Maximising biogas in anaerobic digestion by using engine waste heat for thermal hydrolysis pre-treatment of sludge


*Black & Veatch Contracting UK (E-mail: pickworthb@bv.com)
**Celtic Anglian Water (E-mail: jadam@caw.ie)
***Ebcor Ltd, Cheyne House, Strande Lane, Cookham, Berkshire, SL6 9DL, UK (E-mail: keith@ebcor.freeserve.co.uk)
****Cambi AS Norway, Solbråvn. 10, 1383 Asker, Norway (E-mail: odd.egil.solheim@cambi.no)

Abstract Dublin’s Ringsend WWTP was designed to serve a population of approximately 1.2 million p.e. with a sludge production of 37,000 dry tonnes per year after upgrading to full secondary treatment. Several technical solutions were put forward as part of a design, build, finance and operate (DBFO) competition, with the chosen solution being a proposal by Black and Veatch for a combination of sequencing batch reactor (SBR) technology and anaerobic digestion with Cambi thermal hydrolysis pre-treatment (THP). The THP plant was built by Cambi and handed over to B&V in 2002. The plant is now operated by Celtic Anglian Water. In September 2004 a test was carried out on the mass and energy balance of the plant following 2 years of operation and is detailed in this paper.

The process enables digestion at very high dry solids feed and low hydraulic retention time. The plant was built with three digesters of 4,250 m³ each and is fed with hydrolysed sludge at 11% DS. There are four no. 1 MW Jenbacher engines operating mainly on biogas. Each pair of engines is fitted with a waste heat boiler with a capacity of one tonne steam per hour. These boilers have sufficient capacity to provide 80% of the steam required for the THP, which in turn provides all the heat for the subsequent digestion in the form of hydrolysed feed. There are two main biogas boilers for top up steam and other uses of the biogas including thermal oxidation of concentrated odours.

Keywords Cogeneration; dewatering; digestion; pasteurisation; thermal hydrolysis

Genesis of the project
Prior to 2002 Dublin’s Ringsend wastewater treatment plant (WWTP) was a primary only system with settled sewage discharged to Dublin Bay. Raw sludge was dewatered and dried in two 4 tonne water evaporation Swiss Combi drum dryers. The dried product was marketed to local agriculture. Irish regulations require a Class A product using regulations derived from the USEPA 503 regulations. The drying operation was problematic, especially because the very fibrous nature of the raw sludge prevented good granulation in the back mix pug mill.

Dublin’s Corporation had to comply with the European Urban Waste Water Directive (UWWD). Under UWWD rules, Dublin Bay was classified as sensitive waters and therefore there was a requirement for full secondary treatment. The plant was designed to serve a population of approximately 1.2 million p.e., 22.3 m³/sec peak flow with a sludge production of 37,000 raw dry tonnes per year after upgrading to full secondary treatment. Several technical solutions were put forward as part of a DBFO competition, with the chosen solution being a proposal by Black and Veatch for a combination of SBR technology and anaerobic digestion with Cambi thermal hydrolysis pre-treatment (THP). The bid price was based on life cycle costs over a period of 20 years. This dominated all process
decisions. Particularly important was to make the project as robust as possible to future energy costs. Other bids contained four or five drying trains and were net energy users. The B&V bid used the existing two drying trains and one extra redundant train and was projected to be a net producer of 3 MWs of energy.

The site is extremely constrained; therefore space efficient technologies were required to achieve both liquid effluent and sludge quality specifications. The liquid effluent is treated in a two storey SBR plant which is currently the largest in the world. The digestion system consists of only three 4,250 m$^3$ digesters and has an organic loading of up to 6 kg VS/m$^3$/day.

The plant was selected in 2004 for the Sustainable Energy Award out of a field of 250 entrants in Ireland. The award recognises a commitment to energy management. Dublin’s Ringsend Wastewater Treatment Works was also the winner of the 2004 Chartered Institute of Water and Environment Managers Ken Roberts Award for Technical Innovation in the Water Industry.

**Cambi THP selection**

The Cambi THP process has been in full scale operation since 1995 at HIAS Norway. Subsequently, seven other plants have been built in Europe and Japan and four more are under design or construction in Poland, Belgium, Norway and Australia (Cambi’s latest contract for Brisbane Water’s Oxley Creek WWTP project).

Cambi THP is used prior to anaerobic digestion in order to break down cells and release soluble COD for digestion. Soluble COD, mainly in the form of volatile fatty acids (VFAs), can be as high as 50,000 mg/L in the digester feed. This is achieved by first dewatering the raw sludge to approximately 16% DS and then adding steam to raise the temperature to 165°C, at 7 bar pressure in batch reactors. After up to 30 min hydrolysis at 165°C the sludge is subjected to a rapid pressure drop which causes further disintegration. The hydrolysed sludge is then cooled and fed to the digesters.

The reasons for selecting this process for the Dublin project were as follows:
- complete sterilisation of all known pathogens;
- killing foaming organisms known to cause serious digester foaming problems in BNR plants and their consequent recycling to the aeration plant as a continuous re-seed;
- increase in biogas production and sludge destruction;
- digested sludge can be dewatered to 34% DS;
- net energy production of at least 3 MWs;
- digesters can be fed up to 12% DS reducing digester requirements;
- process is fully automated and enclosed;
- production of safe “Class A” cake and dried pellets.

The major reason for selecting Cambi was the greatly improved digester performance and reduced digester requirement (see Table 1).

**Table 1** Comparison of digestion performance between conventional and THP

<table>
<thead>
<tr>
<th></th>
<th>Conventional digestion</th>
<th>Cambi THP digestion</th>
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<tbody>
<tr>
<td>DS% feed</td>
<td>5%</td>
<td>12%</td>
</tr>
<tr>
<td>Digester volume required</td>
<td>30,500 m$^3$</td>
<td>12,750 m$^3$</td>
</tr>
<tr>
<td>VS destruction (15 d HRT*)</td>
<td>42%</td>
<td>62%</td>
</tr>
<tr>
<td>DS% cake</td>
<td>25%</td>
<td>34%</td>
</tr>
<tr>
<td>Tonnes of cake</td>
<td>92,300</td>
<td>54,200</td>
</tr>
<tr>
<td>Tonnes Water Evap (t WE)/h for drying</td>
<td>11.2 t WE</td>
<td>5.7 t WE</td>
</tr>
<tr>
<td>(= MWs energy required in form of gas)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potential MW (electricity) generated from Biogas</td>
<td>2.9</td>
<td>4.0</td>
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*Hydraulic retention time
Process description

Raw sludge is pumped via progressive cavity pumps to a bank of five gravity belt/belt filter presses. Sludge is dewatered prior to hydrolysis to minimise the volume of sludge required to be treated and therefore reduce the capital cost of the expensive pressure vessels of the hydrolysis process and the steam need. After dewatering, the sludge is conveyed via individual screw conveyors and stored in a 25 m³ hopper prior to further treatment. Sludge is pumped from the hopper with a screw feeder coupled to a progressive cavity pump and further to an inline macerator to the 1st pulper in each stream.

This circulation is intended to further pre-treat and disrupt sludge and to balance the temperature in the pulper. The macerator continually operates on an internal circulation of the 1st pulper when sludge is not being fed to pulper 1. This recycle is intended to further pre-treat and disrupt sludge. The 1st pulper typically increases sludge temperatures to between 60 and 85°C. Sludge is then pumped via a progressive cavity pump to the 2nd pulper and the sludge temperature is again increased with recycled steam to 100°C and further heat treated.

Sludge is then pumped via a progressive cavity pump to one of four reactors that operate on a batch basis in each process train to a set level. The reactors are pressurised by 12 bar steam. The operating pressure and retention time in the reactors is adjustable but typically is operated at 160 to 170°C, and 5–8 bar pressure for 30 min or a minimum of 20 min depending on process throughput needs. After a pre-determined, programmable, time, a pressure release valve is opened until the pressure reduces to 2 bar. The released steam is utilised to pre-heat the sludge in the pulpers. The reactors are operated on a cyclical basis, which simulates a continuous treatment process. Once the reaction is complete, the residual pressure is utilised to effect the transfer of the hydrolysed cake to flash tanks. This sudden reduction in pressure causes the fluid within individual cell walls to rupture, rendering them more amenable to digestion, especially the secondary sludge cells.

The flash tanks function as short term buffer tanks to enable any remaining steam, and hence pressure, to be released. In the original design, hydrolysed sludge was pumped via a progressive cavity pump through three heat exchanger banks, cooling to approximately 38–41°C before entering three anaerobic digesters. The first heat exchanger bank is a boiler feed water pre-heater, the next two heat exchangers operate in parallel to further cool sludge to design temperatures. Hot water recovered from the heat exchangers is used as feed water for boilers, and to preheat and dilute the sludge going into pulper 1.

The gas/steam released from the reactors is highly odorous and is saturated with steam. Before release to the atmosphere it is first passed through a condenser to remove all condensate, prior to being burnt in one of two (duty/assist) thermal oxidisers.

Influence of high fibre sludge

During heat treatment, organic components of the sludge are partly changed to fatty acids (VFAs). This decreases the pH of the hydrolysed sludge to approximately 5.5. The Dublin sludge had an unexpectedly and extremely high fibre content due to release of short fibre from a nearby paper mill. Fibre and fats segregated easily from the water phase in the heat-treated sludge, forming large gelatinous lumps with the tendency to block the heat exchangers. This wax-like layer on the single pass tube in tube heat exchangers built up rapidly after very short periods of intermittent operation between cleaning and flushing. In order to find a cleaning method for the heat exchangers, lab scale experimentation was conducted using a hot alkaline solution to remove the deposit. This successfully dissolved the fatty layer. In addition, an increase in the pH dramatically changed the sludge characteristics, the fat and the fibre remained dispersed in the sludge matrix.
The final pH in the digester was expected to approach 8.0 with ammonia concentrations of approximately 2,500–3,000 mg/L. This sludge also has a high chemical buffer capacity and could therefore be used to increase the pH of the hydrolysed sludge prior to cooling. Therefore, there was a possibility that this sludge would act as a rheology modifier in the heat exchangers. Subsequently, the current recycling system, shown in Figure 1, was installed. Prior to mixing, the hydrolysed sludge is pre-cooled to approximately 75°C by heating the boiler feed water in the first heat exchanger. This reduces the risk of damaging the recycled sludge by locally high temperatures. Recycled sludge is extracted from the digester being fed at a level approximately 0.5 m below the minimum level of the digester. This ensures that start up difficulties do not occur. Recycled digested sludge is introduced prior to the main heat exchanger coolers at a recycle ratio controlled to ensure mix temperatures do not exceed 55°C. This system gives very stable mixing of the hydrolysed and the digested sludge. In fact, the mixing effect is so good that digester B was fed at normal feed rates when the mixer was out of operation for a period of 4 weeks without any detrimental effects. This approach has been successful in preventing the clogging by fibre and has proved to be a better way of operating the coolers generally.

Performance of the digestion process

Theoretical considerations

The enzymatic degradation of cellulose or hemi-cellulose is a very slow process. Over 70 experiments have been carried out aimed at increasing the anaerobic biodegradation of these substances by thermal pre-treatment and mechanical disintegration by increasing the total surface of the substances (McCarthy et al., 1978; Radke, 2001). Owens and Chynoweth (1993) looked at the methane yields of different fractions of municipal solid wastes. For pure cellulose, 375 L CH₄/kg VS added were achieved, for newsprint from unbleached paper containing lignin only 100 L CH₄/kg VS added. With a specific energy content of 1.07 kg COD/kg VS for carbohydrates (Brooks, 1970) the values suggest that for pure cellulose a degradation of 100% is achievable and for newsprint 27%.

Figure 1

Layout of Cambi THP (one of two trains) and digestion including digested recycle modification
Li and Noike (1992) found that steam pre-treatment of municipal sludge had the best effect on surplus activated sludge. The optimal temperature was at 170°C with a 60–70% degradation after only 5 d (Figures 2 and 3).

Nesse et al. (1977, referenced in Pinnekamp (1987)) examined the biological hydrolysis activity from manure with high fibre content after thermal pre-treatment. His results clearly show that duration of treatment (30 min vs 5 or 10 min) is as important as the temperature. An optimum was found at 170°C and 30 min.

Start up and first operational results from the digestion process
In the beginning, the digestion process at Ringsend was mainly controlled by daily measurements of the pH in the sludge and the biogas quality. After some weeks, first assumptions were made to control the degradation by measuring the volatile solids content in both the digester feed and the digested sludge.

Initial results indicated a degree of digestion (or destruction) between 60 and 70% of the volatile solids. For primary sludge rich in fibre using conventional digestion, typical results would be expected of the order 40%. The thermal hydrolysis pre-treatment process results in an increase in volatile solids destruction that is 50% greater than conventional mesophilic digestion. The digestion process was modelled by a simulation model based on 24 h feed rates from the end of November 2002 when all three digesters were in stable operation. The degradation kinetics was based on curves produced by Li and Noike (1992) with a theoretical maximum degradation for volatile solids of 75% after 10 d. Thus, the influence of varying retention times and feed rates can be taken into account (Figure 4).

The initial results suggested that thermal hydrolysis and disintegration is an efficient way to pre-treat this fibre rich sludge prior to digestion. The THP process was at that time operating at 70% of design as one large municipal pipeline was still to be connected to the Ringsend WWTP.

Latest performance tests
Subsequent to the retrofitting of the heat exchanger recirculation system and some other minor modifications, a performance and reliability test was carried out between 20/9/04
and 22/10/04 for the parameters required by the contract guarantees. By this time the Ringsend plant had been on full load for some time and the digesters were now being fed at a much higher rate and with a subsequent lower retention time.

Of note are the following for the test period.

- The THP plant is capable of processing 105.6 dry tonnes per day with a feed solids of 1.34% DS within a 20 h period and with one standby thickener/dewaterer.
- The DS feed from the pre-dewatering was between 19.1 and 21.4% DS.
- Capture rate was 99.87% with a polymer consumption of 3.3 kg/tds.
- Thermal oxidiser maintained H2S below 1 ppm.
- VS destruction in the digesters was 62.5%.
- Digester HRT was 15–18 d.
- Digester feed DS% was 11.8% DS.
- Organic loading was 5.4 kg VS/m3/day.

As a result of the performance test, it was noted that biogas production was lower than theoretical. An energy balance was carried out for the month of September 2004 using data from the performance reports and the daily data.

Figure 3 Biological hydrolysis activity after thermal pre-treatment of manure (Nesse et al., 1977)

Figure 4 Hydraulic retention time and % degradation of volatile solids in the digestion process
Part of the performance test required CODs to be carried out on the raw and digested sludge. The Dublin sludge was predicted to have a specific COD of >1.75 kg COD/kg VS. In fact, the average COD across 10 samples was 1.3; this suggests a high content of carbohydrate and is consistent with the very high fibre content of the sludge. After digestion the average specific COD of the sludge rises to 1.6 which is a typical value of digested biomass. An energy balance using the specific COD of 1.3 fits very well with the measured biogas and power production – see Figure 5. It should be noted that the plant is operated with one of the four 1 MW engines on standby for operation of headworks pumping station in the event of power failure so that maximum average power production in this mode is just under 3 MWs. This could be achieved with typical COD raw sludge at the VS% conversion demonstrated.

Update on operations
Since commissioning the plant there have been a large number of connections from new communities outside of Dublin City’s area. Also, there is a larger industrial and commercial load than predicted.

Currently, the plant is overloaded by a factor of nearly 40% above the 2020 design. Luckily the design of the plant has allowed the operator to adjust to this by by-passing the excess raw sludge to the existing drying plant and by centrifuging the digested sludge to make a pasteurised cake in excess of 30% DS. This is important in Ireland as sludge must be pasteurised if it is to be used in agriculture. So, although the original plan was to have all dried product, the intermediate digested product is also a popular and compliant product.

![Figure 5](https://iwaponline.com/wst/article-pdf/54/5/101/431150/101.pdf)

Approximate daily energy balance based on daily averages from September 2004

- 83.5 dry tonnes
- 81.0% VS
- 1.3 kg COD/kg VS
- 88 t COD per day
- 310 MWh COD energy
- 700 m³ raw feed per day
- 18 d HRT
- 195 MWh of COD converted to biogas
  - 30,000 m³ per day at 65% CH₄
  - equivalent to 63% COD conversion
- 1,500 m³ per day to thermal oxidisers (foul gas removal)
- 4,000 m³ per day to main boiler to produce 1.3 t steam per hour
- 2.8 t steam per hour
- 1.5 t steam per hour
- 1.250 m³ natural gas
- 2.5 MWs electricity
- To Flare Stack
- 1,500 m³/day
- Waste heat boilers
- Flue gas
- 23,000 m³ per day Jenbacher engines
- Flue gas
Summary
The choice of Cambi THP has been justified both in terms of performance and final product quality. The THP digestion plant at Dublin’s Ringsend WWTP is operating to the required throughput and with digester loadings exceeding 5.4 kg VS/m³/day. High VS reduction is being demonstrated, despite the very low HRT. The digested sludge dewateres well and makes a useful pasteurised product. Retrofits to the plant have overcome initial difficulties caused by the fibrous nature of the sludge although the low COD of the sludge appears to depress the biogas yields somewhat. The overall low energy demand of integrated digestion and drying plant combined with the profit from cogeneration has given the operator reduced cost for energy.

References