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Model based design of an agricultural biogas plant – application of Anaerobic Digestion Model No.1 for an improved 4 chamber scheme

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Abstract Different digestion technologies for various substrates are addressed by the generic process description of Anaerobic Digestion Model No. 1. In case of manure or agricultural wastes a priori knowledge about the substrate in terms of ADM1 compounds is lacking and influent characterisation becomes a major issue. The actual project has been initiated for promotion of biogas technology in agriculture and for expansion of profitability also to rather small capacity systems. In order to avoid costly individual planning and installation of each facility a standardised design approach needs to be elaborated. This intention pleads for bio kinetic modelling as a systematic tool for process design and optimisation. Cofermentation under field conditions was observed, quality data and flow data were recorded and mass flow balances were calculated. In the lab different substrates have been digested separately in parallel under specified conditions. A configuration of 4 ADM1 model reactors was set up. Model calibration identified disintegration rate, decay rates for sugar degraders and half saturation constant for sugar as the 3 most sensitive parameters showing values (except the latter) about one order of magnitude higher than default parameters. Finally the model is applied to the comparison of different reactor configurations and volume partitions. Another optimisation objective is robustness and load flexibility, i.e. the same configuration should be adaptive to different load situation only by a simple recycle control in order to establish a standardised design.
Keywords ADM1; agricultural wastes; anaerobic digestion; biogas; manure; modelling

INTRODUCTION

IWA's Anaerobic Digestion Model No.1 (ADM1) represents a universally applicable bio kinetic model for the mathematical description of anaerobic digestion of different types of organic substrates (Batstone *et al.*, 2002a). In the vast majority of investigations on applications of ADM1 done so far sewage sludge was the object of research. Sets of validated parameters for sewage sludge digestion have been suggested (e.g. Blumensaat and Keller, 2005) and transfer across the model interface of information about the feed sludge has been reported (Wett *et al.*, 2005). In case of manure or other agricultural wastes a priori knowledge about the substrate in terms of ADM1 compounds is lacking and influent characterisation becomes a major issue. Only few studies concerning ADM1 parameter estimation for agricultural wastes are available till present day (e.g. Kalfas *et al.*, 2005).

ADM1 describes digestion of particulate composites as a 5-stage process involving disintegration, hydrolysis, acidogenesis, acetogenesis and methanogenesis, of which the last 3 process steps are represented by growth kinetics of the specific degrading biomass (Fig. 1). In the first step composite solids and cells of microorganisms are decomposed to their principal constituents including carbohydrates, proteins and fats. Additionally, inert particulate and soluble matter emerge which are not affected by the subsequent reactions. This process step is named disintegration and represents a characterisation of the input substrate. Subsequently, the macromolecular products are subject to enzymatic degradation and transformed to monosaccharides (MS), amino acids (AA) and long chain fatty acids (LCFA). Further anaerobic digestion leads from an acetogenic and a methanogenic phase to biogas production (CH4, CO2).

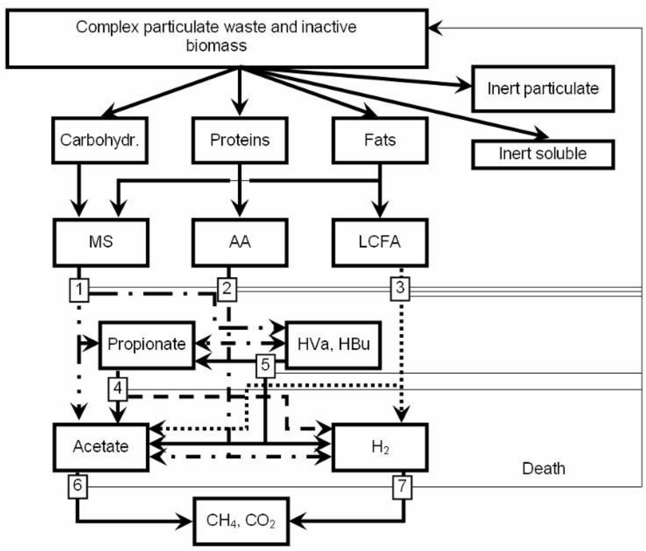

Figure 1. The anaerobic model as implemented including biochemical processes: (1) acidogenesis from sugars, (2) acidogenesis from amino acids, (3) acetogenesis from LCFA, (4) acetogenesis from propionate, (5) acetogenesis from butyrate and valerate, (6) aceticlastic methanogenesis, and (7) hydrogenotrophic methanogenesis (Batstone *et al.*, 2002b)

Due to the model complexity and amount of states only a limited number of variables can be covered by quality measurements. Model calibration procedures allow systematic analysis of the collected data of detected concentrations and provide the possibility to check the results for plausibility. Accurately defined cause-and-effect relationships lead to an increased process comprehension and make the biogas plant more transparent.

Here the model is applied to develop an optimised 4 chamber scheme for an agricultural biogas plant. Compared to a completely mixed reactor the 4-chamber scheme approaches plug-flow characteristics and obviously attains a “better” end-product in terms odour generation and hygienic aspects and additionally yields higher gas production rates. These advantages are paid off by less process stability especially when overloading the first compartment. Required recycle rates and appropriate combination of co-substrates need to be investigated.

METHODS

To cover both tasks – proper influent characterisation of agricultural wastes and close model-design interaction – long term monitoring campaigns were conducted both on the full-scale and lab-scale (Fig. 2 and Fig. 3). In a biogas plant sited on a pig farm (Fig. 2), co-fermentation under field conditions was observed, quality data (TSS, VSS, COD_x, COD_s, N_{total}, NH_4^+-N, C, S, CH_4, CO_2, pH) and flow data were recorded and mass flow balances were calculated. Gas samples were analysed by chromatography (methane and carbon dioxide) and carbon was detected by an IR-based C-S-analyser. In the lab different substrates (biowaste and manure) taken from the farm have been digested separately in parallel under specified conditions in a 2-reactor-system each (continuously stirred anaerobic reactors, Fig. 3). One week prior to feeding with the substrates sewage sludge from WWTP Innsbruck, Austria was put into the reactors and served as inoculum. Moreover variations in the feed-flow have been induced in order to improve parameterization for model calibration.

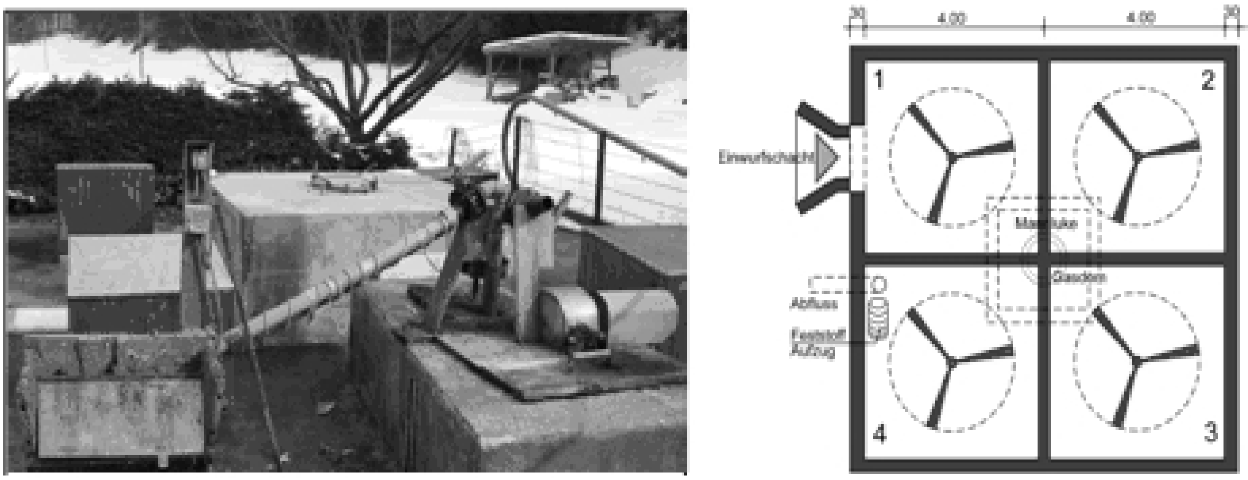

Figure 2. 4-chamber biogas plant for co-fermentation of piggery manure and biowaste with a total volume of 190 m³

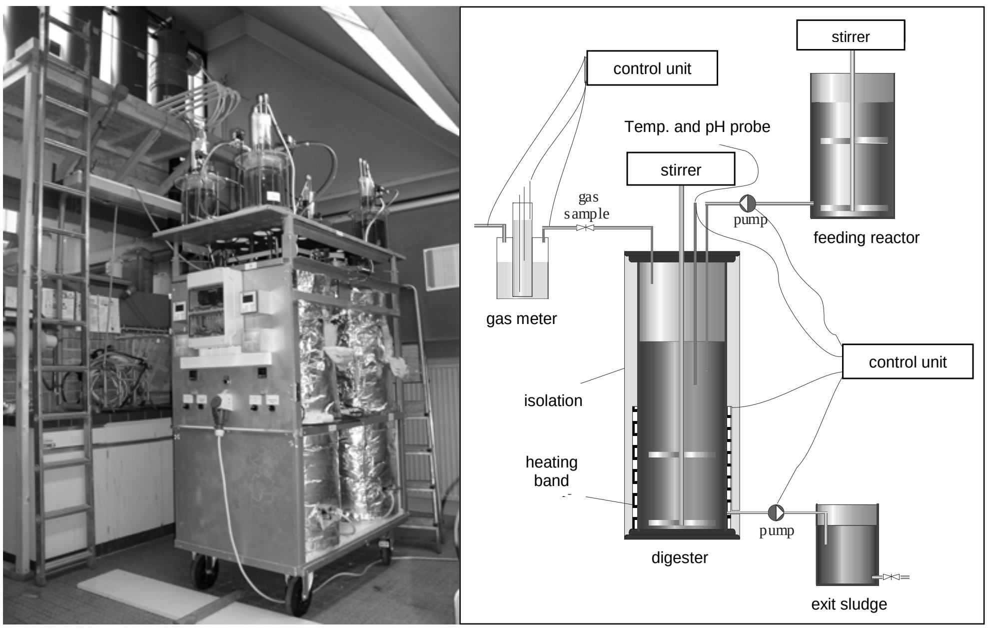

Figure 3. Set-up of 4 lab-scale digesters with a volume of 0.1 m³ each for parallel digestion tests

The subsequent calibration procedure was based on the principle of mass conservation of nitrogen (ammonia release characterising influent proteins) and carbon (gas yield, -composition and corresponding degradation performance). A configuration of 2 ADM1 model reactors was set up by using the Matlab-Simulink® based commercial simulator SIMBA©. Data sets from lab-scale experiments of manure digestion were used for parameter calibration.

The projected 4-chamber pilot plant (Fig. 4) has a layout formed by two concentric cylinders. The inner cylinder and the outer ring contain two chambers each separated by baffles. The mode of operation is as follows: substrate is pumped to chamber 1 (K1) and biogas production starts. Since the construction is gas-tight, gas pressure of the head space of chamber 1 displaces liquid below the baffle to K2. The outflow from K2 to K3 is accomplished by a weir outlet situated right under the top sealing of the reactor. Within K3 and K4 an annular flow is induced intermittently by a stirrer which mobilises settled solids. Deposits in K1 and K2 are avoided by periodical opening of a relief valve causing an oscillation and a subsequent recycle flow between K1 and K2.

For the comparison of different reactor configurations and volume partitions the calibrated parameters were applied to a 4-reactor-model in SIMBA© representing the pilot plant (Fig. 5). Recycle flows from chamber 2 to 1 and chamber 4 to 1 were simulated separately. Another optimisation objective was robustness and load flexibility, i.e. the same configuration should be adaptive to different load situations only by recycle control in order to establish a standardised design. Therefore the optimised scheme was tested for different load scenarios and pH and gas-flow distribution were studied.

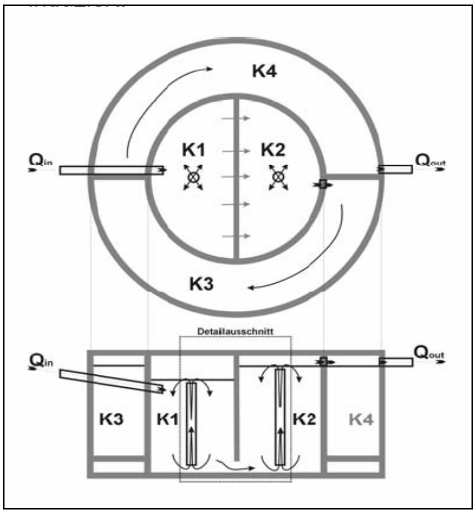

Figure 4. Improved flow scheme of the 4-chamber pilot plant with cylindrical shape

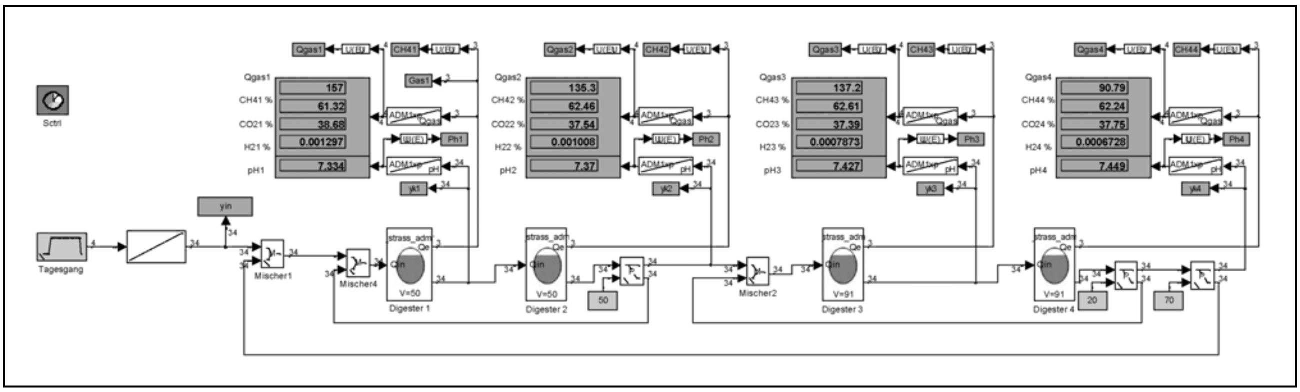

Figure 5. 4-chamber system represented by serial ADM1 digesters edited in the SIMBA-environment for the simulation of gas production in individual chambers

RESULTS

Measured values of the input substrate can be seen from Tab. 1. Gas production and pH was measured daily while feed tanks were refilled and sampled weekly.

Table 1. Input values of manure

week	CSB_s [mg/l]	CSB_x [mg/l]	N_{tot} [mg/l]	NH_4-N [mg/l]	N_{org} [mg/l]	TSS [g/l]	VSS [g/l]	TC [g/l]	TIC [g/l]	S [g/l]
1	-	-	-	-	-	-	-	-	-	-
2	8086	36020	1936	187	1749	36.0	25.3	13.8	0.26	0.11
3	9058	44248	2135	301	1833	44.8	31.2	17.2	0.31	0.14
4	9146	43217	1880	157	1722	41.1	29.7	14.8	0.26	0.13
average	8763	41162	1984	215	1768	40.6	28.7	15.3	0.28	0.13

Figure 6 below shows the results of calibration with the 2-reactor-model. Lab experiments comprised two phases: an initial stabilization phase when the digesters where fed with 75 liters of inoculum each on day 0 and no further feeding for 8 days. After that period the reactors were fed with manure from the pig farm under mesophilic conditions. The feeding was done semicontinously, i.e. a batch of 7.5 liters was put to the reactors once a day.

As can be seen from Fig. 6 simulated and measured values matched well with exception of the period from day 25 to 30. Since there was a continuous feeding up to the end of the 30 day period the decrease in the measured gas production is not explicable and is attributed to errors in the measurement device.

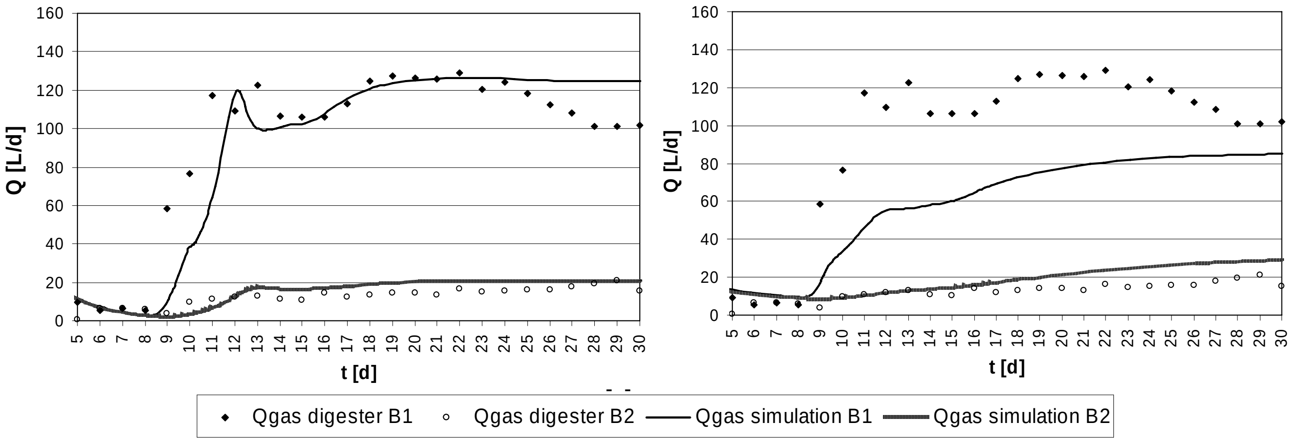

Figure 6. Calibration runs for gas production comparing best fit disintegration rate (*kdis* = 0.5, left) and default parameter (*kdis* = 0.096, right)

While calibrating, the coefficients for disintegration (*kdis* in ADM1 terminology), saturation of sugar (*KS_su*) and decay of sugar degraders (*kdec_Xsu*) as well as the carbon and nitrogen contents of the composite fraction (*Xc*) turned out to be the parameters most sensitive to model behaviour. Especially *kdis* revealed a remarkable influence on the distribution of gas production between both digestion steps (compare Fig. 6). Applying the default disintegration rate for piggery manure (*kdis* = 0.096) leads to an accumulation of particulate substrate and a shift of digestion activity to the second step.

Table 2. Calibrated ADM1 model parameters

parameter	description	unit	chosen value	parameter	description	unit	chosen value	ADM 1 default
fSI_XC	fraction SI from composites Xc	[-]	0.015	C_Xc	carbon content composites Xc	[k mole C/ kg COD]	0.028	
fCH_XC	fraction Xch from composites Xc	[-]	0.34	N_Xc	nitrogen content composites Xc	[k mole N/ kg COD]	0.00215	
fPR_XC	fraction Xpr from composites Xc	[-]	0.18	kdis	disintegration rate	[1/d]	0.5	0.096
fLI_XC	fraction Xli from composites Xc	[-]	0.14	KS_su	half saturation constant sugar	[kg COD/m³]	0.5	0.533
fXP_XC	fraction Xp from composites Xc	[-]	0.2	kdec_Xsu	decay rate Xsu	[1/d]	0.7	0.01

Of course, the fractionizing factors for the composites also play an important role in model performance as they determine a characterisation of the input substrate. Reported compositions of piggery manure from literature (Møller *et al.*, 2004) indicate a relatively high portion of carbo-hydrates compared to proteins and lipids. Namely, proportions average out to ch / pr = 1.9 and ch / li = 2.4. Given substrate ratios have been used in current calibration study in good agreement with measured total nitrogen and carbon content of the influent flow.

Table 2 gives an overview on the applied parameters and their deviation from the default values suggested in the original model description of ADM1 (Batstone et al., 2002a). It should be noted that *kdec_Xsu* (0.7) is of the same order of magnitude as *kdec_Xaa* (0.8, decay rate of amino acid degraders).

After calibration, the parameter set was applied to the 4-reactor-model (Fig. 5) and 3 different scenarios in terms of varying input loadings were calculated. These were model runs with high, medium and low COD loadings and flow rates of the input substrate to cover the projected range of daily biogas production between 150 and 600 m³/d (Tab. 3). The modelled reactors have volumes of 50 m³ (each of the reactors 1 and 2) and 91 m³ (each of the reactors 3 and 4), respectively.

Table 3. Simulated input loadings and resulting gas production rates

	input data					results				
	COD_x	COD_s	TKN	Q	pumping rate reactor 2,1 and 4,3	Qgas reactor 1	Qgas reactor 2	Qgas reactor 3	Qgas reactor 4	totQgas
	[g/m³]	[g/m³]	[g/m³]	[m³/d]	[m³/d]	[m³/d]	[m³/d]	[m³/d]	[m³/d]	[m³/d]
low	80,000	20,000	5,000	5	0/0	157	36	6	1	200
					25/10	112	72	13	3	200
medium	80,000	20,000	5,000	10	0/0	259	94	38	5	396
					50/20	185	139	56	16	396
high	120,000	30,000	5,000	10	0/0	431	118	37	8	594
					50/20	311	206	52	22	591

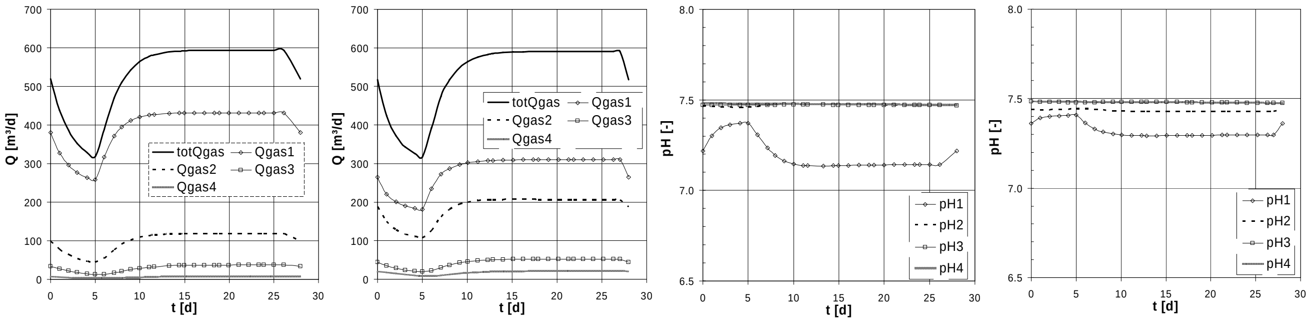

Figure 7. Simulated distribution of gas production and pH within the 4 chamber system at high loading with and without recycling (recycle pumping rates of 0/0 and 50/20 from left to right)

Calculations revealed that the average methane contents of the produced biogas were 60, 66, 64 and 63 % for chambers 1-4 respectively and pH levelled off to around 7.5, with the exception of chamber 1. High nitrogen content of the manure released during digestion leads to high corresponding alkalinity. Due to this buffer capacity excessive acidification of reactor 1 is prevented even at high daily organic loading rates up to 30 kg COD/m³. Slight decrease of pH in reactor 1 can be compensated by recycling the subsequent compartment (Fig. 7).

The simulation results shown in Tab. 3 and Fig. 7 exhibit a more uniform distribution of biogas production to the 4 reactors when recycle flows between reactor 1/2 and 3/4 are applied. Fig. 8 depicts the calculated COD degradation within the system. Again, this process turned out to be independent from the input loading and amounts to 65 % respectively.

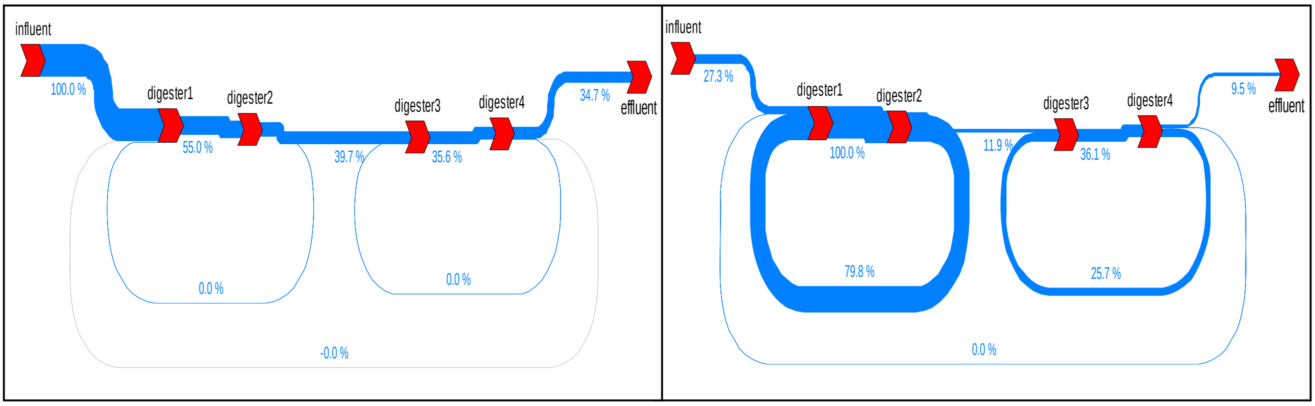

Figure 8. Calculated COD degradation for high loading with recycle pumping rates of 0/0 (left) and 50/20 (right), the value for 100 % is related to the largest COD stream including the recycle flux in each case

CONCLUSIONS

ADM1 applied in a 4-reactor-configuration proofed to be an appropriate tool for process design, optimisation and predictions for biogas plants. Simulated digestion of piggery manure showed high pH-stability which is attributed to the high ammonia content in manure. Therefore a baseflow of manure can serve as an optimum substrate for combination with other more acidic co-substrates like dairy wastes or municipal bio-waste.

Sufficient recycling from chamber 2 to 1 (driven by gas pressure yielding from the high-rate activity in the first reactor) can compensate volume limitations. Recycle flow employs two mechanisms against the threat of overloading – dilution of acidic substrate and mixing of syntrophic biomass, specifically back-feeding of acetogens and of hydrogen consuming methanogens. Depending on the overall retention time SRT chambers 3 and 4 can meet different process requirements: In case of high SRT they serve as hydraulically decoupled low-rate post-fermentation reactors or even as gas-tight storage tanks. High load scenarios (Tab. 3) yield to COD loading rates of 30 kg COD per m^3 volume and day and SRT or HRT of 5 days in the first tank at zero recycling rate (5.3 kg COD per m^3 of total volume and day). A recycle flow from chamber 4 could prevent pH-dropping in chamber 1 and transfers degradation activity to subsequent compartments. The plant appears very flexible concerning substrate flow and thus, applicable to a wide range of livestock on different agricultural sites.

REFERENCES

Batstone D. J., Keller J., Angelidaki I., Kalyuzhnyi S. V., Pavlostathis S. G., Rozzi A., Sanders W. T. M., Siegrist H. and Vavilin V. A. (2002a). *Anaerobic Digestion Model No.1* Scientific and Technical Report, **13**, IWA, London.

Batstone D. J., Keller J., Angelidaki I., Kalyuzhnyi S. V., Pavlostathis S. G., Rozzi A., Sanders W. T. M., Siegrist H. and Vavilin V. A. (2002b). The IWA Anaerobic Digestion Model No 1 (ADM1) *Water Science and Technology*, **45** (10), 65–73.

Blumensaat F. and Keller J. (2005). Modelling of two-stage anaerobic digestion using the IWA Anaerobic Digestion Model No. 1 ADM1 *Water Research*, **39** 171-183.

Kalfas H., Skiadas I. V., Gavala H. N., Stamatelatou K. and Lyberatos G. (2005). Application of ADM1 for the simulation of anaerobic digestion of olive pulp under mesophilic and thermophilic conditions. *The First International Workshop on the IWA Anaerobic Digestion Model No.1 (ADM1), proceedings*, Lyngby-Denmark.

Møller H. B., Sommer S. G. and Ahring B. K. (2004). Methane productivity of manure, straw and solid fractions of manure *Biomass and Bioenergy*, **26** 485 – 495.

Wett B., Eladawy A. and Ogurek M. (2005). Description of nitrogen incorporation and release in ADM1. *International Workshop on the IWA Anaerobic Digestion Model No.1*, Copenhagen, in press.