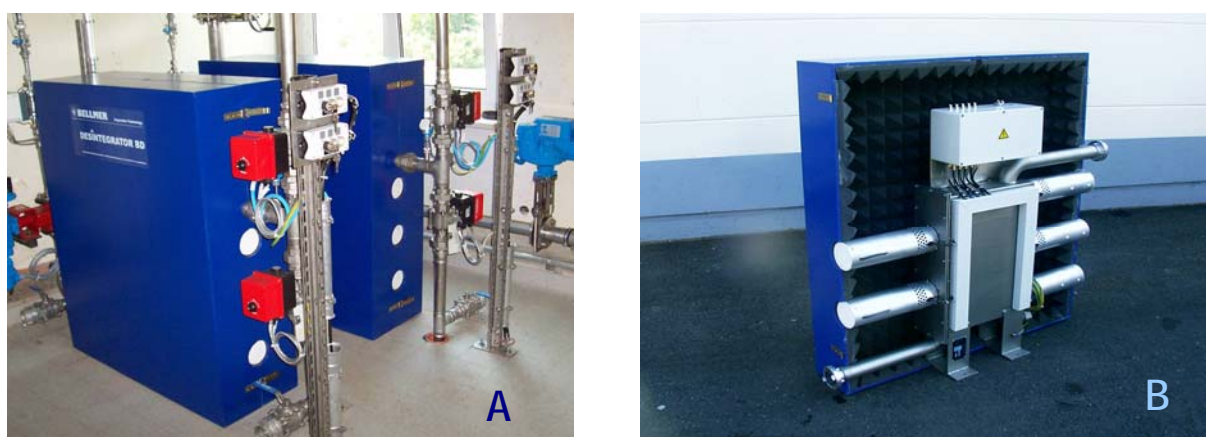


Figure 2 (A) Two sound-insulated Ultrawaves ultrasound reactors at Bamberg STP; (B) Uncovered ultrasound unit for the disintegration of TWAS.

Calculating organic matter mass balances at full-scale STPs is a challenging task. Steady state conditions are never reached. The daily fluctuations as well as less than optimal analytical records make it difficult to objectively assess the performance of the sludge stabilisation system. Even under well controlled pilot scale conditions, a mass balance on the performance of an anaerobic reactor regarding VS often remains incomplete. The assessment of the impact of ultrasonic TWAS disintegration on the anaerobic digestion process at Bamberg was based on routinely-collected data sets. No additional information could be collected. As a result, comparisons are simply based on the period before (1/2003-12/2004) and after (1/2005-12/2006) the start of TWAS treatment.

Table 2 presents a short list of the sludge masses recorded during the studied period. In 2005 and 2006 the ultrasound disintegration of TWAS was in operation all year round with no interruption.

Table 2 Sludge production at Bamberg STP between 2003-2006

Sludge mass (10³ kg/a)	2003	2004	2005	2006
Primary	1,820	1,301	2,472	2,589
Secondary WAS	1,944	2,522	2,034	1,985
Sonicated TWAS	-	-	900*	1,591
Mixed sludge	3,764	3,823	4,506	4,574
VS digested	944	1,088	1,285	1,586

* estimated

The comparison between the pre and post sonication period shows an increase in the percentage VS degraded from 34% in 2003 to 45% in 2006. This increase in digester performance is shown graphically in Figure 3. Table 2 also shows that the share of sonicated TWAS increased considerably, and was about 80% of the total TWAS in 2006. This is due to an improved thickening process at the plant, which eventually led to an average TWAS dry solids concentration of 58 g/l.

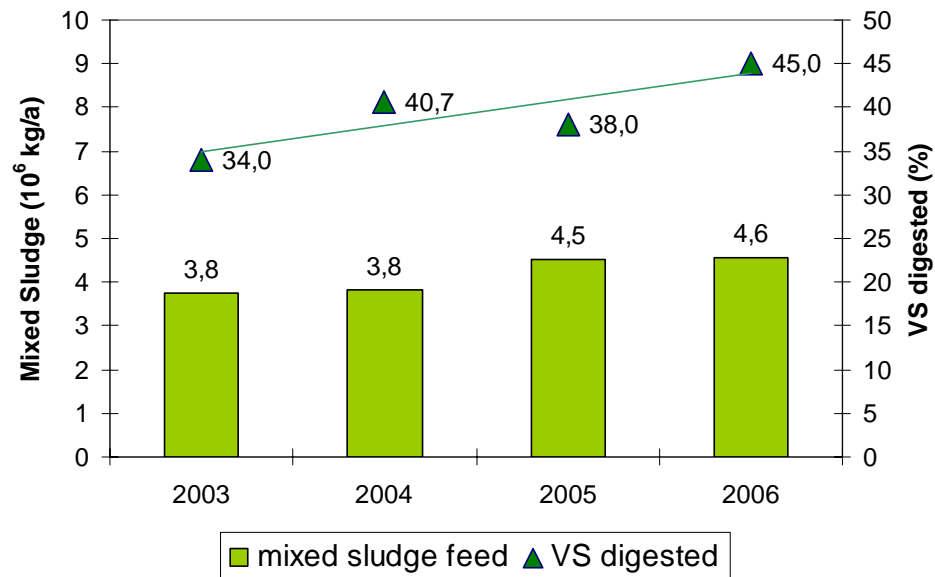


Figure 3 Sludge VS degradation; ultrasonic TWAS disintegration since 08/2004

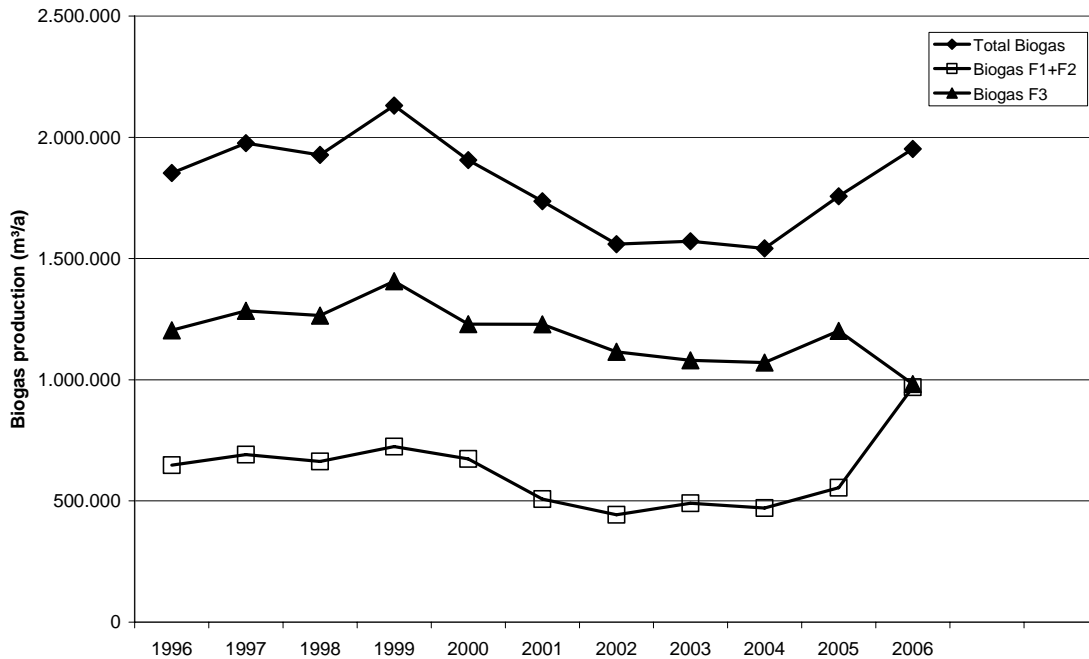


Figure 4 Biogas production; ultrasonic TWAS disintegration since 08/2004.

The increase in the VS destruction implies that more of the organic matter in the sludge was metabolised in the digestion process. This coincides with the increase in gas production (Figure 4). While the specific gas production per kg VS input seems to remain more or less constant over the years, the specific gas production per unit VS degraded decreased. This and data pointing to the unusually high absolute values of the latter are not easily explained.

Table 3 Biogas production at Bamberg STP between 2003-2006

	2003	2004	2005	2006
Biogas (10 ³ m ³ /a)	1,571	1,542	1,756	1,952
Biogas (m ³ /kgVS _{in})	0.57	0.58	0.52	0.55
Biogas (m ³ /kgVS _{deg})	1.66	1.42	1.37	1.23

The total volume of sonicated TWAS in 2006 was 27,440 m³, corresponding to 75 m³/d. This represents an ideal volumetric flow for the two installed ultrasound reactors. The ultrasound units are in operation 24 hours per day all year round and at an average of 80% of the maximum power. The resulting sonication time is 67 seconds. The energy consumed was 70,800 kWh/a, representing 1.5% of the total energy consumption of the plant. The calculated average specific energy dose of the ultrasound units is 2.6 kWh/m³ TWAS (0.044 kWh/kg DS or 159 kJ/kg DS), a value which is well below data published previously from experiences not collected in real life situations at full scale (Lehne and Müller, 1999).

Through the increase in gas production, the self-sufficiency of the plant in terms of energy supply was improved, and the plant was able to supply a large fraction of its operative processes with energy obtained from its anaerobic digestion process.

COST-BENEFIT ANALYSIS

A condensed cost-benefit analysis taking into account the current Bamberg data reveals that considerable economic benefit can be derived from the new ultrasound installations.

Cost

A) Investment 220,000 € for two ultrasound units, PLC, stainless steel pipe connections and sludge pump ⇒ depreciation over 10 years: 32,000 €/a.

B) Operation 10,106 €/a for electrical energy consumption of new installation (70,800 kWh/a), exchange of sonotrodes after 15,000 hours operation time, maintenance (1 hour per week).

Total annual cost: 42,106 €

Benefit

32% increase in digester performance (VS degradation improved from 34% to 45%).

A) Less sludge for disposal: 371,250 kg/a, 0.10 €/kg DS disposal costs ⇒ 37,125 €/a.

B) Extra methane production: 259,875 m³/a, 10 kWh/m³ ⇒ 2,598,750 kWh/a extra energy, 40% efficiency of CHP ⇒ 1,039,500 kWh_{el}/a, 0.08 €/net/kWh_{el} ⇒ 83,160 €/a.

Total annual benefit: 120,285 €

Cost/Benefit ratio: 42,106 € / 120,285 €

It is recognized by the authors that assessing the true practical performance of a sludge treatment system under the prevailing conditions on a big complex sewage treatment plant can only produce results with a certain blur. However the very clear positive result of the cost-benefit calculation underpins the decision for the ultrasound disintegration. This is even more valid considering the unusually low cost for sludge disposal in Bamberg (0.10 €/kg DS). The relevant pay back time for the new ultrasound equipment is about three years.

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