The Biowin Advantage

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Introducing the Thermal Hydrolysis Unit

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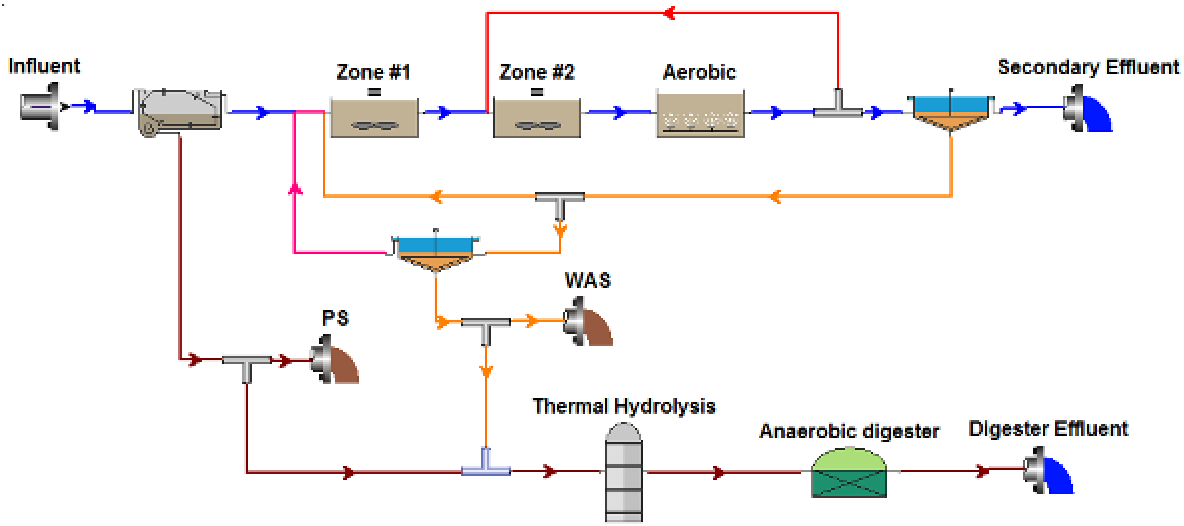
Introduction

In this issue we describe the thermal hydrolysis (TH) unit and demonstrate its application in a whole-plant simulation. The TH unit is used to simulate the breakdown of particulate components in a sludge stream generally into soluble components. The unit allows for simulation of potential impacts of sludge pre-treatment technologies on process performance such as biogas production and soluble nutrient concentrations in downstream digesters.

The TH unit is a dimensionless mass balance converter that instantaneously converts the particulate state variables into predefined sets of other state variables, and the user defines the extent of conversion and the fractional distribution between ‘products’ of hydrolysis.

A picture of the thermal hydrolysis unit in a BioWin flowsheet is shown below:



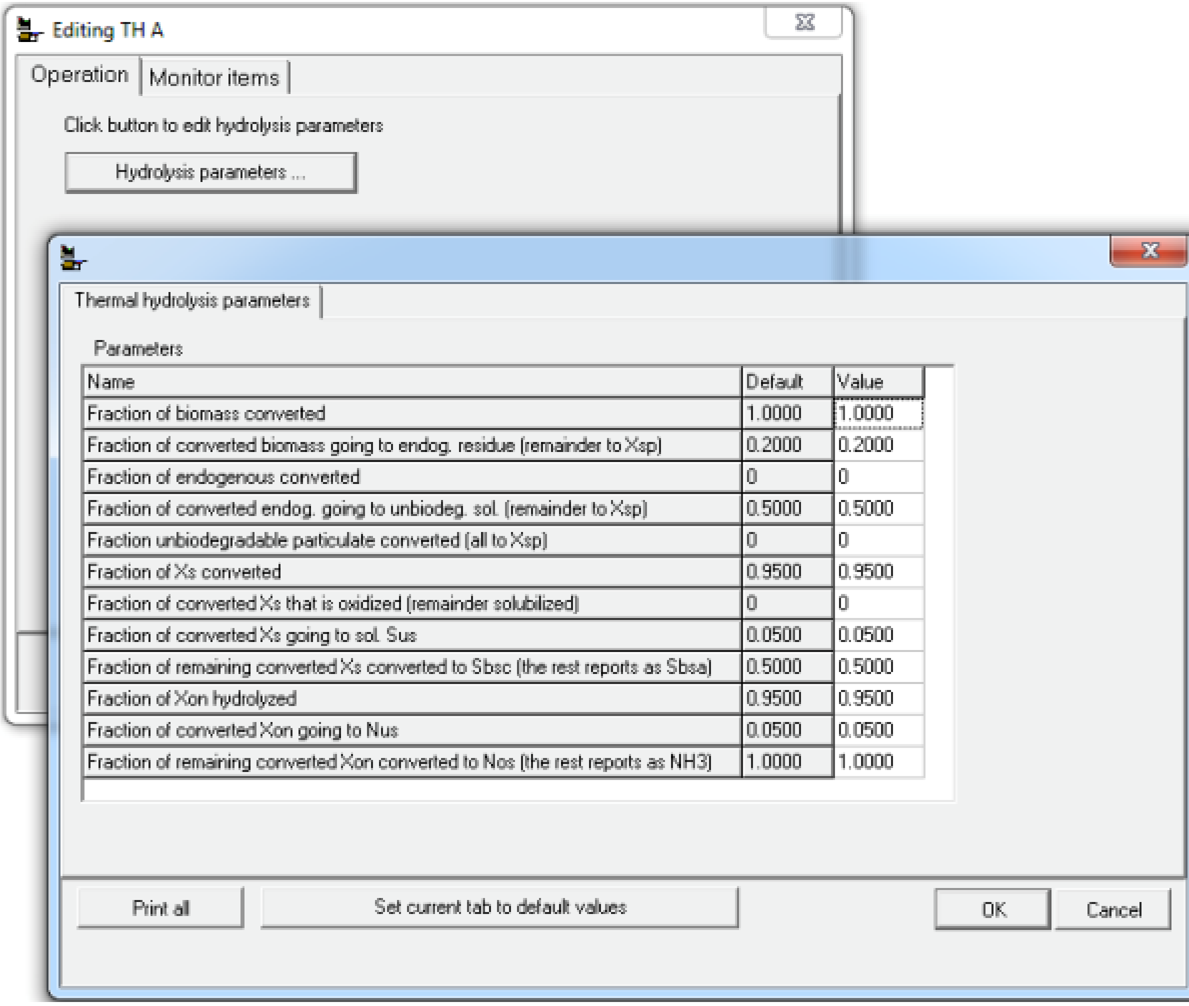
The sets of state variables into which particulate components may be converted are based on an extensive analysis of data for various pretreatment processes. The user adjusts the conversion fractions such that the predicted COD and nutrient concentrations in the pretreated sludge match measured or expected values. Therefore, the TH unit may be used to model the conversions accomplished by any type of pretreatment process (not only high-pressure thermal hydrolysis). Thus other types of pretreatment such as ozonation, sonication and chemical oxidation may be represented in BioWin.

The default conversion fractions in the thermal hydrolysis unit were empirically derived to achieve the conversions typically observed when WAS is treated in a batch high-pressure thermal hydrolysis (HPTH) process at around 160 to 170°C at 7 bars for approximately 30 minutes. The performance indicators associated with this pretreatment are summarized in the following table:

ATTRIBUTE	VALUE
VSS Destruction	30 to 50 %
COD Solubilization	30 to 50 %
Inert Soluble COD Generation	2 to 5 %
Organic N Solubilization	30 to 50 %
TCOD	Conserved
TN	Conserved
Biomass	Inactivated

Exploring the Thermal Hydrolysis Unit

The Operation tab provides access to the hydrolysis parameters. Clicking the Hydrolysis parameters button presents the interface for defining the fate of particulate components of a sludge stream.



The TH unit parameter editor allows users to specify the degree to which major particulate components of sludge VSS (biomass [Z], endogenous residue [Z_E], unbiodegradable particulate COD [X_I], biodegradable particulate COD [X_{SP}]) will be affected by the thermal hydrolysis process. The user may also specify the fraction of biodegradable particulate organic nitrogen [X_{ON}] that is hydrolyzed by pretreatment. Possible products from the conversions of individual components are as follows:

Biomass (OHO, PAO, AOB, NOB, etc.):

- A portion is converted to endogenous residue (Z_E);
- The remainder adds to particulate slowly biodegradable COD (X_{SP}).

Endogenous Residue (Z_E):

- A portion is converted to unbiodegradable soluble COD (S_{US});
- The remainder adds to particulate slowly biodegradable COD (X_{SP}).

Particulate Inert COD from Influent f_{UP} (X_I):

- All the converted X_I adds to particulate slowly biodegradable COD (X_{SP}).

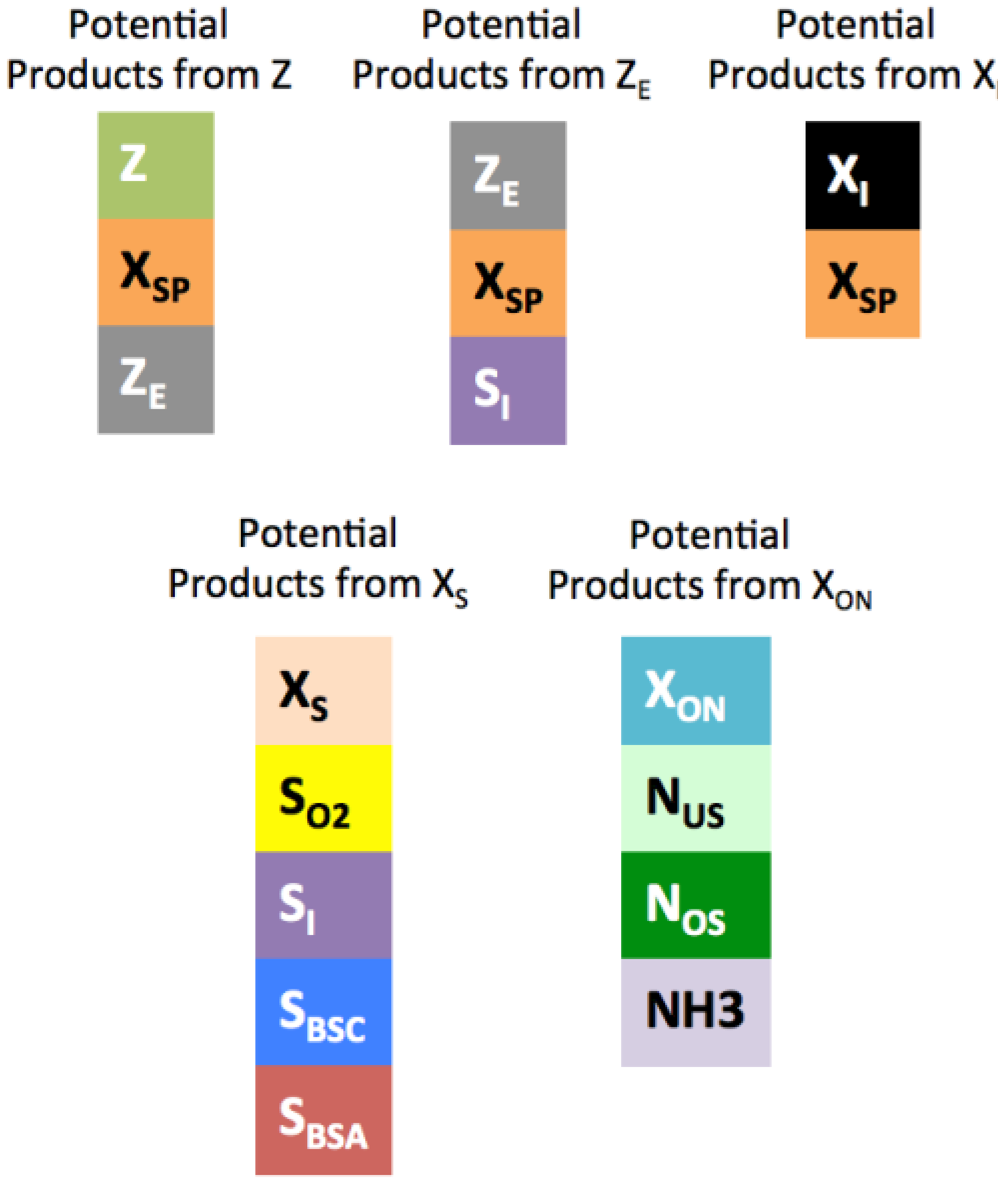
Slowly Biodegradable COD (X_{SP} and X_{SC}):

- A portion may be oxidized and the remainder is solubilized;
- The solubilized portion is distributed between:
  - Unbiodegradable soluble COD (S_{US});
  - Soluble complex readily biodegradable COD (S_{BSC});
  - Acetate (S_{BSA});

Particulate Biodegradable Organic N (X_{ON}):

- A portion may be converted to unbiodegradable soluble organic N (N_{US});
- The remainder is distributed between:
  - Biodegradable soluble organic N (N_{OS});
  - Ammonia.

These conversion pathways are illustrated in the five tables below where the left and right-hand columns of each table represent the conditions before and after pretreatment, respectively:



Each conversion pathway and default conversion fraction is explained in greater detail below:

Conversion of biomass

A setting of 1.0 for Fraction of biomass converted is applied as the default, which means that all of the incoming biomass (i.e. all 9 biomass types in BioWin) will be converted. This value was selected because batch HPTH processes have been shown to essentially sterilize the activated sludge (Donoso-Bravo et al., 2010; Gurieff et al., 2011; Burger et al., 2012). The Fraction of converted biomass going to endogenous residue is set at a default value of 0.2, i.e. the endogenous residue fraction defined by the endogenous respiration approach for organism decay. The remaining converted biomass is reported as X_{SP}. The conversion of biomass in the TH unit releases particulate biodegradable organic N and P, similar to the decay of biomass.

Conversion of endogenous residue

A setting of 0 for Fraction of endogenous converted is applied as the default. This value was selected because HPTH has been shown to increase the rate but not the extent of downstream digestion (Burger et al., 2012). Should the user choose to convert some Z_E, one specifies the Fraction of converted endogenous going to unbiodegradable soluble (S_{US}). The remaining converted Z_E is reported as X_{SP}. Similar to the conversion of biomass, the conversion of Z_E in the TH unit releases particulate biodegradable organic N and P.

Conversion of unbiodegradable particulate COD

Similar to Z_E, which is a form of unbiodegradable particulate COD, a setting of 0 for Fraction of unbiodegradable particulate converted (all to X_{SP}) is applied as the default. Should the user choose to convert some X_I, it is converted entirely to X_{SP}. The conversion of X_I in the thermal hydrolysis unit releases particulate biodegradable organic N and P, similar to the decay of biomass.

Note: By inputting non-zero values for Fraction of endogenous converted and Fraction of unbiodegradable particulate converted (all to X_{SP}) fractions, it is possible to convert components of sludge VSS that BioWin normally considers to be unbiodegradable into a biodegradable form.

Conversion of biodegradable particulate COD

A setting of 0.95 for Fraction of X_S converted is applied as the default. This means that almost all of the biodegradable particulate COD ***entering and produced within*** the TH element is hydrolyzed. Thus almost all of the X_S generated in the conversion of Z, Z_E and X_I in the previously described processes is solubilized in this process. Of the converted X_S, a default fraction of 0 is oxidized since it has been shown that the total COD of the sludge is conserved during HPTH (Morgan-Sagasume et al., 2010). Of the converted X_S, a default value of 0.05 is reported as S_{US} since it has been shown that HPTH at temperatures above 150°C generates a small fraction of refractory compounds, i.e. unbiodegradable soluble COD (Bougrier et al., 2007, Climent et al., 2007, Dwyer et al., 2008, Donoso-Bravo et al., 2010). Of the *remaining* converted X_S, a default value of 0.5 is reported as S_{BSC} and the remainder is reported as S_{BSA}. Morgan-Sagasume et al. 2010 showed that HPTH produces volatile fatty acids.

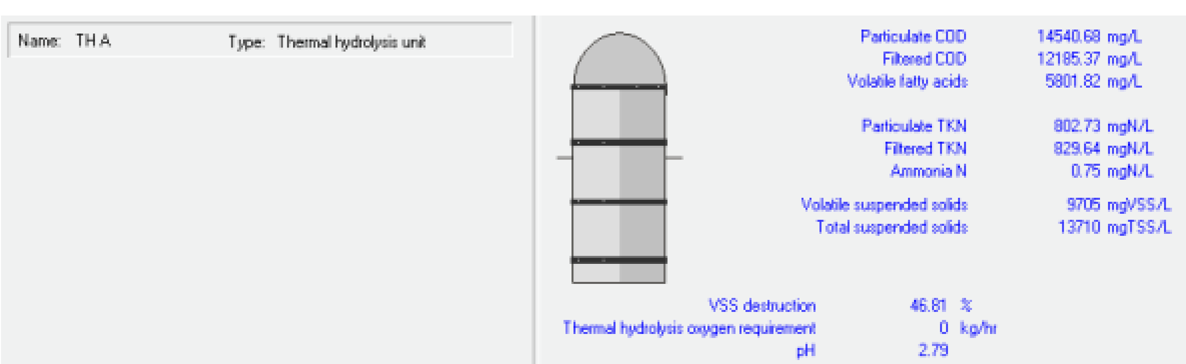
Conversion of biodegradable particulate organic N

A setting of 0.95 for Fraction of X_{ON} hydrolyzed is applied as the default. This value is equivalent to the default hydrolyzed fraction for X_S since it has been shown that all types of organics (proteins, carbohydrates, etc.) are solubilized to the same extent by HPTH pretreatment (Burger et al., 2012). By using different fractions for the hydrolysis of X_{ON} *versus* X_S, the user may force the pretreatment process to favour generation of organics with lower or higher N content. The Fraction of X_{ON} hydrolyzed applies to the X_{ON} *entering and produced within* the TH element. (X_{ON} may be produced within the TH element via Z, Z_E and X_I conversion). The default value for Fraction of converted X_{ON} going to N_{US} is set equivalent to the default value for Fraction of X_S going to soluble S_{US}, i.e. 0.05. The Fraction of remaining converted X_{ON} converted to N_{OS} (the rest reports as NH3) is set at a default of value 1.0. This value was selected because it has been shown that proteins are solubilized rather than mineralized by HPTH (Donoso-Bravo et al., 2010; Bougrier et al., 2008; Burger 2012).

Note: In the TH element, the Fraction of X_S converted is automatically applied to the hydrolysis of X_{OP}.

Summary Process Information for the Thermal Hydrolysis Unit

When you hover your cursor over the thermal hydrolysis element, process information is shown in the summary pane below the drawing board, as depicted in the example below:



The particulate and filtered COD and TKN concentrations, and the VFA and ammonia concentrations are listed, as well as the residual VSS and TSS, and pH. The displayed VSS destruction is calculated identically to that in the anaerobic digester element: (VSS_{IN} – VSS_{OUT}) / VSS_{IN} * 100%.

Any oxygen requirement in the TH unit is reported in units of kg/hr (or lb/hr). This indicates the oxygen required if any X_S is oxidized; that would be applicable in pretreatment processes such as wet air oxidation or ozonation. BioWin assumes this oxygen requirement is automatically satisfied by an internal supply within the pretreatment unit.

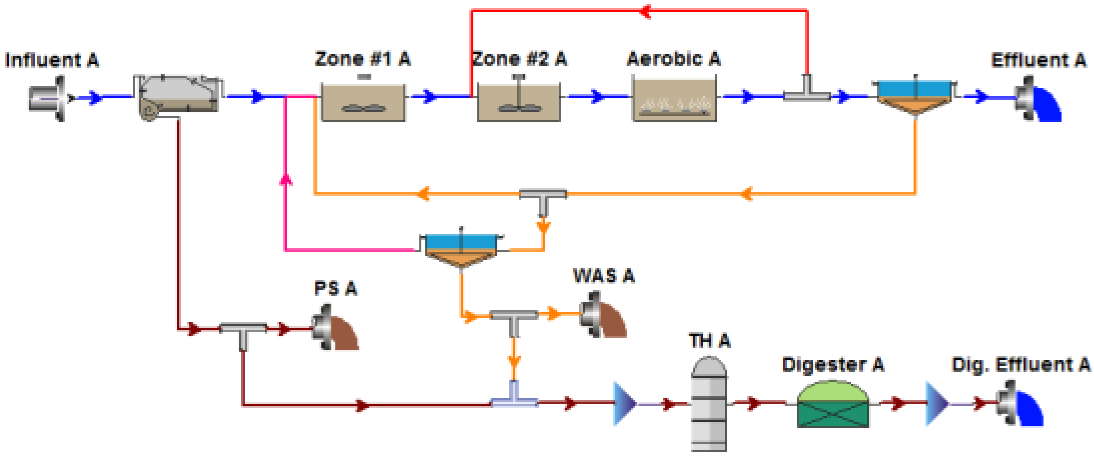
Case Study:

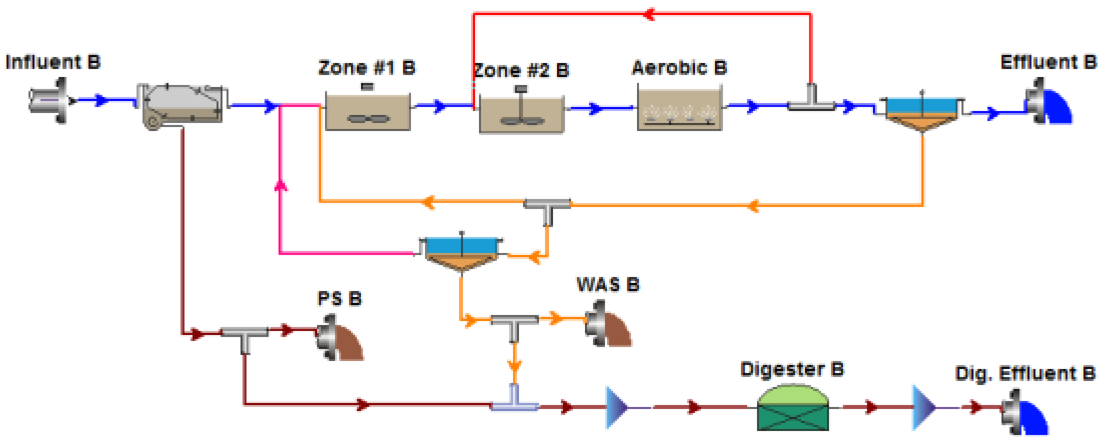
Parallel Treatment Plants with and without Thermal Hydrolysis

The impacts of implementing thermal hydrolysis prior to anaerobic digestion are investigated using this BioWin file. The influent element, physical dimensions and operation of Plants A and B are identical except that Plant A incorporates thermal hydrolysis whereas Plant B does not. Various model scenarios are simulated for a range of volumetric ratios of waste activated sludge to primary sludge (WAS:PS) while maintaining the flow rate to the digester at 45 m^3/d to achieve a constant digester HRT of 20 d. [Reducing digester HRT from 20 to 10 days is also considered for the TH case]. In each scenario, the default conversion fractions are applied in the thermal hydrolysis element hence TCOD is conserved across the element.

As previously mentioned, the default conversion fractions in the TH unit were empirically derived for the HPTH pretreatment of WAS only. It is expected that these default conversion fractions may be applied when the TH unit is used to model the HPTH pretreatment of combined sludge and PS only. Should the user find that the predicted VSS destruction and COD solubilization in the TH unit do not match observed values, it is recommended that the Fraction of X_S converted first be adjusted. Unless it has been shown that thermal hydrolysis favours generation of organics with lower or higher N content, the Fraction of X_{ON} hydrolyzed should also be set equivalent to the Fraction of X_S converted. For example, if the predicted VSS destruction is higher than the measured value, the Fraction of X_S converted should be lowered from the default value of 0.95. However if the Fraction of X_S converted is set at 1.0 and the predicted VSS destruction is still less than the measured value then the Fraction of Z_E converted and/or Fraction of X_I converted may be increased from the default value of 0 until the predicted and measured VSS destruction match.

In each scenario, the steady-state simulation is run from seed values. The SRT in each plant is determined by summing the total solids mass in the reactors (Zone #1, Zone #2 and Aerobic) and the SST and dividing by the sludge wasted *via* the WAS splitter, *i.e.* a constant value of 150 m^3/d. Because the liquid train is operated identically in each plant and scenario, the SRT in both plants is a constant value, *i.e.* 10.8 d. Typical raw wastewater fractions are applied in the influent and the F_{UP} fraction is 0.13.





Model Scenarios

The table below shows the main operating characteristics (input and output) for the TH unit in Plant A. For each scenario, the volumetric WAS:PS ratio is indicated.

ATTRIBUTE	TH Unit	1	2	3	4	5	6
		WAS only	80:20	60:40	40:60	20:80	PS only
VSS (mg/L)	Input	18,245	17,444	16,643	15,841	15,040	14,239
	Output	9,705	8,482	7,258	6,035	4,812	3,589
TSS (mg/L)	Input	23,925	22,537	21,149	19,761	18,374	16,986
	Output	13,710	12,228	10,745	9,263	7,780	6,298
Particulate COD (mg/L)	Input	26,694	25,892	25,091	24,290	23,488	22,687
	Output	14,541	12,777	11,013	9,250	7,486	5,723
Soluble COD (mg/L)	Input	33	70	108	146	184	222
	Output	12,185	13,186	14,186	15,186	16,186	17,186
VFA COD (mg/L)	Input	0	3	6	9	12	14
	Output	5,802	6,265	6,727	7,190	7,653	8,116
Particulate TKN (mgN/L)	Input	1,630	1,421	1,213	1,005	796	588
	Output	803	681	560	438	317	195
Soluble TKN (mgN/L)	Input	3	10	18	25	33	40
	Output	830	750	671	592	513	433
Ammonia (mgN/L)	Input	1	7	14	20	27	33
	Output	1	7	14	20	27	33
PO4 (mgP/L)	Input	1	2	2	3	3	4
	Output	570	492	414	336	258	180
pH	Input	6.8	6.9	7.0	7.1	7.2	7.3
	Output	2.8	2.9	2.9	4.0	3.1	3.1

As shown in the above table, the suspended solids concentration decreases and the soluble COD and TKN concentrations increase across the TH unit in every scenario, as expected. The pH drops across the TH unit. This is mainly due to the considerable amount of VFAs that are formed. In addition, hydrolysis of particulate organic phosphorous generates phosphate which also works to lower the pH. The ammonia concentration is unchanged across the TH unit as the literature has shown that proteins are solubilized rather than mineralized by HPTH.

The pH drop across the TH unit is primarily due to the formation of VFAs. The results of the model scenarios with TH (Plant A) and without TH (Plant B) are summarized in the table below.

ATTRIBUTE	Plant	1 WAS only	2 80:20	3 60:40	4 40:60	5 20:80	6 PS only
* VSS destruction (%)	A	47	51	56	62	68	75
	B	36	42	48	55	63	47
Digester off-gas flow rate (m^3/h)	A	13	14	16	17	19	20
	B	9	11	13	15	17	12
NH3 from digester (mgN/L)	A	783	701	618	536	454	371
	B	641	585	529	472	415	220
N_{OS} from digester (mgN/L)	A	5	4	3	3	2	2
	B	0	0	0	0	0	1
N_{US} from digester (mgN/L)	A	42	38	34	29	25	21
	B	7	6	4	3	2	1
PO4 from digester (mgP/L)	A	570	490	410	330	250	170
	B	463	403	342	281	220	99
S_{US} from digester (mgCOD/L)	A	636	685	734	784	833	883
	B	112	95	79	63	47	30
X_S from digester (mgCOD/L)	A	6	7	7	8	9	9
	B	23	28	34	44	68	6316
pH in digester	A	6.8	6.8	6.7	6.7	6.6	6.5
	B	6.8	6.8	6.7	6.7	6.6	6.4

*The VSS destruction in Plant A essentially occurs entirely in the TH unit.

The above table shows that for each scenario, the VSS destruction and digester off-gas flow rate are both higher in Plant A than in Plant B. This clearly demonstrates the advantage of implementing HPTH pretreatment prior to anaerobic digestion.

There are potential disadvantages of implementing thermal hydrolysis pretreatment. As shown in the table above, pretreating the sludge by HPTH generates more NH3, N_{OS}, N_{US}, PO4 and S_{US} in the digester effluent. This could be problematic for the plant when the digester supernatant is recycled back to the liquid train.

As the volumetric proportion of PS delivered to the digester increases, the VSS destruction and digester off-gas flow rate increases. This is expected since the PS contains more than 20 times the concentration of X_S as is contained in the WAS. This is determined by viewing the mass rate of X_S (i.e. essentially all X_{SP}) in the side stream of the splitters directing PS and WAS to the digester when the volumetric WAS:PS ratio to the digester is set at 50:50.

Increasing the volumetric proportion of PS that each plant digests improves (*i.e*. decreases) the NH3, N_{OS}, N_{US} and PO4 in the digester effluent. This is expected as the majority of these N and P species originate from active biomass (Z) and the biomass content of PS is negligible. By comparison, biomass comprises the majority of the VSS of the WAS.

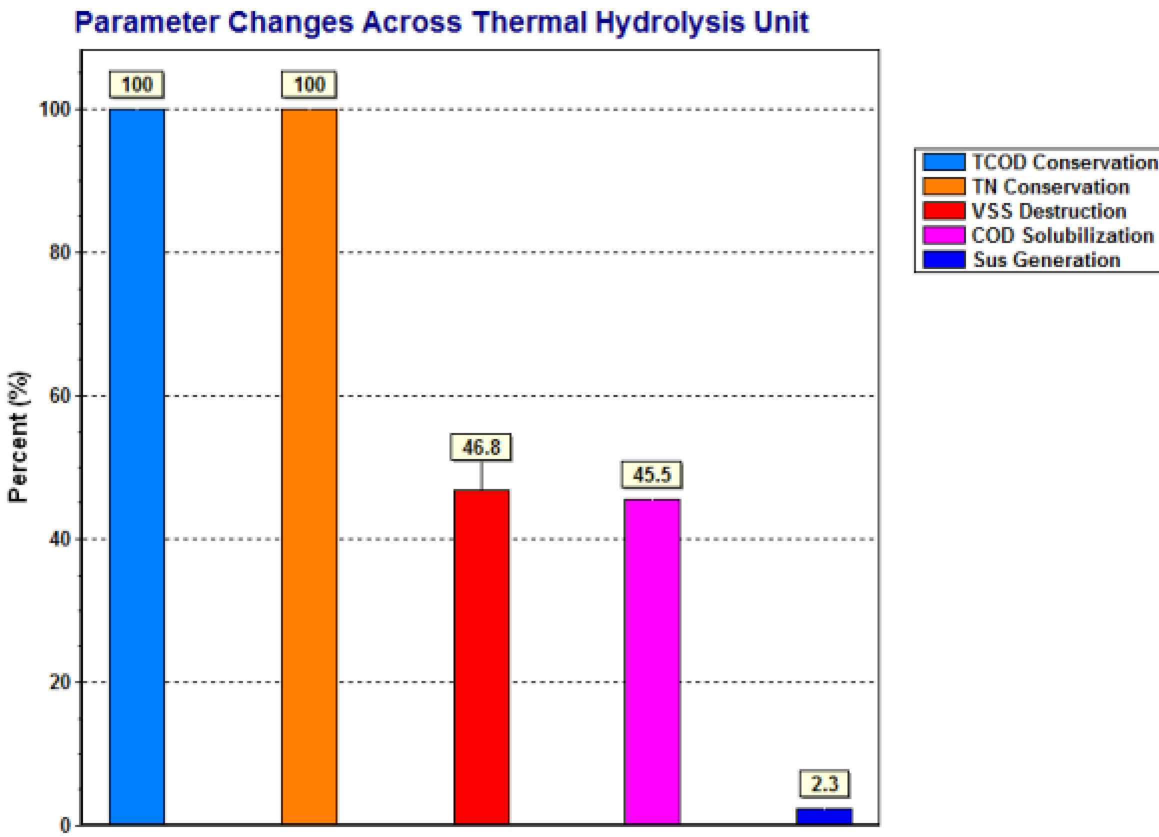
As the volumetric proportion of PS that is digested increases, the S_{US} in the digester effluent also decreases in Plant B. This is expected as the only process in the anaerobic digester that generates S_{US} is the decay of Z_{PAO} and the Z_{PAO} content of PS is negligible. However, the opposite trend occurs in Plant A. The introduction of the TH unit adds up to two other process that generate S_{US}, namely that generated upon X_E and X_S conversion. The VSS of the PS is mostly comprised of X_S; hence S_{US} in the digester effluent increases as the volumetric ratio of PS increases. The default setting for the Fraction of converted X_S going to soluble S_{US} is 0.05. If the predicted plant effluent COD exceeds the measured level at a plant where the digester supernatant is recycled back to the liquid train, the user may consider lowering the Fraction of converted X_S going to soluble S_{US} from the default value when using the thermal hydrolysis unit to model the HPTH pretreatment of combined sludge.

In the above table, the X_S concentration leaving the digester is consistently less than 100 mg COD/L except for Plant B in Scenario 6. An X_S concentration less than 100 mg COD/L leaving the digester indicates that the maximum VSS destruction essentially has been achieved for the digester. In other words, increasing the digester HRT or anaerobic hydrolysis factor will not further improve the VSS destruction. To further increase the VSS destruction in these cases one would need to decrease the influent F_{UP}, decrease the plant SRT or, in the case of Plant A, maximize the fraction of X_S converted or convert some Z_E or X_I in the TH unit. The high X_S concentration leaving the digester in Plant B in Scenario 6 indicates that the digester is undersized. However, by implementing thermal hydrolysis prior to the digester in Scenario 6, the VSS destruction may be maximized.

As shown in the above table, the digester pH is essentially equivalent in Plants A and B for each scenario, even though the digester in Plant A receives pretreated sludge with a low pH. Feeding the digester with thermally pretreated sludge does not cause souring. This is expected as the TH unit and digester in Plant A act similar to a two-stage digester where hydrolysis and acidogenesis take place in the TH unit and acetogenesis and methanogenesis in the digester.

Treatment of WAS Only

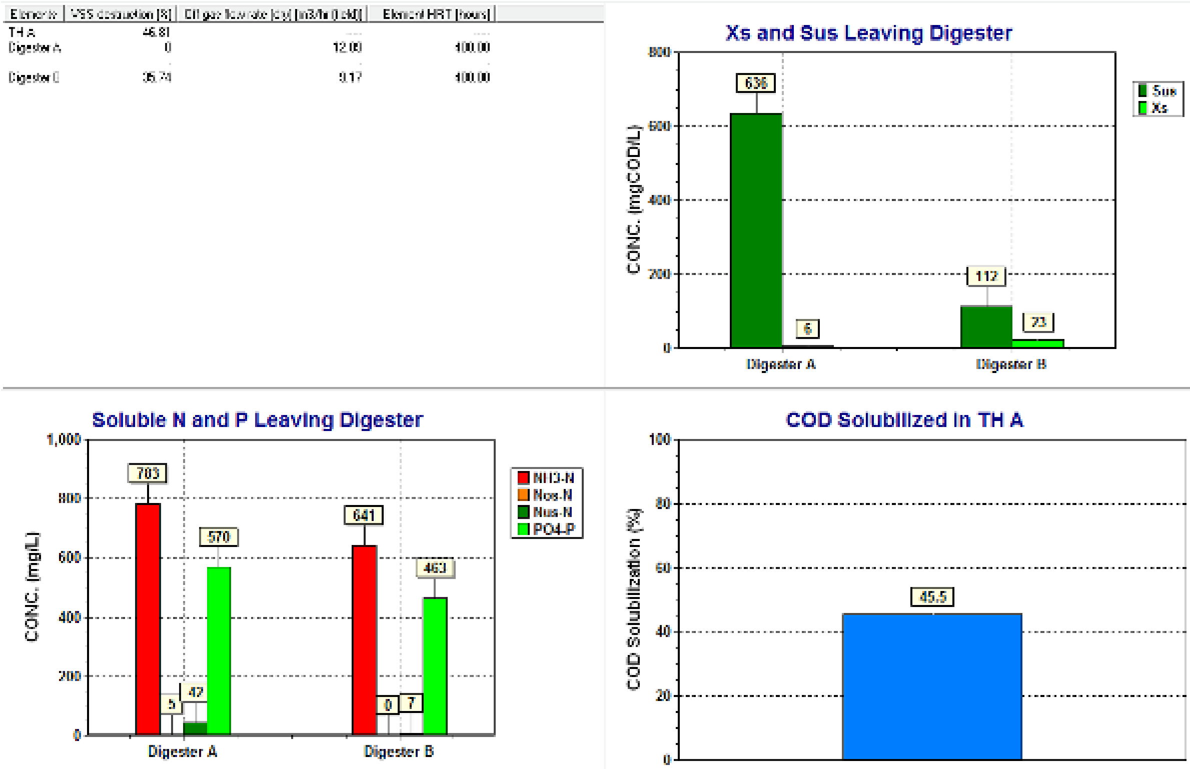
As shown in the screen shot below, the VSS destruction, COD solubilization and S_{US} generation are 47%, 46% and 2%, respectively, in the TH unit. These changes are consistent with those reported in the literature for the treatment of WAS in a batch HPTH process at around 160 to 170°C at 7 bars for approximately 30 minutes.



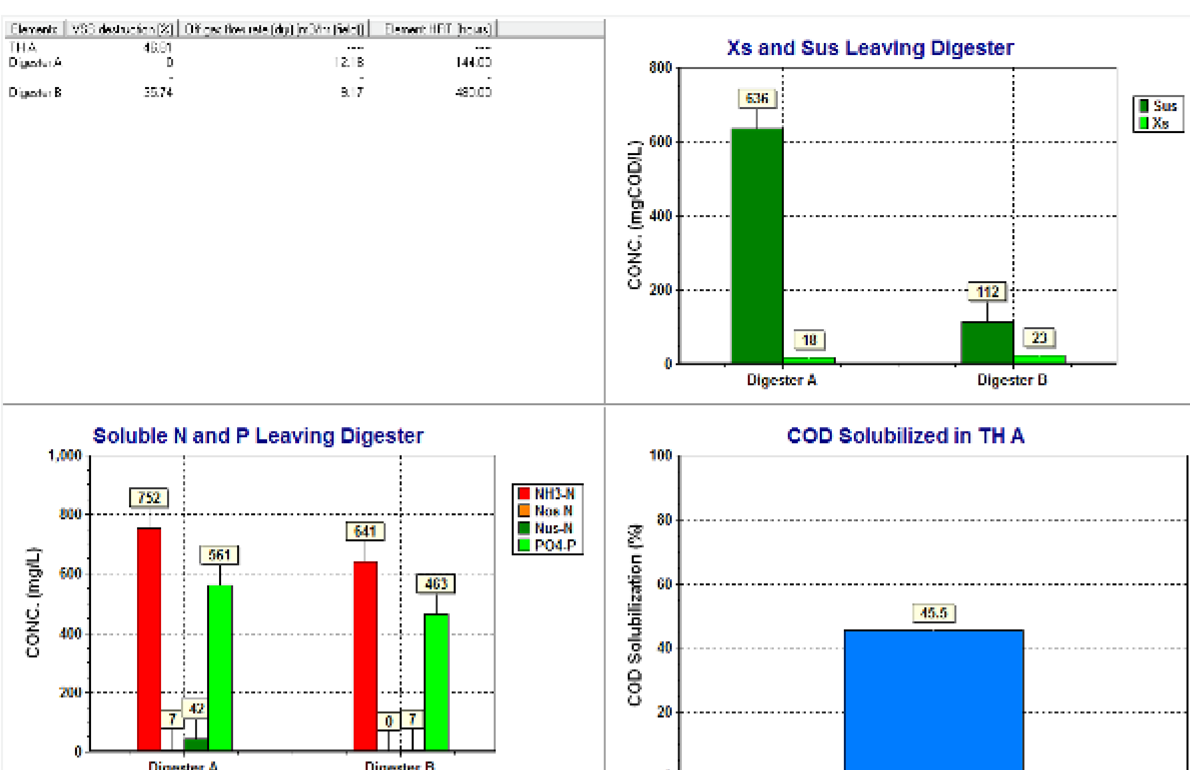
The off-gas flow rate per VSS destroyed and methane flow rate per COD destroyed were calculated for Plants A and B. The calculated values shown in the table below are typical for a digester treating only WAS.

ATTRIBUTE	PLANT A	PLANT B
Off-gas flow rate per mass rate VSS destroyed (m^3/kg)	0.81	0.75
Methane flow rate per mass rate COD destroyed (m^3/kg)	0.38	0.38

The VSS destruction, digester off-gas flow rate, COD solubilization across the TH unit and X_S, S_{US}, NH3, N_{US}, N_{OS} and PO4 concentrations in the digester effluent are shown in the following graphs.



The negligible X_S concentration in the digester effluent in Plant A indicates that the digester HRT may be reduced. The digester volume was reduced by 70%, lowering the digester HRT from 20 to 6 d. As shown in the graphs below, this resulted in negligible changes in the digester off-gas flow rate and the digester effluent X_S concentration in Plant A. This demonstrates how implementing thermal hydrolysis prior to anaerobic digestion substantially reduces the required digestion time.



Conclusion

In this edition of the BioWin Advantage, we introduced the thermal hydrolysis unit and described how the default conversion fractions were empirically derived to represent the transformations occurring in a batch HPTH pretreatment process operated at around 160 to 170°C at 7 bars for approximately 30 minutes. We used a case study to demonstrate the advantages of implementing thermal hydrolysis prior to anaerobic digestion: higher VSS destruction and digester off-gas flow rates and lower required digestion time. We also showed how thermal hydrolysis pretreatment may lead to increased levels of nutrients and soluble unbiodegradable COD in the digester which may be problematic for the plant when the digester supernatant is recycled back to the liquid train.

By adjusting the conversion fractions in the thermal hydrolysis unit to match the predicted and measured COD and nutrient concentrations in the pretreated sludge, the user can customize the TH unit to model the conversions accomplished by different types of pretreatment process, not only HPTH.

We trust that you found this technical topic both interesting and informative.

Please feel free to contact us at support@envirosim.com (Subject: The BioWin Advantage) with your comments on this article or suggestions for future articles.

Thank you, and good modeling.

The EnviroSim Team

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