Thermal hydrolysis of waste activated sludge at Hengelo Wastewater Treatment Plant, The Netherlands

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ABSTRACT

The thermal hydrolysis process (THP) is a sludge treatment technique which affects anaerobic biodegradability, viscosity and dewaterability of waste activated sludge (WAS). In 2011 a THP-pilot plant was operated, connected to laboratory-scale digesters, at the water board Regge en Dinkel and in cooperation with Cambi A.S. and MWH Global. Thermal hydrolysis of WAS resulted in a 62% greater volatile solids (VS) reduction compared to non-hydrolysed sludge. Furthermore, the pilot digesters could be operated at a 2.3 times higher solids loading rate compared to conventional sludge digesters. By application of thermal sludge hydrolysis, the overall efficiency of the sludge treatment process can be improved.

Key words | sludge digestion, thermal hydrolysis, waste activated sludge

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INTRODUCTION

Wastewater sludge management in the Netherlands is controlled by strict regulations for land application. Sludge digestion is a widespread technology which is used for the reduction of sewage sludge and the production and recovery of energy as biogas. Biogas is usually converted into electricity which, in most cases, is used at the wastewater treatment plant (WWTP) itself. Primary sludge (PS) is easily biodegradable and results in a volatile solids (VS) removal of 50 to 60% and high biogas yields. Waste activated sludge (WAS) from WWTPs with low sludge loading rates (≤0.05 kg biochemical oxygen demand (BOD)/kg volatile suspended solids (VSS).d) and a long solids retention time (SRT), has lower biodegradability in sludge digesters and typical VS removal rates are 25 to 50% (Bolzonella *et al.* 2005; STOWA 2011b).

The focus for the use of the thermal hydrolysis process (THP) is on increasing the energy recovery from sludge. The possible improvement in sludge dewatering by use of THP is an adjunct advantage. Experiments with sludge disintegration (ultrasonic) at several sludge digesters in the Netherlands did not result in an expected increase of VS removal, despite promising results in Germany (Luning *et al.* 2008; STOWA 2008). This experience provided the insight that results with WAS from one country cannot be converted to the same expectations in another country. This depends, for example, on a difference in wastewater quality, design standards and effluent requirements. Therefore, verifying the potential of sludge reduction technologies for the particular type of sludge is recommended.

Heating of WAS up to temperatures of 150–190 °C results in solubilisation of chemical oxygen demand (COD) and consequently higher VS removal rates when the sludge is digested (Li & Noike 1992; Bougrier *et al.* 2008). Thermal hydrolysis also effects the viscosity of sludge. It decreases substantially, which makes it possible to feed the digesters with a higher VS concentration. The first full-scale results with thermal sludge hydrolysis date from 1995 in Norway, Denmark and in the UK (STOWA 2011a).

An additional advantage of the process is that the sludge is sterilised, which makes land application possible as fertiliser in the form of biosolids (class A) in several countries. The Dutch legislation for land application is, however, too strict to allow the application of sterilised sludge as a fertiliser in agriculture. Although land application of sewage sludge is not allowed in the Netherlands, the extra energy production, increased anaerobic reduction of VS and the expected improvement of sludge dewatering mean that application of thermal hydrolysis of WAS is still an attractive option.

The water board Regge en Dinkel is considering centralising the sludge treatment of 800,000 population

doi: 10.2166/wst.2014.107

equivalents at one location (Hengelo) in combination with thermal sludge hydrolysis. Expensive revisions of old sludge digesters at Enschede could be avoided in this way and the efficiency of sludge treatment could be further improved. The feasibility of thermal sludge hydrolysis was evaluated in a pilot plant study in 2011. The aim of the study was to determine the effect of THP on the anaerobic biodegradation and dewaterability of WAS.

METHODS

Dewatered WAS (16% total solids (TS)) was treated in a Cambi pilot plant. The sludge was heated by steam injection for 20 min until it reached 165 °C and 6 bar. After 20 min the pressure was lowered to atmospheric pressure by opening a valve, resulting in steam explosion of the sludge. Every week, batches of 20 kg WAS were hydrolysed (Figure 1). To simulate the full-scale operation mode of the digesters, hydrolysed sludge was mixed with PS in a ratio of 80% WAS and 20% PS (based on total solids content). The mixtures were stored for a maximum of 1 week at 4 °C in 450 mL bottles.

The sludge mixtures were digested in four small digesters (8 litre volume each) (Figure 2). Digesters 1 and 2 were fed with a mixture of hydrolysed WAS and PS, and digesters 3 and 4 were fed with a mixture of untreated WAS and PS (80/20%). The feed for digesters 3 and 4 was also prepared weekly. Every day, the digesters were sampled and fed manually, always in the same order between 8.00 and 10.00 a.m. To avoid temperature shocks, the sludge was heated in a microwave to 30 °C before being added to the digesters.

Figure 1 | Pilot thermal sludge hydrolysis (Cambi) at Hengelo WWTP.

Figure 2 | Pilot sludge digesters at Hengelo WWTP.

All digesters were operated at a temperature of 37 °C and a sludge retention time of 20 days. The digesters that were fed with hydrolysed sludge (1 and 2), were started up with digested sludge from a full-scale sludge digester in Denmark where WAS is treated with the THP process. The average sludge loading rate of digesters 1 and 2 was 3.9 kg VS/(m^3 digester.day) and the average sludge loading rate of digesters 3 and 4 was 1.7 kg VS/(m^3 digester.day). The thermal hydrolysis pilot plant and digesters were tested during the 6 months from May to November 2011. Biogas production was measured with gas clocks, and twice a week, digested sludge was sampled and analysed for total solids, ash content, COD, P-tot, NH_4-N and pH, according to standardised analysis methods: NEN-EN 12880 (TS), NEN-EN 12879 (ash content), NEN 6633 (COD), NEN 6645, NEN-EN 15681-2 (total P), NEN-646 (NH_4-N). Table 1 summarises the experimental setup.

Table 1 | Experimental setup of the digesters

	Digesters 1 & 2	Digesters 3 & 4
Volume (litre)	8	8
Average feed sludge mixture	10.4% TS	4.5% TS
WAS	Hydrolysed	Non-hydrolysed
PS	X	X
Sludge loading rate (kg VS/(m^3.day))	3.9	1.7
Sludge retention time	20 days	20 days
Temperature	37 °C	37 °C

As well as the sludge pre-treatment and operation of the four digesters, the following additional laboratory-scale experiments were carried out:

- The foaming potential and stability of hydrolysed sludge was tested at laboratory scale. The test protocol was based on a description in Hug (2006).
- Sludge dewatering was tested by thermogravimetric measurements at laboratory scale (Kopp & Dichtl 2001).

RESULTS

Figure 3 presents the monthly average specific biogas productions in litre biogas/kg VS. For this, gas production for the individual digesters was averaged. The data make clear that the difference in specific biogas production between digesters fed with hydrolysed sludge and non-hydrolysed sludge was 30–40%. The variation in average biogas production between the individual digesters was relatively low at 3.3% (THP) and 2.6% (reference). Furthermore, specific biogas production decreased during the test in all digesters. This can be explained by decreasing anaerobic biodegradability of the WAS during summertime due to higher aerobic mineralisation of the WAS. Because of long SRTs (>20 days) in the digesters, in combination with the storage of sludge, this decrease in VS removal is visible until October. The decrease in specific biogas production is even greater in the reference digesters. This suggests that thermal hydrolysis is more effective in summertime than in wintertime. This is in line with Bougrier *et al.* (2008) who found a similar effect from THP.

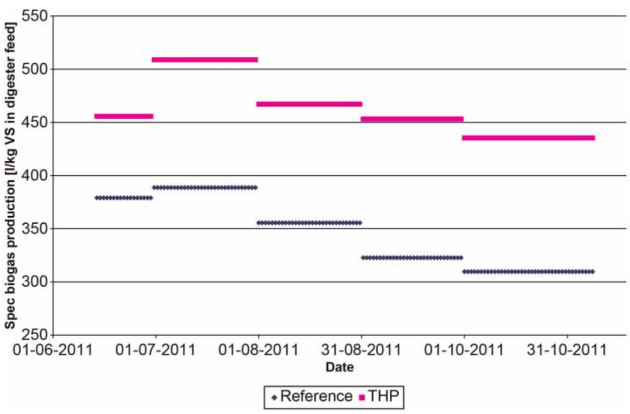

Figure 3 | Monthly average biogas production (l/kg VS feeding to the digester).

Since mixtures of PS and WAS were digested to simulate the planned operation mode of the digesters in full scale, the absolute effect of THP on the VS removal of WAS could not be determined exactly. Therefore, we assumed an average VS removal of 55% for PS and estimated the increase in VS removal of WAS due to thermal hydrolysis. The results of this calculation are presented in Table 2.

Table 2 shows that the estimated VS removal of WAS increased from 26 to 42%, which is an increase of 62%. Pilot experiments with the THP-process of Sustec at the Venlo WWTP in the Netherlands showed a 55% increase of VS removal after thermal hydrolysis of WAS at a temperature of 140 °C (van Dijk & de Man 2010). Pilot experiments at the Amersfoort WWTP in the Netherlands with Sustec (STOWA 2012) showed an increase in VS removal of WAS of 38% at 140 °C. The WAS in our study had a relatively low VS content (67–70.0%). This indicates a high degree

Table 2 | Estimation of VS removal of WAS (14-6-2011–8-11-2011)

	In [g VS/d]	Out [g VS/d]	Removal [g VS/d]	Removal [%]
PS (assumed)				
Reference	2.9	1.31	1.60	55%
THP	6.6	2.97	3.63	55%
WAS sludge (estimated)				
Reference	10.9	8.10	2.81	26%
THP	24.5	14.13	10.37	42%
Total (measured)				
Reference	13.8	9.4	4.4	31.9%
THP	31.1	17.1	14.0	45%

of aerobic mineralisation of the sludge, which could explain the high effect of THP (Bougrier *et al.* 2008).

Performance of the digesters

The pH in the reference digesters was about 7.5 while the pH in the THP digesters was about 8. The higher pH could be explained by high ammonium concentrations in the THP digesters. A high loading rate for the THP digesters and increased VS removal resulted in ammonium concentrations of 3–4 g NH_4-N/L while the ammonium concentration in the reference digesters was about 1 g NH_4-N/L. Inhibition of methanogenesis due to toxic NH_3 would have resulted in increased levels of volatile fatty acids (VFA) but this was not observed. VFA concentrations in the THP digesters were much higher than in the reference digester, but stable. See supplementary information in Table S1 for average concentrations (available online at http://www.iwaponline.com/wst/070/107.pdf). That no inhibition of the digestion process occurred in the THP digesters is remarkable, since other studies report inhibition at THP temperatures of 175 °C and higher (Haug *et al.* 1978). In the study of Haug *et al.* (1978), dilution of the sludge until 4% TS was necessary to avoid inhibition of the digestion process. In our pilot plant, average total solids concentrations in the sludge feed were 10.4% TS (see Table 1). That no inhibition of the digestion occurred is probably caused by the use of inoculum anaerobic sludge from a full-scale digester in Denmark, where WAS is treated with the THP process. Adaptation to inhibiting compounds in THP sludge is necessary when starting up digesters with THP sludge (Stuckey & McCarty 1978).

Foaming

Foaming was observed in all digesters, however, the digesters with hydrolysed sludge seemed to foam more than the reference digesters. This effect could be explained by higher VFA concentration and biogas production. Both parameters are related to foaming problems in digesters (STOWA 2010). A sludge foaming test was executed to determine foaming potential and foam stability. The test protocol was based on a description in Hug (2006). At normal gas velocities, foaming potential and foam stability are not significantly higher when hydrolysed sludge is digested (see supplementary information Table S2 for the test results; available online at http://www.iwaponline.com/wst/070/107.pdf). The gas velocity in a sludge digester is determined by the biogas production/m^2 of the digester surface and the mixing power when mixing by biogas injection is applied. The biogas production will increase substantially when the THP process is applied. This might introduce foaming problems in digesters. However, due to a strong homogenisation effect of the thermal hydrolysis it is expected that less mixing power is required. The gas velocity in the digester does not, therefore, necessarily increase after implementation of the THP process.

Biogas composition

Biogas was sampled and analysed twice, but no significant differences in CH_4 concentrations were found. The average CH_4 concentration in biogas was about 65% in the THP digesters and the reference digesters.

Sludge dewatering test

The sludge dewaterability was tested with a thermogravimetric measurement according to Kopp & Dichtl (2001). The results of the dewatering test are presented in Table 3.

The dewatering tests make clear that better sludge dewatering results can be achieved when thermal sludge hydrolysis is applied. However, the polymer demand for sludge dewatering seems to increase substantially. It should be mentioned that another dewatering test by a polymer supplier showed a specific polymer demand of 13 kg poly electrolyte (PE)/ton TS which is much lower than the 18 kg PE/ton TS that was found in this dewatering test.

Addition of aluminium to the sludge with a Metal:Phosphorus ratio of 1 (mol/mol) resulted in a decreased polymer demand.

In general, the type of polymer and addition of ferric or aluminium chloride will affect the total polymer demand and dewatering result. More data are required to determine more accurately the polymer demand for dewatering of THP sludge.

Although the sludge dewatering was tested at laboratory scale, the test result compared well to the full-scale sludge

Table 3 | Results of thermogravimetric dewatering tests

	% TS	Polymer demand (kg active polymer/ton TS)
Reference sludge Hengelo WWTP	24.1[a]	10.0
Reference digested sludge pilot	26.0	10.5
Hydrolysed sludge pilot	33.9	18.0
Hydrolysed sludge pilot + aluminium addition	34.5	16.0

[a]This result corresponds with the full-scale dewatering at the Hengelo WWTP: 23.3% d.s.

dewatering. The reference sludge of the full-scale dewatering centrifuge at the Hengelo WWTP had a TS content of 23.3%, which is 0.8% lower than the prediction for the test (24.1%). The thermogravimetric dewatering test seems to be quite accurate. However, only one sludge sample from the pilot digesters was tested after 4 months of operation. These results should therefore be interpreted carefully; longer testing of sludge dewatering is necessary to obtain conclusive results.

Other pilot research in the Netherlands showed similar sludge dewatering results. Pilot tests by Sustec on the Venlo and Amersfoort WWTPs showed that sludge could be dewatered until 31% and 25% TS, respectively, when thermal pre-treatment was applied (van Dijk & de Man 2010; STOWA 2012).

Composition of reject water

Thermal pre-treatment of WAS can result in an increase of soluble inert COD (STOWA 2011a, 2012). The amount of inert COD was estimated in digested sludge from the pilot at the Hengelo WWTP. A sludge sample from the digesters with pre-treated sludge was prepared and dewatered by the addition of poly-electrolyte. Soluble inert COD was defined as the difference between COD and (BOD_5/0.65) in the water phase, the reject water. The concentration of inert COD was 1,078 mg/L, which is equivalent to 11 kg COD/ton d.s. dewatered sludge. Application of the THP process on the Hengelo WWTP and digestion of 16,000 ton d.s. sewage sludge/y will result in an increase of 7 mg/L COD in the WWTP effluent. It should be emphasised that this is a worst case scenario. Reject water, containing inert COD, is recycled to activated sludge tanks and part of the COD can still be removed by adsorption to the activated sludge or by biodegradation. Orthophosphate concentrations in reject water from the pre-treated sludge were 129–172 mg P/L. The orthophosphate concentrations in the reject water from the reference sludge were not measured, because only the orthophosphate concentrations in the pre-treated digested sludge are relevant for calculation of the potential additional orthophosphate removal costs in the future.

However the orthophosphate concentrations in reject water from the reference digesters would have been about 100–150 mg P/L, which are common concentrations in reject water after conventional digesters for WAS, from a WWTP with enhanced biological phosphorus removal. Compared to this, the concentrations when using THP are relatively low, especially taking into account the high sludge loading rate and the increased VS removal. The relatively low orthophosphate concentrations in the reject water could be explained by phosphate precipitation in the sludge; at a pH of 8, phosphates can precipitate as struvite (Jeong 2004).

GENERAL DISCUSSION

The results of the pilot test in our study make it clear that thermal hydrolysis of Dutch WAS is significantly improving the VS removal in mesophilic sludge digesters. No inhibition of the digesting process was observed at TS concentrations of 10.4% TS in the feed. Furthermore, a higher sludge loading rate for the sludge digesters is possible, and sludge dewatering will certainly be improved. The results are in line with other studies (see Table 4).

It should be mentioned that the required energy for the THP process (steam production) can have a negative impact on the total energy balance of sludge treatment. However, when a mixture of 40% PS and 60% WAS is digested, the amount of heat that will be generated by the co-generation of heat and electricity will be sufficient to produce steam for thermal hydrolysis of WAS alone.

Although centralised sludge treatment can be beneficial, it should be emphasised that the sludge treatment becomes more complex. Therefore, the following important aspects should be considered carefully before implementation:

- Reject water treatment for nitrogen removal
- Type of energy recovery from biogas
  - co-generation, production of transport fuel or heat generation
- Sludge dewatering and selection of poly-electrolytes
- Logistics planning for sludge transport.

Table 4 | Effect of thermal pre-treatment of WAS

Treatment WAS sludge	Effect mesophilic sludge digestion	References
120–190 °C	40–60% increase VS removal	Haug et al. (1978); Bougrier et al. (2006, 2007); Climent et al. (2007)
60–100 °C	15–48% increase VS removal	Haug et al. (1978); Hiraoka et al. (1984); Barjenbruch & Kopplow (2003)

The preferred technique for reject water treatment is side-stream nitrogen removal technology. The exact effects of high temperatures during the pre-treatment of sludge on side-stream nitrogen removal processes are still unknown. However, it is known that high temperature (>150 °C) pre-treated sludge can be toxic for the anaerobic digestion culture (Stuckey & McCarthy 1984). The potential toxicity for nitrogen side-stream removal should be considered carefully before implementation of high temperature pre-treatment of sludge (Tattersall *et al.* 2011). Further research should investigate the possible inhibiting or toxic effects of the reject water from pre-treated sludge on nitrogen side-stream removal.

Energy recovery from biogas can be realised with different techniques. Depending on the local situation, one technique should be preferred above the others. Sludge dewatering will be improved, but the type of polymer will have a great impact on final dewatering results.

Thermal hydrolysis of WAS is a promising technology that can make domestic wastewater treatment more energy efficient. A few water boards in the Netherlands have already decided to implement this technology, and some water boards are considering implementation. Although the increase in VS removal and sludge dewatering is substantial, the economic feasibility also depends on local aspects. For Regge en Dinkel water board, the main trigger is to omit the expensive revision of an old sludge digester, which can be prevented when the THP process is implemented. The surplus of produced electricity should be delivered for a reasonable price to make centralised sludge treatment economically feasible.

CONCLUSIONS

The following conclusions can be drawn from the pilot research:

- VS removal of WAS increased from 26 to 42% due to thermal hydrolysis, which is an increase of 62%.
- By application of the THP process, the sludge loading rate for sludge digesters could be 2.3 times higher compared to conventional sludge digesters.
- Thermal hydrolysed sludge can be dewatered to 30% TS.

ACKNOWLEDGEMENT

The pilot test was partly financed by STOWA.

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First received 14 August 2013; accepted in revised form 17 February 2014. Available online 20 March 2014