# Simulation of Thermal Hydrolysis at the Blue Plains AWT: A New Toolkit Developed for Full-Plant Process Design

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## ABSTRACT

Model simulations can support design and cost calculations for both anaerobic digestion and sidestream treatment in order to evaluate the implementation of innovative thermal hydrolysis technologies in the context of the entire plant. SBR based influent characterization, sludge production calibration, and bench-scale digestion experiments of TH-treated sludge from Blue Plains WWTP have been conducted. In the mesophilic pilot digesters of 15 and 20 days retention time COD-removal efficiencies of 56% and 60%, respectively, have been achieved compared to 50% in the control. The resulting data set has been used to calibrate the introduced model approach: The mathematical model for growth of acetoclastic methanogens considers free ammonia inhibition and limitations of undissociated acetic acid as substrate. The impacts of these two compounds appeared very relevant for high-solids digestion and the model provided better understanding of these process interactions.

## KEY WORDS

Thermal hydrolysis, disintegration, Cambi, anaerobic digestion, modeling, sludge liquor, ammonia inhibition, acetate inhibition

## INTRODUCTION

The number of utilities considering thermal hydrolysis (TH) as a viable option to improve their sludge processing is growing fast. Thermal hydrolysis is expected to reduce volume of reactors needed for sludge processing (thus reducing both capital costs and life-cycle carbon footprint) and produce Class A biosolids. The principle of this technique is that sludge cells are destructed by applying high temperature typically together with high pressure. The higher degradation efficiency is associated with higher biogas production and a lower content of volatile solids in the digested sludge. As a further consequence dewatering properties of the stabilized sludge are improved and the mass of cake is reduced (Zabranska et al., 2000). The additional gas production and careful cycling of thermal heat from co-generation can cover the energy demand of thermal pre-hydrolysis (Kepp et al., 2000). Thermal pretreatment is supposed to reduce also the very slowly degradable materials (Elliott and Mohmood, 2007), therefore it improves the overall removal efficiency of organics in the digestion process.

The combined impact of heat and pressure yields an improved solubilisation of organic matter before entering the digesters. At a temperature of 180°C the share of soluble COD in total COD exceeds 40% and crosses 50% at 200°C but then generates an increasing amount of inert soluble compounds (Phothilangka et al., 2008). Under selected operating conditions of 150°C in this study a solubilisation rate of 30% was achieved (Figure 1).

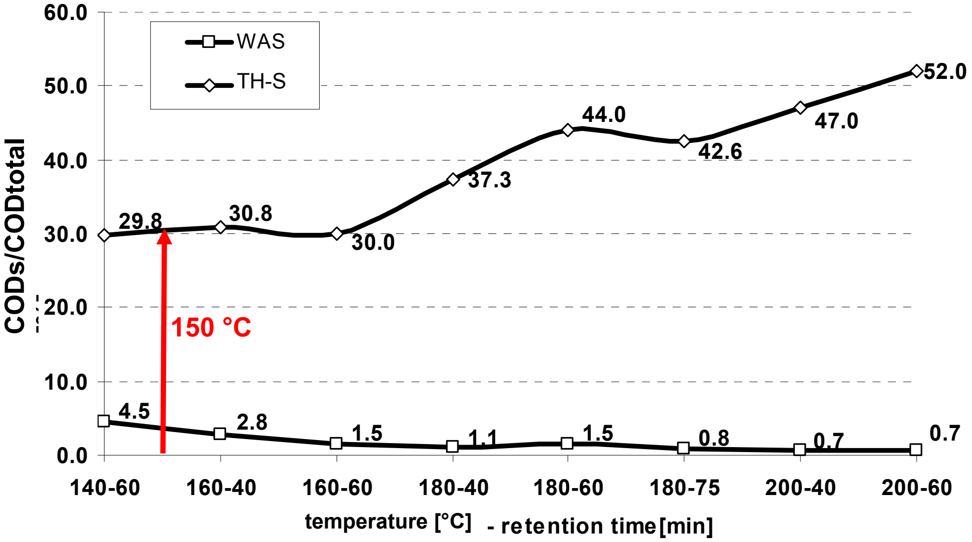


**Figure 1** – Enhancement of hydrolysis by TH-treatment expressed by the ratio of CODs/CODt at different operating conditions

Current whole-plant activated sludge – digestion models (such as the General ASDM in BioWin) were developed based on traditional activated sludge process followed by traditional long SRT digestion. The kinetic rates (such as decay and hydrolysis) reflect the performance of these typical applications. The extent of the degradability is modeled using two types of inert components: those originating from the influent ($X_I$), mostly believed to be lignocellulosic material and keratin (toilet paper, fibers and hair). The second type of inert solids is generated from the biomass upon decay ($X_E$) and have at least twice the nitrogen content compared to $X_I$ (Wett et al., 2006). This approach describes the different degradability of primary and waste sludges, as well as the released ammonia.

During Cambi treatment both biodegradable and inert materials become solubilized or inert materials may become available for biological degradation. Knowing the influent inert fraction ($X_I$) is paramount for accurate description of the process. At the same time low concentrations of soluble inert organics containing dissolved organic nitrogen are formed, which are recycled back to the plant and have a significant impact on low effluent nitrogen limits. The resulting higher rates and higher extent of treatment is not simulated well in models not considering the effect of Cambi treatment. In addition, higher than normal ammonia concentrations (in the range of 2000-3000 mgN/L) during digestion lead to free ammonia inhibition on the acetoclastic methanogenic population, resulting in high VFA concentration in the digested sludge liquors (Angelidaki and Ahring, 1994; Batstone et al. 2002). These complex interactions thus make the modeling of this process quite challenging. Indeed, successful modeling of the Cambi process will overcome much of the existing challenges of anaerobic digestion modeling.

## APPROACH

### Sludge characterization at Blue Plains AWT

The Blue Plains AWTP, is a two sludge plant, with chemically enhanced primary treatment, followed by a high rate BOD removal stage, and a separate nitrification/denitrification stage. With a design flow of 370 mgd the Blue Plains AWTP will need to process 1.5 mgd of raw sludge in the proposed sludge train employing thermal pre-treatment, anaerobic digestion and separate treatment of sludge liquors.

Currently about 66% of solids are produced in primary clarification, 29% and 5% in the biological high-rate stage and the low-rate stage, respectively. Specific lab-SBR tests have been conducted to determine particulate inert matter in the raw wastewater and OUR-tests allowed an estimation of heterotrophic organisms in the influent flow. Both the inert particulate- and the biomass fraction appeared relatively low – each around 10% of the COD load. The raw wastewater characterization was used to feed the full-plant model and model performance was calibrated to operational data. Figure 2 presents the simulated composition of each individual sludge type and also of the blended raw sludge. Comparing primary- with biological sludges obviously the share of substrate decreases and the portion of endogenous products grows, depending on the sludge age (2.5 days SRT for secondary and 15 days for nitrification sludge).

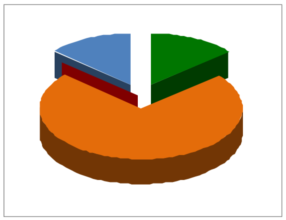
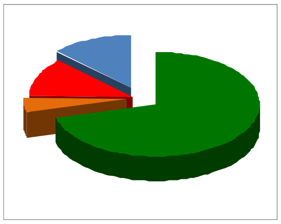
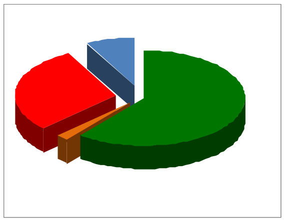
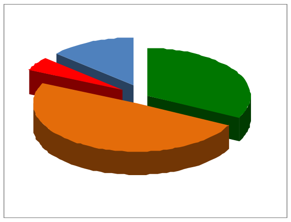
| Primary sludge | Secondary sludge | Nitrification sludge | Blended sludge |
|---|---|---|---|
|  |  |  |  |
| 14% unbiodegradable | 25% unbiodegradable | 37% unbiodegradable | 18% unbiodegradable |

**Figure 2** – Inert and biodegradable solids fractions in three different sludge sources at Blue Plains (blue – influent inert, $X_I$, green: biomass ($X_B$), brown: substrate ($X_S$), red: endogenous residue ($X_E$)

### Pilot-studies on Cambi-digestion

Blended sludge from Blue Plains AWT was thermally hydrolysed at RDP technologies Inc. (Norristown, PA). At Virginia Tech two parallel mesophilic digesters with volumes of 15 and 20L have been operated at 15 days (MAD15) and 20 days (MAD20), respectively. The digesters were operated in a daily batch-feed mode, replacing 1L of digested sludge with 1L of thermally hydrolyzed raw sludge daily. Analytical samples (solids, nitrogen species, pH, fatty acids) were taken from the waste sludge. Mixing was achieved by gas recirculation provided by peristaltic pumps (Cole Parmer-600 RPM, L/S 35 pump heads) operated at 50% of the maximum speed. Biogas was collected in 40L Tedlar bags and metered through a flow-calibrated peristaltic pump to obtain daily biogas production values.

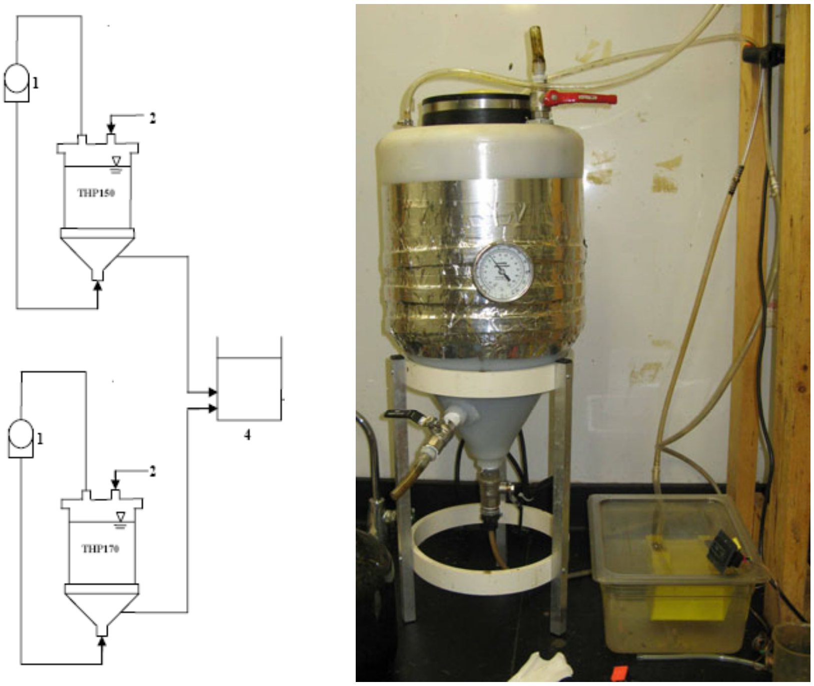


**Figure 3** – Scheme and photo of the pilot Cambi-digesters MAD15 and MAD20

## Model modifications for simulation of thermal hydrolysis

The BioWin$^{TM}$ ASDM model was used as a starting point for development of an extended model for the Cambi heat treatment step and digestion of the heat-treated sludge. The ASDM contains a four population anaerobic digestion model (fermenters, $X_{OHO}$; propionic acetogens, $X_{PRO}$; acetoclastic methanogens, $X_{ACO}$; and hydrogenotrophic methanogens, $X_{HMO}$). The model is calibrated to produce the right amount of volatile solids reduction and biogas generated in digesters processing primary or waste sludges; or a mixture of these. To properly simulate high loaded conditions such as occur during Cambi digestion, several extensions were implemented which have negligible effect on modeling ordinary mesophilic digestion.

The **heat treatment step** itself requires the addition of two new processes: solubilization of particulate COD and pasteurization of biomass.

- **Solubilization**: during Cambi treatment particulate material is converted to soluble components. To be able to describe the high soluble COD content of the treated sludge, a major part of the biodegradable material ($X_S$) needs to be converted to readily degradable counterparts. More soluble material will result in an increase in kinetic rates later in the digestion. This step is described empirically by high-rate first order kinetics.

  $$r_{conv} = k_{Cambi} \cdot X_S \qquad \text{Eq.1)}$$

  The slowly degradable substrate solubilized in Eq.1 is directed towards acetate (40%) and readily biodegradable organics (60%).

The N and P content of the particulate substrate (accounted for in $X_{ND}$ and $X_{PD}$) also have to be solubilized in parallel kinetic expressions.

At DCWASA, where primary and secondary sludges have low inert content, the potential for higher extent of digestion was not observed. Therefore conversion of inerts ($X_E$ or $X_I$) were not included in the model at this stage.

The $k_{Cambi}$ rate constant is essentially a calibration parameter, and must be selected such that the measured amount of soluble COD (30-40%) is generated in the model.

- **Pasteurization**: during the heat treatment step, the sludge is rendered sterile and pathogens and all organisms are absent just before feeding the heat treated sludge to the digester. From the modeling standpoint, a simple, first order kinetic rate can be applied which destroys active organisms that are present in the sludge. The kinetic rate itself has no significance in the model, as long as it converts "most of" the biomass. The important parameter to consider is the fraction of the biomass that is converted to inert material. In this study 20%, the value typically used, was implemented for inert particulate material (considered as endogenous residue). A further 3% of the material was converted to residual inert soluble COD ($S_I$).

**Digestion** of high concentration heat treated sludge tends to run at higher pH values which affects ammonia inhibition and kinetics of methanogenesis.

The kinetic expression typically used to describe acetoclastic methanogenesis (growth of methanogens, $X_{ACO}$, on acetate, $S_{AC}$ as substrate) is shown in Eq.2.

$$r_g = \hat{\mu} \cdot \Theta^{T-20} \cdot X_{ACO} \cdot MS_{Sac} \cdot MI_{O2} \cdot MI_{NO2} \cdot MI_{NO3} \qquad \text{Eq.2)}$$

The Monod inhibition (MI) terms, in the form of MI=Ki/(Ki+S), are used to ascertain that the obligate anaerobic biomass only grows in the lack of oxygen, nitrite and nitrate (true anaerobic conditions). The maximum growth rate depends on temperature (therefore the temperature correction function) and is first order relative to active biomass concentration.

Two modifications/additions are proposed and implemented in the model according to Eq.3)

$$r_g = \hat{\mu} \cdot \Theta^{T-20} \cdot X_{ACO} \cdot \boxed{MS_{HAc}} \cdot MI_{O2} \cdot MI_{NO2} \cdot MI_{NO3} \cdot \boxed{LI_{NH3}} \qquad \text{Eq.3)}$$

- **Undissociated acetic acid** is used as substrate instead of total acetate. A pH model, already available with ASDM (Takacs et al., 2004) is necessary for this model addition. The form of the Haldane term, applied to undissociated acetic acid (HAc) is the following (Eq.4).

$$MS_{HAc} = \frac{[HAc]}{K_{HAc} + [HAc] + \frac{[HAc]^2}{K_{i,HAc}}} \qquad \text{Eq.4)}$$

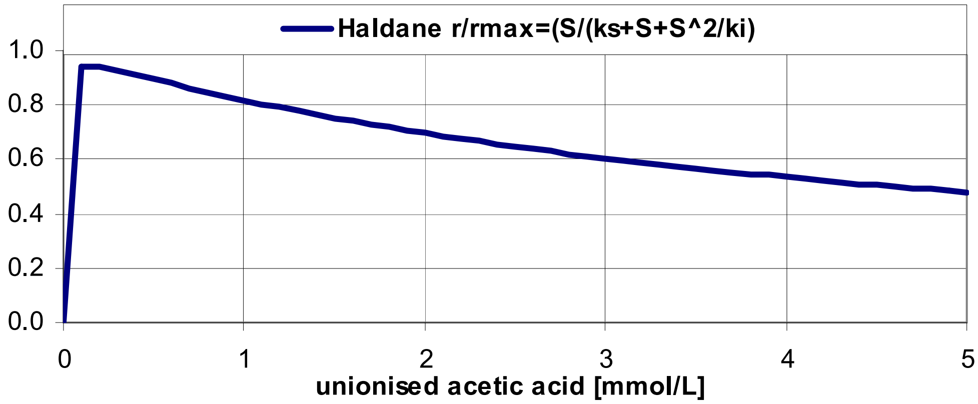


**Figure 4** – Haldane kinetics used to describe substrate limitation and inhibition of acetoclastic biomass ($K_{HAc}$=0.004 mmol/L, $K_I$=4.6 mmol/L; Fukuzaki et al., 1990)

Based on Fukuzaki et al. (1990) $K_{HAC}$ = 4 µmol/L and $K_{i,HAc}$ = 4.6 mmol was used in the Haldane expression (Figure 4).

- **Free ammonia inhibition** ($LI_{NH3}$) is a well known threat to digester operation at elevated pH-value. The inhibiting effect of free ammonia on methanogenic growth has already successfully been implemented in digester models (Angelidaki et al., 1993). This effect at high total ammonia concentrations is well demonstrated in Figure 5 and was added to Eq.2).

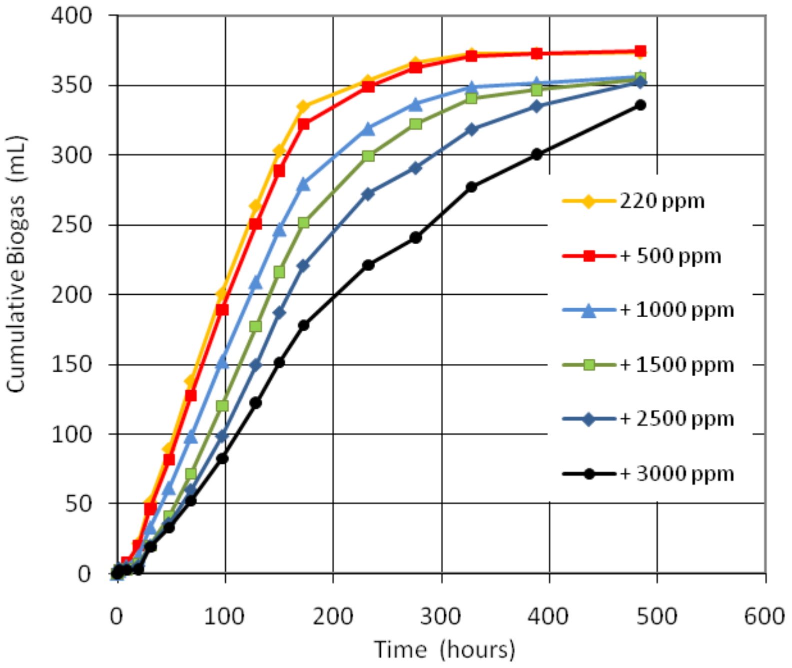


**Figure 5** – Biogas production at different total ammonia concentrations at constant pH=7.5

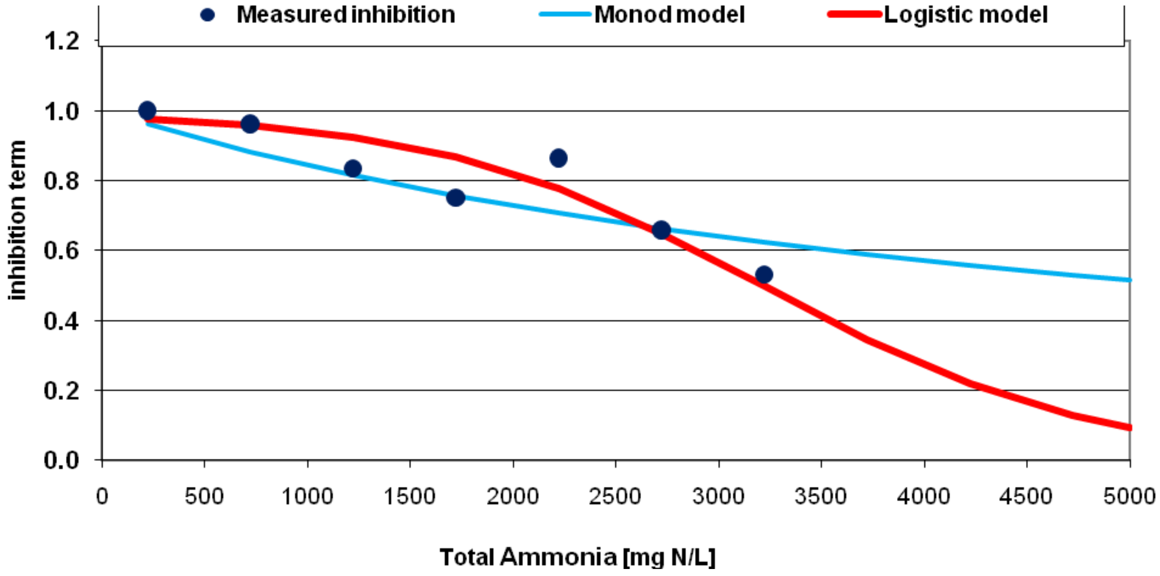


**Figure 6 –** Free ammonia inhibition plotted against total ammonia at constant pH=7.5.

The extent of inhibition can be calculated by the reduced slopes of biogas production, and was plotted as "Measured inhibition" in Figure 6. Two inhibition functions were evaluated – a simple Monod inhibition (MI in Eq.5) and a sigmoidal inhibition (LI as a logistic curve in Eq.6).

$$MI_{NH_3} = \frac{K_{i,NH3}}{K_{i,NH3} + [NH_3]} \qquad \text{Eq.5)}$$

$$LI_{NH_3} = \frac{1}{1 + e^{\left(-I_{NH3\,slope}\left(I_{NH3\,halfval} - [NH_3]\right)\right)}} \qquad \text{Eq.6)}$$

Both inhibition functions, fitted to the experimental data, are shown in Figure 6. It is evident that both Monod and Logistic curves do fit the experimental results in the 0-3000 mgN/L range. In the 2000-3000 mgN/L range the fit of the logistic curve is much better. When the ammonia concentration is in excess of 3000 mgN/L, (assuming a typical pH = 7.8), the expectation is that inhibition becomes more severe and finally at increasing pH methanogenic activity ceases. Thus the logistic inhibition function shows a more realistic behavior in the high ammonia concentration range. Based on this the logistic inhibition function was selected with the following parameters:

$I_{NH3\ slope}$ = 338
$I_{NH3\ halfval}$ = 12 mmol (in terms of free ammonia, where 50% inhibition occurs)

A Cambi model configuration in BioWin is shown in Figure 7.

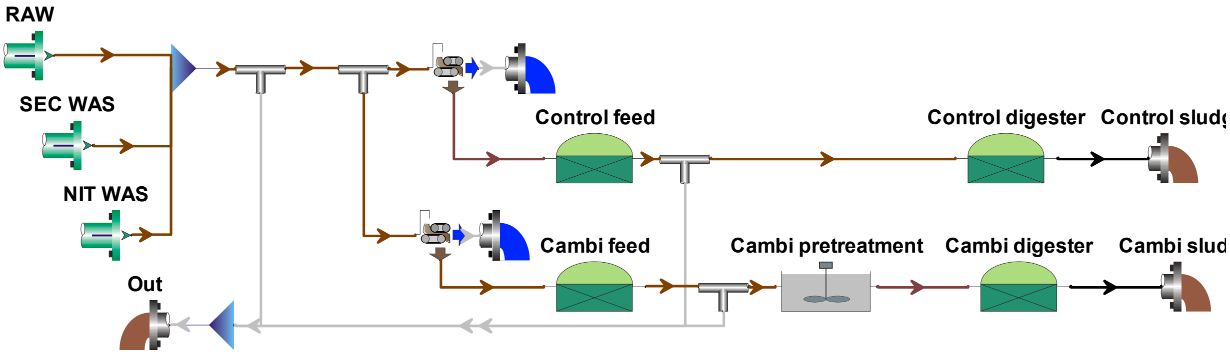


**Figure 7** – Model configuration for evaluating the effect of Cambi pretreatment

## RESULTS AND DISCUSSION

### Pilot results

Experimental results from an intensive monitoring period in September 2008 have been used to compare the digestion performance at 15 and 20 days retention time, respectively. At higher organic loading rates of 5.04 g VSS/L/d in the MAD15 digester compared to 3.78 g VSS/L/d in average in the MAD20 a lower specific gas yield is expected. This agrees with meaurements – the specific gas production in terms of kg methane per kg VSS was 8.7% less (Figure 8). This difference in gas production can only partly be ascribed to improved solids degradation due to the longer digestion period. A significant amount of volatile fatty acids (VFA, mostly acetate), is available but not used as shown in a balance of monthly averaged COD mass-flows (Figure 9).

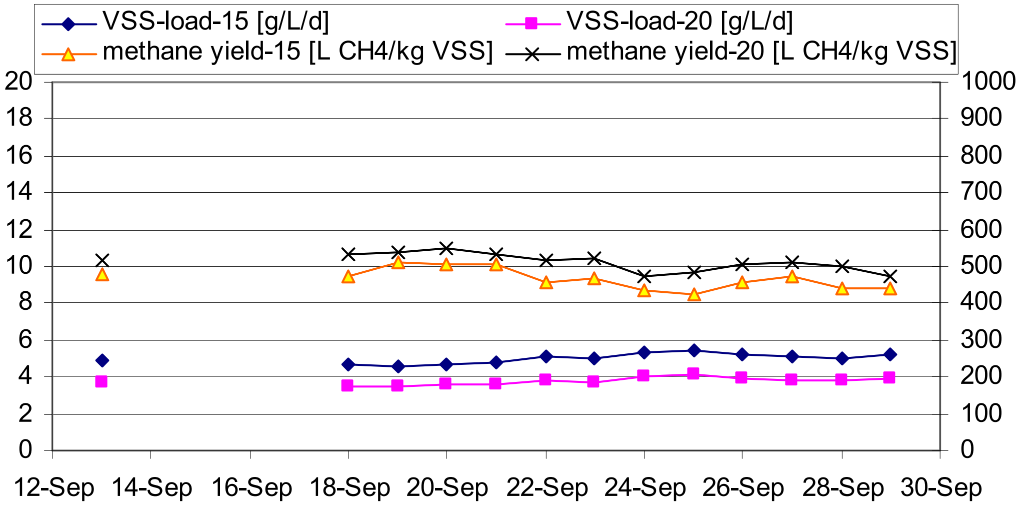


**Figure 8** – Specific loading rates and methane production of the 2 lab-digesters of 15 and 20 days SRT

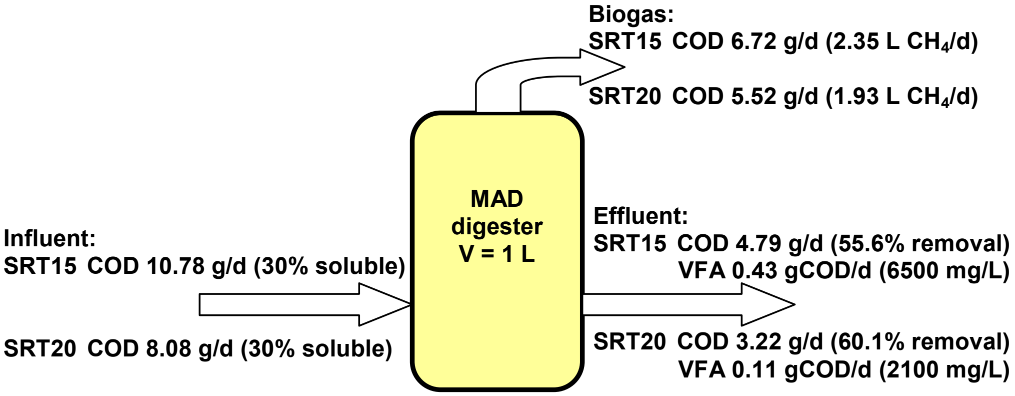


**Figure 9** – Measured average COD mass-balance of both parallel digesters MAD15 and MAD20 normalized to a volume of 1 L (balances close to 6.8% and 8.2%, respectively)

The residual VFA concentration in the MAD15 digester amounts to 6500 mg/L and contributes to a lower COD removal rate of 55.6% compared to 60.1% in the MAD20 (control digester without pre-treatment 50% COD-removal).

The ammonia measurements (Figure 10) revealed surprising results: Although higher ammonia release at advanced digestion is expected the ammonia concentration in the MAD20 digester was consistently lower than in MAD15. A potential explanation is that extended mixing by gas recirculation in the shallow (2-foot deep) digester at pH-values between 7.8 and 7.9 caused substantial ammonia stripping.

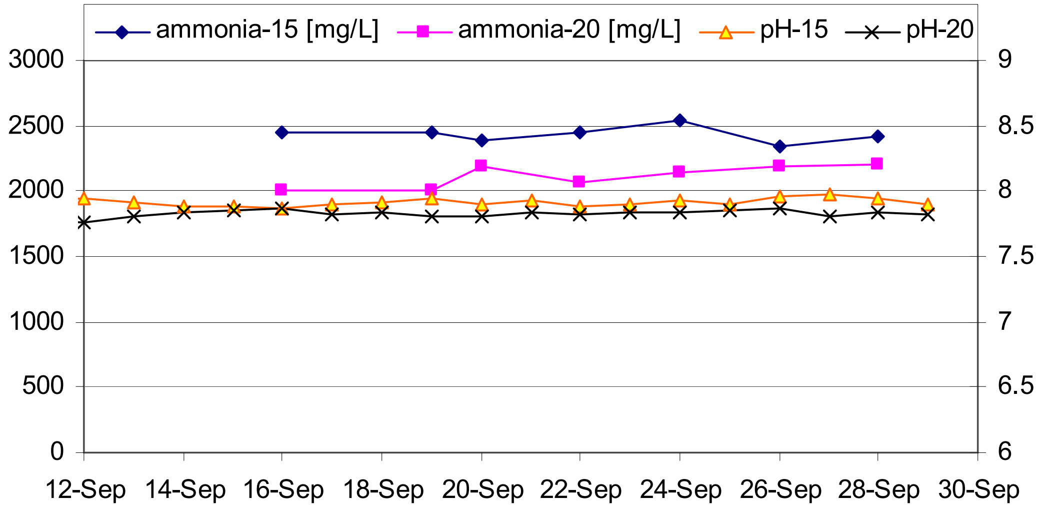


**Figure 10** – Ammonia and pH measurements showing lower values in the MAD20 compared to the MAD15

## Simulation results

- **Validated model** describes ammonia stripping: The observed ammonia concentrations were confirmed by the model simulations which include gas transfer and ammonia stripping. The calibrated gas-liquid transfer coefficients for ammonia and $CO_2$ had been increased by one third in order to consider more extended gas-mixing and –stripping in the MAD20 digester. Ammonia stripping relieved ammonia toxicity to acetoclastic methanogens and allowed a more complete digestion of available acetate (Table 1). More detailed measurements for ammonia concentrations under various mixing conditions are on the way.

**Table 1 –** Simulated acetate and ammonia concentrations affected by gas stripping (calibrated gas-liquid transfer coefficients for free ammonia and $CO_2$)

| digester | $k_{L(NH3)}$ | $k_{L(CO2)}$ | Acetate [mgCOD/L] | Ammonia [mgN/L] |
|---|---|---|---|---|
| MAD 15 | 0.075 | 75 | 5654 | 2464 |
| MAD 20 | 0.1 | 100 | 1944 | 2060 |
| Control MAD | 0.1 | 100 | 1292 | 1888 |

- **Model prediction** of whole-plant effluent concentrations. Soluble organic inerts generated in the digestion process are expected to pass the main treatment process and to be found in the effluent of the plant. This results in a slight increase in predicted COD-values as shown in Table 2. Compared to COD the recycled nitrogen load is more relevant. The installation of TH-pre-treatment and mesophilic digestion would increase the recycled N load from sludge processing from about 8% of the influent load to more than 20% if separate sidestream treatment is not considered.

**Table 2 –** Simulation results for impacts of return loads from dewatering of TH-treated and digested sludge on the whole-plant effluent (without separate sidestream-treatment)

| | N-recycle load | | effluent | |
|---|---|---|---|---|
| sludge treatment | sludge liquors [%] | total N [mg N/L] | nitrate [mgN/L] | total COD [mgCOD/L] |
| no digestion | 8.2 | 5.2 | 3.1 | 21.0 |
| Cambi-digestion | 20.9 | 8.8 | 6.5 | 23.6 |

In the context of a tight effluent nitrogen permit of 3 mgN/L a difference in nitrate concentration from 3.1 to 6.5 mg/L is significant: equals the target value for total nitrogen. Especially in winter periods when nitrogen removal processes become kinetically limited, separate sidestream treatment is the only remedy to mitigate recycled loads from advanced digestion.

## CONCLUSIONS AND OUTLOOK

Thermal hydrolysis such as the Cambi$^{TM}$ process is increasingly used in large plants to optimize three important aspects of sludge treatment: reactor volume, product volume and energy recovery. Even with a series of tests and pilots it is difficult to accurately evaluate the full effect of the pretreatment on these indicators and other aspects of full-plant design (anaerobic digestion and nitrogen impacts from side-stream) as well as operation. A whole-plant model based toolkit was developed for the District of Columbia Water and Sewer Authority for its Blue Plains plant to integrate all of the experimental data for whole-plant design. Results generated with it at Blue Plains show the importance of a holistic approach when adding a new process to a complex existing plant that is making significant changes to both its liquid (total nitrogen design of 3 mg/L) and solids (anaerobic digestion) programs. Specifically the model could reveal artifacts of a bench-scale pilot like ammonia stripping which need to be considered when pilot results are translated to full-scale conditions. The model will be used as a tool to evaluate digester configurations (e.g. 2-stage versus single stage) and measures to relieve ammonia inhibition.

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