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Industrial Electrical Engineering and Automation

Investigation of Anaerobic Digestion Alternatives for Henriksdal's WWTP – Supplement

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by

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1. Introduction

On the request of Dr Daniel Hellström (Stockholm Water AB), IEA was asked to perform a preliminary investigation of two alternatives for anaerobic digestion operation at Henriksdal's WWTP in Stockholm, Sweden. The system should be analysed based on parallel or series operation of two existing AD reactors. Moreover, the input load should be based on the current situation and a future scenario (estimated 10 years ahead). This work was reported in January 2007 (Jeppsson, 2007). Based on the presented results, IEA was asked by Dr Hellström to carry out a supplementary analysis of the digestion systems for Henriksdal. The principle of the analysis was to be the same but more information with regard to the sludge characterization had now been made available and also some changes to the influent sludge load were proposed. A number of questions that arose as a result of the findings presented in the first report are also commented upon in this supplementary report.

The results presented in this and the previous report (Jeppsson, 2007) are compiled to assist Stockholm Water in answering the following main questions:

- How will the existing anaerobic digesters handle the expected increased sludge load (both more internal sludge and more external organic material) during the next ten years? Need for volume expansion or other operational changes?
- What are the potential benefits of changing the current in-parallel operational strategy of the anaerobic digesters into an in-series operational strategy?

2. Methodology

The system is modelled using the IWA Anaerobic Digestion Model no 1 (ADM1) (Batstone *et al.*, 2002). This represents the state-of-the art model for anaerobic digestion (AD) systems. Only COD, nitrogen and pH is considered in the model. The model used is a slightly modified version of the original one (enhancements supported by the IWA ADM1 Task Group) and the updated version has already been distributed to many research groups world-wide. The details are given in Rosen *et al.* (2006), Rosen and Jeppsson (2006) and Jeppsson (2007). In this supplementary report, the simulation model was further updated to allow for a better description of VSS and TSS by the inclusion of mineralized suspended solids (MSS) as a state variable. More details are given below. The simulation results presented in this report are otherwise based on the same set of model parameters as in Jeppsson (2007) in order to avoid confusion. As before, the system is only investigated for steady-state behaviour in this preliminary analysis. Special interface models for connecting the ADM1 to more traditional models (e.g. ASM1) have also been developed in Lund (Nopens *et al.*, 2007) and the Henriksdal system will therefore be analysed from two further aspects (see below). The entire system is simulated using Matlab/Simulink.

For all simulations, the temperature of the AD systems is set to 35°C (mesophilic conditions) and the concentrations of anions and cations in the influent sludge are set so that pH in the digesters is between 7.1 and 7.3, to avoid any significant unwanted effects due to pH inhibition (a stable pH of around 7.2 has been reported from the AD system at Henriksdal). Note that in the cases when interface models are used the anion and cation concentrations are automatically calculated by the interface equations, leading to a pH of between 7.1 and 7.2. When the simulations do not apply the interface model the anion and cation concentrations have to be set artificially.

The total volume of the AD reactors at Henriksdal is 38900 m^3. One reactor (step 1 in series operation) is 23700 m^3 and the second one (step two in series operation) is 15200 m^3. It is assumed that these volumes represent the liquid phase of the reactors and an extra head space volume of about 8% (a total of 3000 m^3) is added (a slight over-pressure of about 5 mbar is maintained in the head space). The head space volume and pressure represents values normally found in Swedish large-scale AD systems and they have very limited impact on the simulation results (no exact information was provided by Stockholm Water). During all simulations, the liquid and head space volumes are assumed constant. When the system is simulated in parallel operation only one reactor of 38900 m^3 is used (from a model point of view the results are the same as if using two smaller reactors in parallel).

3. The Henriksdal WWTP AD system

Based on two reports provided by Stockholm Water during the spring of 2007 (Vallin, 2007; Ascue and Nordberg, 2007) more complete information about the AD process at Henriksdal and the characteristics of the influent and digested sludge were made available for the simulations. For completeness some of the main points in these reports are summarized below.

3.1 Short description

The Henriksdal AD system is made up of seven reactors operated in parallel. Five of the reactors have an individual sludge volume of 5000 m^3 and two of the reactors have an individual sludge volume of 7000 m^3. The sludge input is based on a mixture of primary sludge, secondary sludge and external organic material (today mainly grease from grease traps at restaurants). A centrifuge is used to increase the solids contents of the secondary sludge to about 4.6% TSS. However, the main sludge load to the AD system is made up of primary sludge. In the present situation, the produced gas is used for heat production (combustion) and electricity production (gas motors) although the plant will soon be modified to produce biogas fuel for vehicles. To achieve this the plant will be expanded with a gas purification process, which will have a capacity of about 900 Nm^3 gas per hour and the product will have an approximate 95% methane content. The digested sludge is dewatered to a TSS content of about 30% and the sludge supernatant is recycled back to the activated sludge part of the WWTP, representing 15-20% of the total plant ammonia load (a fairly normal value for this type of plant configuration). The operational temperature of the AD system is 35°C although due to internal problems the temperature sometimes goes as low as 30-31°C. The heating system of the AD is currently being modified. No internal recycling of sludge within the AD system is used, which implies that sludge retention time (SRT) and hydraulic retention time (HRT) are the same. For Henriksdal's AD this means a normal operational SRT of 19-22 days on a yearly average. With regard to mixing capacity of the AD system the equipment has been upgraded and a recent investigation indicates good mixing conditions (i.e. complete mix can be assumed for the simulations). Storage capacity of produced gas is currently limited and during peak production some of the produced gas must be burnt off.

3.2 Influent sludge and gas production

The influent sludge to the AD system of Henriksdal originates from three sources: primary sludge, secondary sludge (from a nitrification/denitrification AS process, i.e. long sludge age) and external organic material, EOM, (various sources but at the present time primarily grease from restaurants). The primary sludge has a TS value of 3.5% on an average and a VS value of 74% of the TS (average flow rate 1450 m^3/d). The COD to VS ratio is 1.556. The secondary sludge has a TS value of 4.6% on an average (after centrifuges) and a VS value of 62% of the TS (average flow rate 390 m^3/d). The COD to VS ratio is 1.518. The EOM has a TS value of 10% and a VS value of 95% of the TS (average flow rate 70 m^3/d) and is considered to contain mainly lipids. The total organic load on the AD between years 2000 and 2005 was 14300 – 19200 ton VS/year with an average load of 17400 ton VS/year.

Between years 2000 and 2005 the AD system produced 0.47 – 0.66 Nm^3/kg VS_in with an average value of 0.535 Nm^3/kg VS_in. It is unclear whether the numbers are related to total gas production or methane production but it seems reasonable that total gas production is the intended unit. This implies that the total gas production in 2000 to 2005 varied between 8.56 to 9.86 MNm^3/year with an average production of 9230000 m^3/year. The COD to VS ratio in the digested sludge was 1.54. The methane content of the produced biogas is normally around 66% (±2%). This value is assumed to be on molar (volume) basis although it is not clear from the report. The VS reduction in the AD between 2000 and 2005 has been 42 – 51% with an average VS reduction of 45%. pH in the AD is normally stable around 7.2 and the alkalinity of the digested sludge is around 3300 mg/l (as HCO_3^-). Volatile fatty acids concentration in the AD has also been measured and normally the value is below 100 mg/l.

A batch digestion experiment in lab scale has also been carried out at JTI (Ascue and Nordberg, 2007). The experiment lasted for 55 days, pH was 7.32 and the temperature was 37°C. A small reactor was loaded with 75.5% primary sludge and 24.5% secondary sludge from Henriksdal and inoculated using sludge from the full scale AD system. The TS and VS contents of the two types of sludge were similar. The total gas production was 0.67 Nm^3/kg VS_in (0.34 Nm^3 CH_4/kg VS_in) and the methane content was 68%. After a period of 15 days 83% of the total methane yield had been achieved and after 23 days the yield was 91% of the totally produced methane after 55 days. A conclusion was that a reduced SRT at Henriksdal's AD system may be considered as a way of increasing the organic load capacity of the plant without reducing the methane yield significantly.

4. Influent sludge characterization for simulations

Based on the above description and a few basic assumptions the sludge input for the current situation can be defined for the simulations. The average total AD hydraulic retention time for the current case is 20.4 days. The following inputs were provided by Stockholm Water (Table 1).

Table 1. Current scenario.

	Flow rate	**TS**	**VS**	**TS**	**VS**
	m^3/d	%	% of TS	ton/d	ton/d
Primary sludge	1450	3.5	74	50.8	37.6
Secondary sludge	390	4.6	62	17.9	11.1
EOM	70	10	95	7	6.7
Total	1910	4.0	73	75.7	55.4

The input data can be created based on direct use of ADM1 state variables or by creating the input based on ASM1 variables and allowing these to be transformed into ADM1 variables via an interface model. Both possibilities are tested. At all times the external organic material (EOM) for the current scenario is added to the AD model using the direct ADM1 state variable 'lipids' (and a small part mineralized solids), i.e. not via the interface. We make the following assumptions:

- TS = VS + MS (for primary, secondary and digested sludge);
- contribution from soluble COD is not considered (very low in comparison);
- input oxygen concentration is set to zero;
- in primary sludge only inert particulate material and particulate substrate are considered in terms of COD;
- in secondary sludge only inert particulate material and biomass are considered in terms of COD;
- a reasonable amount of nitrogen is included;
- COD content of lipids is assumed as 2.90 g COD/g lipid (based on $C_{57}H_{104}O_6$). NOTE: error in Jeppsson (2007), where a value of 1.86 g COD/g lipid was used;
- COD content of carbohydrate is assumed as 1.19 g COD/g carbohydrate (based on $(C_6H_{10}O_5)_n$;
- COD content of protein is assumed as 1.35 g COD/g protein (based on $C_5H_7NO_2$);
- Nitrogen content of slowly biodegradable substrate is set to 0.04 g N/g COD;
- 20% of the total COD in the primary sludge is assumed to be inert COD (assumed reasonable for Swedish raw sewage in a large sewage system, based on discussions with Stockholm Water);
- 38% of the total COD in the secondary sludge is assumed to be inert COD (based on simulations using the principle inputs in Table 1 for a plant with primary clarification and a predenitrifying activated sludge system with a sludge age of about 10 days at 15 °C).

Based on the above assumptions, the influent sludge characteristics for the current case (in ASM1 variables) is defined as below (Table 2).

Table 2. Current scenario, recalculated in more detail based on ASM1 state variables.

CURRENT CASE	Prim sludge (conc)	Prim sludge (kg "unit"/d)	Sec sludge (conc)	Sec sludge (kg "unit"/d)	EOM (conc)	EOM (kg "unit"/d)	TOTAL (kg "unit"/d)
Inert soluble (S_I, mg COD/l)	0	0	0	0	0	0	0
Soluble substrate (S_S, mg COD/l)	0	0	0	0	0	0	0
Inert particulate (X_I, mg COD/l)	8069	11700	16410	6400	0	0	18100
Particulate substrate (X_S, mg COD/l)	32276	46800	0	0	0	0	46800
Heterotrophs (X_{BH}, mg COD/l)	0	0	26795	10450	0	0	10450
Autotrophs (X_{BA}, mg COD/l)	0	0	0	0	0	0	0
Inert from biomass decay (X_P, mg COD/l)	0	0	0	0	0	0	0
Oxygen (S_O, mg –COD/l	0	0	0	0	0	0	0
Nitrate (S_{NO}, mg N/l)	0	0	5	1.95	0	0	1.95
Ammonia (S_{NH}, mg N/l)	30	43.5	5	1.95	0	0	45.45
Soluble organic N (S_{ND}, mg N/l)	0	0	0	0	0	0	0
Particulate organic N (X_{ND}, mg N/l)	1291	1872	0	0	0	0	1404
Alkalinity (mol HCO_3/m^3)	7	619	7	167	0	0	786
Total COD (mg COD/l)	40345	58500	43205	16850	275500 (all lipids)	19285 (all lipids)	94635
MS (mg/l)	9103	13200	17436	6800	5000	350	20350
VS (mg/l)	25931	37600	28462	11100	95000	6650	55350
TS (mg/l)	35035	50800	45897	17900	100000	7000	75700
COD/VS	1.556	1.556	1.518	1.518	2.90	2.90	1.710
COD/TS	1.152	1.152	0.941	0.941	2.775	2.775	1.250
TS/VS	1.351	1.351	1.613	1.613	1.053	1.053	1.368
Flow rate (m^3/d)	1450	1450000	390	390000	70	70000	1910000

The cells marked in grey indicate 'measured' values provided by Stockholm Water. It is obvious that several variables have been neglected in the detailed characterization: oxygen, soluble inerts, readily biodegradable material are all set to zero, we set autotrophs to zero and only consider heterotrophs in the secondary sludge (also X_S is considered negligible), all inerts are included as X_I rather than a combination of X_I and X_P etc. From the point of the digester behaviour these simplifications have very limited impact. Also note that when using ASM1 variables the nitrogen content of biomass and inert organic material is not stated explicitly but it is added as part of the model interface (i.e. X_{ND} only represents the nitrogen associated with X_S).

In comparison to the input data used for the current scenario in Jeppsson (2007) it is clear that the organic load has now been reduced both for primary and secondary sludge in particular on COD basis (total reduction about 29%), whereas the reduced load on VS basis is much less prominent (about 7%). This is a result of the more detailed information provided by Stockholm Water, especially in terms of COD:VS ratios. Also the fractionation of COD has changed since the various COD fractions do not have to be adjusted anymore to account for specific TS:VS ratios, as the new state variable MS has been created for this purpose. However, the selected percentages of inert COD in primary and secondary sludge for the Henriksdal WWTP are not based on true measurements instead the selected values (20 and 38%, respectively) only represent an educated estimate. In particular, the inert fraction of the raw primary sludge may certainly be different. Also the COD:TS ratio of the secondary sludge appears arguably low and the associated TS:VS ratio appears somewhat high (although based on measurements provided by Stockholm Water).

In the case when the interface models are not used to create the AD input and output we simply assume all COD from the primary and secondary sludge to enter the digester as composite material (which will then divide into proteins, carbohydrates, lipids, soluble inerts and particulate inerts in accordance with predefined values of the ADM1 model, see Rosen and Jeppsson (2006)). The total COD (and VS and TS) load on the digester will consequently be the same in both cases, but it will enter the AD system in different forms. The value predicted by the interface model for total inorganic nitrogen will be used also for the inorganic nitrogen input in this latter case, i.e. the inorganic nitrogen loads will for both cases be identical. However, as the nitrogen content of composite material is assumed to be 0.0376 gN/gCOD in ADM1 the nitrogen balance for organic nitrogen will not be perfect (the nitrogen content of the ASM1 state variables X_I and X_{BH} are different). To compensate for this we add an artificial amount of inorganic nitrogen so that the complete nitrogen load on the AD is correct also when the interface model is not used (the interface model handles all these problems automatically). This has basically no impact on gas production etc. but it avoids confusion when studying the results in detail only to find that the effluent inorganic nitrogen concentrations from the AD are very different depending on if the interface model was used or not (now of course the influent inorganic nitrogen concentrations will be different). This nitrogen compensation was not included in Jeppsson (2007). The input concentration of cations is used to adjust the pH to a reasonable value of about 7.2 in the cases when interface models are not used (the interface models contain a complete charge balance and therefore calculates the concentration of cations and anions based on the given input).

Similar principles are then used to define the influent sludge characteristics for the future scenario. The input data presented in Table 3 were selected and provided by Stockholm Water.

Table 3. Future scenario.

	Flow rate	**TS**	**VS**	**TS**	**VS**
	m^3/d	%	% of TS	ton/d	ton/d
Primary sludge	1595	3.5	74	56	41
Secondary sludge	429	4.6	62	20	12
EOM	336	10	95	33.6	31.9
Total	2360	4.6	78	109	85

The average total AD hydraulic retention time for the future scenario is 16.5 days. It was decided by Stockholm Water to use the same COD:VS ratios for primary and secondary sludge as was used in the current scenario. However, the extra added EOM compared to the current scenario should be characterised in accordance to Table 4 (partly based on Ekind *et al.*, 1997), whereas the original 7 tonnes TS of EOM remain all lipids and to a very small extent mineralized solids (i.e. maintaining the characterization used in the current scenario).

Table 4. Characterization of organic household waste (to be used for added EOM = 266 m^3/d).

Total solids content	34.4 %	91.5 ton/d
Volatile solids content	75% of TS	68.6 ton/d
Mineralized solids content	25% of TS	22.9 ton/d
Carbohydrates	51% of VS	35.0 ton/d = 41.6 ton COD/d
Protein	10% of VS	6.86 ton/d = 9.26 ton COD/d
Lipids	22% of VS	15.1 ton/d = 43.8 ton COD/d
Inert organic material	17% of VS	11.64 ton/d = 16.5 ton COD/d*
Total COD load		111.16 ton/d
COD/VS		1.62
COD/TS		1.21
TS/VS		1.33

*For inert organic material the classical ratio of 1.42 gCOD/gVS has been assumed.

However, as the amounts of TS and VS in the total EOM flow have been defined by Stockholm Water (see Table 3) to be 10 and 9.5%, respectively, it is not possible to apply all the information given in Table 4. Instead the extra added EOM (26.6 ton TS and 25.2 ton VS) in the new scenario is characterized on VS basis using the principles marked in grey in Table 4 (% of VS and COD:VS ratios) and the 1.4 ton difference between TS and VS is considered to be mineralized solids (no COD content). It should be noted that the added EOM (26.6 ton/d) represents approximately 35% of all organic household (food) waste in Stockholm.

Based on the above assumptions, the influent sludge characteristics for the complete future scenario (in ASM1 variables) is defined as below (Table 5).

Table 5. Future scenario, recalculated in more detail based on ASM1 state variables.

CURRENT CASE	Prim sludge (conc)	Prim sludge (kg "unit"/d)	Sec sludge (conc)	Sec sludge (kg "unit"/d)	EOM (conc)	EOM (kg "unit"/d)	TOTAL (kg "unit"/d)
Inert soluble (S_I, mg COD/l)	0	0	0	0	0	0	0
Soluble substrate (S_S, mg COD/l)	0	0	0	0	0	0	0
Inert particulate (X_I, mg COD/l)	8000	12760	16121	6916	18140	6095	25771
Particulate substrate (X_S, mg COD/l)	32000	51040	0	0	0	0	51040
Heterotrophs (X_{BH}, mg COD/l)	0	0	26303	11284	0	0	11284
Autotrophs (X_{BA}, mg COD/l)	0	0	0	0	0	0	0
Inert from biomass decay (X_P, mg COD/l)	0	0	0	0	0	0	0
Oxygen (S_O, mg –COD/l	0	0	0	0	0	0	0
Nitrate (S_{NO}, mg N/l)	0	0	5	2.14	0	0	2.14
Ammonia (S_{NH}, mg N/l)	30	47.85	5	2.14	0	0	49.99
Soluble organic N (S_{ND}, mg N/l)	0	0	0	0	0	0	0
Particulate organic N (X_{ND}, mg N/l)	1280	2042	0	0	0	0	2042
Alkalinity (mol HCO_3/m^3)	7	681	7	183	0	0	864
Total COD (mg COD/l)	40000	63800	42424	18200	179238 [45610 (carbs) 10146 (prot) 105342 (lip)]	60224 (total) [15325 (carbs) 3409 (prot) 35395 (lip)]	142224
MS (mg/l)	9404	15000	18648	8000	5060	1700	24700
VS (mg/l)	25705	41000	27972	12000	94940	31900	84900
TS (mg/l)	35110	56000	46620	20000	100000	33600	109600
COD/VS	1.556	1.556	1.518	1.518	1.89	1.89	1.675
COD/TS	1.139	1.139	0.91	0.91	1.79	1.79	1.30
TS/VS	1.366	1.366	1.667	1.667	1.053	1.053	1.29
Flow rate (m^3/d)	1595	1595000	429	429000	336	336000	2360000

As for the current scenario, it is obvious that several variables have been neglected in the detailed characterization: oxygen, soluble inerts, readily biodegradable material are all set to zero, we set autotrophs to zero and only consider heterotrophs in the secondary sludge, all inerts are included as X_I rather than a combination of X_I and X_P etc. Also note that when using ASM1 variables the nitrogen content of biomass and inert organic material is not stated explicitly but it is added as part of the model interface (i.e. X_{ND} only represents the nitrogen associated with X_S). For EOM the nitrogen content of protein is 0.098 gN/gCOD and of inert organics 0.06 gN/gCOD (lipids and carbohydrates have no nitrogen content) but this is handled internally by the ADM1 model and not given as an explicit nitrogen input.

In comparison to the input data used for the future scenario in Jeppsson (2007) it is clear that the organic load has now been reduced both for primary and secondary sludge in particular on COD basis (total reduction about 31%), whereas the reduced load on VS basis is less prominent (about 10%). This is once again a result of the more detailed information provided by Stockholm Water, especially in terms of COD:VS ratios. As for the current scenario the same percentages of inert COD in primary and secondary sludge for the Henriksdal WWTP has been used (20 and 38%, respectively). The COD:TS ratio of the secondary sludge appears arguably low and the associated TS:VS ratio appears somewhat high (although based on data provided by Stockholm Water). For EOM the most important difference is related to the fractionation of the organic load, which in Jeppsson (2007) was assumed to be 100% lipids. The principles of the new fractionation proposed by Stockholm Water were discussed in detail above.

As already stated for the current scenario, when the interface models are not used to create the AD input and output we assume all COD from the primary and secondary sludge to enter the digester as composite material (which will then divide into proteins, carbohydrates, lipids, soluble inerts and particulate inerts in accordance with predefined values of the ADM1 model, see Rosen and Jeppsson (2006)). The total COD (and VS and TS) load on the digester will consequently be the same in both cases, but it will enter the AD system in different forms. The value predicted by the interface model for total inorganic nitrogen will be used also for the inorganic nitrogen input in this latter case, i.e. the inorganic nitrogen loads will for both cases be identical. However, as the nitrogen content of composite material is assumed to be 0.0376 gN/gCOD in ADM1 the nitrogen balance for organic nitrogen will not be perfect (the nitrogen content of the ASM1 state variables X_I and X_{BH} are different). To compensate for this we add an artificial amount of inorganic nitrogen so that the complete nitrogen load on the AD is correct also when the interface model is not used (the interface model handles all these problems automatically). It has basically no impact on gas production etc. but it avoids confusion when studying the results in detail only to find that the effluent inorganic nitrogen concentrations from the AD are very different depending on if the interface model was used or not (now of course the influent inorganic nitrogen concentrations will be different). This nitrogen compensation was not included in Jeppsson (2007). The input concentration of cations is used to adjust the pH to a reasonable value of about 7.2 in the cases when interface models are not used (the interface models contain a complete charge balance and therefore calculates the concentration of cations and anions based on the given input). As before, the EOM input is always fed directly into the digester without the use of any interface models.

5. Modelling the AD process

The anaerobic digestion process involves several steps and several groups of microorganisms used for the degradation of organic matter to intermediary products, which are converted into methane. The digestion process can generally be divided into four main steps: 1) hydrolysis, 2) acidogenesis, i.e. fermentation of organic monomers to form organic acids, 3) acetogenesis, i.e. the production of methanogenic substrates: acetate, carbon dioxide and hydrogen, and 4) methanogenesis by the methanogens.

Hydrolysis

The first step in the AD process is the conversion of particulate and soluble polymers into soluble products, such as amino acids, sugars and fatty acids by enzymatic hydrolysis. The microorganisms that produce the enzymes can be obligate or facultative anaerobes. Hydrolysis can be rate limiting for the AD process in cases where the substrate is in particulate form. Large particles with low surface-to-volume ratio are hydrolysed more slowly than small particles.

Acidogenesis

Acetate, hydrogen and carbon dioxide as well as volatile fatty acids (VFA) and alcohols, are produced from the soluble organic matter by fermentative bacteria or by anaerobic oxidisers. These organisms are represented by both obligate and facultative anaerobes. Acidogenesis is often the fastest step in AD of complex organic matter.

Acetogenesis

In the acetogenesis, acetate, hydrogen and carbon dioxide are produced from degradation of long-chain fatty acids and volatile fatty acids by obligate hydrogen-producing acetogens.

Methanogenesis

Methanogenesis is carried out by the methanogens, the largest group of the archaea microorganisms. Methanogens can be found in natural environments rich in organics but free from oxygen. Methanogens are strict anaerobes that obtain energy by converting carbon dioxide, hydrogen, formate, methanol, acetate and other compounds into either methane or methane and carbon dioxide. CO_2-reducing (hydrogenotrophic) methanogens form CH_4 from CO_2 and H_2, while aceticlastic methanogens cleave acetate to form CO_2 and CH_4. About 2/3 of the methane produced in a digester normally comes from acetate. The methanogens have slow growth rates and are usually considered rate limiting for the anaerobic process.

5.1 Anaerobic Digestion Model no 1 (ADM1)

The above summary description of the four main processes of the AD process is taken from Davidsson (2007). The ADM1 model includes detailed mechanistic descriptions of the above processes but also several additional ones.

- Disintegration: represents the enzymatic breakdown of complex organic material (composite particulates) into particulate carbohydrates, proteins and lipids. Other products of disintegration are inert particulate and inert soluble material. Also the breakdown of dead anaerobic biomass within the AD is modelled via this path. The hydrolysis process of ADM1 represents the further breakdown and solubilisation of carbohydrates, proteins and lipids into monosaccharides, amino acids and long-chain fatty acids.

- Acidogenesis is modelled via two paths: 1) based on amino acids, and 2) based on monosaccharides.
- Inhibition of the AD process due to pH (from various processes), hydrogen inhibition of acetogenic bacteria and free ammonia inhibition of aceticlastic methanogens are included using non-competitive functions.
- Various temperature effects are included.
- Association/dissociation of acid-base pairs is included.
- Liquid-gas transfers for hydrogen, methane and carbon dioxide are modelled.

For a complete description of the ADM1 we refer to Batstone *et al.* (2002).

5.2 Model modifications

The model modifications of the ADM1 suggested by the IWA Task Group on Benchmarking were presented in Jeppsson (2007). For the simulations presented in this report one additional model modification has been incorporated. The ADM1 is completely based on COD to represent organic material and it is therefore difficult to calculate reasonable VSS and TSS values (especially both at the same time). As much of the data provided by Stockholm Water is VSS/TSS related the model has been modified to include a new state variable, mineralised suspended solids (MSS), which represents inert material from a biological point of view and contains no COD. This means that VSS can now be directly related to all COD fractions in the model (by the COD:VSS ratios provided) and the MSS is used to represent the difference between VSS and TSS. Consequently, the input characterization of the sludge is improved as the COD fractions can now be selected to correlate with the VSS values, without considering the TSS.

5.3 Model clarifications

Some question arose based on the previous report and some of these are commented upon here. Some are related to how the interface models work and this cannot be explained in detail in a short report. However, some clarifications are provided.

- *Does the model include disintegration (i.e. the step prior to hydrolysis)?* Yes, it does. The ADM1 uses a set of default parameters to disintegrate particulate composite material into particulate proteins, carbohydrates, lipids and inerts plus soluble inerts. The disintegration step is also used to break down dead anaerobic biomass into the same fractions using the same set of parameters (first order reactions). The parameter set can be used as a calibration means if relevant information is available. However, this is a difficult thing to do and it will affect both how the dead biomass is broken down as well as how the influent sludge is broken down at the same time. This has been an area of much discussion since the ADM1 was presented. However, as much more experience exists of how primary and secondary sludge is usually fractionated a better way is to use the AS to AD interface model. By doing this we separate the disintegration of anaerobic biomass from the disintegration of influent sludge. The disintegration of sludge is instead done in the interface model. By doing so we automatically guarantee mass balances not only of COD but also of nitrogen and charge and we take advantage of the combined COD and nitrogen knowledge available. To conclude I quote from a paper in preparation by the chairman of the IWA Task Group on AD Modelling, Dr Damien Batstone: "The original activated sludge interface proposed by the AD Modelling Task Group (Batstone *et al.*, 2002) is poor, with imbalances in mass and unrealistic outputs. A number of approaches have been proposed (see Batstone and Keller, 2006), but we have used the approach of the IWA Bechmarking Task Group (Nopens et al., (in prep)). Organic inputs were split between particulate inerts, carbohydrates, proteins, lipids, organic acids, ammonia, and bicarbonate, in order to balance particulate and soluble COD, carbon, nitrogen and charge." It is the author's conclusion that results based on the interface models combined with the modified ADM1 are more reliable than when using only the traditional ADM1. So disintegration is always included either as a part of the ADM1 (when the interface model is not used) or as a part of the interface model (the reactions are then instantaneous). Disintegration of dead anaerobic biomass is always a part of the ADM1 and is never handled by the interface model. If the parameter set used for disintegration within the ADM1 happens to produce similar results as the interface model then of course the two versions will not yield very different results. As the sludge retention time is also fairly large the difference in speed for the disintegration process (in the ADM1 and in the interface model) will not be visible in steady state simulations.

- The selected head-space volume and over-pressure have very limited effects on the results and the values used are based on a survey of a number of WWTPs in Sweden and abroad. The exact numbers for Henriksdal is most probably similar.
- Modifying the AD temperature from 35°C to 37°C would have very limited effects on the results.
- The reliability of the results should always be questioned and validated by measurements. However, the ADM1 is the best model available and has already been proven to provide reliable results in many other case studies.
- The VS and TS calculations of the previous report were not very reliable (certainly a VS reduction of 80-90% is not realistic) as they had to be artificially calculated and maintained by some COD modifications. However, as the ADM1 does not use TS and VS but only COD this will always be somewhat of a problem. The modifications proposed in this report do, however, improve the situation but the fact remains – the ADM1 is COD based.
- The conclusions stated in Jeppsson (2007) regarding dynamic benefits of two in-series AD reactors do not come out of the model simulations but are based on more general knowledge.
- The model can be used to predict collapse of the AD system due to short SRT and/or high loads. However, the ADM1 is robust and it is the author's guess that a true system would collapse at an earlier stage than what the model will predict.
- It is not possible at this time to say how significant the simulated differences in gas production between one-step and two-step digestion, as predicted by the model, are. However, the indications of increased gas production by using a two-step approach are promising and would indicate the relevance to discuss the matter further with WWTPs that have already modified their AD system in this way and take advantage of their experiences. If possible, parallel pilot plant AD experiments should be performed at Henriksdal comparing one-step and two-step AD processes. A literature survey on this

topic is also suggested. Personal communication with professor Henri Spanjers (Ghent University, Belgium) also indicates that an increased gas production of 5% is not unrealistic when changing from parallel to series operation.

6. Results

Based on the above characterisation (see Section 4) of the various sludge sources we run the simulations. The detailed results are found below. Eight cases are presented:

- case 1A: Current scenario using interface models, operation in parallel (1 reactor);
- case 1B: Current scenario not using interface models, operation in parallel (1 reactor);
- case 2A: Current scenario using interface models, operation in series (2 reactors);
- case 2B: Current scenario not using interface models, operation in series (2 reactors);
- case 3A: Future scenario using interface models, operation in parallel (1 reactor);
- case 3B: Future scenario not using interface models, operation in parallel (1 reactor);
- case 4A: Future scenario using interface models, operation in series (2 reactors);
- case 4B: Future scenario not using interface models, operation in series (2 reactors);

In all cases based on two reactors in series, the external organic material is fed into the first reactor together with the primary and secondary sludge. The model parameters (kinetic rates etc.) of the digester(s) are identical for all cases, apart from the obvious differences in volumes. Also, when two reactors are simulated in series the parameter set-up is identical for both reactors. In all cases the digesters are considered to be completely mixed reactors.

The numbers need to be studied in much more detail but this will be an effort for Stockholm Water. It is, however, clear that in terms of gas production the results are similar for cases 1A, 1B, 2A and 2B (the same holds for cases 3 and 4), which means that the effects of the model interfaces do not have a significant impact on gas production in steady state (primarily because the default ADM1 decomposition of composite material is in this specific case fairly similar to what the interface calculate and the available degradable COD is therefore in the same range, which basically determines the gas production) and also the effects of operation in parallel versus operation in series are limited. Operation in series will lead to a higher gas production but this is partly due to effect of applying complete mix in two rather than one reactor (the same effects that we see when modelling a large completely mixed AS reactor compared to a plug-flow system of the same volume). In terms of VS and TS reduction the results when using the interface models are considered more reliable (see discussion below). The concentrations of soluble inert COD in the effluent sludge is unrealistically high when the interface models are not used (3-4 gCOD/l), which is a result of the ADM1's internal attempt to characterize the influent composite material. When using the interface models, more realistic values of 100-200 mgCOD/l of inert soluble material are achieved.

The ADM1 is a very robust model and it can be highly loaded before any collapse of the system will appear. Consequently, we see that the model predicts the majority of the gas production in the first reactor (when using in series operation) and a very small contribution from the second reactor. However, the difference is quite clear when using input via the interfaces or the direct approach. When the direct approach is used the input enters the system as composite material and one of the slowest process within the ADM1 is the disintegration process from composite material into lipids, carbohydrates, proteins and inerts. What the interface does is that it considers this process to be immediate (in terms of the input material) since the input is converted directly into lipids, proteins etc. It should, however, be noted that the disintegration process is still used also in the latter case but only for the internal digester material, i.e. when biomass created within the AD decay and gradually forms new substrate and inert materials. This is actually one major reason for the development of the interface, since it allows for the separation between disintegration of incoming sludge from the disintegration of internal digester material, as the disintegration rate of decaying biomass and influent sludge (e.g. primary sludge with a high amount of fairly easily available substrate) are believed to be quite different. In the cases shown below, we are demonstrating the two extremes, i.e. all influent material as composite material or no influent material as composite material.

The choice of using identical model parameters for the first and second reactor (in series operation) is also a simplification that may not be fully realistic. The first reactor is a fairly high loaded system whereas the second digester is low loaded. Naturally this can lead to different biomass populations and thereby promote different pathways of the digester process.

Digesters are often characterized in terms of VS. This is somewhat difficult in this case since VS is not a variable considered in the ADM1, which is instead based on COD. However, since COD:VS ratios were also provided the results in this report are considerably more reliable compared to Jeppsson (2007). The model modification to introduce mineralised solids (MS) as a separate state to maintain a reasonable TS:VS ratio further improved the results from a VS and TS point of view. For calculating the VS content of the digested sludge the COD:VS ratio of 1.54 as provided by Stockholm Water has been used in all cases and the TS value is then calculated as VS + MS. From a theoretical basis we can consider the theoretical maximum biogas potential (Nm^3 CH_4 per ton VS) for the standard components of the sludge:

- Lipids (based on $C_{57}H_{104}O_6$) = 1014 Nm^3 CH_4 per ton VS;
- Protein (based on $C_5H_7NO_2$) = 496 Nm^3 CH_4 per ton VS;
- Carbohydrate (based on $(C_6H_{10}O_5)_n$ = 415 Nm^3 CH_4 per ton VS.

The above chemical compositions were used to characterize lipids, protein and carbohydrates in the simulations (see Section 4). For the current scenario, we have an input of 55.4 tonnes of VS/d (according to numbers provided by Stockholm Water, which is slightly higher than what has been recorded at Henriksdal in the years 2000 to 2005). The methane gas produced in the simulations for this case (1A) is about 25300 Nm^3 CH_4 per day (= 16000 kg CH_4/d), which amounts to 458 Nm^3 CH_4 per ton VS_in. This would appear to be a reasonable value (values from Stockholm Water in the years 2000-2005 range from 310 – 436 Nm^3 CH_4/ton VS_in). The methane content in the simulated results is 63.3% (compared to Stockholm Water data of 66±2% during the years 2000 to 2005). The concentration of volatile fatty acids in the simulated results is 102 mg COD/l, which is similar to measurements carried out by Stockholm Water. Also pH is approximately the same. VS reduction in the simulated AD system is 64%, which is significantly higher than the actual data between the years 2000 and 2005 of 42 – 51%. The alkalinity in the simulated system is about 4700 mg HCO_3^-/l, whereas measured data from Stockholm Water gives a value of 3300 mg HCO_3^-/l. So an overall view based on case 1A demonstrates results fairly close to what has been measured in the true AD system of Henriksdal WWTP although the simulated system appears to be somewhat more efficient. This fact significantly increases the probability that also the results from the fictive cases (2, 3 and 4) are realistic and reliable.

The results from case 1B may give an impression that simulation results when not using the interface models could be more reliable. However, this is not the view of the author although the results are closer to those actually measured by Stockholm Water. The methane gas produced in the simulations for this case (1B) is about 23300 Nm^3 CH_4 per day (= 14700 kg CH_4/d), which amounts to 422 Nm^3 CH_4 per ton VS_in. This is closer to the true data (values from Stockholm Water in the years 2000-2005 range from 310 – 436 Nm^3 CH_4/ton VS_in). The methane content in the simulated results is 65.1% (compared to Stockholm Water data of 66±2% during the years 2000 to 2005). The concentration of volatile fatty acids in the simulated results is 102 mg COD/l, which is similar to measurements carried out by Stockholm Water. Also pH is approximately the same. VS reduction in the simulated AD system is 58%, which is at least closer to the actual data between the years 2000 and 2005 of 42 – 51%. However, it must be noted that no attempts have been made to calibrate the ADM1 to the provided data. The main reason why the results from case 1B are closer to the measured data is because of the fractionation of COD from primary and secondary sludge. In case 1B, the ADM1 default values will divide the influent composite material into 30% inert COD, 20% carbohydrates, 20% proteins and 30% lipids. In case 1A, the interface model fractionates the influent COD from primary and secondary sludge into 28% inert COD, 12% carbohydrates, 34% proteins and 26% lipids. It does so in order to also fulfil the mass balances for nitrogen and charge, which are not fulfilled for case 1B (we artificially add nitrogen and anions). It is actually more of a coincidence that the results form case 1B are closer to the true data. Moreover, the results from the model simulations should actually, since no specific calibration effort has been made, predict more efficient operation of the AD than the true data indicate, as is discussed below.

There are several reasons why it should be expected that the simulated AD system is more efficient than the true system when analysed by these simple steady state simulations. The simulated AD is not exposed to any process disturbances whatsoever, i.e. the internal mixing is perfect, the influent sludge flow rate is perfectly constant, the pH and temperature are optimal during the entire operation, no inhibitions (or toxicity) of any kind affects the system during the complete year, etc. It is highly unlikely that any full-scale AD system at a WWTP is operating for a full year without any types of process disturbances. If we would assume that the Henriksdal AD system on an average has a true production capacity 80-90% of its optimal performance during a year, it is clear that the values predicted by the simulations for case 1A (gas production, VS reduction, amount of CH_4/kg VS_in, etc.) would be in almost perfect agreement with the available Henriksdal AD measurements.

For the future scenario an input of 84.9 tonnes of VS (according to numbers provided by Stockholm Water) is used. The methane gas produced in the simulations for this case (3A) is about 38800 Nm^3 CH_4, which amounts to 457 Nm^3 CH_4 per ton VS_in.

The results of each simulated case are presented in detail in the following sub-sections and a short summary of the results is given in Section 6.9.

6.1 CASE 1A

Current scenario using interface models, operation in parallel (1 reactor).

Combined input of primary and secondary sludge prior to ASM2ADM interface:

SI (inert soluble) = 0 mg COD/l
SS (readily biodegradable substrate) = 0 mg COD/l
XI (inert particulate) = 9836.9293 mg COD/l
XS (slowly biodegradable substrate) = 25434.8913 mg COD/l
XBH (heterotrophic biomass) = 5679.375 mg COD/l
XBA (autotrophic biomass) = 0 mg COD/l
XP (particulate inert from biomass decay) = 0 mg COD/l
SO (oxygen) = 0 mg -COD/l
SNO (nitrate and nitrite) = 1.0598 mg N/l
SNH (ammonia) = 24.7011 mg N/l
SND (soluble organic nitrogen) = 0 mg N/l
XND (particulate organic nitrogen) = 1017.3641 mg N/l
SALK (alkalinity) = 7 mol HCO3/m3 = 427 mg HCO3/l
VS (volatile solids) = 26467.462 mg VS/l
TS (total solids) = 37336.6957 mg TS/l
MSS (mineralised suspended solids) = 10869.2337 mg MSS/l
VSS (volatile suspended solids) = 26467.462 mg VSS/l
TSS (total suspended solids)= 37336.6957 mg SS/l
Flow rate = 1840 m3/d
Temperature = 15 degC

SI_load = 0 kg COD/d
SS_load = 0 kg COD/d
XI_load = 18099.95 kg COD/d
XS_load = 46800.2 kg COD/d
XBH_load = 10450.05 kg COD/d
XBA_load = 0 kg COD/d
XP_load = 0 kg COD/d
SO_load = 0 kg -COD/d
SNO_load = 1.95 kg N/d
SNH_load = 45.45 kg N/d
SND_load = 0 kg N/d
XND_load = 1871.95 kg N/d
SALK_load = 12.88 kmol HCO3/d = 785.68 kg HCO3/d
VS_load = 48700.13 kg VS/d
TS_load = 68699.52 kg TS/d
MSS_load = 19999.39 kg MSS/d
VSS_load = 48700.13 kg VSS/d
TSS_load = 68699.52 kg SS/d

Combined primary and secondary sludge after ASM2ADM interface

Ssu = monosacharides (kg COD/m3) = 0
Saa = amino acids (kg COD/m3) = 0
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0
Sva = total valerate (kg COD/m3) = 0
Sbu = total butyrate (kg COD/m3) = 0
Spro = total propionate (kg COD/m3) = 0
Sac = total acetate (kg COD/m3) = 0
Sh2 = hydrogen gas (kg COD/m3) = 0
Sch4 = methane gas (kg COD/m3) = 0
Sic = inorganic carbon (kmole C/m3) = 0.0080054
Sin = inorganic nitrogen (kmole N/m3) = 0.0017644
Si = soluble inerts (kg COD/m3) = 0
Xc = composites (kg COD/m3) = 0
Xch = carbohydrates (kg COD/m3) = 4.7182
Xpr = proteins (kg COD/m3) = 13.9048
Xli = lipids (kg COD/m3) = 10.6708
Xsu = sugar degraders (kg COD/m3) = 0
Xaa = amino acid degraders (kg COD/m3) = 0
Xfa = LCFA degraders (kg COD/m3) = 0
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0
Xpro = propionate degraders (kg COD/m3) = 0
Xac = acetate degraders (kg COD/m3) = 0
Xh2 = hydrogen degraders (kg COD/m3) = 0
Xi = particulate inerts (kg COD/m3) = 11.6543
Scat+ = cations (base) (kmole/m3) = 0
San- = anions (acid) (kmole/m3) = 0.0053111
Flow rate (m3/d) = 1840
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 26.4694
TS = total solids (kg/m3) = 37.3386
MSS = mineralised suspended solids (kg/m3) = 10.8692
VSS = volatile suspended solids (kg/m3) = 26.4694
TSS = total suspended solids (kg/m3) = 37.3386

Combined primary and secondary sludge after ASM2ADM interface + external sludge input, i.e. total input to digester

Ssu = monosacharides (kg COD/m3) = 0
Saa = amino acids (kg COD/m3) = 0
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0
Sva = total valerate (kg COD/m3) = 0
Sbu = total butyrate (kg COD/m3) = 0
Spro = total propionate (kg COD/m3) = 0
Sac = total acetate (kg COD/m3) = 0
Sh2 = hydrogen gas (kg COD/m3) = 0
Sch4 = methane gas (kg COD/m3) = 0
Sic = inorganic carbon (kmole C/m3) = 0.007712

Sin = inorganic nitrogen (kmole N/m3) = 0.0016997
Si = soluble inerts (kg COD/m3) = 0
Xc = composites (kg COD/m3) = 0
Xch = carbohydrates (kg COD/m3) = 4.5453
Xpr = proteins (kg COD/m3) = 13.3952
Xli = lipids (kg COD/m3) = 20.3766
Xsu = sugar degraders (kg COD/m3) = 0
Xaa = amino acid degraders (kg COD/m3) = 0
Xfa = LCFA degraders (kg COD/m3) = 0
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0
Xpro = propionate degraders (kg COD/m3) = 0
Xac = acetate degraders (kg COD/m3) = 0
Xh2 = hydrogen degraders (kg COD/m3) = 0
Xi = particulate inerts (kg COD/m3) = 11.2272
Scat+ = cations (base) (kmole/m3) = 0
San- = anions (acid) (kmole/m3) = 0.0051164
Flow rate (m3/d) = 1910
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 28.981
TS = total solids (kg/m3) = 39.6351
MSS = mineralised suspended solids (kg/m3) = 10.6541
VSS = volatile suspended solids (kg/m3) = 28.981
TSS = total suspended solids (kg/m3) = 39.6351

Digester output (steady state)

Ssu = monosacharides (kg COD/m3) = 0.011805
Saa = amino acids (kg COD/m3) = 0.0052812
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0.10087
Sva = total valerate (kg COD/m3) = 0.011469
Sbu = total butyrate (kg COD/m3) = 0.013478
Spro = total propionate (kg COD/m3) = 0.016569
Sac = total acetate (kg COD/m3) = 0.0605
Sh2 = hydrogen gas (kg COD/m3) = 2.3852e-07
Sch4 = methane gas (kg COD/m3) = 0.056078
Sic = inorganic carbon (kmole C/m3) = 0.072633
Sin = inorganic nitrogen (kmole N/m3) = 0.071444 (= 1.0002 kg N/m3)
Si = soluble inerts (kg COD/m3) = 0.1387
Xc = composites (kg COD/m3) = 0.1362
Xch = carbohydrates (kg COD/m3) = 0.023564
Xpr = proteins (kg COD/m3) = 0.066805
Xli = lipids (kg COD/m3) = 0.10159
Xsu = sugar degraders (kg COD/m3) = 0.41368
Xaa = amino acid degraders (kg COD/m3) = 0.77312
Xfa = LCFA degraders (kg COD/m3) = 0.83373
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0.28937
Xpro = propionate degraders (kg COD/m3) = 0.098876
Xac = acetate degraders (kg COD/m3) = 0.91122
Xh2 = hydrogen degraders (kg COD/m3) = 0.41944

Xi = particulate inerts (kg COD/m3) = 11.5046
Scat+ = cations (base) (kmole/m3) = 2.0524e-24
San- = anions (acid) (kmole/m3) = 0.0051164
Flow rate (m3/d) = 1910
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 10.3811
TS = total solids (kg/m3) = 21.0353
MSS = mineralised suspended solids (kg/m3) = 10.6541
VSS = volatile suspended solids (kg/m3) = 10.1118
TSS = total suspended solids (kg/m3) = 20.766
pH = pH within AD system = 7.173
S_H+ = protons (kmole/m3) = 6.7144e-08
Sva- = valerate (kg COD/m3) = 0.011414
Sbu- = butyrate (kg COD/m3) = 0.013418
Spro- = propionate (kg COD/m3) = 0.016485
Sac- = acetate (kg COD/m3) = 0.060267
Shco3- = bicarbonate (kmole C/m3) = 0.063938
Sco2 = carbon dioxide (kmole C/m3) = 0.0086956
Snh3 = ammonia (kmole N/m3) = 0.0011622
Snh4+ = ammonium (kmole N/m3) = 0.070282
Sgas,h2 = hydrogen concentration in gas phase (kg COD/m3) = 9.9189e-06
Sgas,ch4 = methane concentration in gas phase (kg COD/m3) = 1.607
Sgas,co2 = carbon dioxide concentration in gas phase (kmole C/m3) = 0.012411
pgas,h2 = partial pressure of hydrogen gas (bar, true value i.e. not normalized) = 1.5883e-05
pgas,ch4 = partial pressure of methane gas (bar, true value i.e. not normalized) = 0.64333
pgas,co2 = partial pressure of carbon dioxide gas (bar, true value, i.e. not normalized) = 0.31797
pgas,total = total head space pressure of H2+CO2+CH4+H2O (bar, true value, i.e. not normalized) = 1.017
qgas = gas flow rate normalized to atmospheric pressure (Nm3/d) = 40041.348

Extra calculated outputs
Volatile fatty acids (kg COD/m3) = 0.10202
Produced hydrogen gas (kg H2/d) = 0.049451
Produced methane gas (kg CH4/d) = 16023.5329
Produced carbon dioxide gas (kg CO2/d) = 21779.496
Energy content of methane gas (MJ/d) = 801400.9737
Energy content of methane gas (kWh/d) = 222611.3816
VS reduction (%) = 64.1795
VSS reduction (%) = 65.1088
TS reduction (%) = 46.9277
TSS reduction (%) = 47.6072
Specific methane production (Nm3 CH4/kg VS_in) = 0.45759
Specific gas production (Nm3 gas/kg VS_in) = 0.72337

Digester sludge output after ADM2ASM interface

SI (inert soluble) = 138.6986 mg COD/l
SS (readily biodegradable substrate) = 219.9701 mg COD/l

XI (inert particulate) = 11504.6045 mg COD/l
XS (slowly biodegradable substrate) = 3282.329 mg COD/l
XBH (heterotrophic biomass) = 0 mg COD/l
XBA (autotrophic biomass) = 0 mg COD/l
XP (particulate inert from biomass decay) = 785.284 mg COD/l
SO (oxygen) = 0 mg -COD/l
SNO (nitrate and nitrite) = 0 mg N/l
SNH (ammonia) = 1149.5021 mg N/l
SND (soluble organic nitrogen) = 0.51756 mg N/l
XND (particulate organic nitrogen) = 122.7446 mg N/l
SALK (alkalinity) = 76.9906 mol HCO3/m3 = 4696.4268 mg HCO3/l
VS (volatile solids) = 10344.7314 mg VS/l
TS (total solids) = 20998.8623 mg TS/l
MSS (mineralised suspended solids) = 10654.1309 mg MSS/l
VSS (volatile suspended solids) = 10111.8296 mg VSS/l
TSS (total suspended solids)= 20765.9605 mg SS/l
Flow rate = 1910 m3/d
Temperature = 15 degC

SI_load = 264.9143 kg COD/d
SS_load = 420.1429 kg COD/d
XI_load = 21973.7946 kg COD/d
XS_load = 6269.2485 kg COD/d
XBH_load = 0 kg COD/d
XBA_load = 0 kg COD/d
XP_load = 1499.8925 kg COD/d
SO_load = 0 kg -COD/d
SNO_load = 0 kg N/d
SNH_load = 2195.549 kg N/d
SND_load = 0.98854 kg N/d
XND_load = 234.4423 kg N/d
SALK_load = 147.0521 kmol HCO3/d = 8970.1751 kg HCO3/d
VS_load = 19758.4369 kg VS/d
TS_load = 40107.8269 kg TS/d
MSS_load = 20349.39 kg MSS/d
VSS_load = 19313.5946 kg VSS/d
TSS_load = 39662.9846 kg SS/d

6.2 CASE 1B

Current scenario not using interface models, operation in parallel (1 reactor).

Total input to digester

Ssu = monosacharides (kg COD/m3) = 0
Saa = amino acids (kg COD/m3) = 0
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0
Sva = total valerate (kg COD/m3) = 0
Sbu = total butyrate (kg COD/m3) = 0
Spro = total propionate (kg COD/m3) = 0
Sac = total acetate (kg COD/m3) = 0
Sh2 = hydrogen gas (kg COD/m3) = 0
Sch4 = methane gas (kg COD/m3) = 0
Sic = inorganic carbon (kmole C/m3) = 0
Sin = inorganic nitrogen (kmole N/m3) = 0.037631 (of which 0.035931 for N-balance)
Si = soluble inerts (kg COD/m3) = 0
Xc = composites (kg COD/m3) = 39.45
Xch = carbohydrates (kg COD/m3) = 0
Xpr = proteins (kg COD/m3) = 0
Xli = lipids (kg COD/m3) = 10.097
Xsu = sugar degraders (kg COD/m3) = 0
Xaa = amino acid degraders (kg COD/m3) = 0
Xfa = LCFA degraders (kg COD/m3) = 0
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0
Xpro = propionate degraders (kg COD/m3) = 0
Xac = acetate degraders (kg COD/m3) = 0
Xh2 = hydrogen degraders (kg COD/m3) = 0
Xi = particulate inerts (kg COD/m3) = 0
Scat+ = cations (base) (kmole/m3) = 0.005
San- = anions (acid) (kmole/m3) = 0.0051164
Flow rate (m3/d) = 1910
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 28.979
TS = total solids (kg/m3) = 39.633
MSS = mineralised suspended solids (kg/m3) = 10.654
VSS = volatile suspended solids (kg/m3) = 28.979
TSS = total suspended solids (kg/m3) = 39.633

Digester output (steady state)

Ssu = monosacharides (kg COD/m3) = 0.011807
Saa = amino acids (kg COD/m3) = 0.0052818
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0.10088
Sva = total valerate (kg COD/m3) = 0.01052
Sbu = total butyrate (kg COD/m3) = 0.014093
Spro = total propionate (kg COD/m3) = 0.016572
Sac = total acetate (kg COD/m3) = 0.060374

Sh2 = hydrogen gas (kg COD/m3) = 2.3854e-07
Sch4 = methane gas (kg COD/m3) = 0.057106
Sic = inorganic carbon (kmole C/m3) = 0.07196
Sin = inorganic nitrogen (kmole N/m3) = 0.066405 (= 0.92967 kg N/m3)
Si = soluble inerts (kg COD/m3) = 3.7174
Xc = composites (kg COD/m3) = 3.6505
Xch = carbohydrates (kg COD/m3) = 0.036327
Xpr = proteins (kg COD/m3) = 0.036327
Xli = lipids (kg COD/m3) = 0.10382
Xsu = sugar degraders (kg COD/m3) = 0.6
Xaa = amino acid degraders (kg COD/m3) = 0.42027
Xfa = LCFA degraders (kg COD/m3) = 0.85214
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0.18316
Xpro = propionate degraders (kg COD/m3) = 0.089934
Xac = acetate degraders (kg COD/m3) = 0.82334
Xh2 = hydrogen degraders (kg COD/m3) = 0.40626
Xi = particulate inerts (kg COD/m3) = 7.4349
Scat+ = cations (base) (kmole/m3) = 0.005
San- = anions (acid) (kmole/m3) = 0.0051164
Flow rate (m3/d) = 1910
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 12.0981
TS = total solids (kg/m3) = 22.7521
MSS = mineralised suspended solids (kg/m3) = 10.654
VSS = volatile suspended solids (kg/m3) = 9.5045
TSS = total suspended solids (kg/m3) = 20.1585
pH = pH within AD system = 7.2057
S_H+ = protons (kmole/m3) = 6.2277e-08
Sva- = valerate (kg COD/m3) = 0.010472
Sbu- = butyrate (kg COD/m3) = 0.014035
Spro- = propionate (kg COD/m3) = 0.016494
Sac- = acetate (kg COD/m3) = 0.060158
Shco3- = bicarbonate (kmole C/m3) = 0.0639
Sco2 = carbon dioxide (kmole C/m3) = 0.0080604
Snh3 = ammonia (kmole N/m3) = 0.0011631
Snh4+ = ammonium (kmole N/m3) = 0.065242
Sgas,h2 = hydrogen concentration in gas phase (kg COD/m3) = 1.0158e-05
Sgas,ch4 = methane concentration in gas phase (kg COD/m3) = 1.6633
Sgas,co2 = carbon dioxide concentration in gas phase (kmole C/m3) = 0.011513
pgas,h2 = partial pressure of hydrogen gas (bar, true value i.e. not normalized) = 1.6266e-05
pgas,ch4 = partial pressure of methane gas (bar, true value i.e. not normalized) = 0.66588
pgas,co2 = partial pressure of carbon dioxide gas (bar, true value, i.e. not normalized) = 0.29498
pgas,total = total head space pressure of H2+CO2+CH4+H2O (bar, true value, i.e. not normalized) = 1.0166
qgas = gas flow rate normalized to atmospheric pressure (Nm3/d) = 35624.9387

Extra calculated outputs
Volatile fatty acids (kg COD/m3) = 0.10156
Produced hydrogen gas (kg H2/d) = 0.045077
Produced methane gas (kg CH4/d) = 14762.2859
Produced carbon dioxide gas (kg CO2/d) = 17984.071
Energy content of methane gas (MJ/d) = 738320.9671
Energy content of methane gas (kWh/d) = 205089.1575
VS reduction (%) = 58.2523
VSS reduction (%) = 67.202
TS reduction (%) = 42.5931
TSS reduction (%) = 49.137
Specific methane production (Nm3 CH4/kg VS_in) = 0.4216
Specific gas production (Nm3 gas/kg VS_in) = 0.64363

6.3 Case 2A

Current scenario using interface models, operation in series (2 reactors).

Combined input of primary and secondary sludge prior to ASM2ADM interface (identical to case 1A):

SI (inert soluble) = 0 mg COD/l
SS (readily biodegradable substrate) = 0 mg COD/l
XI (inert particulate) = 9836.9293 mg COD/l
XS (slowly biodegradable substrate) = 25434.8913 mg COD/l
XBH (heterotrophic biomass) = 5679.375 mg COD/l
XBA (autotrophic biomass) = 0 mg COD/l
XP (particulate inert from biomass decay) = 0 mg COD/l
SO (oxygen) = 0 mg -COD/l
SNO (nitrate and nitrite) = 1.0598 mg N/l
SNH (ammonia) = 24.7011 mg N/l
SND (soluble organic nitrogen) = 0 mg N/l
XND (particulate organic nitrogen) = 1017.3641 mg N/l
SALK (alkalinity) = 7 mol HCO3/m3 = 427 mg HCO3/l
VS (volatile solids) = 26467.462 mg VS/l
TS (total solids) = 37336.6957 mg TS/l
MSS (mineralised suspended solids) = 10869.2337 mg MSS/l
VSS (volatile suspended solids) = 26467.462 mg VSS/l
TSS (total suspended solids)= 37336.6957 mg SS/l
Flow rate = 1840 m3/d
Temperature = 15 degC

SI_load = 0 kg COD/d
SS_load = 0 kg COD/d
XI_load = 18099.95 kg COD/d
XS_load = 46800.2 kg COD/d
XBH_load = 10450.05 kg COD/d
XBA_load = 0 kg COD/d
XP_load = 0 kg COD/d
SO_load = 0 kg -COD/d
SNO_load = 1.95 kg N/d
SNH_load = 45.45 kg N/d
SND_load = 0 kg N/d
XND_load = 1871.95 kg N/d
SALK_load = 12.88 kmol HCO3/d = 785.68 kg HCO3/d
VS_load = 48700.13 kg VS/d
TS_load = 68699.52 kg TS/d
MSS_load = 19999.39 kg MSS/d
VSS_load = 48700.13 kg VSS/d
TSS_load = 68699.52 kg SS/d

Combined primary and secondary sludge after ASM2ADM interface (identical to case 1A)

Ssu = monosacharides (kg COD/m3) = 0
Saa = amino acids (kg COD/m3) = 0
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0
Sva = total valerate (kg COD/m3) = 0
Sbu = total butyrate (kg COD/m3) = 0
Spro = total propionate (kg COD/m3) = 0
Sac = total acetate (kg COD/m3) = 0
Sh2 = hydrogen gas (kg COD/m3) = 0
Sch4 = methane gas (kg COD/m3) = 0
Sic = inorganic carbon (kmole C/m3) = 0.0080547
Sin = inorganic nitrogen (kmole N/m3) = 0.0017644
Si = soluble inerts (kg COD/m3) = 0
Xc = composites (kg COD/m3) = 0
Xch = carbohydrates (kg COD/m3) = 4.7182
Xpr = proteins (kg COD/m3) = 13.9048
Xli = lipids (kg COD/m3) = 10.6708
Xsu = sugar degraders (kg COD/m3) = 0
Xaa = amino acid degraders (kg COD/m3) = 0
Xfa = LCFA degraders (kg COD/m3) = 0
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0
Xpro = propionate degraders (kg COD/m3) = 0
Xac = acetate degraders (kg COD/m3) = 0
Xh2 = hydrogen degraders (kg COD/m3) = 0
Xi = particulate inerts (kg COD/m3) = 11.6543
Scat+ = cations (base) (kmole/m3) = 0
San- = anions (acid) (kmole/m3) = 0.0053111
Flow rate (m3/d) = 1840
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 26.4694
TS = total solids (kg/m3) = 37.3386
MSS = mineralised suspended solids (kg/m3) = 10.8692
VSS = volatile suspended solids (kg/m3) = 26.4694
TSS = total suspended solids (kg/m3) = 37.3386

Combined primary and secondary sludge after ASM2ADM interface + external sludge input, i.e. total input to digester 1 (identical to case 1A)

Ssu = monosacharides (kg COD/m3) = 0
Saa = amino acids (kg COD/m3) = 0
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0
Sva = total valerate (kg COD/m3) = 0
Sbu = total butyrate (kg COD/m3) = 0
Spro = total propionate (kg COD/m3) = 0
Sac = total acetate (kg COD/m3) = 0
Sh2 = hydrogen gas (kg COD/m3) = 0
Sch4 = methane gas (kg COD/m3) = 0
Sic = inorganic carbon (kmole C/m3) = 0.0077595

Sin = inorganic nitrogen (kmole N/m3) = 0.0016997
Si = soluble inerts (kg COD/m3) = 0
Xc = composites (kg COD/m3) = 0
Xch = carbohydrates (kg COD/m3) = 4.5453
Xpr = proteins (kg COD/m3) = 13.3952
Xli = lipids (kg COD/m3) = 20.3766
Xsu = sugar degraders (kg COD/m3) = 0
Xaa = amino acid degraders (kg COD/m3) = 0
Xfa = LCFA degraders (kg COD/m3) = 0
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0
Xpro = propionate degraders (kg COD/m3) = 0
Xac = acetate degraders (kg COD/m3) = 0
Xh2 = hydrogen degraders (kg COD/m3) = 0
Xi = particulate inerts (kg COD/m3) = 11.2272
Scat+ = cations (base) (kmole/m3) = 0
San- = anions (acid) (kmole/m3) = 0.0051165
Flow rate (m3/d) = 1910
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 28.981
TS = total solids (kg/m3) = 39.6351
MSS = mineralised suspended solids (kg/m3) = 10.6541
VSS = volatile suspended solids (kg/m3) = 28.981
TSS = total suspended solids (kg/m3) = 39.6351

<u>Digester output from first reactor of 23700 m^3 (steady state), also serves as input to second reactor (from state Ssu until state temperature)</u>

Ssu = monosacharides (kg COD/m3) = 0.017373
Saa = amino acids (kg COD/m3) = 0.0077505
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0.17107
Sva = total valerate (kg COD/m3) = 0.017386
Sbu = total butyrate (kg COD/m3) = 0.020459
Spro = total propionate (kg COD/m3) = 0.027105
Sac = total acetate (kg COD/m3) = 0.10289
Sh2 = hydrogen gas (kg COD/m3) = 3.5271e-07
Sch4 = methane gas (kg COD/m3) = 0.061149
Sic = inorganic carbon (kmole C/m3) = 0.069881
Sin = inorganic nitrogen (kmole N/m3) = 0.069395 (= 0.97153 kg N/m3)
Si = soluble inerts (kg COD/m3) = 0.08876
Xc = composites (kg COD/m3) = 0.14306
Xch = carbohydrates (kg COD/m3) = 0.037757
Xpr = proteins (kg COD/m3) = 0.10851
Xli = lipids (kg COD/m3) = 0.16503
Xsu = sugar degraders (kg COD/m3) = 0.456
Xaa = amino acid degraders (kg COD/m3) = 0.86248
Xfa = LCFA degraders (kg COD/m3) = 0.92694
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0.3218
Xpro = propionate degraders (kg COD/m3) = 0.10933
Xac = acetate degraders (kg COD/m3) = 1.0109

Xh2 = hydrogen degraders (kg COD/m3) = 0.46567
Xi = particulate inerts (kg COD/m3) = 11.4047
Scat+ = cations (base) (kmole/m3) = -1.4133e-28
San- = anions (acid) (kmole/m3) = 0.0051165
Flow rate (m3/d) = 1910
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 10.7312
TS = total solids (kg/m3) = 21.3854
MSS = mineralised suspended solids (kg/m3) = 10.6541
VSS = volatile suspended solids (kg/m3) = 10.3975
TSS = total suspended solids (kg/m3) = 21.0516
pH = pH within AD system = 7.1519
S_H+ = protons (kmole/m3) = 7.0491e-08
Sva- = valerate (kg COD/m3) = 0.017298
Sbu- = butyrate (kg COD/m3) = 0.020364
Spro- = propionate (kg COD/m3) = 0.026961
Sac- = acetate (kg COD/m3) = 0.10247
Shco3- = bicarbonate (kmole C/m3) = 0.06115
Sco2 = carbon dioxide (kmole C/m3) = 0.0087309
Snh3 = ammonia (kmole N/m3) = 0.0010761
Snh4+ = ammonium (kmole N/m3) = 0.068319
Sgas,h2 = hydrogen concentration in gas phase (kg COD/m3) = 1.2968e-05
Sgas,ch4 = methane concentration in gas phase (kg COD/m3) = 1.6072
Sgas,co2 = carbon dioxide concentration in gas phase (kmole C/m3) = 0.012405
pgas,h2 = partial pressure of hydrogen gas (bar, true value i.e. not normalized) = 2.0766e-05
pgas,ch4 = partial pressure of methane gas (bar, true value i.e. not normalized) = 0.6434
pgas,co2 = partial pressure of carbon dioxide gas (bar, true value, i.e. not normalized) = 0.31784
pgas,total = total head space pressure of H2+CO2+CH4+H2O (bar, true value, i.e. not normalized) = 1.0169
qgas = gas flow rate normalized to atmospheric pressure (Nm3/d) = 39391.3881

Extra calculated outputs
Volatile fatty acids (kg COD/m3) = 0.16784
Produced hydrogen gas (kg H2/d) = 0.063606
Produced methane gas (kg CH4/d) = 15766.0621
Produced carbon dioxide gas (kg CO2/d) = 21418.1761
Energy content of methane gas (MJ/d) = 788523.8299
Energy content of methane gas (kWh/d) = 219034.3972
VS reduction (%) = 62.9715
VSS reduction (%) = 64.123
TS reduction (%) = 46.0444
TSS reduction (%) = 46.8864
Specific methane production (Nm3 CH4/kg VS_in) = 0.45024
Specific gas production (Nm3 gas/kg VS_in) = 0.71163

Digester output from second reactor of 15200 m^3 (steady state)

Ssu = monosacharides (kg COD/m3) = 0.00095445
Saa = amino acids (kg COD/m3) = 0.00022882
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0.0050147
Sva = total valerate (kg COD/m3) = 0.00064119
Sbu = total butyrate (kg COD/m3) = 0.00077884
Spro = total propionate (kg COD/m3) = 0.0011503
Sac = total acetate (kg COD/m3) = 0.0032998
Sh2 = hydrogen gas (kg COD/m3) = 1.5572e-08
Sch4 = methane gas (kg COD/m3) = 0.048672
Sic = inorganic carbon (kmole C/m3) = 0.074053
Sin = inorganic nitrogen (kmole N/m3) = 0.072033 (= 1.0085 kg N/m3)
Si = soluble inerts (kg COD/m3) = 0.14721
Xc = composites (kg COD/m3) = 0.14691
Xch = carbohydrates (kg COD/m3) = 0.0019194
Xpr = proteins (kg COD/m3) = 0.0027974
Xli = lipids (kg COD/m3) = 0.0042243
Xsu = sugar degraders (kg COD/m3) = 0.40943
Xaa = amino acid degraders (kg COD/m3) = 0.75994
Xfa = LCFA degraders (kg COD/m3) = 0.82479
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0.28599
Xpro = propionate degraders (kg COD/m3) = 0.098282
Xac = acetate degraders (kg COD/m3) = 0.90342
Xh2 = hydrogen degraders (kg COD/m3) = 0.415
Xi = particulate inerts (kg COD/m3) = 11.5216
Scat+ = cations (base) (kmole/m3) = -2.2609e-29
San- = anions (acid) (kmole/m3) = 0.0051165
Flow rate (m3/d) = 1910
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 10.1184
TS = total solids (kg/m3) = 20.7725
MSS = mineralised suspended solids (kg/m3) = 10.6541
VSS = volatile suspended solids (kg/m3) = 9.9833
TSS = total suspended solids (kg/m3) = 20.6375
pH = pH within AD system = 7.197
S_H+ = protons (kmole/m3) = 6.354e-08
Sva- = valerate (kg COD/m3) = 0.00063826
Sbu- = butyrate (kg COD/m3) = 0.00077558
Spro- = propionate (kg COD/m3) = 0.0011447
Sac- = acetate (kg COD/m3) = 0.0032878
Shco3- = bicarbonate (kmole C/m3) = 0.065609
Sco2 = carbon dioxide (kmole C/m3) = 0.0084439
Snh3 = ammonia (kmole N/m3) = 0.0012371
Snh4+ = ammonium (kmole N/m3) = 0.070796
Sgas,h2 = hydrogen concentration in gas phase (kg COD/m3) = 8.0738e-07
Sgas,ch4 = methane concentration in gas phase (kg COD/m3) = 1.6151
Sgas,co2 = carbon dioxide concentration in gas phase (kmole C/m3) = 0.012134
pgas,h2 = partial pressure of hydrogen gas (bar, true value i.e. not normalized) = 1.2929e-06

pgas,ch4 = partial pressure of methane gas (bar, true value i.e. not normalized) = 0.64656
pgas,co2 = partial pressure of carbon dioxide gas (bar, true value, i.e. not normalized) = 0.31088
pgas,total = total head space pressure of H2+CO2+CH4+H2O (bar, true value, i.e. not normalized) = 1.0131
qgas = gas flow rate normalized to atmospheric pressure (Nm3/d) = 1116.3065

Extra calculated outputs
Volatile fatty acids (kg COD/m3) = 0.0058701
Produced hydrogen gas (kg H2/d) = 0.00011265
Produced methane gas (kg CH4/d) = 450.6762
Produced carbon dioxide gas (kg CO2/d) = 595.922
Energy content of methane gas (MJ/d) = 22540.1203
Energy content of methane gas (kWh/d) = 6261.1445
VS reduction (%) = 5.7111
VSS reduction (%) = 3.9835
TS reduction (%) = 2.8659
TSS reduction (%) = 1.9674
Specific methane production (Nm3 CH4/kg VS_in) = 0.034758
Specific gas production (Nm3 gas/kg VS_in) = 0.054463

Second digester sludge output after ADM2ASM interface

SI (inert soluble) = 147.215 mg COD/l
SS (readily biodegradable substrate) = 12.0681 mg COD/l
XI (inert particulate) = 11521.6373 mg COD/l
XS (slowly biodegradable substrate) = 3076.3558 mg COD/l
XBH (heterotrophic biomass) = 0 mg COD/l
XBA (autotrophic biomass) = 0 mg COD/l
XP (particulate inert from biomass decay) = 776.3373 mg COD/l
SO (oxygen) = 0 mg -COD/l
SNO (nitrate and nitrite) = 0 mg N/l
SNH (ammonia) = 1156.6478 mg N/l
SND (soluble organic nitrogen) = 0.022425 mg N/l
XND (particulate organic nitrogen) = 115.6089 mg N/l
SALK (alkalinity) = 77.501 mol HCO3/m3 = 4727.5592 mg HCO3/l
VS (volatile solids) = 10086.762 mg VS/l
TS (total solids) = 20740.8929 mg TS/l
MSS (mineralised suspended solids) = 10654.1309 mg MSS/l
VSS (volatile suspended solids) = 9983.3314 mg VSS/l
TSS (total suspended solids)= 20637.4623 mg SS/l
Flow rate = 1910 m3/d
Temperature = 15 degC

SI_load = 281.1806 kg COD/d
SS_load = 23.05 kg COD/d
XI_load = 22006.3272 kg COD/d
XS_load = 5875.8396 kg COD/d
XBH_load = 0 kg COD/d

XBA_load = 0 kg COD/d
XP_load = 1482.8042 kg COD/d
SO_load = 0 kg -COD/d
SNO_load = 0 kg N/d
SNH_load = 2209.1972 kg N/d
SND_load = 0.042831 kg N/d
XND_load = 220.8131 kg N/d
SALK_load = 148.0269 kmol HCO3/d = 9029.638 kg HCO3/d
VS_load = 19265.7154 kg VS/d
TS_load = 39615.1054 kg TS/d
MSS_load = 20349.39 kg MSS/d
VSS_load = 19068.163 kg VSS/d
TSS_load = 39417.553 kg SS/d

6.4 Case 2B

Current scenario not using interface models, operation in series (2 reactors).

Total input to digester 1 (identical to case 1B)

Ssu = monosacharides (kg COD/m3) = 0
Saa = amino acids (kg COD/m3) = 0
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0
Sva = total valerate (kg COD/m3) = 0
Sbu = total butyrate (kg COD/m3) = 0
Spro = total propionate (kg COD/m3) = 0
Sac = total acetate (kg COD/m3) = 0
Sh2 = hydrogen gas (kg COD/m3) = 0
Sch4 = methane gas (kg COD/m3) = 0
Sic = inorganic carbon (kmole C/m3) = 0
Sin = inorganic nitrogen (kmole N/m3) = 0.037631 (of which 0.035931 for N-balance)
Si = soluble inerts (kg COD/m3) = 0
Xc = composites (kg COD/m3) = 39.45
Xch = carbohydrates (kg COD/m3) = 0
Xpr = proteins (kg COD/m3) = 0
Xli = lipids (kg COD/m3) = 10.097
Xsu = sugar degraders (kg COD/m3) = 0
Xaa = amino acid degraders (kg COD/m3) = 0
Xfa = LCFA degraders (kg COD/m3) = 0
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0
Xpro = propionate degraders (kg COD/m3) = 0
Xac = acetate degraders (kg COD/m3) = 0
Xh2 = hydrogen degraders (kg COD/m3) = 0
Xi = particulate inerts (kg COD/m3) = 0
Scat+ = cations (base) (kmole/m3) = 0.005
San- = anions (acid) (kmole/m3) = 0.0051164
Flow rate (m3/d) = 1910
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 28.979
TS = total solids (kg/m3) = 39.633
MSS = mineralised suspended solids (kg/m3) = 10.654
VSS = volatile suspended solids (kg/m3) = 28.979
TSS = total suspended solids (kg/m3) = 39.633

Digester output from first digester of 23700 m^3 (steady state), also serves as input to digester 2 (from state Ssu until state temperature)

Ssu = monosacharides (kg COD/m3) = 0.017376
Saa = amino acids (kg COD/m3) = 0.0077517
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0.17111
Sva = total valerate (kg COD/m3) = 0.015907
Sbu = total butyrate (kg COD/m3) = 0.021425
Spro = total propionate (kg COD/m3) = 0.02711

Sac = total acetate (kg COD/m3) = 0.1004
Sh2 = hydrogen gas (kg COD/m3) = 3.5276e-07
Sch4 = methane gas (kg COD/m3) = 0.061535
Sic = inorganic carbon (kmole C/m3) = 0.067729
Sin = inorganic nitrogen (kmole N/m3) = 0.062903 (= 0.88065 kg N/m3)
Si = soluble inerts (kg COD/m3) = 3.4742
Xc = composites (kg COD/m3) = 5.5997
Xch = carbohydrates (kg COD/m3) = 0.05555
Xpr = proteins (kg COD/m3) = 0.05555
Xli = lipids (kg COD/m3) = 0.16405
Xsu = sugar degraders (kg COD/m3) = 0.63238
Xaa = amino acid degraders (kg COD/m3) = 0.44129
Xfa = LCFA degraders (kg COD/m3) = 0.92135
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0.1918
Xpro = propionate degraders (kg COD/m3) = 0.094189
Xac = acetate degraders (kg COD/m3) = 0.87739
Xh2 = hydrogen degraders (kg COD/m3) = 0.43409
Xi = particulate inerts (kg COD/m3) = 6.9484
Scat+ = cations (base) (kmole/m3) = 0.005
San- = anions (acid) (kmole/m3) = 0.0051164
Flow rate (m3/d) = 1910
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 13.1899
TS = total solids (kg/m3) = 23.8439
MSS = mineralised suspended solids (kg/m3) = 10.654
VSS = volatile suspended solids (kg/m3) = 10.6596
TSS = total suspended solids (kg/m3) = 21.3136
pH = pH within AD system = 7.1799
S_H+ = protons (kmole/m3) = 6.6081e-08
Sva- = valerate (kg COD/m3) = 0.015831
Sbu- = butyrate (kg COD/m3) = 0.021332
Spro- = propionate (kg COD/m3) = 0.026975
Sac- = acetate (kg COD/m3) = 0.10002
Shco3- = bicarbonate (kmole C/m3) = 0.059734
Sco2 = carbon dioxide (kmole C/m3) = 0.0079951
Snh3 = ammonia (kmole N/m3) = 0.0010394
Snh4+ = ammonium (kmole N/m3) = 0.061864
Sgas,h2 = hydrogen concentration in gas phase (kg COD/m3) = 1.3584e-05
Sgas,ch4 = methane concentration in gas phase (kg COD/m3) = 1.6713
Sgas,co2 = carbon dioxide concentration in gas phase (kmole C/m3) = 0.01138
pgas,h2 = partial pressure of hydrogen gas (bar, true value i.e. not normalized) = 2.1753e-05
pgas,ch4 = partial pressure of methane gas (bar, true value i.e. not normalized) = 0.66909
pgas,co2 = partial pressure of carbon dioxide gas (bar, true value, i.e. not normalized) = 0.29156
pgas,total = total head space pressure of H2+CO2+CH4+H2O (bar, true value, i.e. not normalized) = 1.0163
qgas = gas flow rate normalized to atmospheric pressure (Nm3/d) = 33518.8477

Extra calculated outputs
Volatile fatty acids (kg COD/m3) = 0.16484
Produced hydrogen gas (kg H2/d) = 0.056729
Produced methane gas (kg CH4/d) = 13959.3516
Produced carbon dioxide gas (kg CO2/d) = 16727.9885
Energy content of methane gas (MJ/d) = 698163.0092
Energy content of methane gas (kWh/d) = 193934.1692
VS reduction (%) = 54.4845
VSS reduction (%) = 63.2163
TS reduction (%) = 39.8381
TSS reduction (%) = 46.2227
Specific methane production (Nm3 CH4/kg VS_in) = 0.39867
Specific gas production (Nm3 gas/kg VS_in) = 0.60558

Digester output from second digester of 15200 m^3 (steady state)

Ssu = monosacharides (kg COD/m3) = 0.0036941
Saa = amino acids (kg COD/m3) = 0.0017377
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0.017005
Sva = total valerate (kg COD/m3) = 0.0034802
Sbu = total butyrate (kg COD/m3) = 0.0045641
Spro = total propionate (kg COD/m3) = 0.0048939
Sac = total acetate (kg COD/m3) = 0.01259
Sh2 = hydrogen gas (kg COD/m3) = 6.0825e-08
Sch4 = methane gas (kg COD/m3) = 0.048405
Sic = inorganic carbon (kmole C/m3) = 0.076372
Sin = inorganic nitrogen (kmole N/m3) = 0.06875 (= 0.96251 kg N/m3)
Si = soluble inerts (kg COD/m3) = 3.9671
Xc = composites (kg COD/m3) = 1.2388
Xch = carbohydrates (kg COD/m3) = 0.012923
Xpr = proteins (kg COD/m3) = 0.012923
Xli = lipids (kg COD/m3) = 0.020387
Xsu = sugar degraders (kg COD/m3) = 0.64245
Xaa = amino acid degraders (kg COD/m3) = 0.45209
Xfa = LCFA degraders (kg COD/m3) = 0.88259
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0.19792
Xpro = propionate degraders (kg COD/m3) = 0.097135
Xac = acetate degraders (kg COD/m3) = 0.86973
Xh2 = hydrogen degraders (kg COD/m3) = 0.4275
Xi = particulate inerts (kg COD/m3) = 7.9342
Scat+ = cations (base) (kmole/m3) = 0.005
San- = anions (acid) (kmole/m3) = 0.0051164
Flow rate (m3/d) = 1910
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 10.9429
TS = total solids (kg/m3) = 21.5969
MSS = mineralised suspended solids (kg/m3) = 10.654
VSS = volatile suspended solids (kg/m3) = 8.3043
TSS = total suspended solids (kg/m3) = 18.9583

pH = pH within AD system = 7.1731
S_H+ = protons (kmole/m3) = 6.7126e-08
Sva- = valerate (kg COD/m3) = 0.0034634
Sbu- = butyrate (kg COD/m3) = 0.0045439
Spro- = propionate (kg COD/m3) = 0.0048691
Sac- = acetate (kg COD/m3) = 0.012541
Shco3- = bicarbonate (kmole C/m3) = 0.067231
Sco2 = carbon dioxide (kmole C/m3) = 0.0091409
Snh3 = ammonia (kmole N/m3) = 0.0011186
Snh4+ = ammonium (kmole N/m3) = 0.067632
Sgas,h2 = hydrogen concentration in gas phase (kg COD/m3) = 2.9933e-06
Sgas,ch4 = methane concentration in gas phase (kg COD/m3) = 1.553
Sgas,co2 = carbon dioxide concentration in gas phase (kmole C/m3) = 0.013116
pgas,h2 = partial pressure of hydrogen gas (bar, true value i.e. not normalized) = 4.7932e-06
pgas,ch4 = partial pressure of methane gas (bar, true value i.e. not normalized) = 0.62171
pgas,co2 = partial pressure of carbon dioxide gas (bar, true value, i.e. not normalized) = 0.33605
pgas,total = total head space pressure of H2+CO2+CH4+H2O (bar, true value, i.e. not normalized) = 1.0134
qgas = gas flow rate normalized to atmospheric pressure (Nm3/d) = 4257.7774

Extra calculated outputs
Volatile fatty acids (kg COD/m3) = 0.025528
Produced hydrogen gas (kg H2/d) = 0.0015924
Produced methane gas (kg CH4/d) = 1652.3706
Produced carbon dioxide gas (kg CO2/d) = 2456.1484
Energy content of methane gas (MJ/d) = 82641.6657
Energy content of methane gas (kWh/d) = 22956.0182
VS reduction (%) = 17.0361
VSS reduction (%) = 22.0955
TS reduction (%) = 9.424
TSS reduction (%) = 11.0506
Specific methane production (Nm3 CH4/kg VS_in) = 0.10368
Specific gas production (Nm3 gas/kg VS_in) = 0.16901

6.5 Case 3A

Future scenario using interface models, operation in parallel (1 reactor).

Combined input of primary and secondary sludge prior to ASM2ADM interface:

SI (inert soluble) = 0 mg COD/l
SS (readily biodegradable substrate) = 0 mg COD/l
XI (inert particulate) = 9721.2989 mg COD/l
XS (slowly biodegradable substrate) = 25217.3913 mg COD/l
XBH (heterotrophic biomass) = 5575.0924 mg COD/l
XBA (autotrophic biomass) = 0 mg COD/l
XP (particulate inert from biomass decay) = 0 mg COD/l
SO (oxygen) = 0 mg -COD/l
SNO (nitrate and nitrite) = 1.0598 mg N/l
SNH (ammonia) = 24.7011 mg N/l
SND (soluble organic nitrogen) = 0 mg N/l
XND (particulate organic nitrogen) = 1008.6957 mg N/l
SALK (alkalinity) = 7 mol HCO3/m3 = 427 mg HCO3/l
VS (volatile solids) = 26185.5054 mg VS/l
TS (total solids) = 37548.8315 mg TS/l
MSS (mineralised suspended solids) = 11363.3261 mg MSS/l
VSS (volatile suspended solids) = 26185.5054 mg VSS/l
TSS (total suspended solids)= 37548.8315 mg SS/l
Flow rate = 2024 m3/d
Temperature = 15 degC

SI_load = 0 kg COD/d
SS_load = 0 kg COD/d
XI_load = 19675.909 kg COD/d
XS_load = 51040 kg COD/d
XBH_load = 11283.987 kg COD/d
XBA_load = 0 kg COD/d
XP_load = 0 kg COD/d
SO_load = 0 kg -COD/d
SNO_load = 2.145 kg N/d
SNH_load = 49.995 kg N/d
SND_load = 0 kg N/d
XND_load = 2041.6 kg N/d
SALK_load = 14.168 kmol HCO3/d = 864.248 kg HCO3/d
VS_load = 52999.463 kg VS/d
TS_load = 75998.835 kg TS/d
MSS_load = 22999.372 kg MSS/d
VSS_load = 52999.463 kg VSS/d
TSS_load = 75998.835 kg SS/d

Combined primary and secondary sludge after ASM2ADM interface

Ssu = monosacharides (kg COD/m3) = 0

Saa = amino acids (kg COD/m3) = 0
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0
Sva = total valerate (kg COD/m3) = 0
Sbu = total butyrate (kg COD/m3) = 0
Spro = total propionate (kg COD/m3) = 0
Sac = total acetate (kg COD/m3) = 0
Sh2 = hydrogen gas (kg COD/m3) = 0
Sch4 = methane gas (kg COD/m3) = 0
Sic = inorganic carbon (kmole C/m3) = 0.0082371
Sin = inorganic nitrogen (kmole N/m3) = 0.0017644
Si = soluble inerts (kg COD/m3) = 0
Xc = composites (kg COD/m3) = 0
Xch = carbohydrates (kg COD/m3) = 4.6758
Xpr = proteins (kg COD/m3) = 13.7516
Xli = lipids (kg COD/m3) = 10.578
Xsu = sugar degraders (kg COD/m3) = 0
Xaa = amino acid degraders (kg COD/m3) = 0
Xfa = LCFA degraders (kg COD/m3) = 0
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0
Xpro = propionate degraders (kg COD/m3) = 0
Xac = acetate degraders (kg COD/m3) = 0
Xh2 = hydrogen degraders (kg COD/m3) = 0
Xi = particulate inerts (kg COD/m3) = 11.5053
Scat+ = cations (base) (kmole/m3) = 0
San- = anions (acid) (kmole/m3) = 0.0053112
Flow rate (m3/d) = 2024
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 26.1867
TS = total solids (kg/m3) = 37.55
MSS = mineralised suspended solids (kg/m3) = 11.3633
VSS = volatile suspended solids (kg/m3) = 26.1867
TSS = total suspended solids (kg/m3) = 37.55

Combined primary and secondary sludge after ASM2ADM interface + external sludge input, i.e. total input to digester

Ssu = monosacharides (kg COD/m3) = 0
Saa = amino acids (kg COD/m3) = 0
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0
Sva = total valerate (kg COD/m3) = 0
Sbu = total butyrate (kg COD/m3) = 0
Spro = total propionate (kg COD/m3) = 0
Sac = total acetate (kg COD/m3) = 0
Sh2 = hydrogen gas (kg COD/m3) = 0
Sch4 = methane gas (kg COD/m3) = 0
Sic = inorganic carbon (kmole C/m3) = 0.0070643
Sin = inorganic nitrogen (kmole N/m3) = 0.0015132
Si = soluble inerts (kg COD/m3) = 0
Xc = composites (kg COD/m3) = 0

Xch = carbohydrates (kg COD/m3) = 10.5037
Xpr = proteins (kg COD/m3) = 13.2383
Xli = lipids (kg COD/m3) = 24.0698
Xsu = sugar degraders (kg COD/m3) = 0
Xaa = amino acid degraders (kg COD/m3) = 0
Xfa = LCFA degraders (kg COD/m3) = 0
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0
Xpro = propionate degraders (kg COD/m3) = 0
Xac = acetate degraders (kg COD/m3) = 0
Xh2 = hydrogen degraders (kg COD/m3) = 0
Xi = particulate inerts (kg COD/m3) = 12.4499
Scat+ = cations (base) (kmole/m3) = 0
San- = anions (acid) (kmole/m3) = 0.004555
Flow rate (m3/d) = 2360
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 35.9753
TS = total solids (kg/m3) = 46.4412
MSS = mineralised suspended solids (kg/m3) = 10.4659
VSS = volatile suspended solids (kg/m3) = 35.9753
TSS = total suspended solids (kg/m3) = 46.4412

Digester output (steady state)

Ssu = monosacharides (kg COD/m3) = 0.013839
Saa = amino acids (kg COD/m3) = 0.0061848
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0.12426
Sva = total valerate (kg COD/m3) = 0.012834
Sbu = total butyrate (kg COD/m3) = 0.016489
Spro = total propionate (kg COD/m3) = 0.020166
Sac = total acetate (kg COD/m3) = 0.064397
Sh2 = hydrogen gas (kg COD/m3) = 2.8011e-07
Sch4 = methane gas (kg COD/m3) = 0.058792
Sic = inorganic carbon (kmole C/m3) = 0.06545
Sin = inorganic nitrogen (kmole N/m3) = 0.062765 (= 0.87871 kg N/m3)
Si = soluble inerts (kg COD/m3) = 0.14633
Xc = composites (kg COD/m3) = 0.17756
Xch = carbohydrates (kg COD/m3) = 0.065105
Xpr = proteins (kg COD/m3) = 0.081595
Xli = lipids (kg COD/m3) = 0.14779
Xsu = sugar degraders (kg COD/m3) = 0.89763
Xaa = amino acid degraders (kg COD/m3) = 0.80882
Xfa = LCFA degraders (kg COD/m3) = 1.0387
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0.33515
Xpro = propionate degraders (kg COD/m3) = 0.14849
Xac = acetate degraders (kg COD/m3) = 1.1813
Xh2 = hydrogen degraders (kg COD/m3) = 0.56743
Xi = particulate inerts (kg COD/m3) = 12.7426
Scat+ = cations (base) (kmole/m3) = 1.3861e-29
San- = anions (acid) (kmole/m3) = 0.004555

Flow rate (m3/d) = 2360
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 12.114
TS = total solids (kg/m3) = 22.5799
MSS = mineralised suspended solids (kg/m3) = 10.4659
VSS = volatile suspended solids (kg/m3) = 11.8131
TSS = total suspended solids (kg/m3) = 22.279
pH = pH within AD system = 7.0813
S_H+ = protons (kmole/m3) = 8.2934e-08
Sva- = valerate (kg COD/m3) = 0.012757
Sbu- = butyrate (kg COD/m3) = 0.016399
Spro- = propionate (kg COD/m3) = 0.02004
Sac- = acetate (kg COD/m3) = 0.064091
Shco3- = bicarbonate (kmole C/m3) = 0.056037
Sco2 = carbon dioxide (kmole C/m3) = 0.0094131
Snh3 = ammonia (kmole N/m3) = 0.00082918
Snh4+ = ammonium (kmole N/m3) = 0.061936
Sgas,h2 = hydrogen concentration in gas phase (kg COD/m3) = 1.0352e-05
Sgas,ch4 = methane concentration in gas phase (kg COD/m3) = 1.551
Sgas,co2 = carbon dioxide concentration in gas phase (kmole C/m3) = 0.013377
pgas,h2 = partial pressure of hydrogen gas (bar, true value i.e. not normalized) = 1.6577e-05
pgas,ch4 = partial pressure of methane gas (bar, true value i.e. not normalized) = 0.62091
pgas,co2 = partial pressure of carbon dioxide gas (bar, true value, i.e. not normalized) = 0.34274
pgas,total = total head space pressure of H2+CO2+CH4+H2O (bar, true value, i.e. not normalized) = 1.0193
qgas = gas flow rate normalized to atmospheric pressure (Nm3/d) = 63703.9193

Extra calculated outputs
Volatile fatty acids (kg COD/m3) = 0.11389
Produced hydrogen gas (kg H2/d) = 0.081922
Produced methane gas (kg CH4/d) = 24547.531
Produced carbon dioxide gas (kg CO2/d) = 37263.2313
Energy content of methane gas (MJ/d) = 1227720.2166
Energy content of methane gas (kWh/d) = 341033.3935
VS reduction (%) = 66.327
VSS reduction (%) = 67.1632
TS reduction (%) = 51.3797
TSS reduction (%) = 52.0274
Specific methane production (Nm3 CH4/kg VS_in) = 0.45705
Specific gas production (Nm3 gas/kg VS_in) = 0.75033

Digester sludge output after ADM2ASM interface

SI (inert soluble) = 146.3346 mg COD/l
SS (readily biodegradable substrate) = 258.1654 mg COD/l
XI (inert particulate) = 12742.5951 mg COD/l
XS (slowly biodegradable substrate) = 4404.3165 mg COD/l
XBH (heterotrophic biomass) = 0 mg COD/l

XBA (autotrophic biomass) = 0 mg COD/l
XP (particulate inert from biomass decay) = 1045.2855 mg COD/l
SO (oxygen) = 0 mg -COD/l
SNO (nitrate and nitrite) = 0 mg N/l
SNH (ammonia) = 1075.1286 mg N/l
SND (soluble organic nitrogen) = 0.60611 mg N/l
XND (particulate organic nitrogen) = 162.5256 mg N/l
SALK (alkalinity) = 72.2397 mol HCO3/m3 = 4406.6237 mg HCO3/l
VS (volatile solids) = 12075.7773 mg VS/l
TS (total solids) = 22541.6807 mg TS/l
MSS (mineralised suspended solids) = 10465.9034 mg MSS/l
VSS (volatile suspended solids) = 11813.115 mg VSS/l
TSS (total suspended solids)= 22279.0183 mg SS/l
Flow rate = 2360 m3/d
Temperature = 15 degC

SI_load = 345.3498 kg COD/d
SS_load = 609.2703 kg COD/d
XI_load = 30072.5243 kg COD/d
XS_load = 10394.187 kg COD/d
XBH_load = 0 kg COD/d
XBA_load = 0 kg COD/d
XP_load = 2466.8737 kg COD/d
SO_load = 0 kg -COD/d
SNO_load = 0 kg N/d
SNH_load = 2537.3036 kg N/d
SND_load = 1.4304 kg N/d
XND_load = 383.5605 kg N/d
SALK_load = 170.4858 kmol HCO3/d = 10399.632 kg HCO3/d
VS_load = 28498.8344 kg VS/d
TS_load = 53198.3664 kg TS/d
MSS_load = 24699.532 kg MSS/d
VSS_load = 27878.9513 kg VSS/d
TSS_load = 52578.4833 kg SS/d

6.6 Case 3B

Future scenario not using interface models, operation in parallel (1 reactor).

Total input to digester

Ssu = monosacharides (kg COD/m3) = 0
Saa = amino acids (kg COD/m3) = 0
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0
Sva = total valerate (kg COD/m3) = 0
Sbu = total butyrate (kg COD/m3) = 0
Spro = total propionate (kg COD/m3) = 0
Sac = total acetate (kg COD/m3) = 0
Sh2 = hydrogen gas (kg COD/m3) = 0
Sch4 = methane gas (kg COD/m3) = 0
Sic = inorganic carbon (kmole C/m3) = 0
Sin = inorganic nitrogen (kmole N/m3) = 0.033029 (of which 0.031516 for N-balance)
Si = soluble inerts (kg COD/m3) = 0
Xc = composites (kg COD/m3) = 34.7458
Xch = carbohydrates (kg COD/m3) = 6.4936
Xpr = proteins (kg COD/m3) = 1.4445
Xli = lipids (kg COD/m3) = 14.9979
Xsu = sugar degraders (kg COD/m3) = 0
Xaa = amino acid degraders (kg COD/m3) = 0
Xfa = LCFA degraders (kg COD/m3) = 0
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0
Xpro = propionate degraders (kg COD/m3) = 0
Xac = acetate degraders (kg COD/m3) = 0
Xh2 = hydrogen degraders (kg COD/m3) = 0
Xi = particulate inerts (kg COD/m3) = 2.5826
Scat+ = cations (base) (kmole/m3) = 0.02
San- = anions (acid) (kmole/m3) = 0.004555
Flow rate (m3/d) = 2360
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 35.9746
TS = total solids (kg/m3) = 46.4407
MSS = mineralised suspended solids (kg/m3) = 10.4661
VSS = volatile suspended solids (kg/m3) = 35.9746
TSS = total suspended solids (kg/m3) = 46.4407

Digester output (steady state)

Ssu = monosacharides (kg COD/m3) = 0.013841
Saa = amino acids (kg COD/m3) = 0.0061856
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0.12428
Sva = total valerate (kg COD/m3) = 0.011606
Sbu = total butyrate (kg COD/m3) = 0.017147
Spro = total propionate (kg COD/m3) = 0.020169
Sac = total acetate (kg COD/m3) = 0.070661

Sh2 = hydrogen gas (kg COD/m3) = 2.8014e-07
Sch4 = methane gas (kg COD/m3) = 0.05973
Sic = inorganic carbon (kmole C/m3) = 0.079453
Sin = inorganic nitrogen (kmole N/m3) = 0.057749 (= 0.80849 kg N/m3)
Si = soluble inerts (kg COD/m3) = 3.2335
Xc = composites (kg COD/m3) = 3.9234
Xch = carbohydrates (kg COD/m3) = 0.078156
Xpr = proteins (kg COD/m3) = 0.047708
Xli = lipids (kg COD/m3) = 0.14894
Xsu = sugar degraders (kg COD/m3) = 1.0601
Xaa = amino acid degraders (kg COD/m3) = 0.47276
Xfa = LCFA degraders (kg COD/m3) = 1.0468
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0.23296
Xpro = propionate degraders (kg COD/m3) = 0.13852
Xac = acetate degraders (kg COD/m3) = 1.0878
Xh2 = hydrogen degraders (kg COD/m3) = 0.54959
Xi = particulate inerts (kg COD/m3) = 9.0496
Scat+ = cations (base) (kmole/m3) = 0.02
San- = anions (acid) (kmole/m3) = 0.004555
Flow rate (m3/d) = 2360
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 13.8919
TS = total solids (kg/m3) = 24.358
MSS = mineralised suspended solids (kg/m3) = 10.4661
VSS = volatile suspended solids (kg/m3) = 11.5821
TSS = total suspended solids (kg/m3) = 22.0482
pH = pH within AD system = 7.2149
S_H+ = protons (kmole/m3) = 6.0967e-08
Sva- = valerate (kg COD/m3) = 0.011555
Sbu- = butyrate (kg COD/m3) = 0.017078
Spro- = propionate (kg COD/m3) = 0.020076
Sac- = acetate (kg COD/m3) = 0.070414
Shco3- = bicarbonate (kmole C/m3) = 0.07072
Sco2 = carbon dioxide (kmole C/m3) = 0.008733
Snh3 = ammonia (kmole N/m3) = 0.0010329
Snh4+ = ammonium (kmole N/m3) = 0.056717
Sgas,h2 = hydrogen concentration in gas phase (kg COD/m3) = 1.0675e-05
Sgas,ch4 = methane concentration in gas phase (kg COD/m3) = 1.6103
Sgas,co2 = carbon dioxide concentration in gas phase (kmole C/m3) = 0.012425
pgas,h2 = partial pressure of hydrogen gas (bar, true value i.e. not normalized) = 1.7094e-05
pgas,ch4 = partial pressure of methane gas (bar, true value i.e. not normalized) = 0.64467
pgas,co2 = partial pressure of carbon dioxide gas (bar, true value, i.e. not normalized) = 0.31834
pgas,total = total head space pressure of H2+CO2+CH4+H2O (bar, true value, i.e. not normalized) = 1.0187
qgas = gas flow rate normalized to atmospheric pressure (Nm3/d) = 57286.3757

Extra calculated outputs
Volatile fatty acids (kg COD/m3) = 0.11958
Produced hydrogen gas (kg H2/d) = 0.076015
Produced methane gas (kg CH4/d) = 22933.6797
Produced carbon dioxide gas (kg CO2/d) = 31143.4413
Energy content of methane gas (MJ/d) = 1147005.0583
Energy content of methane gas (kWh/d) = 318612.5162
VS reduction (%) = 61.3842
VSS reduction (%) = 67.8049
TS reduction (%) = 47.5504
TSS reduction (%) = 52.5241
Specific methane production (Nm3 CH4/kg VS_in) = 0.42701
Specific gas production (Nm3 gas/kg VS_in) = 0.67475

6.7 Case 4A

Future scenario using interface models, operation in series (2 reactors).

Combined input of primary and secondary sludge prior to ASM2ADM interface (identical to case 3A):

SI (inert soluble) = 0 mg COD/l
SS (readily biodegradable substrate) = 0 mg COD/l
XI (inert particulate) = 9721.2989 mg COD/l
XS (slowly biodegradable substrate) = 25217.3913 mg COD/l
XBH (heterotrophic biomass) = 5575.0924 mg COD/l
XBA (autotrophic biomass) = 0 mg COD/l
XP (particulate inert from biomass decay) = 0 mg COD/l
SO (oxygen) = 0 mg -COD/l
SNO (nitrate and nitrite) = 1.0598 mg N/l
SNH (ammonia) = 24.7011 mg N/l
SND (soluble organic nitrogen) = 0 mg N/l
XND (particulate organic nitrogen) = 1008.6957 mg N/l
SALK (alkalinity) = 7 mol HCO3/m3 = 427 mg HCO3/l
VS (volatile solids) = 26185.5054 mg VS/l
TS (total solids) = 37548.8315 mg TS/l
MSS (mineralised suspended solids) = 11363.3261 mg MSS/l
VSS (volatile suspended solids) = 26185.5054 mg VSS/l
TSS (total suspended solids)= 37548.8315 mg SS/l
Flow rate = 2024 m3/d
Temperature = 15 degC

SI_load = 0 kg COD/d
SS_load = 0 kg COD/d
XI_load = 19675.909 kg COD/d
XS_load = 51040 kg COD/d
XBH_load = 11283.987 kg COD/d
XBA_load = 0 kg COD/d
XP_load = 0 kg COD/d
SO_load = 0 kg -COD/d
SNO_load = 2.145 kg N/d
SNH_load = 49.995 kg N/d
SND_load = 0 kg N/d
XND_load = 2041.6 kg N/d
SALK_load = 14.168 kmol HCO3/d = 864.248 kg HCO3/d
VS_load = 52999.463 kg VS/d
TS_load = 75998.835 kg TS/d
MSS_load = 22999.372 kg MSS/d
VSS_load = 52999.463 kg VSS/d
TSS_load = 75998.835 kg SS/d

Combined primary and secondary sludge after ASM2ADM interface (identical to case 3A)

Ssu = monosacharides (kg COD/m3) = 0
Saa = amino acids (kg COD/m3) = 0
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0
Sva = total valerate (kg COD/m3) = 0
Sbu = total butyrate (kg COD/m3) = 0
Spro = total propionate (kg COD/m3) = 0
Sac = total acetate (kg COD/m3) = 0
Sh2 = hydrogen gas (kg COD/m3) = 0
Sch4 = methane gas (kg COD/m3) = 0
Sic = inorganic carbon (kmole C/m3) = 0.0083199
Sin = inorganic nitrogen (kmole N/m3) = 0.0017644
Si = soluble inerts (kg COD/m3) = 0
Xc = composites (kg COD/m3) = 0
Xch = carbohydrates (kg COD/m3) = 4.6758
Xpr = proteins (kg COD/m3) = 13.7516
Xli = lipids (kg COD/m3) = 10.578
Xsu = sugar degraders (kg COD/m3) = 0
Xaa = amino acid degraders (kg COD/m3) = 0
Xfa = LCFA degraders (kg COD/m3) = 0
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0
Xpro = propionate degraders (kg COD/m3) = 0
Xac = acetate degraders (kg COD/m3) = 0
Xh2 = hydrogen degraders (kg COD/m3) = 0
Xi = particulate inerts (kg COD/m3) = 11.5053
Scat+ = cations (base) (kmole/m3) = 0
San- = anions (acid) (kmole/m3) = 0.0053112
Flow rate (m3/d) = 2024
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 26.1867
TS = total solids (kg/m3) = 37.55
MSS = mineralised suspended solids (kg/m3) = 11.3633
VSS = volatile suspended solids (kg/m3) = 26.1867
TSS = total suspended solids (kg/m3) = 37.55

Combined primary and secondary sludge after ASM2ADM interface + external sludge input, i.e. total input to first digester (identical to case 3A)

Ssu = monosacharides (kg COD/m3) = 0
Saa = amino acids (kg COD/m3) = 0
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0
Sva = total valerate (kg COD/m3) = 0
Sbu = total butyrate (kg COD/m3) = 0
Spro = total propionate (kg COD/m3) = 0
Sac = total acetate (kg COD/m3) = 0
Sh2 = hydrogen gas (kg COD/m3) = 0
Sch4 = methane gas (kg COD/m3) = 0
Sic = inorganic carbon (kmole C/m3) = 0.0071353

Sin = inorganic nitrogen (kmole N/m3) = 0.0015132
Si = soluble inerts (kg COD/m3) = 0
Xc = composites (kg COD/m3) = 0
Xch = carbohydrates (kg COD/m3) = 10.5037
Xpr = proteins (kg COD/m3) = 13.2383
Xli = lipids (kg COD/m3) = 24.0698
Xsu = sugar degraders (kg COD/m3) = 0
Xaa = amino acid degraders (kg COD/m3) = 0
Xfa = LCFA degraders (kg COD/m3) = 0
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0
Xpro = propionate degraders (kg COD/m3) = 0
Xac = acetate degraders (kg COD/m3) = 0
Xh2 = hydrogen degraders (kg COD/m3) = 0
Xi = particulate inerts (kg COD/m3) = 12.4499
Scat+ = cations (base) (kmole/m3) = 0
San- = anions (acid) (kmole/m3) = 0.004555
Flow rate (m3/d) = 2360
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 35.9753
TS = total solids (kg/m3) = 46.4412
MSS = mineralised suspended solids (kg/m3) = 10.4659
VSS = volatile suspended solids (kg/m3) = 35.9753
TSS = total suspended solids (kg/m3) = 46.4412

Digester output from first reactor of 23700 m^3 (steady state), also input to second reactor (from state Ssu until state Temperature)

Ssu = monosacharides (kg COD/m3) = 0.020793
Saa = amino acids (kg COD/m3) = 0.0092607
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0.22587
Sva = total valerate (kg COD/m3) = 0.01999
Sbu = total butyrate (kg COD/m3) = 0.025798
Spro = total propionate (kg COD/m3) = 0.034809
Sac = total acetate (kg COD/m3) = 0.11471
Sh2 = hydrogen gas (kg COD/m3) = 4.2341e-07
Sch4 = methane gas (kg COD/m3) = 0.066527
Sic = inorganic carbon (kmole C/m3) = 0.062342
Sin = inorganic nitrogen (kmole N/m3) = 0.060507 (= 0.8471 kg N/m3)
Si = soluble inerts (kg COD/m3) = 0.090943
Xc = composites (kg COD/m3) = 0.18112
Xch = carbohydrates (kg COD/m3) = 0.10536
Xpr = proteins (kg COD/m3) = 0.13232
Xli = lipids (kg COD/m3) = 0.24001
Xsu = sugar degraders (kg COD/m3) = 0.97969
Xaa = amino acid degraders (kg COD/m3) = 0.88462
Xfa = LCFA degraders (kg COD/m3) = 1.1328
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0.36558
Xpro = propionate degraders (kg COD/m3) = 0.16158
Xac = acetate degraders (kg COD/m3) = 1.2867

Xh2 = hydrogen degraders (kg COD/m3) = 0.61879
Xi = particulate inerts (kg COD/m3) = 12.6318
Scat+ = cations (base) (kmole/m3) = 4.0875e-30
San- = anions (acid) (kmole/m3) = 0.004555
Flow rate (m3/d) = 2360
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 12.5513
TS = total solids (kg/m3) = 23.0172
MSS = mineralised suspended solids (kg/m3) = 10.4659
VSS = volatile suspended solids (kg/m3) = 12.1561
TSS = total suspended solids (kg/m3) = 22.622
pH = pH within AD system = 7.0525
S_H+ = protons (kmole/m3) = 8.8608e-08
Sva- = valerate (kg COD/m3) = 0.019863
Sbu- = butyrate (kg COD/m3) = 0.025648
Spro- = propionate (kg COD/m3) = 0.034577
Sac- = acetate (kg COD/m3) = 0.11412
Shco3- = bicarbonate (kmole C/m3) = 0.052856
Sco2 = carbon dioxide (kmole C/m3) = 0.0094863
Snh3 = ammonia (kmole N/m3) = 0.0007488
Snh4+ = ammonium (kmole N/m3) = 0.059759
Sgas,h2 = hydrogen concentration in gas phase (kg COD/m3) = 1.3204e-05
Sgas,ch4 = methane concentration in gas phase (kg COD/m3) = 1.5502
Sgas,co2 = carbon dioxide concentration in gas phase (kmole C/m3) = 0.013386
pgas,h2 = partial pressure of hydrogen gas (bar, true value i.e. not normalized) = 2.1144e-05
pgas,ch4 = partial pressure of methane gas (bar, true value i.e. not normalized) = 0.62058
pgas,co2 = partial pressure of carbon dioxide gas (bar, true value, i.e. not normalized) = 0.34296
pgas,total = total head space pressure of H2+CO2+CH4+H2O (bar, true value, i.e. not normalized) = 1.0192
qgas = gas flow rate normalized to atmospheric pressure (Nm3/d) = 62699.218

Extra calculated outputs
Volatile fatty acids (kg COD/m3) = 0.1953
Produced hydrogen gas (kg H2/d) = 0.10285
Produced methane gas (kg CH4/d) = 24150.0898
Produced carbon dioxide gas (kg CO2/d) = 36702.7707
Energy content of methane gas (MJ/d) = 1207842.5913
Energy content of methane gas (kWh/d) = 335511.8309
VS reduction (%) = 65.1112
VSS reduction (%) = 66.2099
TS reduction (%) = 50.4379
TSS reduction (%) = 51.289
Specific methane production (Nm3 CH4/kg VS_in) = 0.44965
Specific gas production (Nm3 gas/kg VS_in) = 0.73849

Digester output from second reactor of 15200 m^3 (steady state)

Ssu = monosacharides (kg COD/m3) = 0.00078031
Saa = amino acids (kg COD/m3) = 0.00030556
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0.006319
Sva = total valerate (kg COD/m3) = 0.00079179
Sbu = total butyrate (kg COD/m3) = 0.00099939
Spro = total propionate (kg COD/m3) = 0.0012197
Sac = total acetate (kg COD/m3) = 0.0035123
Sh2 = hydrogen gas (kg COD/m3) = 1.8155e-08
Sch4 = methane gas (kg COD/m3) = 0.047998
Sic = inorganic carbon (kmole C/m3) = 0.066586
Sin = inorganic nitrogen (kmole N/m3) = 0.063321 (= 0.8865 kg N/m3)
Si = soluble inerts (kg COD/m3) = 0.1535
Xc = composites (kg COD/m3) = 0.19426
Xch = carbohydrates (kg COD/m3) = 0.0035237
Xpr = proteins (kg COD/m3) = 0.0039359
Xli = lipids (kg COD/m3) = 0.0065389
Xsu = sugar degraders (kg COD/m3) = 0.89164
Xaa = amino acid degraders (kg COD/m3) = 0.80227
Xfa = LCFA degraders (kg COD/m3) = 1.0365
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0.33415
Xpro = propionate degraders (kg COD/m3) = 0.14841
Xac = acetate degraders (kg COD/m3) = 1.18
Xh2 = hydrogen degraders (kg COD/m3) = 0.56569
Xi = particulate inerts (kg COD/m3) = 12.7569
Scat+ = cations (base) (kmole/m3) = -2.6358e-29
San- = anions (acid) (kmole/m3) = 0.004555
Flow rate (m3/d) = 2360
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 11.7787
TS = total solids (kg/m3) = 22.2447
MSS = mineralised suspended solids (kg/m3) = 10.4659
VSS = volatile suspended solids (kg/m3) = 11.6389
TSS = total suspended solids (kg/m3) = 22.1048
pH = pH within AD system = 7.123
S_H+ = protons (kmole/m3) = 7.5338e-08
Sva- = valerate (kg COD/m3) = 0.00078749
Sbu- = butyrate (kg COD/m3) = 0.00099444
Spro- = propionate (kg COD/m3) = 0.0012127
Sac- = acetate (kg COD/m3) = 0.0034972
Shco3- = bicarbonate (kmole C/m3) = 0.057771
Sco2 = carbon dioxide (kmole C/m3) = 0.0088156
Snh3 = ammonia (kmole N/m3) = 0.00091964
Snh4+ = ammonium (kmole N/m3) = 0.062401
Sgas,h2 = hydrogen concentration in gas phase (kg COD/m3) = 9.3082e-07
Sgas,ch4 = methane concentration in gas phase (kg COD/m3) = 1.5813
Sgas,co2 = carbon dioxide concentration in gas phase (kmole C/m3) = 0.012664
pgas,h2 = partial pressure of hydrogen gas (bar, true value i.e. not normalized) = 1.4905e-06

pgas,ch4 = partial pressure of methane gas (bar, true value i.e. not normalized) = 0.63304
pgas,co2 = partial pressure of carbon dioxide gas (bar, true value, i.e. not normalized) = 0.32447
pgas,total = total head space pressure of H2+CO2+CH4+H2O (bar, true value, i.e. not normalized) = 1.0132
qgas = gas flow rate normalized to atmospheric pressure (Nm3/d) = 1775.9838

Extra calculated outputs
Volatile fatty acids (kg COD/m3) = 0.0065232
Produced hydrogen gas (kg H2/d) = 0.0002066
Produced methane gas (kg CH4/d) = 701.9679
Produced carbon dioxide gas (kg CO2/d) = 989.4333
Energy content of methane gas (MJ/d) = 35108.224
Energy content of methane gas (kWh/d) = 9752.2844
VS reduction (%) = 6.1554
VSS reduction (%) = 4.2547
TS reduction (%) = 3.3565
TSS reduction (%) = 2.2863
Specific methane production (Nm3 CH4/kg VS_in) = 0.037461
Specific gas production (Nm3 gas/kg VS_in) = 0.059957

Second digester sludge output after ADM2ASM interface

SI (inert soluble) = 153.5025 mg COD/l
SS (readily biodegradable substrate) = 13.928 mg COD/l
XI (inert particulate) = 12756.9308 mg COD/l
XS (slowly biodegradable substrate) = 4125.5956 mg COD/l
XBH (heterotrophic biomass) = 0 mg COD/l
XBA (autotrophic biomass) = 0 mg COD/l
XP (particulate inert from biomass decay) = 1041.3164 mg COD/l
SO (oxygen) = 0 mg -COD/l
SNO (nitrate and nitrite) = 0 mg N/l
SNH (ammonia) = 1082.6267 mg N/l
SND (soluble organic nitrogen) = 0.029945 mg N/l
XND (particulate organic nitrogen) = 154.9818 mg N/l
SALK (alkalinity) = 72.7753 mol HCO3/m3 = 4439.2906 mg HCO3/l
VS (volatile solids) = 11747.5801 mg VS/l
TS (total solids) = 22213.4835 mg TS/l
MSS (mineralised suspended solids) = 10465.9034 mg MSS/l
VSS (volatile suspended solids) = 11638.859 mg VSS/l
TSS (total suspended solids)= 22104.7624 mg SS/l
Flow rate = 2360 m3/d
Temperature = 15 degC

SI_load = 362.266 kg COD/d
SS_load = 32.8701 kg COD/d
XI_load = 30106.3568 kg COD/d
XS_load = 9736.4056 kg COD/d
XBH_load = 0 kg COD/d

XBA_load = 0 kg COD/d
XP_load = 2457.5067 kg COD/d
SO_load = 0 kg -COD/d
SNO_load = 0 kg N/d
SNH_load = 2554.9989 kg N/d
SND_load = 0.070669 kg N/d
XND_load = 365.757 kg N/d
SALK_load = 171.7496 kmol HCO3/d = 10476.7258 kg HCO3/d
VS_load = 27724.2891 kg VS/d
TS_load = 52423.8211 kg TS/d
MSS_load = 24699.532 kg MSS/d
VSS_load = 27467.7072 kg VSS/d
TSS_load = 52167.2392 kg SS/d

6.8 Case 4B

Future scenario not using interface models, operation in series (2 reactors).

Total input to digester 1 (identical to case 3B)

Ssu = monosacharides (kg COD/m3) = 0
Saa = amino acids (kg COD/m3) = 0
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0
Sva = total valerate (kg COD/m3) = 0
Sbu = total butyrate (kg COD/m3) = 0
Spro = total propionate (kg COD/m3) = 0
Sac = total acetate (kg COD/m3) = 0
Sh2 = hydrogen gas (kg COD/m3) = 0
Sch4 = methane gas (kg COD/m3) = 0
Sic = inorganic carbon (kmole C/m3) = 0
Sin = inorganic nitrogen (kmole N/m3) = 0.033029 (of which 0.031516 for N-balance)
Si = soluble inerts (kg COD/m3) = 0
Xc = composites (kg COD/m3) = 34.7458
Xch = carbohydrates (kg COD/m3) = 6.4936
Xpr = proteins (kg COD/m3) = 1.4445
Xli = lipids (kg COD/m3) = 14.9979
Xsu = sugar degraders (kg COD/m3) = 0
Xaa = amino acid degraders (kg COD/m3) = 0
Xfa = LCFA degraders (kg COD/m3) = 0
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0
Xpro = propionate degraders (kg COD/m3) = 0
Xac = acetate degraders (kg COD/m3) = 0
Xh2 = hydrogen degraders (kg COD/m3) = 0
Xi = particulate inerts (kg COD/m3) = 2.5826
Scat+ = cations (base) (kmole/m3) = 0.02
San- = anions (acid) (kmole/m3) = 0.004555
Flow rate (m3/d) = 2360
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 35.9746
TS = total solids (kg/m3) = 46.4407
MSS = mineralised suspended solids (kg/m3) = 10.4661
VSS = volatile suspended solids (kg/m3) = 35.9746
TSS = total suspended solids (kg/m3) = 46.4407

Digester output from first digester of 23700 m^3 (steady state), also input to digester 2 (from state Ssu to state Temperature)

Ssu = monosacharides (kg COD/m3) = 0.020797
Saa = amino acids (kg COD/m3) = 0.0092625
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0.22595
Sva = total valerate (kg COD/m3) = 0.017949
Sbu = total butyrate (kg COD/m3) = 0.026899
Spro = total propionate (kg COD/m3) = 0.034819

Sac = total acetate (kg COD/m3) = 0.12455
Sh2 = hydrogen gas (kg COD/m3) = 4.2349e-07
Sch4 = methane gas (kg COD/m3) = 0.066472
Sic = inorganic carbon (kmole C/m3) = 0.074784
Sin = inorganic nitrogen (kmole N/m3) = 0.054005 (= 0.75608 kg N/m3)
Si = soluble inerts (kg COD/m3) = 2.9786
Xc = composites (kg COD/m3) = 5.932
Xch = carbohydrates (kg COD/m3) = 0.12276
Xpr = proteins (kg COD/m3) = 0.072977
Xli = lipids (kg COD/m3) = 0.23598
Xsu = sugar degraders (kg COD/m3) = 1.1235
Xaa = amino acid degraders (kg COD/m3) = 0.48761
Xfa = LCFA degraders (kg COD/m3) = 1.1136
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0.24149
Xpro = propionate degraders (kg COD/m3) = 0.14515
Xac = acetate degraders (kg COD/m3) = 1.1461
Xh2 = hydrogen degraders (kg COD/m3) = 0.58115
Xi = particulate inerts (kg COD/m3) = 8.5397
Scat+ = cations (base) (kmole/m3) = 0.02
San- = anions (acid) (kmole/m3) = 0.004555
Flow rate (m3/d) = 2360
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 15.0957
TS = total solids (kg/m3) = 25.5618
MSS = mineralised suspended solids (kg/m3) = 10.4661
VSS = volatile suspended solids (kg/m3) = 12.8195
TSS = total suspended solids (kg/m3) = 23.2856
pH = pH within AD system = 7.185
S_H+ = protons (kmole/m3) = 6.5316e-08
Sva- = valerate (kg COD/m3) = 0.017865
Sbu- = butyrate (kg COD/m3) = 0.026784
Spro- = propionate (kg COD/m3) = 0.034647
Sac- = acetate (kg COD/m3) = 0.12409
Shco3- = bicarbonate (kmole C/m3) = 0.066046
Sco2 = carbon dioxide (kmole C/m3) = 0.0087376
Snh3 = ammonia (kmole N/m3) = 0.00090268
Snh4+ = ammonium (kmole N/m3) = 0.053103
Sgas,h2 = hydrogen concentration in gas phase (kg COD/m3) = 1.3958e-05
Sgas,ch4 = methane concentration in gas phase (kg COD/m3) = 1.6138
Sgas,co2 = carbon dioxide concentration in gas phase (kmole C/m3) = 0.01236
pgas,h2 = partial pressure of hydrogen gas (bar, true value i.e. not normalized) = 2.2351e-05
pgas,ch4 = partial pressure of methane gas (bar, true value i.e. not normalized) = 0.64606
pgas,co2 = partial pressure of carbon dioxide gas (bar, true value, i.e. not normalized) = 0.31667
pgas,total = total head space pressure of H2+CO2+CH4+H2O (bar, true value, i.e. not normalized) = 1.0184
qgas = gas flow rate normalized to atmospheric pressure (Nm3/d) = 54421.8903

Extra calculated outputs
Volatile fatty acids (kg COD/m3) = 0.20422
Produced hydrogen gas (kg H2/d) = 0.094448
Produced methane gas (kg CH4/d) = 21839.8932
Produced carbon dioxide gas (kg CO2/d) = 29438.5988
Energy content of methane gas (MJ/d) = 1092300.4167
Energy content of methane gas (kWh/d) = 303416.7824
VS reduction (%) = 58.038
VSS reduction (%) = 64.3651
TS reduction (%) = 44.9583
TSS reduction (%) = 49.8595
Specific methane production (Nm3 CH4/kg VS_in) = 0.40664
Specific gas production (Nm3 gas/kg VS_in) = 0.64101

Digester output from second digester of 15200 m^3 (steady state)

Ssu = monosacharides (kg COD/m3) = 0.0028581
Saa = amino acids (kg COD/m3) = 0.001969
Sfa = long chain fatty acids (LCFA) (kg COD/m3) = 0.018548
Sva = total valerate (kg COD/m3) = 0.0035624
Sbu = total butyrate (kg COD/m3) = 0.0047202
Spro = total propionate (kg COD/m3) = 0.0042969
Sac = total acetate (kg COD/m3) = 0.012463
Sh2 = hydrogen gas (kg COD/m3) = 6.0107e-08
Sch4 = methane gas (kg COD/m3) = 0.04882
Sic = inorganic carbon (kmole C/m3) = 0.083367
Sin = inorganic nitrogen (kmole N/m3) = 0.060001 (= 0.84002 kg N/m3)
Si = soluble inerts (kg COD/m3) = 3.4784
Xc = composites (kg COD/m3) = 1.5521
Xch = carbohydrates (kg COD/m3) = 0.017161
Xpr = proteins (kg COD/m3) = 0.0164
Xli = lipids (kg COD/m3) = 0.026534
Xsu = sugar degraders (kg COD/m3) = 1.1024
Xaa = amino acid degraders (kg COD/m3) = 0.50735
Xfa = LCFA degraders (kg COD/m3) = 1.0838
Xc4 = valerate and butyrate degraders (kg COD/m3) = 0.24888
Xpro = propionate degraders (kg COD/m3) = 0.14611
Xac = acetate degraders (kg COD/m3) = 1.1398
Xh2 = hydrogen degraders (kg COD/m3) = 0.57321
Xi = particulate inerts (kg COD/m3) = 9.5394
Scat+ = cations (base) (kmole/m3) = 0.02
San- = anions (acid) (kmole/m3) = 0.004555
Flow rate (m3/d) = 2360
Temperature (degC) = 35
VS = volatile solids (kg/m3) = 12.681
TS = total solids (kg/m3) = 23.1471
MSS = mineralised suspended solids (kg/m3) = 10.4661
VSS = volatile suspended solids (kg/m3) = 10.3592
TSS = total suspended solids (kg/m3) = 20.8253

pH = pH within AD system = 7.2098
S_H+ = protons (kmole/m3) = 6.1692e-08
Sva- = valerate (kg COD/m3) = 0.0035465
Sbu- = butyrate (kg COD/m3) = 0.0047011
Spro- = propionate (kg COD/m3) = 0.0042769
Sac- = acetate (kg COD/m3) = 0.012419
Shco3- = bicarbonate (kmole C/m3) = 0.074107
Sco2 = carbon dioxide (kmole C/m3) = 0.0092601
Snh3 = ammonia (kmole N/m3) = 0.0010608
Snh4+ = ammonium (kmole N/m3) = 0.05894
Sgas,h2 = hydrogen concentration in gas phase (kg COD/m3) = 2.891e-06
Sgas,ch4 = methane concentration in gas phase (kg COD/m3) = 1.543
Sgas,co2 = carbon dioxide concentration in gas phase (kmole C/m3) = 0.013278
pgas,h2 = partial pressure of hydrogen gas (bar, true value i.e. not normalized) = 4.6294e-06
pgas,ch4 = partial pressure of methane gas (bar, true value i.e. not normalized) = 0.6177
pgas,co2 = partial pressure of carbon dioxide gas (bar, true value, i.e. not normalized) = 0.3402
pgas,total = total head space pressure of H2+CO2+CH4+H2O (bar, true value, i.e. not normalized) = 1.0136
qgas = gas flow rate normalized to atmospheric pressure (Nm3/d) = 5690.771

Extra calculated outputs
Volatile fatty acids (kg COD/m3) = 0.025042
Produced hydrogen gas (kg H2/d) = 0.0020553
Produced methane gas (kg CH4/d) = 2193.9429
Produced carbon dioxide gas (kg CO2/d) = 3322.8731
Energy content of methane gas (MJ/d) = 109727.8595
Energy content of methane gas (kWh/d) = 30479.961
VS reduction (%) = 15.9956
VSS reduction (%) = 19.1922
TS reduction (%) = 9.4463
TSS reduction (%) = 10.5659
Specific methane production (Nm3 CH4/kg VS_in) = 0.097349
Specific gas production (Nm3 gas/kg VS_in) = 0.15974

6.9 Summary of results

Below some of the results presented in the previous sub-sections are summarized. For the two-reactors systems (cases 2 and 4) the values represent the combined effects of both reactors.

- case 1A: Current scenario using interface models, operation in parallel (1 reactor);
- case 1B: Current scenario not using interface models, operation in parallel (1 reactor);
- case 2A: Current scenario using interface models, operation in series (2 reactors);
- case 2B: Current scenario not using interface models, operation in series (2 reactors);
- case 3A: Future scenario using interface models, operation in parallel (1 reactor);
- case 3B: Future scenario not using interface models, operation in parallel (1 reactor);
- case 4A: Future scenario using interface models, operation in series (2 reactors);
- case 4B: Future scenario not using interface models, operation in series (2 reactors);

case	VS in (kg/d)	Biogas production (Nm^3/d)	Methane production (kg CH_4/d)	Methane content (%)	VS reduction (%)	Methane exchange (Nm^3 CH_4/kg VS_in)	SRT (days)
1A	55350	40041	16024	63.3	64.2	0.458	20.4
1B	55350	35624	14762	65.5	58.2	0.422	20.4
2A	55350	40508	16217	63.3	65.1	0.463	20.4
2B	55350	37777	15612	65.3	62.2	0.446	20.4
3A	84900	63704	24548	60.9	66.3	0.457	16.5
3B	84900	57286	22934	63.3	61.4	0.427	16.5
4A	84900	64475	24852	60.9	67.3	0.462	16.5
4B	84900	60113	24034	63.2	64.8	0.447	16.5

The simulations indicate an increase in methane production by series operation rather than parallel operation of the AD system by:

- current A: 1.2%
- current B: 5.8%
- future A: 1.2%
- future B: 4.8%

The simulations also suggest that the existing AD volumes will be large enough to handle the expected increased sludge load during the next ten years without a significant decrease in methane yield. For this reason, cases 1A and 1B were simulated using a reduced AD volume (31500 m^3), which gives a SRT of 16.5 days. For case 1A the total methane production was thereby reduced by 0.7% and for case 1B by 2.1%.

7. Conclusions

As may be expected no major differences between the results from the two system principles are visible during normal operating conditions, i.e. what can be seen in steady state. The potential advantages of a two-stage digestion system are more to be found during dynamic conditions and problematic operation (i.e. start-up, toxic and inhibitory events etc.) as a result of its higher flexibility. However, a somewhat higher gas production can be expected by series operation. The simulations do support the conclusion that the AD system at Henriksdal WWTP can manage a higher organic load than what is used today without any expected process disturbances, utilizing the volumes already available, thereby reducing the need for volume expansions during the next ten years. It must, however, be noted that when operating a system closer to its limitations (e.g. reduced SRT) the demands on the associated monitoring and control systems increase since unexpected process disturbance are then more likely to create dramatic process problems, i.e. the inherent robustness of the system is reduced.

In this study, the AD process has only been investigated using a steady-state perspective. Future studies could also include process optimisation, start-up procedures (i.e. the dynamic behaviour of the system) and other specific situations. Examples of studied parameters to improve and optimise the anaerobic process are process temperature, mixing rate, feed rate, feed concentration and retention time. Enhanced monitoring and control strategies have a significant potential to increase the performance of AD systems further. Many digesters are today operated far below their maximum capacity to avoid overload. With closer monitoring (on-line) and control the organic loading rate can be increased and more waste can be added to the existing digesters, generating more biogas without costly volume expansions.

No specific calibration efforts have been performed for these simulations (identical model set-up as used in Jeppsson, 2007). Default model parameters for the ADM1 and the AS/AD model interface have been used throughout the simulations. However, results from case 1 indicate large similarities with the current AD system at Henriksdal WWTP in terms of gas production, pH, alkalinity, VS reduction, production of methane per mass of VS_in, methane content in gas, concentration of volatile fatty acids, etc., taking into account that the simulated AD system is not exposed to any process disturbances whatsoever, i.e. the internal mixing is perfect, the influent sludge flow rate is perfectly constant, the pH and temperature are optimal during the entire operation, no inhibitions (or toxicity) of any kind affects the system during the complete year, etc. It is highly unlikely that any full-scale AD system at a WWTP is operating for a full year without any types of process disturbances. If we would assume that the Henriksdal AD system on an average has a true production capacity 80-90% of its optimal performance during a year, it is clear that the values predicted by the simulations for case 1A (gas production, VS reduction, amount of CH_4/kg VS_in, etc.) would be in almost perfect agreement with the available Henriksdal AD measurements. As case 1 can be compared and partly validated with true data, this is also an indication that results from simulation cases 2, 3 and 4 are realistic and reliable under ideal conditions. Certainly, the results presented in this report represent a significantly better prediction of the future scenario than the results in Jeppsson (2007), primarily due to the more detailed characterisation of the influent sludge and the associated data provided by Stockholm Water.

Another topic, which has received attention during the last years but is not discussed in this report, is pre-treatment of sludge prior to anaerobic digestion. Methods that have been studied are related to solids disintegration by using ultrasonic treatment, thermal treatment and enhanced enzymatic hydrolysis. Other issues that have not been studied are, for example, heavy metal contents of the digested sludge, struvite production (magnesium related) and processes related to sulphur and phosphorus in the sludge. None of these processes are currently included in the ADM1.

If the investigation is continued the following topics may be relevant to approach:

- calibration of the ADM1 using more data from existing operation including inhibition, toxicity etc.;
- literature review on series operation of digesters and how dynamics, conversion rates, biomass fractionation, etc. are affected;
- collect experiences from other plants, which have converted their AD system from parallel to series operation;
- pilot scale tests of AD series operation using Henriksdal's sludge;
- include and develop monitoring and control strategies for the digestion process;
- analysing dynamics by means of simulations in terms of start-up and recovery procedures and other aspects;
- potential benefits from various pre-treatment methods for influent sludge.

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