Continuous thermal hydrolysis and energy integration in sludge anaerobic digestion plants

F. Fdz-Polanco, R. Velazquez, S. I. Perez-Elvira, C. Casas, D. del Barrio, F. J. Cantero, M. Fdz-Polanco, P. Rodriguez, L. Panizo, J. Serrat and P. Rouge

ABSTRACT

A thermal hydrolysis pilot plant with direct steam injection heating was designed and constructed. In a first period the equipment was operated in batch to verify the effect of sludge type, pressure and temperature, residence time and solids concentration. Optimal operation conditions were reached for secondary sludge at 170°C, 7 bar and 30 minutes residence time, obtaining a disintegration factor higher than 10, methane production increase by 50% and easy centrifugation In a second period the pilot plant was operated working with continuous feed, testing the efficiency by using two continuous anaerobic digester operating in the mesophilic and thermophilic range. Working at 12 days residence time, biogas production increases by 40–50%. Integrating the energy transfer it is possible to design a self-sufficient system that takes advantage of this methane increase to produce 40% more electric energy.

Key words | anaerobic digestion, biogas, sludge, thermal hydrolysis

F. Fdz-Polanco
R. Velazquez
S. I. Perez-Elvira
C. Casas
D. del Barrio
F. J. Cantero
M. Fdz-Polanco
Departamento de Ingeniería Química y Tecnología del Medio Ambiente,
Universidad de Valladolid,
Spain
E-mail: *ffp@iq.uva.es*; *rvelaz@iq.uva.es*; *sarape@iq.uva.es*; *ccasas@iq.uva.es*; *dbarrio@iq.uva.es*; *fjcantero@iq.uva.es*; *maria@iq.uva.es*

P. Rodriguez
L. Panizo
J. Serrat
P. Rouge
SOREA – Aguas de Barcelona,
Torre Agbar. Av. Diagonal 211,
080118 Barcelona,
Spain
E-mail: *prodiguez@agbar.net*; *mlpanizo@agbar.net*; *jserrat@agbar.net*; *prouge@agbar.net*

INTRODUCTION

Owing to environmental, economic, social and legal factors the treatment and disposal of excess sludge represents a bottleneck for wastewater treatment plants. In an overview of the state of the art Perez-Elvira *et al.* (2006) shows that there are three different strategies: (i) to reduce aerobic sludge production introducing additional steps to lower the cellular yield coefficient, (ii) sludge pre-treatment before anaerobic digestion, (iii) sludge elimination. Taking into account that anaerobic digestion is widely used to stabilize sludge, pre-treatment technologies are gaining acceptance. The methanogenic process is generally limited by hydrolysis rate of suspended matter. By improving the hydrolysis step solid substrates are more accessible to anaerobic bacteria, accelerating the digestion, increasing the volume of biogas produced and decreasing the amount of sludge to be disposed. The main physical pre-treatments founded at research or commercial level are: High pressure homogenizers, (Stephenson *et al.* 2004), Ultrasonic homogenizers (Hogan *et al.* 2004) and thermal hydrolysis (Li & Noike 1992; Tanaka *et al.* 1997). At industrial scale, the main proved features of thermal hydrolysis CAMBI process (Panter 2006) are: production of sterilized sludge, VS reduction >60%, 40% increase in biogas production and change on rheological sludge properties that dramatically improve mixing characteristics and dewaterability. With more than 10 plants CAMBI is a well contrasted technology but limited by the batch operation mode of the hydrolysis reactor. Several patents, Ohsol & Callery (1997), Rivard &

doi: 10.2166/wst.2008.072

Nagle (1998), Solheim (2004), approach the continuous operation but literature does not provide experimental results.

The aim of this work is to optimize the operation parameters and present the main characteristics of a thermal hydrolysis pilot plant that can operate with a continuous feed and underline the energy integration possibilities.

METHODS

A scheme of the thermal hydrolysis pilot plant designed and constructed for the treatment of sludge with direct steam injection is shown in Figure 1. The system consists of a feeding tank, a progressive cavity pump ($P_{max} = 12$ bar), a steam boiler, a 20 L total volume hydrolysis reactor ($V_{utile} = 10$ L) connected to a flash tank ($V = 100$ L) with outlet pipes for steam and hydrolyzed sludge. The pilot plant is equipped with automatic valves that control the steam entrance from the boiler and the sludge exit from the reactor to the flash. A data acquisition and control system is used to measure pressure and temperature and automatically control the steam inlet and the hydrolyzed sludge exit to the flash.

Anaerobic biodegradability was calculated following the methane production, using an automatic equipment and the experimental conditions described in Fdz-Polanco *et al.* (2005). All the tests were made by duplicate. Centrifugation tests were made using a Kubota 5100 lab centrifuge. A weighted volume of sludge (V_0, M_0, T_0SS) is centrifuged at a certain speed (g) during 1 min. The liquid phase is separated and weighted to determine its solid concentration (V_L, M_L, T_LSS). The percentage of solid elimination by centrifugation is calculated as: % elimin. $= (V_0 \cdot TSS_0 - V_L \cdot TSS_L) \cdot 100/(V_0 \cdot TSS_0)$

The filtration tests were performed in a Millipore equipment (glass fiber prefilters, filter type: 1.2 μm, White RAWP, 47 mm) maintaining a pressure of 2 bar and measuring the volume filtered with respect to time by means of a test tube and a chronometer. The capillary suction time was determined using an CST Triton Electronics Type 319 equipment that automatically measures the time that the filtered liquid needs to advance between two electrodes. All the analyses have been made in agreement with the *Standard Methods for Examination of Water and Wastewater* (2005).

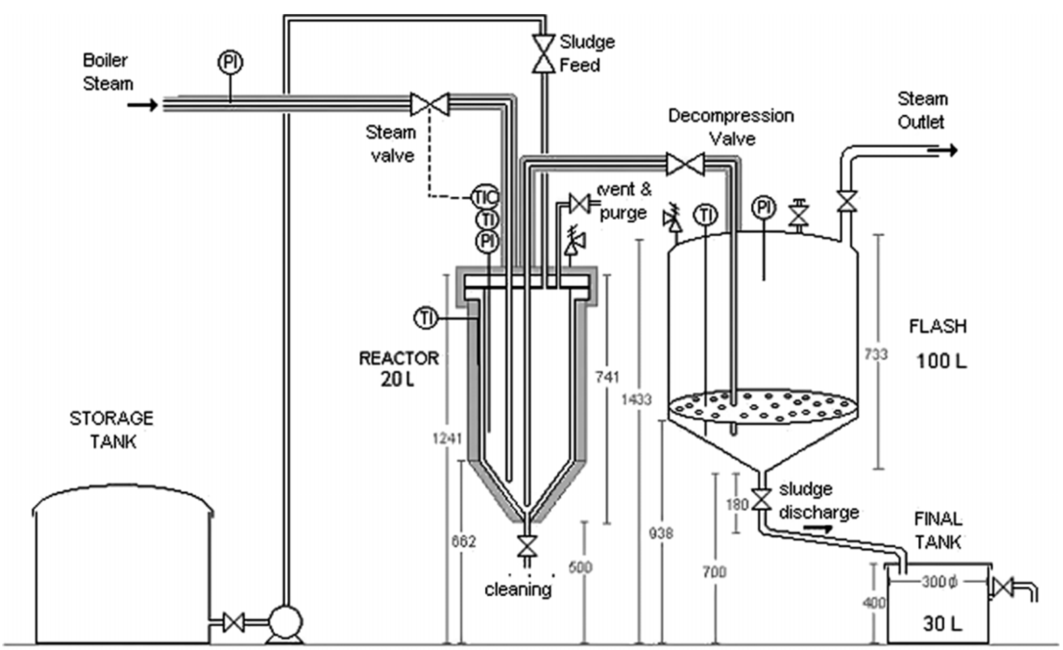

Figure 1 | Thermal hydrolysis pilot plant with direct steam injection heating.

RESULTS AND DISCUSSION

The discussion of results is made using three fundamental parameters: sludge disintegration, biodegradability increase and dewaterability. Sludge solubilization is quantified by means of the disintegration factor proposed by Baier & Schmidheiny (1997), calculated as ratio between the soluble COD of the sludge before and after hydrolysis. The biodegradability increase is calculated comparing the specific methane production (mL CH_4/g VS_{feed}) of raw sludge and treated sludge, in this way biodegradability is directly related to methane production increase.

Batch experiments

In order to verify if the hydrolysis equipment can reproduce the values proposed in literature and to fix the operational conditions, the reactor was operated in a batch mode. According to Figure 1, the pump introduces in the reactor 10 L of sludge, next the steam valve is opened until pressure and temperature reach de reference level. At the end of the reaction time the decompression valve is automatically opened and the hydrolyzed sludge flows to the flash tank. In agreement with previous experiences made in a pilot-laboratory equipment ($V = 1$ L), the reaction time maintained for all the experiments was 30 minutes.

Pressure and temperature influence

The objective is to experimentally verify the bibliographic values for different operating conditions (temperature-pressure), feeding the reactor with secondary sludge. Figure 2 shows the disintegration factor values calculated for different hydrolysis temperatures. The results demonstrate that in the range tested the degree of sludge solubilización is directly related to the hydrolysis temperature. Analyzing the biodegradability factor (methane increase) at different temperatures, Figure 2 shows a clear maximum at 170°C. In spite of the solubility increase, for temperatures higher than 170°C a reduction in biodegradability due to the formation of recalcitrant compounds is observed. This fact has also been indicated by Li & Noike (1992).

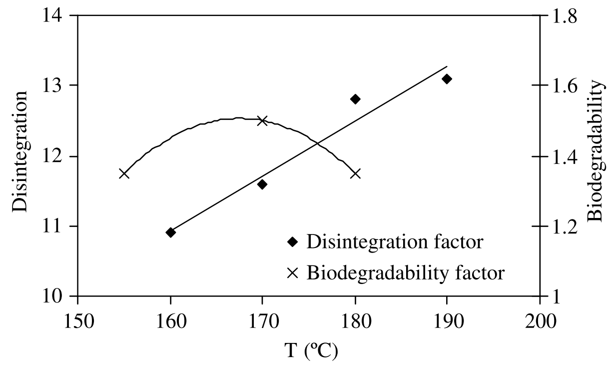

Figure 2 | Disintegration and biodegradability factors for different hydrolysis temperatures.

Dewatering characteristics

Biological sludge treated at different hydrolysis temperatures were studied to know their behavior in the final dewatering step. Applying the protocol defined in the section Methods, Figure 3 clearly indicate that the centrifugation characteristics of hydrolyzed sludge are radically better than those of fresh sludge. This effect is particularly remarkable when working at low "g" number (low speed). The temperature effect is also evident; centrifugation quality improves for sludge hydrolyzed at a higher temperature. Although from a practical point of view, filtration is less determining than centrifugation, experimental data of capillary suction time (CST) and filterability have been determined. Comparing fresh and hydrolyzed sludge, both CST and filterability results at low temperature are similar or even worse for hydrolyzed sludge. For higher temperatures, the behavior changes, marking a clear positive effect of the hydrolysis process.

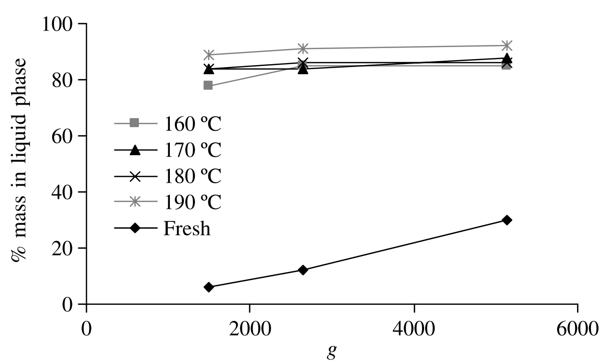

Figure 3 | Effect of hydrolysis temperature and "g" factor on dewatering.

Analyzing these experimental results it is possible to conclude that although disintegration and filterability increase with temperature the biodegradability factor presents a thermal limit. Above this limit temperature biogas production decreases due to the formation of recalcitrant species. The optimal operational conditions are 170°C and 7 bar. The greater increase in methane productivity and a remarkable improvement in centrifugation are obtained operating in this range.

Sludge type influence

To verify the effectiveness of the process on the different types of sludge, experiments with thickened primary sludge and secondary sludge (biological sludge) were performed. The more relevant results appear in Table 1. Both disintegration factor and methane production increase are higher for biological sludge. Thermal hydrolysis seems suitable as pretreatment for biological sludge, being hardly justifiable in the case of primary sludge.

Sludge concentration influence

The sludge concentration is a parameter of enormous importance and can be a limiting factor in the energy balance of the process. In order to quantify this effect three different sludge concentrations were studied. A sample of recirculated secondary sludge (8 g TS/L) was centrifuged until obtaining samples of 16, 22 and 36 g TS/L. Figure 4 show the experimental results for disintegration factor and methane production increase of the samples hydrolyzed at 170°C during 30 minutes. For both parameters an improvement in the behavior is observed when the sludge concentration increases. According to these results, the efficiency of the thermal hydrolysis seems to be advantageously related to the sludge concentration.

As in previous cases the effect of thermal hydrolysis on centrifugation is very marked. Figure 5 indicates that, for

Table 1 | Influence of the type of sludge (primary and secondary)

Sludge	Disintegration factor	Methane production increase
Primary	3.1	1.21
Secondary	9.6	1.62

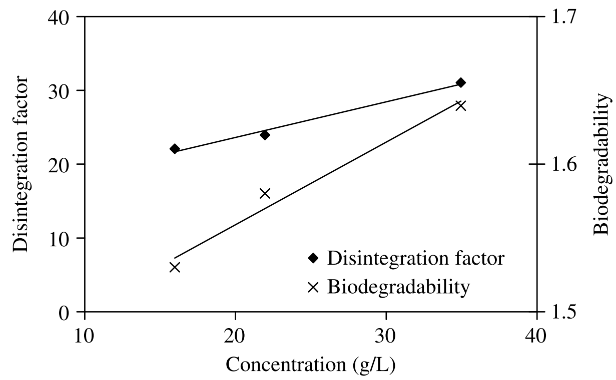

Figure 4 | Effect of sludge concentration on disintegration and biodegradability factor.

the whole concentration range studied, the hydrolyzed samples can be easily centrifuged. The difference between fresh and hydrolyzed sludge is more evident for low "*g*" numbers. Working at similar rotation speed the less concentrate samples produce higher quality effluents. Information about CST and filterability is not relevant and the results are similar to the ones previously discussed.

Continuous operation

Taking into account the results obtained for methane production increase and centrifugation in the batch experiments, the operation parameters chosen to work trying to obtain a steady state with continuous feed and exit were: temperature 170°C, pressure 7 bar, residence time 30 minutes. Maintaining these values, the control system was modified to work in continuous. The progressive cavity feeding pump was equipped with a speed controller that allows a fixed 20 L/h flow rate, continuously entering the

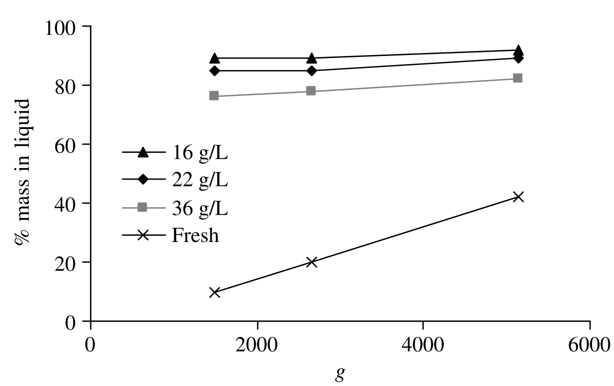

Figure 5 | Effect of sludge concentration on biodegradability increase.

reactor. Based on P and T values measured in the reactor, the automatic valve located at the steam line is opened and closed, maintaining stable operation conditions. The decompression valve opening/closing is temporized so that the volume that arrives at the flash tank is the sum of feeding and heating steam condensed in the reactor.

In order to test the effectiveness of the thermal pretreatment process, the pilot plant was operated at the Municipal Wastewater Treatment Plant of Vic (Spain), using fresh mixed sludge (primary + secondary). Hydrolyzed sludge feeds two anaerobic reactors ($V = 200$ L) placed in parallel; one operates in the mesophilic range (35°C) and the other in the thermophilic range (55°C). Both of them are continuously fed.

Mesophilic reactor

The mesophilic reactor was inoculated with anaerobic digested sludge and directly fed with thermically hydrolyzed mixed sludge using a hydraulic residence time of 20 days, without any acclimation period. The hydraulic residence time was decreased step by step until it reached a stable value of 12 days.

Thermophilic reactor

The thermophilic digester was also inoculated with anaerobic digested sludge and according to Bouskova *et al.* (2005) temperature suddenly risen to 55°C. Starting with 120 days hydraulic residence time an following a pseudo-steady state strategy, measuring VFA concentration and biogas production, the volume of hydrolyzed sludge fed was gradually increased.

The main average operation data for both anaerobic digesters working in continuous after a period of 16 weeks appears in Table 2. Methane production increase was calculated taking as reference values obtained in the full scale mesophilic digester fed with the same mixed sludge.

Table 2 | Mesophilic and thermophilic anaerobic digesters behavior

Reactor	HRT (d)	VS_{remov} (%)	Biogas (L/kg VS_f)	CH_4 incr. (%)
Mesophilic	12	45–60	445	55
Thermophilic	16	40–55	405	48

These results indicate that operating at short residence time it is possible to increase by 50% the methane production decreasing the final amount of sludge to be disposed.

Energy integration

The economic viability of the thermal hydrolysis process is directly related to its global energy consumption and must be integrated in an electricity production system through biogas combustion. The rules that control the energy balance are: (i) high concentration of sludge to limit the amount of energy wasted heating water, (ii) to exploit the high temperature and enthalpy of streams like vapor produced in the flash, hydrolyzed sludge, exhaust gases and hot water from the gas engine. Other important points to be considered are odor problems caused by non condensable gases and volatile organic compounds and pumps maintenance due to the high temperature level of hydrolyzed sludge.

Acording to the points underlined above secondary sludge is dewatered to 10–20% TS and led to a closed storage silo. In the silo the sludge is preheated with vapor coming from the flash tank; non-condensable gases and VOC's were carried to a treatment system. A progressive cavity or membrane pump transports the sludge to the hydrolysis reactor through a double heat exchanger system. In the first heat exchanger fresh sludge is heated by hot hydrolyzed sludge while in the second exhaust gases are used. In the reactor both operation pressure and temperature are maintained by controlling steam injection. A small excess of steam is added to mix the reacting mass. The opening of the automatic valve allows the exit of controlled amounts of hydrolyzed sludge to the flash tank. Being the pump that transports hot sludge quite sensitive, pressure in the flash tank is high enough to allow direct flow through the heat exchanger.

Considering a 500,000 inhabitants municipal wastewater treatment plant, now producing 320 Nm^3 biogas/h, equivalent to a volatile solid reduction in the anaerobic digestion of 10 t VS_{rem}/d, the electrical production is 900 kW with a typical efficiency around 37%. Usually heat losses can be recuperated in exhaust gas and refrigeration water; in our case supposing a temperature gradient between 520 and 200°C for an air flow of 1.9 kg/s heat recuperation from exhaust gas is 660 kWh/h. Also an important flow of hot water (T = 80°C) can be utilized to heat the secondary sludge until 50°C to improve the centrifugation behavior and save polyelectrolyte. The temperature increase that can be obtained using this exhaust gas is related to the sludge solid concentration. As the average amount of biological sludge ranges 650 kg TS/h, for a concentration of 10% temperature can be increased 87°C while if concentration is 15% temperature increment is higher than 130°C. This energy balance proves that the energy liberated during electricity generation is enough in quantity and quality to fulfill the sludge heating requirements. The proposed system is energetically self-sufficient; the whole increase in biogas production can be utilized for electricity generation. In this case the green electricity surplus is higher than 200 kW with an associated value of $ 300,000 per year.

CONCLUSION

The main conclusion of this experimental work is that using automatic valves it is possible to control a thermal hydrolysis reactor operating in continuous. With 30 minutes residence time at 170°C and 7 bar, methane production increase digesting hydrolyzed sludge is above 50%. Energy integration is a key factor for the process economic viability, the methane surplus obtained with the thermal hydrolysis pre-treatment can be totally used for electricity generation.

ACKNOWLEDGEMENTS

This work was supported by the Spanish Ministerio de Medio Ambiente (Proyecto 558/2006/2-4.3). The authors would like to express their gratitude to the Vic municipal wastewater treatment plant staff for their technical support.

REFERENCES

Baier, U. & Schmidheiny, P. 1997 Enhanced anaerobic degradation of mechanically disintegrated sludge. *Water Sci. Technol.* **36**(11), 137–143.

Bousková, A., Dohányos, M., Schmidt, J. E. & Angelidaki, I. 2005 Strategies for changing temperature from mesophilic to thermophilic conditions in anaerobic CSTR reactors treating sewage sludge. *Water Res.* **39**(8), 1481–1488.

Fdz-Polanco, F., Nieto, P., Pérez Elvira, S. I., van der Zee, F. P., Fdz-Polanco, M. & García, P. A. 2005 Automated equipment for anaerobic sludge parameters determination. *Water Sci. Technol.* **52**(1–2), 479–485.

Hogan, F. M., Mormede, S., Clark, P. B. & Crane, M. J. 2004 Ultrasonic sludge treatment for enhanced anaerobic digestion. *Water Sci. Technol.* **50**(9), 25–32.

Li, Y. Y. & Noike, T. 1992 Upgrading of anaerobic digestion of waste activated sludge by thermal pretreatment. *Water Sci. Technol.* **26**(3–4), 857–864.

Ohsol, E. O. & Callery, T. G. 1997 *Production of dry, free moving solids from bio-waste sludge*. US Patent 5593591.

Panter, K. 2006 Energy prices rises fuel advanced digestion. *World Water Environ. Eng. Magazine*, March/April 143.

Perez-Elvira, S. I., Nieto-Diez, P. & Fdz-Polanco, F. 2006 Sludge minimization technologies. *Rev. Environ. Sci. BioTechnol.* **5**, 375–398.

Rivard, Ch. J. & Nagle, N. J. 1998 *Pretreatment of high solid microbial sludge*. US Patent 5785852.

Solheim, O. E. 2004 *Method and arrangement for continuous hydrolysis of organic material*. US Patent 0168990.

Stephenson, R. J., Laliberte, S. & Elson, P. 2004 Use of a high-pressure homogenizer to pre-treat municipal biosolids: introducing the Microsludge process. *Proceedings 10th AD World Congress, Montreal, Canada*.

Tanaka, S., Kobayashi, T., Kamiyama, K. I. & Bildan, L. N. S. 1997 Effects of thermochemical pretreatment on the anaerobic digestion of waste activated sludge. *Water Sci. Technol.* **35**(8), 209–215.