REVIEW OF THE PERFORMANCE OF AN ADVANCED DIGESTION PROCESS

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ABSTRACT

The United Kingdom has seen a renewed interest in anaerobic digestion and in particular Advanced Digestion systems. The benefits claimed for these systems are many including increased biogas production, high pathogen kill to Treated and Enhanced Treated standards and better dewaterability of digested sludge to name a few.

This paper reviews performance of three Enzymic Hydrolysis plants operating in the UK and compares their relative performance to conventional digestion. Important parameters are identified to provide the designer of future plants with a basis for evaluating the expected performance compared with others systems on the market.

Performance of these plants in terms of biogas production, net power generation, pathogen reduction and sludge dewaterability improvement are reported.

KEY WORDS

Advanced Digestion, Pathogen Reduction, Dewatering, Biogas Production, Power Generation.

INTRODUCTION

Drivers in the UK for improved anaerobic digestion of sewage sludge are compliance to the Safe Sludge Matrix, reduction of quantities of sludge recycled to land, increased biogas generation to provide income offsetting the cost of treatment and reduction in carbon emission. Achieving all these criteria are challenging at the best of times. There are two pre-treatment processes which have been rapidly adopted in recent years for improved digestion; thermal and biological hydrolysis. There are at several plants of each variant in the UK treating up to 250,000 tonnes of sludge per annum. In this paper, it is intended to concentrate on the biological hydrolysis process where in recent years several fully integrated plants have been installed and currently operational. Performance in terms of biogas production, compliance and net power generation are provided for a number of recent installations.

The effect of biological hydrolysis on sludge digestibility

Sewage sludge is a non-homogenous medium with varying composition. The sludge composition and type of organic matter to a large degree influence its biodegradation during anaerobic digestion process. In Table 1 compositional analyses of several sludges from 3 sites in the UK are reported [Gonzalez, 2006]. Primary sludges are often characterised by high lipids and fibre contents and surplus activated sludge (SAS) by high amount of proteins. Conventional anaerobic digestion results in conversion of most of the lipids, fibres and to a lesser extent the proteins and carbohydrates to biogas.

Anaerobic biodegradability of sludge is a multi stage process consisting of Hydrolysis, Acidogensis, Acetogenesis and Methanogenesis. The Hydrolysis stage is the rate limiting step in the degradation of particulate organic compounds whilst Methanogenesis is the rate limiting step for fermentation of soluble organics. Siegrist et al [1992] in Vavilin et al [1996] estimated the rate constant for each stage of the digestion process by assuming the first order kinetics and completely mixed system. The figures are shown in Table 2.

Table 1: Compositional analysis of different sludges from 3 sites in UK (Gonzalez, 2006)

SLUDGE TYPE	SITE	PROTEINS (% of dry matter %)	CARBOHYDRATES (% of dry matter)	FIBRE (% of dry matter)	LIPIDS (% of dry matter)
DIGESTED	SITE A	16.6	32.3	3.8	9.02
	SITE B	24.9	31	3.9	2.4
	SITE C	24.9	28.9	3.7	2.4
PRIMARY	SITE A	15.8	27.7	17.6	14.8
	SITE B	20.1	18.4	25.5	6.4
	SITE C	23.4	27	23.4	7.4
SAS	SITE A	44.8	28.1	1.22	2.52
	SITE B	43.1	25.5	0.4	0.8
	SITE C	33.4	25.2	0.15	1.2

Table 2: Rate constants for each stage during MAD

Stage of process	Rate constant, day^{-1}
Hydrolysis	0.25
Acidogensis	5.0, 5.0
Acetogenesis	0.8
Methanogenesis	0.5, 2.0

Therefore, the hydrolysis step with the lowest rate constant controls the rate of hydrolysis of sludge whilst Acidogensis is much faster reaction and to a lesser extent Acetogenesis. The Methanogenesis stage is the rate limiting for conversion of soluble products from the previous stages.

As a result of hydrolysis, solubilisation of organic compounds occur. The degree of this solubilisation depends on the sludge composition as well as on the process specific parameters, e.g., temperature, retention time, mixing efficiency, reactor configuration. As a consequence of biological hydrolysis volatile fatty acids (VFA) concentration, soluble COD, pH and rheological properties of sludge are affected. To examine the effect of biological hydrolysis on VFA and COD, several workers measured the specific COD solubilisation and specific VFA production rates. The specific COD solubilisation rate is expressed in terms of total COD per gram of VSS fed and the VFA production rate is expressed as total VFA generated per unit mass of VSS fed. Yu et al (2001) for example reported the result of several studies where these rates were quoted to be in the range of 43-73 mg COD/g VSS.day and 36-62 mg VFA/g VSS.day for CSTR type reactors.

Another approach to examine the digestibility of sludge was proposed by Kepp et al (2000) where the ratio of total COD to volatile solids (VS) of a sludge feed was used to express its digestibility. The higher the COD/VS ratio, the more digestible the sludge would be.

To examine the effect of hydrolysis on the digestibility of sludge, Lee et al [2007] proposed a hydrolytic model based on the first order kinetics. The model was used to examine the effect of the Enzymic Hydrolysis (EH) process on volatile solids conversion during mesophilic digestion. Data from several EH sites were used to validate it. Lee used a term combining the rate constant and digester performance, principally the mixing efficiency.

OPERATIONAL PERFORMANCE

Operational and performance data from three plants using biological Enzymic Hydrolysis pre-treatment were collected over several months of operation. Two of these sites were retrofitted with the EH pre-treatment and the third was a new sludge treatment centre using the Enhanced Enzymic Hydrolysis (EEH) pre-treatment, a high temperature variant of EH. Detailed descriptions of these processes are provided in a paper by Bungay *et al* [2008]. Table 3 shows details of the plants.

Total solids of sludge feed ranged from 5.5 to 7%. Site 2 received cake imports, which were back mixed with endogenous sludge to the required dry solids. Site 1 employed separate mechanical thickening of primary and surplus activated sludge (SAS) whilst at Site 3, mixed primary and SAS sludge was thickened mechanically. The hydrolysis pre-treatment temperature ranged from 35-42^{o}C and was chosen depending on the operational practices of the individual site. The SAS contents of feed sludges at the Sites were approximately from 30% up to 60% of the total feed on mass basis.

Table 3: General overview of the site

Site	Pre-treatment	Sludge composition, Primary :SAS	Feed solids	Digestion HRT, days	Operating temp of EH/EEH, ^{o}C	Annual solids load, tds/annum
1	EH1	70:30	6.3 - 6.5	14	42	31,000
2	EH2	60:40	5.3 – 6.0	11	35	9,700
3	EEH	40:60	4.4 – 7.0	22-25	42	19,100

Volatile solids (VS) loading, biogas yield and VS reduction (VSr)

The VS loadings of the plants ranged from 2.2 to 4.5 Kg VS/m3/day. The highest organic loading belonged to the plant with the lowest digestion HRT of 12 days whilst the plant with the lowest load, had yet to approach its full design load, having an extended HRT of 22 days.

Figure 1 shows the theoretical relationship between the VS load, HRT and feed solids of 4, 5, 6 and 7% and a feed %VS content of 75%. The VS loadings of the three sites are shown as large dots in Figure 1. UK's standard organics loading of conventional digestion is around 2.5 Kg VS/m3/d. Organic loadings in excess of 4.5 Kg VS/m3/day have been quoted previously using acid hydrolysis pre-treatment. For instance Shea [2001], reported organic loadings in excess of 5 KgVS/m3/d while Erdel et al [2008] reported HRT of 11 days in methane digesters. Therefore, there are justifiable evidence that it should be possible to increase the O&M loading beyond 4.5 Kg/m3/d without endangering digestion operation.

The biogas yields reported from these sites were in the range of 380 to 420 Nm^3/per tonne dry solids fed. No discernible correlation was found between the specific biogas yield, the HRT in the hydrolysis stage and the digestion HRT.

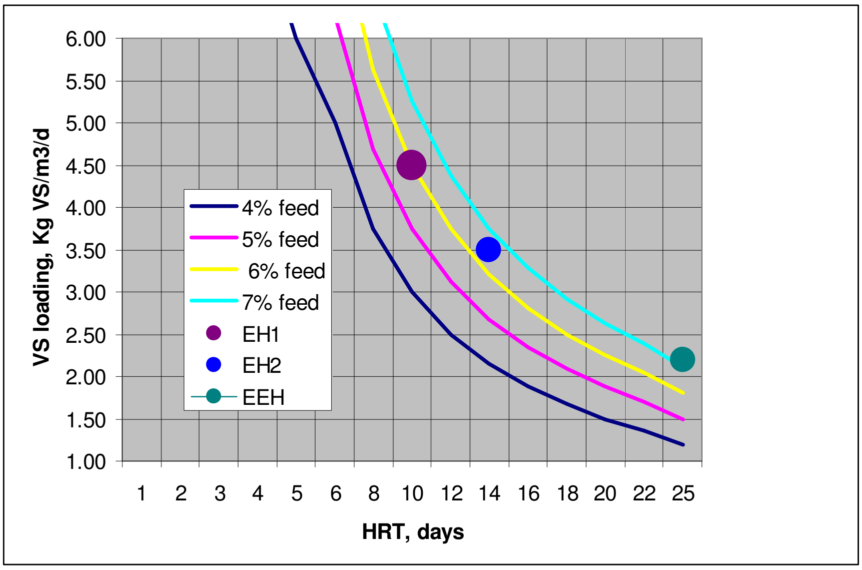

Figure 1: Profile of volatile organic loading for a sludge feed of 75% VS content at different total % feed solids.

Figure 2 shows the volatile solids reduction (VSr) figures of the three sites plotted on the hydrolytic model proposed by Lee et al [2007]. The %VSr figures of the sites were found to be between 53 and 55%. Generally, there was good agreement between the figures found from the plants and those in the model. Comparing the curves drawn for conventional and EH+ digestion indicate that the rate constant term for the conventional digestion increased from 0.25 d^{-1} to about 0.4 d^{-1} for the EH pre-treated digestion process. This indicates an increased hydrolysis rate of 37%.

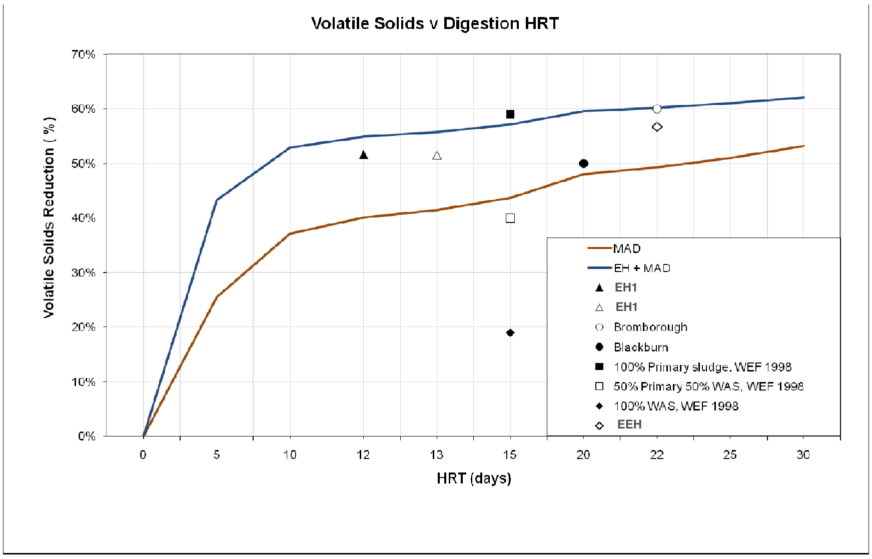

Figure 2: The Hydrologic model and the data from the EH and EEH sites.

VFA production and COD solubilisation

Biological hydrolysis results in increased formation of VFA and solubilisation of COD in sludge. The specific COD solubilisation rate and specific VFA production rate may be used to examine the efficiency of the hydrolysis of organic matter during acid hydrolysis. To quantify these parameters, sludge samples at the inlet and outlet of one of the EH sites were analysed for total and volatile solids, VFA and total COD over a 3-months period. Table 4 shows the average figures of these parameters.

Table 4: Average values of total and volatile solids, total COD and VFA in raw and EH treated sludges

	At EH inlet	At exit of EH
TSS, %	6.2	6.13
VSS, %	4.71	4.64
Total COD, mg/kg dry matter	1,352,667	1,628,777
VFA, mg/lit	4,713	6,808

Using the values in Table 4, the specific COD solubilisation rate and VFA generation rate were calculated. The COD solubilisation rate was 144 mg COD/g VS.day. This figure compares favourably with the values reported in the literature, which are in the range of 43-73 mg COD/g VS.day [Yu et al, 2001]. The VFA generation rate was 18 mg VFA/g VSS.day compared with 36-62 mg VFA/g VS.day for CSTR type reactors. The VFA generation is rather low indicating that the inlet VFA concentration of raw sludge at this plant was higher than what is generally found indicating aged sludge already in the process of hydrolysis.

Cake dewaterability and centrate quality

Cake dry solids reported from the three sites were between 23 to 26%, all from centrifuge dewatering plants. Previously, Lee el al [2007] reported obtaining cake solids in excess of 28% from centrifuge dewatering of an EEH pre-treated digestion site.

No clear correlation was found between cake solids, digester HRT, final VS contents of sludge or VSd across the digestion process.

Although improved dewaterability is expected as a result of increased digestibility of sludge, other factors will impact on the performance of dewatering plants. In addition to the sludge characteristics, cake quality can be affected by many variables including the hydraulic and solids loading of the machine, polymer type and dose, centrate quality required, mechanical state of the plant and experience level of the operator. At the outset of this investigation, to discount these variables, it was decided to carry out a series of dewatering trials at each site using a packaged mobile centrifuge machine. However, this activity had to be postponed due to site specific constraints at two of the three sites.

Data is being gathered on the centrate quality from these sites at present but there has been no report of any treatability issues with the centrates.

Compliance

Table 4 shows the *E-coli* and Salmonella data across various points of the sludge stream from the sites with EEH pre-treatment. The figures, expressed in Log_{10} counts, show the removal of *E-coli* and Salmonella below the detection limit at the EEH outlet, at the digester outlet and in the centrifuged cake. Further analysis of the cake after several days of storage showed no bacterial growth. Therefore, the cake quality was treated to the enhanced treated standard at the point of cake production.

Table 4: *E-coli* and Salmonella counts in various points along the sludge stream of an EHH pre-treated site

Raw sludge		EEH outlet		Digester outlet		Centrifuged cake	
Ecoli Log count/gdw	Salmonella, (counts/2 g dw)	Ecoli Log (count/gdw)	Salmonella, (counts/2 g dw)	Ecoli Log (count/gdw)	Salmonella, (counts/2 g dw)	Ecoli Log (count/gdw)	Salmonella, (counts/2 g dw)
5.56-7.22	>880	<2	<40	<2.2	<50	<1.34	<10

Energy and parasitic load

The heat recovered from the engine jacket and CHP exhaust is used to provide heat the hydrolysis stage by means of a water to sludge heat exchanger to 42°C. In the case of EEH, the process operates in two temperature regimes. At the 1st stage, as before sludge is heated up to 42°C where biological hydrolysis takes place, and in the 2nd stage the sludge temperature increased to 55°C, where pasteurisation is carried out. For the stage 2 heating, energy is provided from the high-grade heat of the CHP flue gas, preferably using a waste heat boiler to raise steam which is consumed in the pasteurisation stage. In the EEH process 2/3 of the heat is provided in the first stage whilst the rest is supplied in the second stage.

Table 5 shows the power generation figures from the three plants. These figures were compared with historical published data [Red files, 2008] before the installation of the pre-treatment processes. The Renewable Energy Foundation publishes the performance of the renewable electricity sector in the UK on annual basis, covering all generators registered under the Renewables Obligation.

Table 5: Power generation from the EH and EEH sites

Site	Pre-treatment	Published Power of site, KWh before installation of EH/EEH	Current power generated, KWh	Power generation per unit of feed, KWh/tds fed
1	EH1	1990	2900	935
2	EH2	300	595	850
3	EEH	--	1194	850

The figures for Site 1 and 2 show that the power generation has increased from the historical values reported. For Site 3, a newly built plant, no historical data was available.

With regard to the parasitic energy for both EEH and EH plants, the absorbed power at full load was reported to be between 3-4 kW per m^3 depending on the individual site. These figures include EH/EEH feed pumps, digester feed pumps, power consumption for the plant including MCC and lighting. Generally, the parasitic energy per tonne of dry solids is linked to the feed concentration; the higher the feed solids the more energy efficient the plant.

CONCLUSIONS

The VS loadings of the plant investigated were in the range 2.2 to 4.5 Kg VS/m3.day. The lower figure was for a plant yet to reach its design load.

The specific biogas yields of the plants were in the range of 380-420 m3 biogas/tds fed whilst the VS conversion ranged between 53-55%.

Cake solids of up to 26% from centrifuge dewatering was produced.

The centrifuged cake produced from the site with the EEH pre-treatment process was treated to the "Enhanced Treated" quality standard as defined by the Safe Sludge Matrix.

In terms of the parasitic load, the absorbed power at full load for both EEH and EH plants is between 3-4 kW per m^3 depending on the individual site.

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