Improvement of anaerobic digestion of sludge

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Abstract. Anaerobic digestion improvement can be accomplished by different methods. Besides optimization of process conditions is frequently used pretreatment of input sludge and increase of process temperature. Thermophilic process brings a higher solids reduction and biogas production, the high resistance to foaming, no problems with odour, the higher effect of destroying pathogens and the improvement of the energy balance of the whole treatment plant. Disintegration of excess activated sludge in lysate centrifuge was proved in full-scale conditions causing increase of biogas production. The rapid thermal conditioning of digested sludge is acceptable method of particulate matter disintegration and solubilization.
Keywords: Anaerobic digestion improvement, thermophilic anaerobic digestion, sludge disintegration, rapid thermal treatment

Introduction

The principal benefit of anaerobic digestion is that the sludge is stabilized to an innocuous and easily dewatered substance - **biosolids**, the quantity of solids and the volume of sludge requiring disposal are reduced. Reduction of sludge solids is only one of the objectives of this process, which is normally pursuit together with the other objectives as production of energy in the form of biogas, improvement of dewaterability and a high quality final product. Biosolids contain nitrogen and phosphorus compounds and other nutrients as well as residual organic material that can improve the fertility and texture of soil. Significant inactivation of pathogens occurs during the anaerobic digestion dependent on the process temperature and technological arrangement.

The disadvantage of anaerobic sludge digestion is the quality of the supernatant from treated sludge thickening and dewatering. It contains suspended solids, dissolved and particulate organic materials, high concentration of ammonia nitrogen, some phosphorus and other compounds. This return flow increases the loads of the solids, oxygen demand and nutrients of the wastewater treatment system, but can be treated separately dependent on the local conditons.

Nevertheless the anaerobic sludge stabilization, which is already widely used, will become even more important in the future, since it guarantees that reduced sludge volume can be stored and handled easily without strong odor nuisances. In future for any type of agricultural reuse sludge stabilization has to be a part of the treatment. Even power station operators nowadays often demand stabilized sludges for co-combustion, in order to safely prevent odor nuisances.

In the last years a great effort was put into minimizing sludge quantities and enhancement of biosolids quality by improvement of anaerobic digestion process. There are several approaches in the following fields that are of a great importance:

- Intensification of standard sludge digestion by optimizing of process conditions (reactor feeding, efficient mixing, thickening of input sludge, etc.)
- Increased process temperature used in single or multi-stage thermophilic operation
- Pre-treatment of input sludge:

Disintegration of waste activated sludge with various technical devices Enzymatic and/or thermal pre-treatment

Chemical and/or thermal treatment or hydrolysis respectively

- Co-digestion and co-fermentation

All approaches follow the same goal, to minimize the left sludge weights that have to be disposed of and maximize the sludge quality, in order to limit ecological and economical disadvantages of their handling.

Intensification of the process

Optimization of process conditions

The way and frequency of reactor feeding is important especially in intensive and high loaded processes. The higher frequency of lesser amount of fed sludge (close to continuous way) and a sufficient homogenization of primary with excess sludge contribute to higher stability and better efficiency of anaerobic digestion. The similar positive effect can be reached by improvement of mixing that brings the better distribution of substrate to active anaerobic biomass and lower the dead volume of digesters. Better utilization of an active volume of digesters is also connected with enhancement of input sludge concentration by excess activated sludge thickening. The further contribution could be a preheating of input sludge by some source of excess heat to avoid any temperature unhomogeinity in fermentation mixture.

Staging and a higher operation temperature

Staging and a higher operation temperature can remarkably intensify the process of anaerobic digestion. If acidogenic and methanogenic processes are separated in different stages (each of them takes place in different reactors), we are speaking about a „two phase process"or „phase separation". By integrating of external acidogenic reactor to the process we can substantially save the overall reactors volume.

The main contribution of thermophilic temperature to the sludge treatment is concerned with the higher degradation efficiency in solids reduction of the thermophilic anaerobic digestion in comparison with the mesophilic one, the higher biogas production, the improvement of the energy balance of the treatment plant, the high resistence of thermophilic digester to foaming, with no problems with odour of thermophilic biogas (Zábranská et al., 2000) and the considerably higher efficiency in destroying pathogens in the thermophilic digester (Nielsen and Petersen, 1999, Oles et al., 1997). The change of temperature from the mesophilic to thermophilic conditions consequently avoids the digester overloading. Based on the feeding frequency, the mixing efficiency and the guaranteed retention time we can differentiate intensive and extensive thermophilic processes.

If the acidogenic and methanogenic processes are not separated and both take place in separated but serially arranged reactors, the stages can differ in the temperature. The first or the second stage can be operated at thermophilic conditions, and consequently improve the efficiency in destroying pathogens and decrease residual organics. Also a combination of thermophilic aerobic digestion followed by mesophilic anaerobic process in the second stage (dual system) can be used. In the temperature-phased process the acidogenic reactor is frequently operated at thermophilic temperature.

Pretreatment of the input sludge

Pre-treatment processes are an additional step in the sewage sludge treatment technology and have been developed to improve subsequent sludge treatment and final output quality. They can be used in various applications (Müller, 2000).

During the anaerobic treatment of solid wastes and sludges the process limitation by the rate of the hydrolysis of suspended organic matter is of particular importance. By means of an efficient pretreatment the substrate can be made better accessible for the anaerobic bacteria, optimizing the methanogenic potential of the waste to be treated. The objective is to accelerate the digestion of input sludge, rise the degree of degradation, and thus to decrease the amount of sludge to be disposed.

The improvement of the biodegradability of particular substrate in the input sludge is mainly based on an enlargement of particles surface causing better accessibility of the substrate for extracellular enzymes. There are several methods of treatment of solid particles present in sludge: *mechanical disintegration methods*; *ultrasonic treatment*; *chemical treatment* - the destruction of complex organic compounds by means of strong mineral acids or alkalis; *thermal pretreatment* -

thermal hydrolysis able to split and decompose a remarkable part of the sludge solid fraction into soluble and less complex molecules and to contribute significantly to pathogens destruction. *Enzymatic pretreatment* is based on the enhancement of enzymatic attack of macromolecules of biopolymers by addition of some industrially produced enzymes as lipases, proteinases, cellulases and hydrolases.

Disintegration of waste activated sludge with various technical devices. The insufficient reduction of organic matter and low yield of biogas from activated sludge is caused by a low biodegradability of the cell walls and extracellular biopolymers formed in activated sludge; even some of the cells may remain during the fermentation intact. Disintegration of waste activated sludge can overwhelm this problem; improve degradability of the biological cell material and to liquefy solids as much as possible. Different disintegrating devices, mechanical as stirred ball mills, homogenizers, ultra-sound and other systems can be introduced in sludge treatment technology line after thickening of waste activated sludge, even can be directly integrated into thickening machine (lysate centrifuge). (Dohanyos at al., 1997)

A great number of research studies have been conducted on this topic in the last years, experiences gained can be summarized as follows (Dichtl 2003): The degree of disintegration is often but not always directly proportional to the amount of energy input. Mass and energy balances for the process step of disintegration are not easy to calculate and have not been established yet. Justifiable degrees of disintegration and justifiable corresponding energy input will lead to an increase in biogas of 10 to 20% depending on boundary conditions. The same can be said for the minimization of sludge solids related to the organic fraction. But it can be observed that already nowadays this type of process technology can be used efficiently in individual cases. It will surely be an important application for the future.

Co-digestion and co-fermentation

Common digestion of mixed different materials (e.g. municipal sludge, agricultural wastes, wastes of food or pharmaceutical industry, organic fraction of municipal solid wastes etc.) can improve overall efficiency and biogas yield because of higher substrate diversity and consequently cause better utilization of reactor volume. In the case of difficult degradable material, an addition of easy degradable substrate can improve degradation on the molecular level and couple the degradation pathways bringing the higher energetic yield and better degradation of problematic compounds.

Experience with thermophilic anaerobic digestion

Our experience is based on the full-scale applications to the three wastewater treatment plants with different ways of transferring process temperature – the long-term adaptation with a full loading rate and the slowly increasing temperature, and the quickly increased temperature and slow increasing loading rate in the other case. The main reason for applying thermophilic temperatures was the better sanitizing effect of the higher process temperature and the need for more digesting capacity and more energy.

The first long-term full-scale experiment of thermophilic process was carried out in the Central Wastewater Treatment Plant in Prague. The sludge treatment facility in the plant consists of 12 digesters, each of volume 4800 m^3. Six 1^{st} stage digesters are mixed and heated, 2^{nd} stage digesters (provided with a gasholder) are without heating and mixing. Operational temperature is 38 °C in mesophilic digesters and 55 °C in thermophilic digester.

One two stages digester unit was selected for the experiment of thermophilic digestion. During a start-up of thermophilic process under the full loading of the digester the temperature was increased very slowly and carefully. The stable operation was reached in 10 months and this digester has already been succesfully operated at the thermophilic temperature of 55 °C more than 4 years. The 2^{nd} stage has maintained the temperature due to a good insulation property almost at the same level as in the first stage (only one or two degrees less) contrary to an expectation.

The loading rates have varied dependent to the actual operational volume, which was connected with an incidence of the intensive foaming in mesophilic digesters. The high resistence of thermophilic sludge to foaming was very good result and has been verified by no occurence of foaming during the whole operation time till now. The thermophilic digester has always disposed of a full volume of the tank, so the average loading rate of the first stage thermophilic digesters during the normal operation were 4.1 kg /m^3.d of volatile solids compare to 3.1 kg /m^3.d in mesophilic digesters.

Biogas production and quality

The average specific biogas productions from thermophilic digester during the last two years compare to mesophilic digesters are presented in Table 1.

Table 1. Specific biogas production per input volatile solids in mesophilic and thermophilic digesters.

Operational temperature		**THERMOPHILIC** 55 °C	Mesophilic 35 °C
Specific biogas production	(m^3/kg)	0.71	0.54
Standard conditions	(Nm^3/kg)	0.61	0.48

Biogas is utilized in cogeneration units for the electricity and heat energy production. The higher energy consumption for the thermophilic temperature is influenced by insulation properties of tanks and an average air daily temperature. Results showed that it was fully covered by the heat energy of increased biogas amount and even surplus electric energy is yielded.

The concentration of the main components of biogas from thermophilic digesters was the same as from the other digesters and was very stable, the methane content ranging from 66.1 % to 66.5 %. The difference is in the water content, thermophilic biogas is more wet and water has necessary be removed prior biogas is burned in motor-generators. Samples of biogas from mesophilic and thermophilic digesters were analysed on hydrogen sulphide and volatile odorous organic compounds.

From the analyses it was evident that mesophilic biogas contained in average 30 mg/m^3 of hydrogen sulphide, in thermophilic biogas there was determined lesser value about 20 mg/m^3. Analyses of volatile organic compounds in mesophilic and thermophilic biogas (Zábranská at al., 2000) showed that thermophilic biogas contained only lightweight volatile hydrocarbons and some volatile oxygenated organics and except for hydrogensulphide none other odorous sulphuric organic substance in determinable quantity. In mesophilic biogas besides the higher amount of hydrogensulphide there were found also dimethylsulfide, dimethyldisulfide a methylpropyldisulfide, which are strongly odorous compounds, nevertheless their absolute concentrations were low.

Foaming problems

The emergence of filamentous organisms in excess activated sludge is one of the reasons that can lead to problems with foam in digesters. Some filaments may during the process stay intact being protected by a high mechanical and biochemical resistance of cell membrane. When the digesters are operated near the limits of theirs loading capacity, the presence of filamentous bacteria may cause serious problems of foaming. The amount and quality of filaments were microscopically observed in the period, when filamentous organisms like *Microthrix parvicela* and *Nostocoida limicola* occurred in activated sludge. In the thermophilic sludge there were much less and shorter filaments, which seemed to be damaged. The microscopic observation proved the more efficient destroying of filaments in thermophilic sludge and thus a less susceptibility to foaming.

Mixing efficiency

Mixing in the first stages of digesters is ensured by a sludge recirculation combined with biogas mixing. Hydraulic dead zones in the digester and a short-circuiting reduce the effective hydraulic retention time and thus have detrimental effect on the digestion efficiency. Results of the experiment with the tracer showed that the installation of biogas recirculation mixing besides of sludge recirculation increased hydraulic efficiency, but still only 75 % of the digester volume was utilized. The mean retention time of sludge particles in the first stage digester was determined as 5.1 days. The useful volume of the second tank is only 40 %.

Nowadays the installation of new mechanical mixers (with propellers) in the first stage digesters is planned and a preliminary determination of hydraulic efficiency of those mixers indicated the improvement of the useful volume in the first tank to 82 %. The introduction of biogas mixing into second stage digesters is also suggested for the further improvement of hydraulic efficiency.

Pathogens removal

The effect of destroying pathogens in the thermophilic digester was monitored as counts of thermotolerant coliforms and enterococci per g of total solids of sludges. The input sludge contained usually 10^8 - 10^9 CFU/g TS of all groups of bacteria. Thermophilic sludge in average reduced enterococci to 10^3 – 10^4 CFU/g TS. The amount of these bacteria in the output of mesophilic process was 10^4 - 10^5 CFU/g TS. Thermophilic sludge with the mean residence time of 5.1 days was not able to reach the class A biosolids, but the relative frequency of samples meeting this limit was 40 %.

The insufficient hygienization effect was probably influenced by a lower real mean retention time caused by inadequate mixing. Results of assessment of indicator bacteria removal kinetics in laboratory batch experiments with the same input raw sludge and anaerobic sludge showed 3 days of reaching Class A even for higher resistant enterococci. The proposed better mixing in digesters will increase the real retention times and could also improve pathogens removal rate.

Experience with excess sludge disintegration

Excess activated sludge disintegration was realized by a full-scale thickening centrifuge with disintegration device integrated into the centrifuge (Lysate centrifuge). The partial destruction of activated sludge cells during the centrifugation by means of a lysate-centrifuge increases the portion of more easily degradable constituents of thickened activated sludge and produces cell lysate. The amount of bacteria cells content (lysate) released to a bulk liquid from the mechanically disintegrated cells of excess activated sludge – disintegration efficiency - is difficult to determine directly. The lysate activity is closely connected to the increment of soluble COD in total COD of thickened sludge, the increment of volatile soluble solids in total volatile solids of thickened sludge, the increment of lower fatty acids in a liquid phase of thickened sludge. The presence of the cell lysate in thickened excess activated sludge stimulates the anaerobic digestion process and causes a substantial increase in both methane yield and biodegradability of thickened activated sludge in comparison with untreated excess sludge.

The first full-scale lysate-centrifuge was BSC-4-2 (Baker Hughes) with input sludge flow 100 - 110 m^3/h, installed in the Central Wastewater Treatment Plant in Prague (1 200 000 PE). Daily excess activated sludge input flow during the normal operation was cca 4600 m^3 (7 g/l TS), and the thickened sludge production was about 650 m^3/d (50 g/l TS).

The improvement of methane yield and biodegradability is influenced by the quality of input excess activated sludge and the parameters and efficiency of the thickening centrifuge. The improvement of methane yield from thickened activated sludge measured in batch laboratory tests was on average 11.5 -31.3 % dependent on the sludge quality.

After the preliminary laboratory experiments that proved a stimulating effect of lysate on methane production and degradation rate, (Dohanyos at al., 1997) all four thickening centrifuges BSC-4-2 were adapted as lysate-centrifuges (equipped with a disintegrating device) and were kept in continuous stable operation for three months. A longer period for results evaluation was impossible due to starting reconstruction of activated basins of the plant and substantial changes of technology.

The influence of the disintegration of activated sludge was evident from comparison of the overall biogas production in the plant before and after the installation of the disintegration device. The average daily biogas production increased from 30 000 m^3/d to 38 000 m^3/d, average specific biogas production (per input volatile solids of raw sludge) was before disintegration 0.489 Nm^3/kg, during disintegration period reached 0.526 Nm^3/kg and was still slowly increasing, but the time of the experiment was limited and the conditions of the plant operation were not so stable as it would be required. The specific biogas production increment was 7.5 %. The operation of lysis-thickening centrifuges in the Prague Central Wastewater Treatment Plant proved the possibility of full scale application of the disintegration method.

From 2002 there is in operation further full-scale lysate-centrifuge in WWTP in Liberec (150 000 PE), where the specific biogas production increased from 0.443 Nm^3/kg to 0.560 Nm^3/kg, which represents increment of 26 %.

Experience with rapid thermal treatment

The problems of the application of thermal treatment to a full-scale anaerobic digestion are the costs of the process and the quality of produced material. As a result of high pressure and temperature in a longer time thermal pre-treatment biologically active compounds could be inactivated and some toxic products formed. The main feature of the rapid thermal reactor is a short retention time of sludge in the reactor (about 60 sec) at a high pressure and temperature (170 °C, 0.8 MPa). The reactor is supplied by pressure and heat from a steam generator. The design of a pilot-scaled rapid thermal reactor (RTR) was made by K&H Kinetic, Czech.Rep. (Zábranská at al., 1997).

The rapid thermal conditioning of digested sludge is the very good technically acceptable method of particulate matter disintegration and solubilization. Due to a short retention time of anaerobic biomass in the reactor (about 60 sec) at a high pressure and temperature, the cells are after a shock pressure release disrupted with a high efficiency, but an inactivation of enzymes does not take place in a high extent. It means that this method besides enhancements of degradability of remain organics in sludge also produces the cell lysate from anaerobic bacteria with some stimulating activity. The heat energy of the treated sludge can be used for maintenance of digester operation temperature.

The laboratory batch experiments were carried out with digested sludge conditioned in pilot-scale RTR at different temperature (120 - 170 °C) and flow rates (1 - 3.5 m^3/h). Hydraulic retention time of sludge in the reactor, which was kept lower than 1 minute, was controlled by a flow rate. The disintegration efficiency increased with increasing temperature (Fig.1), but was not significantly influenced by flow rate in the tested range.

The influence of the digested sludge treated in the RTR on the anaerobic degradation of raw sludge (primary and excess sludge) was followed by the batch methanogenic activity tests. As inoculum was used the 90 % of untreated digested sludge refilled with 10 % of sludge treated at different temperatures. The significant increase of biogas production (Fig.2) was found compared to untreated sludge. The stimulation effect of anaerobic lysate in treated sludge can caused the improvement of methane yield of raw sludge in the range 35 - 49 % dependent on the lysate amount.

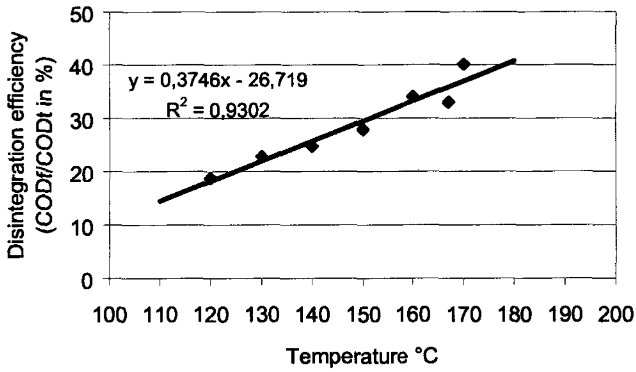

Figure 1. Dependence of disintegration efficiency on the RTR operational temperature.

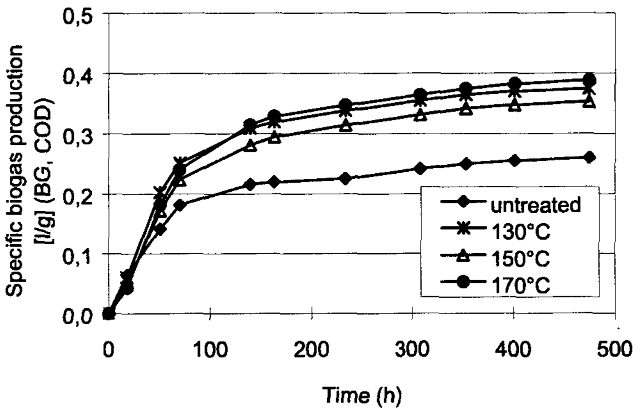

Figure 2. Specific biogas production from the raw sludge and digested sludge containing 10 % of digested sludge treated at 130, 150 and 170 °C.

The remaining degradation activity of treated sludge was also determined; results of batch experiments showed that the rapid thermal treatment caused a deterioration of the sludge activity, but it can be regenerated. The portion of the thermally treated sludge in digested sludge could be up to 40 % without any negative influence on the degradation activity, even stimulating effect was observed.

The rapid thermal treatment seems to be a very promising new method of the intensification of anaerobic sludges digestion and usable for upgrading of conventional digesters, where can be combine with a digestor heating. The treated sludge flow rate in the loop will depend on the input sludge flow and operational temperature.

Conclusions

The main contribution of thermophilic process to the more stable sludge treatment operation in the large wastewater treatment plant is concerned with the higher stability for solids reduction and the higher biogas production of the thermophilic anaerobic digestion in comparison with the mesophilic one. This process also brings the high resistence of thermophilic digester to foaming, no problems with odour of thermophilic biogas, the higher effect of destroying pathogens and the improvement of the energy balance of the whole treatment plant.

The influence of the disintegration of activated sludge in full-scale lysate-centrifuges was evident from comparison of the overall biogas production in the plant before and after the installation of the disintegration device. The specific biogas production increment in the large treatment plant was reached 7.5 %, in middle size treatment plant increment represents of 26 %.

Implementation of thermophilic anaerobic digestion (55 °C) and excess sludge disintegration by means of lysate-thickening centrifuge can improve the raw sludge biodegradation and biogas production in such extent, that the WWTP can be energetically self-sufficient. The energy balance is calculated for daily loading of 80000 kg of organic solids and for biogas specific production rate 0.61 Nm^3/kg of input organic solids. Total biogas production can be utilized in cogeneration units and corresponds to 108.1 MWh/d of electric energy and 167 MWh/d of heat energy. In the combination with a heat recuperation of sludge output it could cover the total energy demand even in wintertime.

The rapid thermal conditioning of digested sludge is the very good technically acceptable method of particulate matter disintegration and solubilization, usable for the intensification of anaerobic sludges digestion and for upgrading of conventional digesters, where can be combined with a digestor heating.

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