OPTIMISATION OF ASSETS BY ULTRASOUND TO ACHIEVE LOWEST OPERATIONAL COSTS

Vergara, L.¹, Nickel, K.² and Neis, U.²,³
¹Ultrawaves Reactors Ltd, UK. ²Ultrawaves GmbH, Germany,
³Technical University of Hamburg - Harburg, Germany
Email: luis@ultrawaves.co.uk

Abstract
Wastewater treatment plants (WWTPs) are typically designed under conservative design guidelines and are operated based on historic practices. Such facilities often have considerable additional capacity that can be realized through optimisation. Improvements in wastewater and sludge treatment units mean an important saving in operational costs which take a special importance due to the unmanageable quantities of sludge produced by the rapid urbanization growth and difficult economic situations nowadays. Ultrawaves ultrasonic technology has been mainly designed to improve WWTPs biological processes as anaerobic stabilisation and biological reactor. The first full-scale applications of Ultrawaves technology were installed more than ten years ago in Germany for the pre-treatment of waste activated sludge (WAS) prior to anaerobic digestion (AD). Today more than 150 ultrasound reactors worldwide maximise anaerobic digesters as well as biological reactors in many WWTPs, providing confirmation of the success of this technology. Research is still carried out to better understand how ultrasound manifestations can impact specifically on aerobic processes since activated sludge contains numerous microorganisms which are imbedded in a slime-matrix and it is not easy to interpret the impact of sonication on all aerobic biomass. This article reports on fundamental research as well as full scale Ultrawaves experience for the following applications:

- Biogas production enhancement.
- Excess sludge reduction.
- Combating bulking and foaming.
- Improving nitrogen removal.

Keywords
Ultrasound, optimisation, aerobic process, anaerobic digestion, excess sludge, nitrogen removal, filamentous microorganisms.

Introduction
Ultrasound technology in environmental engineering started in the mid-nineties last century and was mainly driven by work in Germany. From the beginning it was stated to be a very effective mechanical pre-treatment method to enhance the AD of the sewage sludge produced during the biological wastewater treatment process. The AD process had been in use for more than half a century with no major improvement and no serious attempt to overcome its technical limitations. The Ultrawaves idea was to overcome the rate limiting hydrolysis step of the sludge AD by ultrasound, which disintegrates sludge cells and subsequently intensifies the anaerobic
degradation process, eventually resulting in more biogas and less residual sludge. The first fullscale installation appeared in Germany after the turn of the millennium and today WWTPs equipped with Ultrawaves technology can be found around the world in different countries like Spain, Ireland, Brazil, Switzerland, the Netherlands, Denmark, Poland, Hungary, Australia, and others.

It has been demonstrated that low frequency ultrasound waves generate the cavitation necessary to produce mechanical shear forces associated with sludge disintegration. Combined with high intensity ultrasound, the cell aggregates as well as single cells are destroyed and enzymatic and intracellular material is released into the medium resulting in a higher degree of substrate bio-availability for the remaining living microorganisms. In effect, the enzymatic biological hydrolysis, which is the initial and rate limiting of the biological food chain, is substituted and catalysed by this mechanical disintegration of the sludge (Tiehm et al., 2001).

Continuous research and development has created Ultrawaves ultrasound technology new and revolutionary applications in aerobic processes. There has been a big effort to understand the best way to optimise a biological reactor with ultrasound which has now been reached through different applications. It is now possible the complete elimination of associated problems with bulking and foaming through a selective sonication of a very tiny amount of Returned Activated Sludge (RAS). In addition it is also possible to enhance a dramatic excess sludge reduction when a partial WAS flow is disintegrated and returned back to the biological reactor whenever a cell lysis and cryptic growth process is induced. Sonication causes cell lysis with the consequent solubilisation of cellular constituents which become substrate available for further biodegradation which in turn results in an overall reduction of the excess sludge production (Hamer and Mason 1987; Canales et al., 1994). The most recent application has been carried out in nitrogen removal biologically, where sonicated WAS represents a very good readily biodegradable autochthonous carbon source to denitrify. When WAS is sonicated and recycled back to the anoxic zone of the biological reactor, then is used as carbon source to support denitrification and the facility transforms a waste into a resource with the subsequent saving in carbon source purchase and sludge disposal cost.

**Ultrasound in environmental engineering**

Ultrasound is defined as a sound wave with a frequency beyond 20 kHz. Depending on the frequency range (generally between 20 and 40 kHz) as well as the intensity (25 to 50 W/cm²) it is possible to apply ultrasound for environmental protection. There is a special interest in water engineering application because ultrasound wave propagation over these frequencies and intensities produce physical and chemical changes in the liquid system. These changes result from the effects of the formation and collapse of cavitation bubbles induced by acoustic waves propagation under adequate frequencies and intensities (Mason, 1991). When sonicating liquids at low frequencies and high intensities, the sound waves that propagate into the liquid media result in alternating high-pressure (compression) and low-pressure (rarefaction) cycles, with rates depending on the frequency. During the low-pressure cycle, high-intensity ultrasonic waves create small vacuum bubbles in the liquid. When the bubbles attain a volume at which
they can no longer absorb energy they collapse violently during a high-pressure cycle. This phenomenon is known as ultrasonic cavitation.

**Figure 1: Ultrasonic cavitation phenomenon**

During the bubbles implosion very high temperatures (approx. 5,000 °C) and pressures (approx. 500 bar) are reached. Among the most important cavitation effects high mechanical shear forces, thermal breakdown of volatile hydrophobic substances and oxidising reactions (creation of H⁺ and OH⁻ radicals) represent a big potential to disintegrate sludge, which is a key step for anaerobic as well as aerobic processes optimisation (Tiehm et al., 2001).

**How to assess sludge disintegration with ultrasound**

Ultrasound de-agglomerates biological flocs and disrupts the large organic particles into smaller size particles. The shear force breaks down bacterial cell wall and releases the intracellular substances into aqueous phase. This changes the physical, chemical and biological properties of sludge during the pre-treatment by ultrasonication. It is not the target of this paper to supply a full description about these changes but a rough mention provides a good approximation about what to measure and why.

**Physical changes**

As well as being important for the biological process, physical parameter evaluations are used as qualitative measurements of sludge disintegration. There are a lot of physical parameters like particle size analysis, sludge settleability, dewaterability, turbidity, mass composition and microscopic image among others which are used to assess the ultrasonic disintegration. Some of them, the most relevant ones for Ultrawaves technology, will be detailed in this paper.

The modification of the Particle Size Distribution (PSD) through ultrasound is very interesting because makes it possible to eliminate the big particles fraction in the suspended matter as
shown in the figure 2. It is important to note that initially around 60% of the solids in the wastewater are bigger than 50 μm in diameters and after the sonication (even with lower dose) this fraction accounts for just 5% of the total count, meaning an important particle size reduction. As known, methane production in the AD is proportional to the net rate of particle solubilisation (Gujer, 1983) which gives importance to the ultrasonic effect over PSD.

![Figure 2: Measurement of the sonication effect on PSD](image)

Sludge dewaterability is another important physical parameter to be considered. With the right sonication dose (kWh/m³ or equally Wh/l) it is possible to increase dewaterability. Capillary Suction Time (CST) is the parameter arranged to assess sludge dewatering properties. It has been studied that sludge dewaterability decreases, that is CST increases, with an increase in sonication intensity (Quarmby et al., 1999). In order to reach an optimum CST/dewatering value it has been studied the relation between sludge dewaterability and the DD$_{\text{COD}}$. Sludge dewaterability will increase when DD$_{\text{COD}}$ lies between 2 and 5% (Huan et al., 2009) which coincides with the DD$_{\text{COD}}$ applied by Ultrawaves in sludge treatment processes where an improve in dewatering is obtained (more details in chemical changes).

The final physical parameter to be considered is the microscopic examination of the sludge. Due to ultrasonication disintegrates the sludge flocs and lysis the cell walls, the microscopic image evaluation before and after the ultrasonic treatment can be used to evaluate how sludge structure is modified (Khanal et al. 2006). For low sonication dose with the Ultrawaves ultrasound reactor (around 1 Wh/l) the integrity of filamentous microorganisms is significantly disrupted without appreciable destruction of bacterial cells, as can be observed by microscopic examination. This is the way in which Ultrawaves solves bulking and foaming associated problems. Figure 3 shows microscopic images. As can be observed with a low ultrasound dose it is possible to disaggregate the flocs, which is enough for removing from the system the
filamentous microorganisms but not the floc-forming bacteria. If the ultrasound dose increases then the biomass is destroyed and disintegrated.

![Image of conventional floc, sonicated floc at 1 kWh/m³, and sonicated floc at 5 kWh/m³.]

**Figure 3:** Conventional floc (left), sonicated floc at 1 kWh/m³ (centre) and sonicated floc at 5 kWh/m³ (right)

**Chemical changes.**

This evaluation is 90% more quantitative and mainly focuses on sludge disintegration efficiency. The Disintegration Degree of the COD (DDCOD) is the most used chemical parameter to quantify the sludge disintegration efficiency.

\[
\text{DD}_{\text{COD}} = \left( \frac{\text{COD}_{\text{ultrasound}} - \text{COD}_{\text{original}}}{\text{COD}_{\text{NaOH}} - \text{COD}_{\text{original}}} \right) \times 100 \, (\%)
\]

COD is the chemical Oxygen Demand and the subscripts are referred respectively to the samples treated with ultrasound, original and after a chemical hydrolysis in a 0.5 molar NaOH solution at 20 °C for 22 hours. All the COD measurements are commonly expressed in mg/l. According to Ultrawaves experience a DDCOD around 5% is enough to allow an increase in the volatile solids (VS) degradation around 20% (Tiehm et al., 2001), which means the same improvement in the biogas production in the sludge AD process.

When an Ultrawaves reactor is used for nitrogen removal application another important chemical parameter has to be taken into account. Indeed when WAS is disintegrated and recycled into the pre-denitrification stage (anoxic zone) the released COD is then used as a readily biodegradable carbon source to support denitrification, but only when the COD/Nitrogen ratio is adequate in terms of the amount of COD released per unit of nitrogen released (more details in nitrogen application). Ultrasonication increases organic nitrogen and ammonia concentration in the sludge treated and has to be considered in a nitrogen balance. The experience demonstrates that WAS disintegration balance through Ultrawaves reactor always overcomes the value of 6 g COD/g N-NO₃ necessary to denitrify (Ekama and Marais, 1984).

For some authors this can be another sort of parameter but for this paper the Sludge Volumetric Index (SVI) is considered as an empirical and chemical measurement. The SVI is the volume in millilitres occupied by 1 gram of suspended solids after 30 min settling. This parameter is very helpful to monitor settling characteristics of activated sludge because high values mean poor settling properties while low values mean a tend to settle well. According to the German
normative ATV-DVWK-A131E at SVI over 150 ml/g the sludge will bulk and the clarifier will stop operating properly. One of the most interesting applications of the Ultrawaves technology is precisely combating bulking & foaming associated problems where reductions over 50% in the SVI are reached with low energy doses (around 1 kWh/m³) to treat “only” around 1% of RAS flow.

**Biological changes**

The breakdown of bacterial cell walls by disruption after the ultrasonic treatment can be assessed by using biological utilization test due to a considerable amount of the WAS contains aerobic and facultative bacteria. The Oxygen Utilization Rate (OUR) is used to characterize microbiological activity. This parameter is useful when the Ultrawaves reactor is applied to excess sludge reduction because it symbolizes the rate of the oxygen consumption (-d[O₂]/dt) by the microorganisms existing in the WAS during the endogen respiration and the organic substrate degradation. The term Degree of Inactivation (DD\text{OUR}) can be measured as follows.

\[
\text{DD}_{\text{OUR}} = \left[ 1 - \frac{\text{OUR}_{\text{ultrasound}}}{\text{OUR}_{\text{original}}} \right] \times 100 \text{ (\%)}
\]

Subscripts ultrasound and original are referred to the corresponding OUR value for samples sonicated and original (Camacho et al., 2002). OUR provides a curve known as respirogram which is integrated over the time to give the net amount of oxygen consumed (ΔO₂) during the biodegradation. Finally, ΔO₂ is converted to an equivalent amount of biodegradable COD which represents the COD released by the ultrasonic treatment. As utilised as OUR or even more so SOUR which is OUR divided by the Mixed Liquor Volatile Suspended Solids (MLVSS). The normal unit for SOUR is mg O₂/g VSS*h and may vary from 15 for conventional sludge up to 30 for sonicated sludge. However this parameter predicts the biomass reaction when contacting with the biodegradable organic matter in the biological reactor and is used more for the excess sludge reduction assessment, which is another Ultrawaves application.

The last parameter but maybe one of the most important to mention is the enzymatic activity. In the activated sludge process Extracellular Polymeric Substances (EPS) and cells form bio-aggregates such as biofilms and sludge flocs in a way that almost all the extracellular enzymes are immobilized by the flocs (Frolund et al., 1995). On the other hand EPS and cells hydrolysis together with the sludge flocs limits the rate and extent of biodegradation (Higgins and Novak, 1997). Since EPS rather than cells represent the major organic fraction determining flocs structure, integrity and strength, the disruption of EPS matrix could enhance the rate and extent of sludge biodegradation during the aerobic process. Ultrasonic treatment of sludge gives a positive influence on the activities of the hydrolytic enzymes when the ultrasound dose does not go beyond of 8 Wh/l. Under these conditions protease and α-glucosidase increase their activities 4.75 and 4.37 times respectively (Leiyu et al., 2010). Higher ultrasound dose creates negative effects on the activity of the hydrolytic enzymes and the reason might be attributed to the fact that more bacteria in WAS are disrupted and even damaged or killed. Once again these levels of
ultrasound dose goes in parallel with the Ultrawaves application as doses between 4 and 5 kWh/m³ are applied.

Some physical, chemical and biological parameters have been described in order to achieve a better comprehension of the changes produced after the ultrasonic treatment. These tools together with a systemic knowledge of the inherent wastewater engineering process are the resources utilised by Ultrawaves to justify how the ultrasound technology can be introduced and assessed in different WWTPs unitary processes.

The following matter to consider is relevant to the different ways in which the technology can be applied as well as providing real case studies for the applications. As unitary processes the AD and the biological reactor will be optimised. Ultrasonic effects on biogas production, digested sludge reduction, increase in dewatering, removing bulking & foaming associated problems, excess sludge reduction and denitrification will be assessed and certified with real examples of installations.

**Anaerobic digestion - Bamberg WWTP**

The first (because is the oldest) application to be considered is how ultrasound can enhance the AD process. There will be firstly explained by the way in which AD is optimised through ultrasound and the following real information about the installation will be also provided.

*How to improve anaerobic digestion with ultrasound*

The AD is a standard technique to stabilise sludge in order to enable an environmentally safe utilization or disposal. It is a complex process that converts degradable organic compounds to methane (CH₄) and carbon dioxide (CO₂) in the absence of oxygen with a series of microbiological sub-processes. The conversion pathway of the substrate (sludge) to biogas occurs in four stages, namely, hydrolysis, acidogenesis, acetogenesis and methanogenesis by different groups of bacteria. This complete microbial digestion process of the substrate to biogas is a slow process and requires high retention time inside the digesters. In particular, complex substrates (proteins, carbohydrates, fats, etc.) solubilisation and conversion to the lower molecular weight compounds (aminoacids, sugars, fatty acids, etc.) of solids degradable organics such as sludge through hydrolysis is a rate limiting step (Eastman and Ferguson, 1981).

The lower microbial conversion rates during conventional AD process result in high Hydraulic Retention Time (HRT) in the digester and larger digester volume, which are the first drawbacks of the conventional AD technology. The non-availability of the readily biodegradable soluble and organic matters and lower digestion constant necessitates sludge pre-treatment. Sludge pre-treatment, actually WAS pre-treatment because primary sludge has an acceptable biodegradation, is required to rupture the cell wall and to facilitate the release of intracellular matter into the aqueous phase to increase biodegradability and to enhance the AD with lower HRT and with higher biogas production (Tiehm and Neis, 2000). By applying the Ultrawaves ultrasound technology to the WAS this limiting hydrolysis step is overcome because sonicated biomass is more readily available for the subsequent biological enzymatic degradation process.
Ultrasound causes disintegration of the floc structure and release of exo-enzymes even with small energy inputs. This also creates more interfaces between the solid and liquid phase and therefore facilitates the enzymatic attack of the active microorganisms. A higher energy input results in the breakdown of bacteria cells, causing the cell contents and endo-enzymes to be released. These enzymes further accelerate the degradation process. The entire digestion process is intensified and the organic fraction is further degraded. An important advantage from this is a significantly increased production of biogas and reduction of the quantity of residual sludge to be disposed.

As a result of the smaller quantity of residual organic matter in the digested sludge as well as because new floc aggregates are formed, the dewaterability of digested sludge is also facilitated (less polymers to be added) and enhanced (higher degree of dewatering). The first result is caused by a less organic matter content in the digested sludge, consequence of a higher amount of VS are transformed into biogas. The second effect is produced with the ultrasonic disintegration of a partial WAS flow rate which leads to a re-arrangement of sludge aggregates forming more compact and stronger structures. Figure 4 shows a comparison between both aggregates, conventional sludge and sonicated.

![Figure 4: Digested sludge after polymer addition. Conventional (left) and sonicated (right)](image)

It is interesting to note that dewatering depends crucially on the size of the suspended particles (Friedrich and Potthof, 1988). The broadening of the size distribution leads to a considerably enhanced dewatering behaviour. Therefore it is reasonable to destroy partially WAS aggregates prior to digestion and polymer addition. Better results have been found with no more than 50% or WAS treated. In addition, partial WAS flow to be treated has to be destroyed up to reach cell lysis in order to release intracellular bounded water into the medium which can be easier to remove from the sludge with the mechanical dewatering units.

Recent investigations have shown that mixed sludge where a partial WAS flow has been previously sonicated is the most appropriate sludge to be dewatered as compared with mixed sludge where 100% of WAS is sonicated and conventional mixed sludge (Friedrich and Potthof, 1988). The content of dried matter after dewatering when WAS is 100% is disintegrated
increases around 11% with respect to the conventional case. However, when WAS is partially disintegrated the dried matter content increases around 19%. It should be understood that in this context mixed sludge means a mixture of primary and secondary sludge both of them thickened and mixed just as this mix is received by the anaerobic digester.

Although for dewatering reasons it is necessary to sonicate a partial flow rate, there is another important reason to justify this criterion. According to Ultrawaves experience the optimum between economical and technical equations in terms of energy applied/results as well as investment/results, is placed where energy applied covers only a range between 30 and 50% of the WAS flow.

Case study
Bamberg WWTP was designed for 220,000 PE. However, as a result of an improvement and extension of the sewerage system, the load on the plant in 2002 increased up 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 plant operator 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 biogas production showed a marked increase of almost 30%. 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 40% VS degradation was not only met, but surpassed.

It was decided in 2004 to purchase two Ultrawaves reactors (2 x 5 kW) instead of building a new digester thus 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 40%. 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.

Figure 5: Two 5 kW units installed in Bamberg WWTP (left) and the standard 5 kW reactor (right)
As is clear in both photos, 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. The assessment of the impact of ultrasonic TWAS disintegration on the anaerobic digestion process at Bamberg is based on routinely-collected data sets. No additional information could be collected. As a result, comparison can be made only between the period before (1/2003-12/2004) and after the start of ultrasound application followed by long term recording of the data in order to assess the reliability of the new technology. Figure 6 presents the recorded data regarding digester performance since the beginning of year 2003 up to the end of year 2010.

![Figure 6: Biogas production and VS degradation on Bamberg WWTP](image)

The increase in the VS destruction implies that more of the organic matter in the sludge is metabolised in the digestion process which coincides with the increase in biogas production (figure 6). The ultrasound units are in operation 24 hours per day all year round and the annual energy consumed was 70,800 kWh, representing only 1.5% of the total energy consumption at the Bamberg WWTP (Neis et al., 2009).

**Excess sludge reduction - Leinetal WWTP**

Unlike the previous case, excess sludge reduction tries to optimise the biological reactor which is considered as wastewater process and not as sludge handling unit.

**How to improve excess sludge reduction with ultrasound**

One of the mechanisms for excess sludge reduction to be integrated in the biological reactor is known as cell lysis and cryptic growth. The term cryptic growth was introduced to indicate the reutilisation of intracellular compounds (both carbonaceous compounds and nutrients) released from cell lysis for the growth of viable cells of the same population. The organic autochthonous substrate cannot be distinguished from the growth on the original organic substrate in influent wastewater, and by this is named cryptic growth. In spite of this further, cryptic growth, this
form of repeated metabolism of the same carbon reduces the overall biomass production. This reduction occurs because during each metabolic process a portion of the carbon is mineralized as product of respiration (Wei et al., 2003). It has been tested that sonication is a good cell lysing technique and it has been assessed the solubilisation rate of biomass after sonication (Gaudy et al., 1971). Ultrasound causes cell lysis with the consequent solubilisation of cellular constituents, which become substrate available for further biodegradation. Cryptic growth process is thus induced which results in an overall reduction of sludge production. The effect of this sludge treatment it is indicated in the figure 7. The maximum Growth Yield for heterotrophic bacteria under aerobic conditions ($Y_H$) is typically 0.67 mg COD$_{synthesized}$/mg COD$_{removed}$. In the presence of cell lysis and cryptic growth $Y_H$ can reach 0.43 mg COD$_{synthesized}$/mg COD$_{removed}$ for pure cultures (Canales et al., 1994) meaning an important reduction.

![Figure 7: Effect of ultrasonic treatment (US) on cell death and lysis, affecting sludge production](image)

In order to control the process and avoiding undesirable results it is necessary to monitor the right percentage of WAS to treat. If too much WAS is disintegrated and recycle back to the biological reactor then there would be insufficient microorganisms in the aeration zone to remove the organic contamination in the wastewater as well as the substrate presented in the disintegrated WAS. Stress Factor (SF) provides a good approach and is termed as follows.

$$SF\ (d^{-1}) = \frac{\text{Amount of sludge treated per day (kg} \times d^{-1})}{\text{Amount of sludge in the biological reactor (kg)}}$$

Furthermore, although theoretically it is possible to achieve a zero excess sludge production, it should not be done because up to 30% of inorganic compounds and persistent hazards (high effluent COD values and SVI as well) might accumulate in the wastewater treatment system and deteriorate the process efficiency. Best excess sludge reduction rates are obtained for SF not higher than 0.2 $d^{-1}$ (Camacho et al., 2002).

**Case study**
Leinetal WWTP has a design capacity for 46,000 PE but a fast increase in the urbanization and industrialization of surrounding areas increased the wastewater to be treated up to 55,000 PE
which is the actual loading. Biological reactor capacity was overloaded under a design sketch where phosphorous and nitrogen were removed through precipitation (Fe$^{3+}$) and intermittent denitrification respectively. Wastewater treatment is characterized by the absence of primary sedimentation and sludge ages around 18 days are necessary to stabilize the biomass. Sludge handling units include sludge thickening, dewatering and post-conditioning with calcium carbonate prior to disposal. Leinetel operator was interested in avoiding the construction of an additional aerobic tank in order to reach an adequate aerobic sludge stabilisation and the Ultrawaves alternative was chosen. In 2003 the installation was carried out and consisted of a 5 kW reactor to treat around the 30% of the TWAS. Ultrasound dose was set around 4 kWh/m$^3$ to guarantee the desired sludge disintegration degree. Once the TWAS was disintegrated it was recycled back to the biological reactor system to force cell lysis and cryptic growth process.

The results and benefits of the ultrasonic disintegration are based upon the minimization of the excess sludge produced which ranged around 25% as showed in the figure 8. Additionally, as consequence of the organic content reduction, a better end stabilized sludge for disposal is reached. However, and for the same reasons as considered in the AD, an increase in dewaterability is also achieved. Up to 2 more points have to be added to the final cake dryness, meaning an important saving in polymer addition and sludge disposal. The last positive benefit is relevant with a tremendous reduction in the SVI. Indeed working with sludge ages around 18 days means an excessive growth of the filamentous microorganisms which leads to bulking and foaming problems. After the Ultrawaves application SVI decreased from 140 up to 85 ml/g, removing from the system filamentous microorganisms and associated troubles.

![Figure 8: Sludge reduction in Leinetel WWTP](image)

**Combating bulking and foaming - Seevetal WWTP**

Together with the former application this one is also referred to the biological reactor but now the sludge to treat is RAS instead of WAS and the energy applied is much lower.

**How to solve bulking and foaming associated problems with ultrasound**

The destruction of the filamentous sludge is mainly caused by hydro-mechanical effects in the advent of the collapse of cavitation bubbles generated by ultrasonic waves. Low ultrasound
Doses are able to destroy the filamentous network of bulking or floating sludge. The thin filaments are much more exposed to the ultrasonic shearing forces than the flocs and are cut into small pieces. Since the remaining flocs are not interconnected by filamentous organisms any longer, the activated sludge flocs become smaller and much more compact after sonication (Nickel, 1999). The smaller floc size improves the settling properties of the activated sludge in the secondary clarifier.

In this regard ultrasonic treatment of the return sludge from the secondary clarifier is an interesting approach to overcome problems with floating suspended matter discharged from secondary clarifiers, which could be eliminated without using chemicals. This leads to sonicate a partial flow RAS and recycling back to the aeration tank.

**Case study**

Seevetal WWTP has a capacity of 165,000 PE and biologically treats municipal sewage (activated sludge including biological nitrogen removal). The sludge age normally turns around 25 days. In winter the formation of bulking sludge on the activated sludge tanks is quite common, which affords additional efforts by the operating staff to remove the sludge layers from the surface of the tanks. In 2008 intensive tests were conducted with a standard 5 kW ultrasound unit in order to demonstrate the potential of Ultrawaves technology to combat bulking sludge.

The idea was to apply ultrasound with rather low energy on a small fraction (approx. 1%) of the return sludge flow, which, of course, is populated by filamentous organisms. By this method it was set up a loop of sonicated (and stressed) biomass which permanently is fed to the activated sludge tank. So after a certain period in time the complete biomass has been hit by the ultrasound/cavitation impact. Results show how the Ultrawaves ultrasound unit could selectively eliminate the filamentous bacteria without hampering the treatment efficiency. The bulking sludge disappeared rapidly (SVI reduction around 50%) as is shown in figure 9.
Figure 9: Activated sludge tank of Seevetal during conventional operation (left) and RAS sonication (right)

Improving nitrogen removal - Bünde WWTP

This application has a big potential for the biological reactor optimisation because it also includes sludge reduction and bulking & foaming applications. The format is basically the same for excess sludge reduction but now sonicated WAS is recycled back into the denitrification zone as carbon source transforming a waste (WAS) into a resource (carbon source) which means a significant saving in operational costs.

How to improve nitrogen removal with ultrasound

Biological nitrogen removal from the activated sludge process depends largely on the ratio COD/TKN (Total Kjedahl Nitrogen) in the influent wastewater. This ratio is normally insufficient to achieve acceptable denitrification process efficiency, especially in those WWTPs with primary sedimentation. When primary sludge is removed from the wastewater around 40% of the COD and no more than 15% of the TKN are also removed which further worsens the COD/TKN imbalance. Thus an addition of a supplementary carbon source is necessary to achieve desired removal of nitrogen.

Methanol has been the most common carbon source (electron donor) for heterotrophic denitrification. Despite its widespread use, methanol gives slower denitrification kinetics than others carbon sources and presents severe handling difficulties. Others alternatives like acetate have been found but typically are much more costly. Nevertheless, a typical WWTP has a natural internal carbon source in its WAS and reusing WAS as a carbon source for denitrification might
replace the addition of external sources. However, WAS already being well stabilized has a low fraction of readily biodegradable COD and a pre-treatment is necessary in order to increase WAS bioavailability. This is the point where ultrasonic disintegration takes place.

WAS sonication produces an increase in soluble COD between 2 and 5 times compared with the conventional WAS. Is then provided an autochthonous carbon source readily biodegradable to be used in the denitrification process. However, sonication also modifies the hydrolysis rate of the WAS endogen particulate COD. Recent studies carried out with the Ultrawaves reactor have demonstrated that the hydrolysis rate for the sonicated WAS can reach around 1.7 d⁻¹ while conventional WAS remained 0.7 d⁻¹ (Trillo et al., 2012). Thus sonication does not only provide soluble COD but additionally enhances hydrolysis, which has a very positive effect over the denitrification process because sludge endogen COD is used faster in anoxic zones (it is necessary a lower HRT and lower volume in the aeration tank).

**Case study**

One Ultrawaves ultrasound reactor (5 kW) has been in operation at the Bünde WWTP (actual load 54,000 PE) since September 2006. The nitrogen elimination at the plant occurs via intermittent denitrification. The reason for implementing the ultrasound technology on the plant was that denitrification efficiency was suffering as a result of insufficient carbon source for the denitrifying bacteria. Using sonicated thickened waste activated sludge as an internal carbon source to improve denitrification was seen as a viable option. In total 30% of the daily TWAS stream was sonicated and conveyed back to the activated sludge tank, providing the process with the carbon source needed. After sonication ceased for a time, concentrations climbed again to the pre-ultrasound levels observed in 2005. Thus, sonicating a partial stream of the thickened waste activated sludge before it goes back to the activated sludge tank provided the carbon source necessary to facilitate the denitrification.

Utilizing sonicated TWAS as an internal carbon source for the purpose of improving denitrification yielded several positive effects. First, a significant reduction of nitrogen in circulation at the plant was achieved, which means that denitrification had been improved. More than 60 kg/d of inorganic nitrogen were removed meaning a final effluent quality with less than 5 mg/l. In addition, there were secondary effects that contributed to a higher efficiency of the plant operations. The amount of excess sludge was reduced by 25%, dewaterability increased by 2 points and foaming and bulking sludge in the activated sludge tank was virtually eliminated (three effects already explained in former applications).

It is apparent that several positive advantages were reached through the use of ultrasonically treated sludge. Regarding economics, reimbursement of the investment was immediate as reduced sewage fees associated with sludge disposal and nitrogen concentrations were achieved. Hence, the advantages are visible from an economic perspective as well as on the operational level itself. Adding to economic advantages, it must be mentioned that the plant avoided being forced into purchasing an external carbon source. The plant was ultimately able
to conserve resources, optimize existing process and acquire a higher degree of operational stability through the incorporation of this ultrasound technology.

![Graph showing concentration of N-nitrogen in effluent and dissolved sludge tank over time](image)

Figure 10: Sonication effect over the denitrification step in Bünde WWTP

References


